AQU@TEACH

OUTPUT 4:
AQUAPONICS TEXTBOOK

AQU@TEACH:

Innovative educational techniques to promote learning among European students using aquaponics

Erasmus+

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Ranka Junge, Nadine Antenen

1. AQUAPONIC TECHNOLOGY

1.1 Introduction to aquaponic technology

Today, as a result of rapid population growth, increased food requirements and urbanization, the amount of agricultural land is rapidly declining and our oceans are overfished. To meet future demands for food, there is a need for innovative, space-saving, and ecological food production technologies. Aquaponics is a polyculture (integrated multi-trophic production system) consisting of two technologies: aquaculture (a fish farm) and soil-less (hydroponic) cultivation of vegetables. The primary goal of aquaponics is to reuse the nutrients contained in fish feed and fish faeces in order to grow crops (Graber & Junge 2009; Lennard & Leonard 2004; Lennard & Leonard 2006; Rakocy *et al.* 2003). The integration of two systems into one removes some of the unsustainable factors of running aquaculture and hydroponic systems independently (Somerville *et al.* 2014).

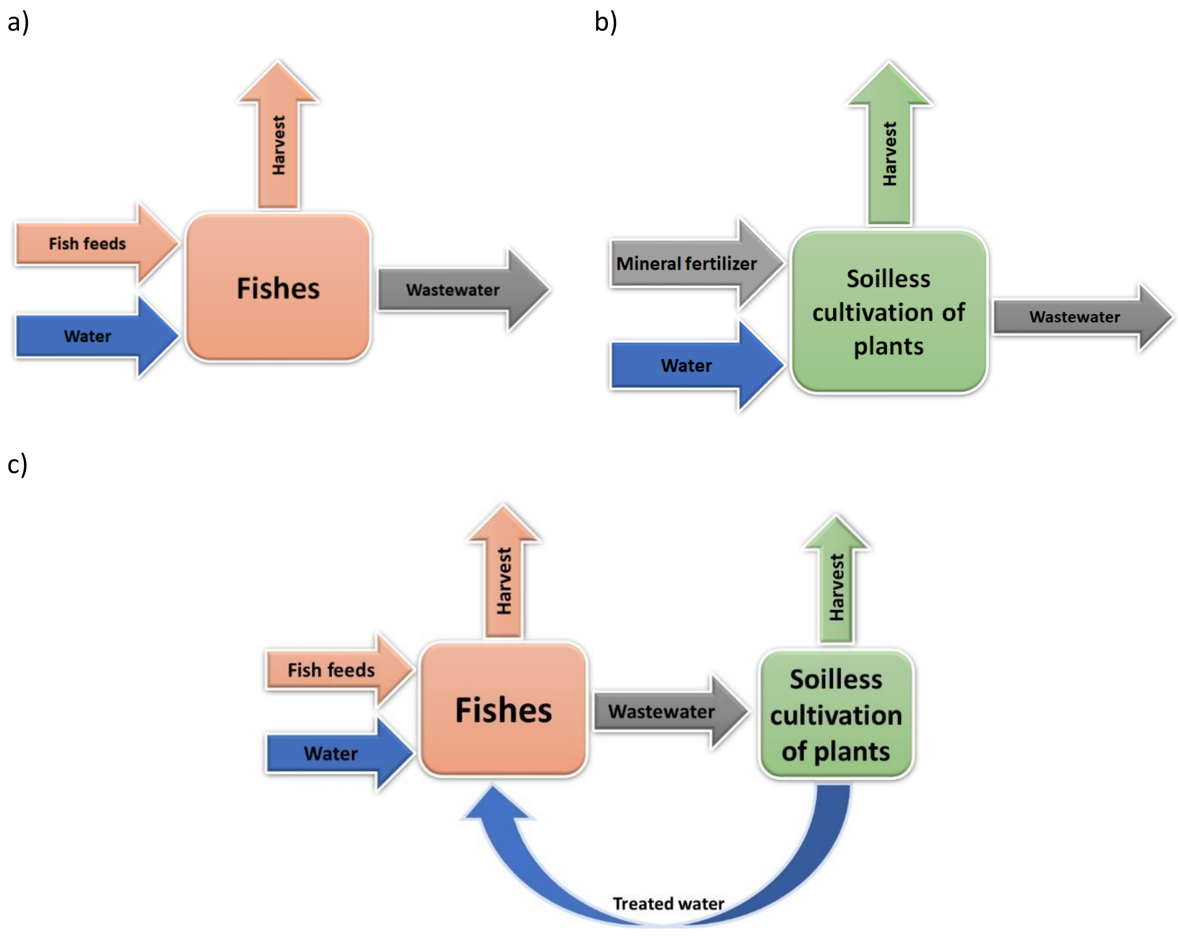

Figure 1: Basic material flows in aquaculture (a), hydroponic (b), and aquaponic (c) systems

Fish excrement can be used by plants either directly or after bacteria have converted the ammonia to nitrite and nitrate. The fish feed adds a continuous supply of nutrients to the plants, thereby solving the need for any discharge and replacement of depleted nutrient solutions or, in the case of extensively operated systems, the adjustment of the solutions as in hydroponics. As the need to buy additional fertiliser for the plant crop is reduced, the profit potential of the system increases.

Aquaponics is a rapidly emerging agricultural practice that therefore offers a series of potential benefits; however, there are also major weaknesses to this potentially sustainable agricultural production system (Table 1).

Table 1: Benefits and weaknesses of aquaponics (Diver 2006; Joly *et al.* 2015; Somerville *et al.* 2014)

Benefits	Weaknesses
Conservation of water resources	The start-up is more expensive when compared to other technologies
Efficient use of nutrient source (fish feed)	Thorough knowledge of the organisms (fish, plants, bacteria) involved is necessary
Recycling of non-renewable resources (like phosphorus, potassium) and also of renewable, but scarce, ones (like water)	The requirements of fish and plants can be different, and cannot be met in all locations without major investment in greenhouse technologies
No use of chemical herbicides or pesticides, as the recycling of water within the system hinders their use due to their adverse effects either on the fish or on the plants	Daily management is necessary
Very restricted use of pesticides of biological origin	It requires electricity, supply of seedlings and fingerlings (young fish)
Higher level of biosecurity and fewer contaminants	In most European countries the legal status of aquaponics is unclear (business activity, agricultural activity)
Reduced operating costs (compared to aquaculture or hydroponics separately)	
Can be used on non-arable land	
Construction materials and information are widely available	
Can be operated in different climates and in both rural and urban locations, thereby enabling the production of family food or cash crops	
Can increase the productivity of the available space, because two crops can be harvested from the same surface area (if the fish tanks are placed below the plant production unit)	

In theory, the concept could contribute, on both a regional and a global level, to the solution of some of the crucial problems our planet is facing: availability and use of potable and irrigation water, pollution of surface waters through animal farming, and management of non-renewable fertilizer resources. However, there are still many theoretical and practical obstacles to the expansion of this promising technology.

Thus, aquaponics tends to be an ecological and climate-friendly method for producing nutritious food and, at the same time, for meeting consumer demand for a sustainable and healthy lifestyle. Provided that the investment is not too high, aquaponics is ideal for developing countries because the fish provide much-needed protein and a second source of income. High value cash crops, such as vegetables, can be grown with aquaponics in areas where conventional farming methods can only produce grains. Because the system is usually enclosed in a greenhouse, aquaponics is resistant to climate and weather changes. However, aquaponics has also been successfully implemented outdoors. For a less expensive option, the plants can be covered with a simple roof (that provides shelter from inclement weather and prevents the access of birds and other animals) rather than a full greenhouse. This is especially viable for developing nations in the tropics. In spite of weaknesses, aquaponics is thought to become a future production method for locally grown food, e.g. in an urban environment with smaller production units designed for homes and restaurants. Both research and education are needed in order to develop this emerging technology. In particular, research is needed to optimize the production system towards safe and economical production. The technique opens up new perspectives for creating new 'green jobs'. The increasing number of aquaponic farms will necessitate the rise of a new profession: the aquaponic farmer (Graber *et al.* 2014a).

1.2 Elements of aquaponic systems

The 'hardware' of an aquaponic system consists of (i) the fish tank, (ii) the water and air pumps, (iii) the solids removal units (drum filters, settlers), (iv) the biofilter, (v) the plant grow beds, and (vi) the plumbing materials. These elements are populated by a community, where the primary producers (plants) are separated from consumers (mostly fishes), and ubiquitous microorganisms build a 'bridge' between the two main groups.

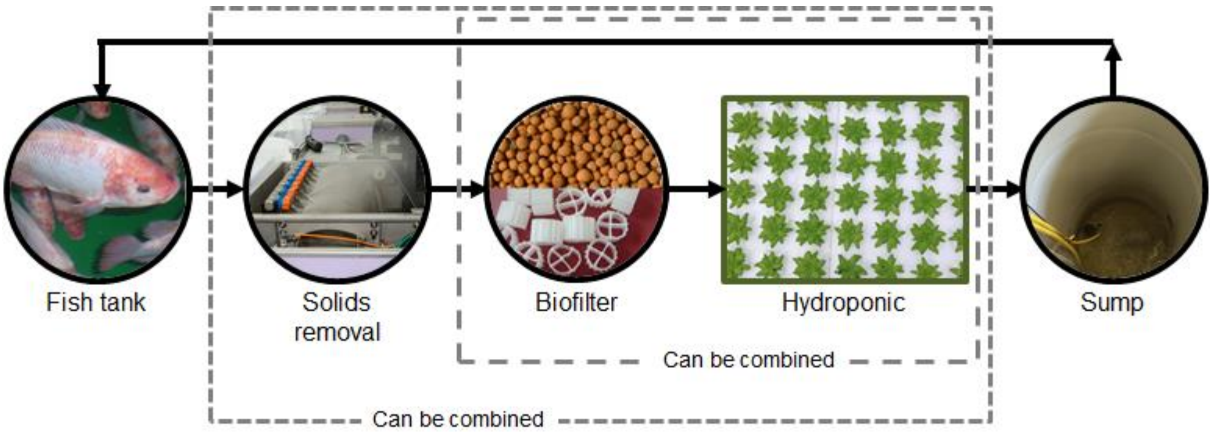

Figure 2: Main components of an aquaponic system (redrawn after Rakocy *et al.* 2006)

1.2.1 Aquaculture

Aquaculture is the captive rearing and production of fish and other aquatic animal and plant species under controlled conditions (Somerville *et al.* 2014). Aquaculture is becoming an increasingly important source of global protein production, while decreasing the pressure on the overfished oceans. However, aquaculture techniques such as open-water systems, pond cultures, and flow-through systems, all release nutrient-rich wastewater into the environment, causing eutrophication and hypoxia in the water bodies. In recirculating aquaculture systems (RAS) this waste water is treated and re-used within the system. However, these systems consume much energy and generate a lot of fish sludge which has to be treated separately. Thus, aquaponics can also be viewed as a form of RAS, or an extension of RAS.

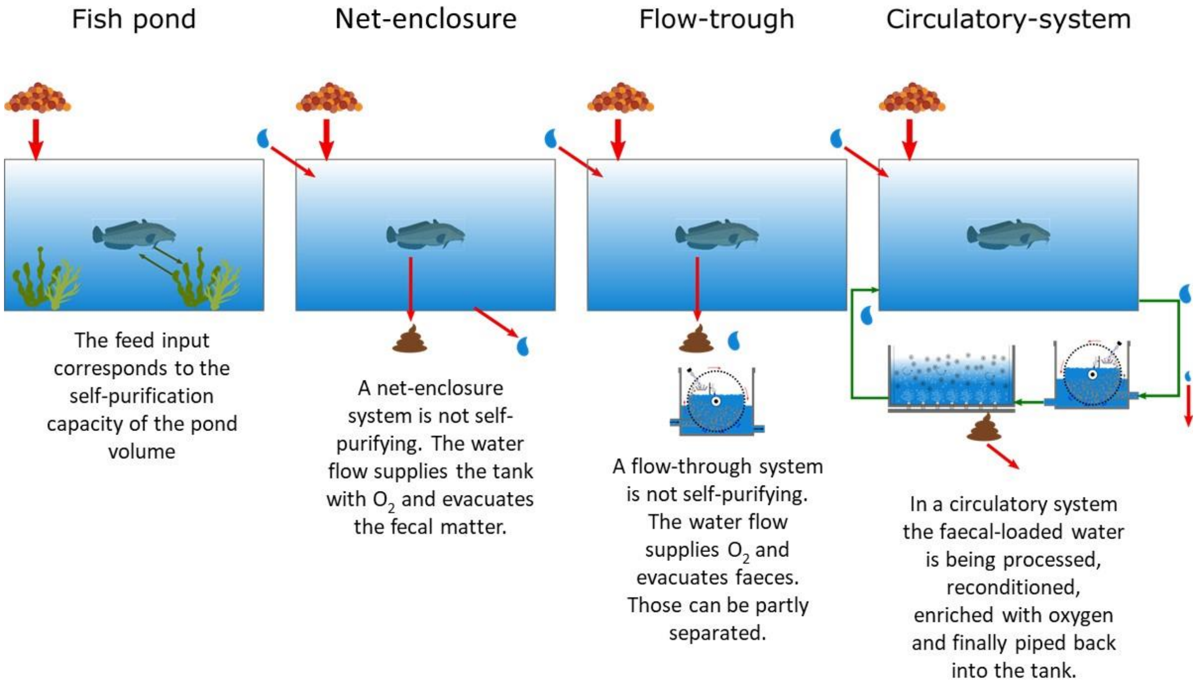

Figure 3: The main types of aquaculture systems. For details see Chapter 2

1.2.2 Hydroponics

The development of hydroponics can be traced back to the work by Dr William Gericke at the University of California in 1929 (Gericke 1937). Hydroponics has been expanding in the last decades, primarily because it allows increased yields by reducing pests and soil-borne diseases, and by manipulating growing conditions to meet optimal plant requirements, while increasing water- and fertilizer-use efficiency. It also allows for the development of agriculture on poor-quality land (Somerville *et al.* 2014). However, so-called conventional hydroponic cultivation also has its drawbacks. It utilizes costly, and often unsustainably sourced, mineral fertilizers to produce crops, and it consumes energy. Hydroponic systems require a considerable amount of macronutrients (C, H, O, N, P, K, Ca, S, Mg) and micronutrients (Fe, Cl, Mn, B, Zn, Cu, Mo, Ni), which are essential for the growth of plants. The nutrients are added to hydroponic solutions in ionic form, while C, H and O are available from air and water. The concentrations of nutrients need to be monitored. Aquaponic systems, on the other hand, use water that is rich in fish waste as the source of nutrients for plant growth. However, the nutrient composition of the water is not always perfectly matched to the plants' requirements. Some nutrients are often deficient, so they need to be added to adjust their concentration, for example iron, phosphate, and potassium (Bittsanszky *et al.* 2016a). Chapters 5 and 6 explain more about nutrients.

1.3 Classification of aquaponics

The delineation between aquaponics and other integrated technologies is sometimes unclear. Palm *et al.* (2018) proposed a new definition of aquaponics, where the majority (> 50%) of nutrients sustaining plant growth must be derived from waste originating from feeding the aquatic organisms.

Aquaponics in the narrower sense (aquaponics *sensu stricto*) is only applied to systems with hydroponics and without the use of soil. Some of the new integrated aquaculture systems which combine fish with algae production would also fall under this concept. On the other hand, the term aquaponics in the wider sense (aquaponics *sensu lato*) can be applied to systems which include horticulture and crop production techniques which utilize the mineralization processes, buffer and nutrient storage function of the different substrates, including soil. Palm *et al.* (2018) propose the term 'aquaponic farming' for these activities.

Table 2: A classification of aquaponics according to different design principles with examples for each category (adapted from Maucieri *et al.* 2018)

Design goal	Categories	Examples
Objective or main stakeholder	Commercial crop production	ECF Farm
	Household sufficiency	Somerville *et al.* 2014
	Education	Graber *et al.* 2014a Junge *et al.* 2014
	Social enterprise	Laidlaw & Magee 2016
	Greening and decoration	Schnitzler 2013
Size	L large (>1000 m^2)	Monsees *et al.* 2017
	M medium (200-1000 m^2)	Graber *et al.* 2014b
	S small (50-200 m^2)	Roof Water Farm
	XS very small (5-50 m^2)	Podgrajšek *et al.* 2014
	XXS micro systems (<5 m^2)	Maucieri *et al.* 2018 Nozzi *et al.* 2016
Operational mode of the aquaculture compartment	Extensive (allows for integrated sludge usage in grow beds)	Graber & Junge 2009
	Intensive (obligatory sludge separation)	Schmautz *et al.* 2016b Nozzi *et al.* 2018
Water cycle management	Closed loop ('coupled' systems): water is recycled to aquaculture	Graber & Junge 2009 Monsees *et al.* 2017
	Open loop or end-of pipe ('decoupled' systems): after the hydroponic component, the water is either not or only partially recycled to the aquaculture component	Monsees *et al.* 2017
Water type	Freshwater	Schmautz *et al.* 2016b Klemenčič & Bulc 2015
	Salt water	Nozzi *et al.* 2016
Type of hydroponic system	Grow beds with different media	Roosta & Afsharipoor 2012 Buhmann *et al.* 2015
	Ebb-and-flow system	Nozzi *et al.* 2016
	Grow bags	Rafiee & Saad 2010
	Drip irrigation	Schmautz *et al.* 2016b
	Deep water cultivation (floating raft culture)	Schmautz *et al.* 2016b
	Nutrient film technique (NFT)	Lennard & Leonard 2006 Goddek *et al.* 2016a
Use of space	Horizontal	Schmautz *et al.* 2016b Klemenčič & Bulc 2015
	Vertical	Khandaker & Kotzen 2018

Aquaponics can address various goals or stakeholders, from research and development, educational and social activities, to subsistence farming and commercial scale food production. It can be implemented in various ways and environments, such as on arid and polluted land, backyard production, urban agriculture, etc. While a system can simultaneously fulfill several objectives, including greening and decoration, social interaction, and food production, normally it cannot achieve all of these at the same time. To perform satisfactorily for each of the possible goals, the components of a system have to fulfil different, sometimes contrasting, requirements. The choice of a suitable aquaponic system for a particular situation should be based on realistic assessments (including a sound business plan, where appropriate) and should result in a tailor-made solution. If we follow the classification of Maucieri *et al*. (2018), which categorizes aquaponic systems according to various different categories (e.g. type of stakeholder, operational mode, size, type of hydroponic system, etc.), several distinct options for choosing a suitable aquaponic system emerge (Table 2). Any decision has to be made within the limits of the available budget, though it is possible to construct a system at very low cost.

1.3.1 Classification according to operational mode: extensive (with integrated sludge usage) and intensive (with sludge separation)

One part of the aquaponic system is the fish tank, where the fish are fed and, through their metabolism, faeces and ammonia are excreted into the water. However, high concentrations of ammonia are toxic for fish. Through nitrifying bacteria, ammonia is transformed to nitrite and then into nitrate, which is relatively harmless to fish and is the favoured form of nitrogen for growing crops such as vegetables. Extensive production integrates the biofilter as well as the sludge removal directly within the hydroponic unit, by using substrates that provide the appropriate support for the growth of the biofilm, such as gravel, sand, and expanded clay. Intensive production uses a separate biofilter and sludge separation system. Both operational methods have their advantages and disadvantages. Whilst integrated sludge usage allows for complete nutrient recycling, the negative aspects include turbid water, and rather low biofilter performance, which only allow limited fish stocking. Separate sludge removal and biofilter, on the other hand, allow intensive fish stocking of up to 100 or more kg/m^3. The positive aspects include clear water, lower BOD (biochemical oxygen demand) concentration, lower microbial load, and optimized biofilter performance. However, these systems only allow for partial nutrient recycling. An additional sludge treatment step (on-site or off-site), such as connecting sludge biodigesters or vermicomposting, may be necessary (Goddek *et al.* 2016b).

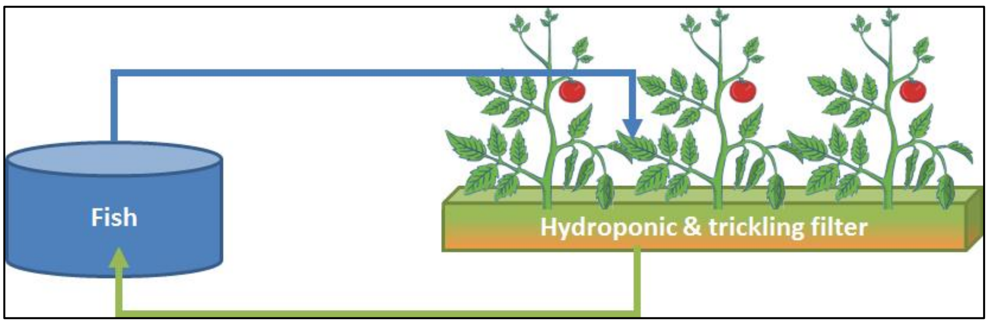

Figure 4: Aquaponic system with integrated sludge usage

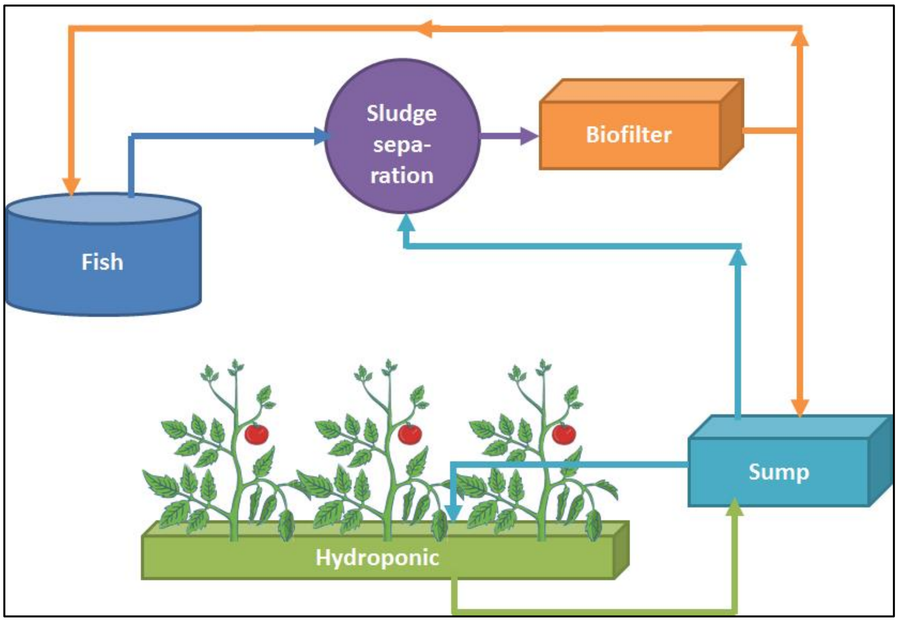

Figure 5: Possible arrangement of an aquaponic system with sludge separation

1.3.2 Water cycle management

Closed loop (coupled) systems: aquaponic systems can be constructed and operated as a recirculating loop, with the water flow moving in both directions, from fish basin to the hydroponic unit, and vice versa. Water is constantly circulated from the RAS to the hydroponic unit, and back to the RAS.

Open loop systems: recently there have been developments towards independent control over each system unit, mostly because of the different environmental requirements of fish and plants. Such systems, where aquaculture, hydroponics and, if applicable, fish sludge remineralization can be controlled independently, are called decoupled aquaponic systems (DAPS). Decoupled aquaponic systems consist of a RAS connected to the hydroponic unit (with additional reservoir) via a one-way valve. Water is separately recirculated within each system and is supplied on-demand from the RAS to the hydroponic unit, but it does not flow back (Goddek *et al.* 2016a; Monsees *et al.* 2017).

Figure 6 shows a schematic illustration of coupled and decoupled aquaponics. In the coupled (closed loop) system consisting of a RAS (blue: rearing tanks, clarifier and biofilter) directly connected to the hydroponic unit (green: NFT-trays), water is constantly circulated from the RAS to the hydroponic unit and back to RAS. In the decoupled (open-loop) aquaponic system consisting of a RAS connected to the hydroponic unit (with additional reservoir) via a one-way-valve, water is separately recirculated within each system and water is supplied on-demand from the RAS to the hydroponic unit, but does not go back to the RAS.

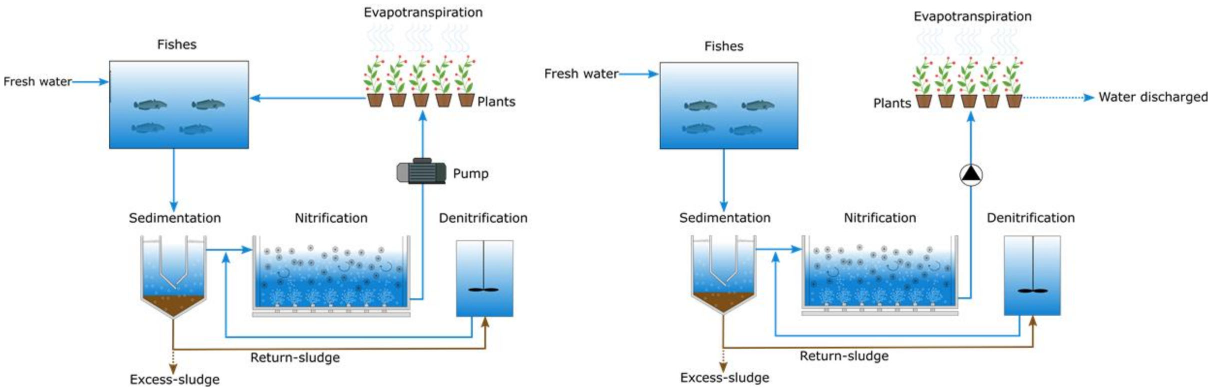

Figure 6: Schematic illustration of coupled (left) and decoupled (right) aquaponics.

1.3.3 Types of hydroponic system used in aquaponics

Nutrient Film Technique

In Nutrient Film Technique (NFT) systems, water from a fish tank is passed through the bottom of a horizontal PVC pipe, in a thin film. These pipes have holes cut into the top, in which plants are grown in such a way that their roots dangle in the water flowing on the bottom. Nutrients from the tank water are absorbed by the plants, and as their roots are only partly submerged, this allows them to be in contact with atmospheric oxygen as well.

Table 3: Advantages and disadvantages of NFT

Advantages	Disadvantages
• Constant water flow • Small sump tank needed • Ease of maintenance and cleaning • Require smaller volume of water • Light hydroponic infrastructure, well-suited for rooftop farming	• Requires prior filtration to prevent clogged roots • Expensive materials • Less stable system (if there is less water) • Only suitable for growing leafy vegetables and herbs which have smaller root systems • Sensitive to temperature variations

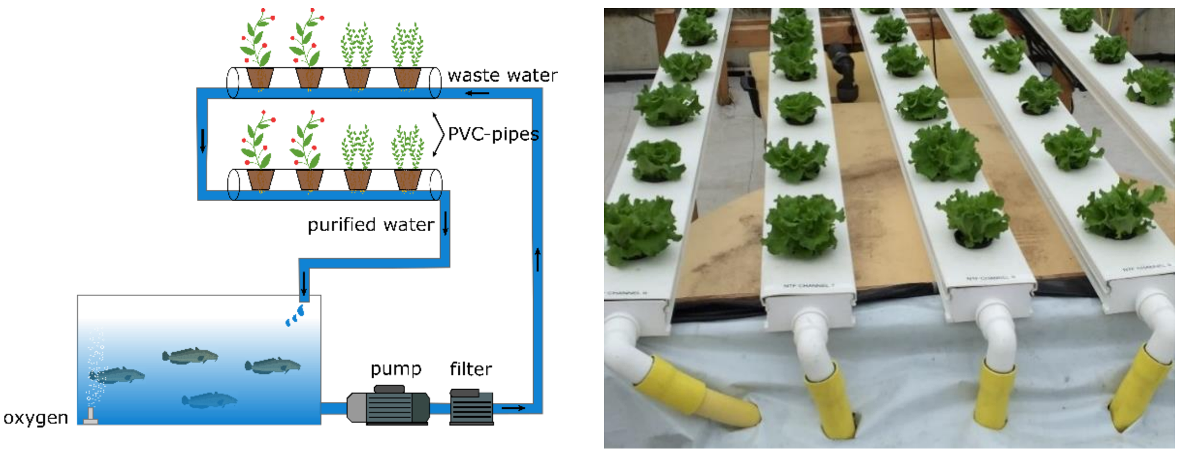

Figure 7: Nutrient film technique (NFT). Left – Diagram of an entire system. Right – Photo of the system (Photo ZHAW)

Media bed technique

Media-filled bed units are the most popular design for small-scale aquaponics. These designs use space efficiently, have a relatively low initial cost, and are suitable for beginners because of their stability and simplicity. In media bed units, the medium is used to support the roots of the plants and functions as a mechanical and biological filter.

Table 4: Advantages and disadvantages of media bed technique

Advantages	Disadvantages
• Biofiltration: medum serves as a substrate for nitrifying bacteria • Acts as a solids filtering medium • Mineralization takes place directly in the grow bed • Substrate can be colonized by a broad range of microflora, some of which can have beneficial effects	• Some media and infrastructure are very heavy: not always suitable for rooftop farming • Can become unwieldy and relatively expensive at a larger-scale • Maintenance and cleaning are difficult • Clogging can lead to water channelling, inefficient biofiltration and thus also inefficient nutrient delivery to the plants • Media can become clogged if fish stocking densities exceed the beds' carrying capacity, and this can require separate filtration • Water evaporation is higher in media beds with more surface area exposed to the sun • If flood and drain method is implemented, sizing is important, and a large sump tank is needed

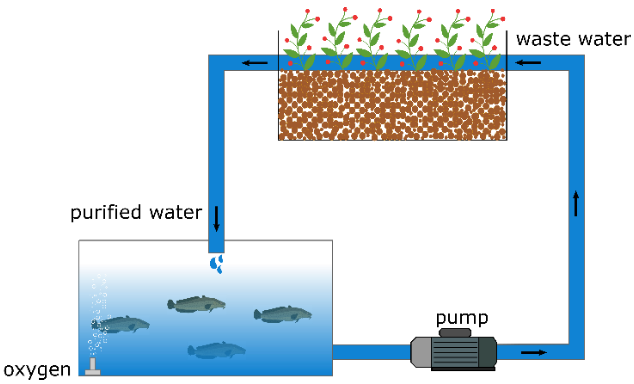

Figure 8: Media bed technique. Left – Diagram of an entire system. Right – An example from ZHAW Waedenswil (Photo: Robert Junge)

Deep Water or Floating Raft Culture

Deep Water Culture (DWC) systems use a polystyrene 'raft' which floats on about 30 cm of water. The raft has holes in which plants are grown in net pots, such that their roots are immersed in the water. The raft can also be placed to float directly in the fish tank, or it can have water pumped from the tank to a filtration system and then to channels containing a series of rafts. An aerator provides oxygen to both the water in the tank and that containing the raft. Since the roots have no medium to adhere to, this system can only be used to grow leafy greens or herbs, and not larger plants. It is the most popular system for commercial purposes, due to the speed and ease of harvest.

Table 5: Advantages and disadvantages of Deep Water Culture

Advantages	Disadvantages
• Constant water flow • Small sump tank needed • Ease of maintenance and cleaning	• Separate biofilter needed • Requires a high volume of water • Heavy hydroponic infrastructure • Device for root aeration necessary

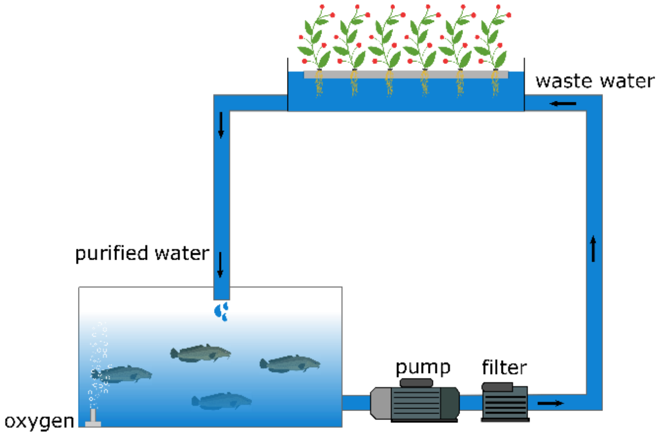

Figure 9: Deep water or floating raft culture. Left – Diagram of an entire system. Right – Lettuce growing in a styrofoam raft with roots suspended in water

1.3.4 Use of space: horizontal and vertical systems

Most aquaponic systems use horizontal grow tanks or beds, emulating traditional land-based arable growing to produce vegetables. However, over the years, new living wall and vertical farming technologies have arisen and evolved which, when linked to the aquaculture part of the aquaponic system, may allow more plants to be grown vertically rather than horizontally, and thus make the systems more productive (Khandaker & Kotzen 2018).

Horizontal systems have the advantage of efficiently using daylight, and may well function without additional lighting, even in winter. Therefore they have low electric energy consumption. The initial investment costs are medium/low, especially if the land price is low.

Vertical systems present an optimal space-saving solution, making them very suitable for urban facilities, either for decoration of for hyper-local food production. However, they require grow lights above the grow beds. They also require fewer water pumps, but of higher power, which all adds up to higher electric energy consumption. The initial investment costs are also high.

1.4 History of aquaponics

The concept of using fish excrement to fertilize plants has existed for millennia, with early civilizations in both Asia and South America using this method. The most well-known examples are the ‘stationary islands’ or Aztec chinampas set up in shallow lakes in central America (1150–1350 BC), and the rice-fish aquaculture system introduced in Asia about 1500 years ago, and still used today. Both the rice-fish aquaculture system and the chinampas were listed by the FAO as Globally Important Agricultural Heritage Systems (Koohafkan & Altieri 2018).

In Europe, the early RAS date back to the late 1970s (Bohl 1977). At the same time Naegel (1977) had already tested the integration of hydroponics with the water and nutrient cycles of RAS. Contemporary aquaponics in the USA started with the pioneering research of Todd, as referred to in Love *et al.* (2014), together with studies by Goldman *et al.* 1974 and Ryther *et al*. 1975 of the reuse of nutrients from wastewater for plant and animal production. Prior to the technological advances of the 1980s, most attempts to integrate hydroponics and aquaculture had limited success. The 1980s and 1990s saw advances in system design, biofiltration, and the identification of the optimal fish-to-plant ratios that led to the creation of closed systems that allow for the recycling of water and nutrient buildup for plant growth. The pioneers of aquaponics who inspired many followers were:

- Dr Mark McMurtry (McMurtry *et al.* 1990) began working on aquaponics when he was at North Carolina State University in the mid-eighties to early nineties. He called the method ‘Integrated AquaVegeculture System’ (IAVS). Today’s flood-and-drain systems, as favoured by backyard practitioners, are derived from this model.
- Dr James Rakocy designed what is perhaps the most widely copied design, The University of Virgin Islands (UVI) Aquaponic system in 1980 (Rakocy *et al.* 2003; Rakocy *et al.* 2004). He has developed vital ratios and calculations in order to maximize production of both fish and vegetables while maintaining a balanced ecosystem.
- In Australia, Dr Wilson Lennard has also produced key calculations and production plans for other types of system (Lennard & Leonard 2004; Lennard & Leonard 2006).
- In Canada, Dr Nick Savidov (Savidov & Brooks 2004) showed that, when some key nutrients levels were met, aquaponic systems had significantly superior production of tomatoes and cucumbers when compared with hydroponic systems.

These research breakthroughs, as well as many others, have paved the way for various practitioner groups and companies that are beginning to sprout worldwide. However, aquaponics research really took off only after 2010 (see the comparative number of scientific publications on hydroponics, aquaculture, and aquaponics in Figure 10). There is, however, a big difference between what the world is ‘talking’ about, and what is being currently researched. Junge *et al.* (2017) coined the term 'hype ratio' as an indicator of the popularity of a subject in the public media compared with academia. It is calculated as search results in Google divided by search results in Google Scholar. Aquaponics has a 'hype ratio' of over 1000, which is significantly higher than, for example hydroponics (over 100) and aquaculture (about 20). In this regard, aquaponics can be termed 'an emerging technology' and an emerging science topic.

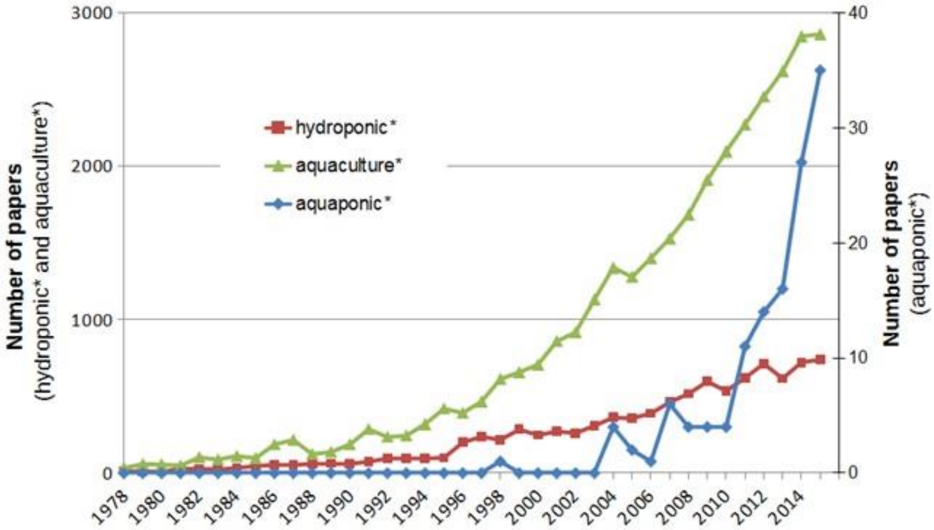

Figure 10: The number of papers published on hydroponic*, aquaculture*, and aquaponic*‡ from 1978 to 2015 (data were collected from the Scopus database on 17 September 2016). ‡ Please note that the scale for aquaponic* is two orders of magnitude lower than hydroponic* or aquaculture* (from Junge *et al.* 2017).

1.5 Examples of aquaponic systems around the world

A wide range of aquaponic systems exist in all continents. Table 6 summarizes several systems and their main characteristics.

1.5.1 Europe

Between the years of 2014-2018, the European Union funded COST Action FA1305 'EU Aquaponics Hub', which involved the cooperation of member countries in the research of aquaponic systems as a pertinent technology for the sustainable production of fish and vegetables in the EU. The website of the action is a very good source of information, with links to fact sheets, publications, and training school videos. The same group performed a survey of the use of aquaponics in Europe, underlining that most units are small and related to research (Villarroel *et al*. 2016). A map of nearly all known aquaponics facilities in Europe was published in Google Maps.

Figure 11: Map of aquaponic facilities

The map includes the location of all the research institutes (blue) and companies (red) currently actively working on aquaponics. It cannot be edited directly, but researchers and companies that want to be added can send their details to morris.villarroel@upm.es. As is apparent from the map, industry collaboration is essential for aquaponics to fulfil its promise as a viable system of local food production in the EU. The map currently lists 50 research centres and 45 companies, suggesting a nice balance between research and development.

Table 6: Summary of some aquaponic systems around the world

Country	Purpose & type	Fish	Plants	Author(s)
Australia	Research Backyard system (ebb-and-flow)	Murray cod	Lettuce	Lennard & Leonard 2004
Barbados	Research Backyard system (ebb-and-flow)	Red Tilapia	Basil and okra (growth medium: coconut husk)	Connolly & Trebic 2010
United States Virgin Islands	Research Commercial system Raft hydroponic	Tilapia	Basil, okra	Rakocy *et al.* 2003
China	Large commercial system (ponds)	Environment for natural spawning of native fish	Rice, canna flowers	Duncan 2014
Germany, Berlin	Research, demonstration, education (NFT and NGS* channels)	Trout	Strawberries, pak choi, mini cucumber, salads	Roof Water Farm
Hawaii	Large commercial system	Tilapia	Salads	Kunia Country Farms
Hungary, Kaposvar	Social institution (grow beds, NFT)	Wels catfish	Herbs, lettuce, tomatoes, strawberries	Passive Aquaponics
Iceland	Research Small commercial system (grow beds, raft cultures, NFT channels)	Tilapia	Tomatoes, beans, lettuce	Thorarinsdottir 2015
Iran	Research Based on UVI Model Raft, grow beds	Common carp, grass carp and silver carp	Tomatoes	Roosta & Afsharipoor 2012
Slovenia, Naklo	Vocational education Based on 'Waedenswil' model (grow beds, raft cultures, NFT channels)	Carp	Salads	Podgrajšek *et al.* 2014
United Arab Emirates	Large commercial system Raft hydroponic	Tilapia, barramundi	Salads	Smith 2015
Vietnam	Research Backyard system (grow beds)	Tilapia	Canna flowers, water spinach, salads	Trang & Brix 2014

* *New growing system: www.ngsystem.com*

Iceland: The aquaponic system of Svinna-verkfraedi Ltd consists of three 4 m^3 fish tanks, a drumfilter, a biofilter, a sump tank, and NFT channels. The hydroponic part has been used to grow tomatoes, beans, and lettuce. The company is testing different hydroponic systems (grow beds, raft cultures, NFT channels), and has recently added crayfish to the system to make use of the sludge from the fish tanks (Thorarinsdottir 2015).

Hungary: A passive aquaponics house at the 'Somogy County Association of Disabled Persons' social enterprise was built by the Hungarian company Passive Aquaponics. The house is heated by gas (70%) combined with a compost heater (30%). Wels catfish (*Silurus glanis*) is reared in small tanks. Hydroponic units, filled with expanded clay, are used to grow herbs (basil, mint), lettuce, tomatoes, peppers, strawberries, and even banana plants.

Germany: Roof Water Farm in Berlin is a demonstration project for innovative urban water management and food production. The focus is on a hygienically safe use of rainwater, greywater and blackwater combined with decentralised water treatment technologies, for aquaponic and hydroponic food production.

Figure 12: Left – Roof Water Farm (Photo: Grit Bürgow). Right – Strickhof agricultural educational centre (Photo: Roger Bolt)

Switzerland: An experimental aquaponic system was built mainly for educational purposes in 2012 at the Strickhof agricultural educational centre in Zürich canton. Constructed at the back of an old greenhouse on an area of approximately 36 m^2, it consists of a 3 m^3 fish tank, five NFT channels, and two ebb-and-flow tables.

1.5.2 Asia

China: To our knowledge, the largest aquaponic system ever built is on Taihu Lake. The lake has extensive aquaculture industry, which caused eutrophication and thus problems with algal bloom. This situation prompted researchers to search for new solutions. They decided to try a technology called Aqua Biofilter, which is designed to remove the nutrients that cause algal blooms. This resulted in an aquaponic system which covers 1.6 hectares, and is used to cultivate rice in fish ponds (Duncan 2014).

Vietnam: Trang and Brix (2014) constructed an aquaponic system in the Mekong Delta, which is one of the most productive aquaculture areas in Vietnam. They built three outdoor pilot-scale closed integrated aquaponic systems (3 x approx. 2 m^3), and showed that these can provide significant water savings and enable nutrient recycling compared with traditional fish ponds, and also bring additional profit to the fish farmers.

Iran: An experimental aquaponic system was designed at the Vali-e-Asr University of Rafsanjan based on the UVI model in order to investigate the effects of foliar applications of some micro- and macronutrients on tomato growth and yield in comparison with a hydroponic system. The aquaponic system consists of three separate identical aquaponic units. Each unit has a fish rearing tank, a clarifier, a filter tank, a degassing tank, and a plant growth bed unit (Roosta & Afsharipoor 2012).

United Arab Emirates: In late 2013 one of the world's biggest commercial aquaponic systems was built by Paul Van der Werf from Queensland's Earthan Group. The farm consists of a 4,500 m^2 shed which produces around 40 tonnes of tilapia. The facility is also piloting a breeding program for juvenile barramundi. The systems use waste water from a nearby food manufacturer, which would otherwise be dumped in the desert. The only vulnerability of the system is that without evaporative cooling, temperatures in the greenhouse can reach 68°C (Smith 2015).

1.5.3 Americas

Barbados has a tropical oceanic climate with little variation in temperatures (approx. 20-32 °C) due to the cooling easterly trade winds from the Atlantic Ocean. An experimental aquaponic system with a volume of approximately 6 m^3 was constructed in 2009 with the purpose of obtaining parameters for improving the system, and to make management recommendations with the goal of optimizing fish and plant biomass outputs (Connolly & Trebic 2010).

United States Virgin Islands: The University of the Virgin Islands (UVI) commercial scale aquaponic system has become the model for many subsequent systems. The aquaponic system performed well over a sustained period of time, and produced tilapia continuously for 4 years. During that time, two trials were conducted to evaluate the production of basil and okra, which was found to be dramatically higher than in control field production (Rakocy *et al.* 2003).

Hawaii: Kunia Country Farms began operations in 2010, and is now one of the largest aquaponic farms and producer of leafy greens in the state of Hawaii. Their system is composed of three fish tanks containing tilapia, eighteen grow beds (deep water culture with styrofoam floats), and one sump tank. Each grow bed can hold between 1650 and 3300 plants. The whole system has a water volume of approximately 380 m^3. Since the electrical needs of the system are low but still very costly in Hawaii, they plan to build 20 kW photovoltaic system which will generate enough solar power to make the farm electric grid-neutral.

1.5.4 Australia

Lennard & Leonard 2004 used Murray cod (*Maccullochella peelii peelii*) and lettuce (*Lactuca sativa*) to test differences between two aquaponic flood regimes: (a) reciprocal flow, and (b) constant flow.

Their experimental system consisted of 12 separate identical aquaponic units. Each unit had one fish tank, a biofilter, and a hydroponic grow bed. Both systems performed well, but the system with constant flow showed better results in terms of lettuce yield.

1.6 Current research themes in aquaponics

1.6.1 Trends in technology

As we saw above, the design of successful aquaponic systems depends on the user group. High-yield, soil-less production requires a high input of technology (pumps, aerators, loggers) and knowledge, and is therefore mostly suited for commercial operations. However, it is entirely possible to design and operate low-tech aquaponic systems that require less skill to operate, and still yield respectable results. This implied trade-off (high-tech/low-tech) and the broad range of applications of aquaponics have consequences for further development pathways for the technology, system design, and socio-economic aspects. Aquaponic technology might develop in at least two directions: on the one hand towards low-tech solutions (probably mostly in developing countries and for non-professional applications) and, on the other hand, towards highly efficient hi-tech installations (predominantly in developed countries and with professional/commercial partners) (Junge *et al.* 2017).

While the technology itself does not pose limits to an area of the farm (because it can be modular), the size of urban farms is determined by (i) the characteristics of the available area, which is necessarily fragmented in a city (brownfield sites, underutilized or vacant buildings, and rooftops); and (ii) the constraints posed by the economics of crop production. As a rule of thumb, the area required to break even for commercial operations is around 1000 m^2. Hobby and backyard installations can of course be much smaller. Aquaponic farms can grow/expand by increasing the number of operating systems (or modules), or by going vertical, although they cannot be scaled up too much without steeply increasing construction and energy costs. The size range of urban aquaponic farms will probably range between 150 m^2 and 3000 m^2, due to space, economic, and management limitations, but this could be enough to cover the basic requirements for an assortment of fresh vegetables for part of the urban population. Peri-urban aquaponic farms could be larger, and modified to include inland aquaculture systems or to re-use nutrient rich effluent or composted fish sludge in rural areas.

Aquaponic technology itself can be considered to be immature, since there are still problems to be solved. Simply linking a state-of-the-art aquaculture system with a state-of-the-art hydroponic system does not take into account other factors, such as problems with clogged drum filters, inefficient settlers, oxygen failures, poorly designed settlers, and clogged water pipes. Even though the influence of plant grow beds (NFT, drip irrigation, deep water culture) is already well known in hydroponic systems, the choice of those beds in aquaponic systems needs to be further studied since it will have consequences for productivity and operation. Further research is required in other areas as well. Since microorganisms are ubiquitous, they play an important part in all stages of aquaponic production. The influence of environmental conditions on their abundance, diversity, and roles could be investigated, for example by further use of Novel Generation of Sequencing methods

(Schmautz *et al.* 2016a). One of the central questions is appropriate pest and disease control for aquaponics systems. Problems related to plant protection in aquaponics were discussed by Bittsanszky *et al.* (2016b). They concluded that since very few tools are available for plant protection in aquaponics, emphasis should be placed on precautionary measures to minimize the infiltration of pests and pathogens. On the other hand, the biological pest control methods currently available for organic agriculture have to be adapted to aquaponics (See Chapter 8).

If aquaponics is to be developed as a successful high-tech method of food production, one focus will need to be on reducing manpower requirements. While some automation is already well developed (for watering and feeding, online monitoring and alarms for many parameters, especially oxygen), it needs to be refined in order to allow for more precise and labour efficient operations, which will require the development of suitable sensors. One option to reduce manpower might be to use robots. Versatile systems, similar to FarmBot, should be developed for dedicated use in aquaponics.

1.6.2 Trends in systems design

While aquaponics has the potential to be sustainable, comprehensive life cycle analysis (LCA) studies of aquaponic operations and products are scarce (Forchino *et al.* 2017; Maucieri *et al*. 2018). However, it is clear that the ecological impact of aquaponics could be further improved by tapping into renewable sources of energy, developing daylight harvesting methods to avoid the use of electrical energy, using pre-treated or recycled water or rainwater, and improving the climate control of greenhouses. In an urban environment, aquaponics ought to be further integrated into buildings, allowing for gas, water and energy exchange between greenhouses and buildings. Improvements are also needed regarding organic material cycles. Fish feed is the main nutrient input and defines, to a large extent, the sustainability of the operation. Aquaponics (just like RAS) requires optimal nutrition for fish, and the fish feeds should consist of sustainable, locally sourced materials (organic, vegetarian, insects). The aquaponic loop should be further closed by digesting the fish sludge in order to re-use the nutrients in the aquaponic system, or by rearing redworms and/or insects on plant residues and using these for fish feed, with the residual fish sludge and plant waste being composted. The goal is to arrive at a zero-waste concept on the farm in order to reduce the carbon footprint. Studies on greenhouse gas emissions could make this picture complete. Finally, the possibility of using novel organisms in aquaponics (e.g. aquatic plants, marine fish, algae and seaweeds, crustaceans etc.) should be further explored in order to expand the ecological cycle. New aquaculture and plant products could also have implications for the economic viability of the technology, as the following section discusses.

1.6.3 Socio-economic research

Currently, aquaponics is a small but emerging business sector. Although food production is the basic goal of the operation, it is often combined with tourism and education in order to improve profitability. Because of its relatively novel technological cross-cutting approach, aquaponics has no clear legal status within the existing regulations in Europe (Joly *et al.* 2015). Whilst in the US aquaponic produce can be certified as organic, in Europe this is currently not possible because aquaponics involves soil-less plant production and RAS, both of which are not permitted by EU organic regulations.

Despite the potential of aquaponics as a food production technology, there are still open questions. As we have shown above, aquaponics is a prominent topic in the social media, but little is known about consumer knowledge and acceptance, which need be understood in different cultural and market settings. In general, we do not know enough about how the sustainability advantages of aquaponics should be communicated to consumers, compared to product quality such as taste, freshness, health, and price (Newman *et al.* 2014).

Until now, most research on aquaponics has focused on developing functional facilities. One way to improve profitability could be to improve efficiency. Efficient use of alternative energy sources, water, and the recycling of organic effluents will save on production costs, but they need to be evaluated against higher investment costs. To increase commercial production, novel business models must also be developed in relation to the emerging ideas of circular and local economies, yet managing interfaces increases complexity. Here, questions of framework conditions for operating costs, local logistics and determinants of vegetable and fish shopping behaviour will need to be addressed. Besides improvement in technological efficiency, there are also issues about operational management, and it could be interesting to explore new transport-sensitive varieties of crops in order to obtain a sufficiently high market price by avoiding competition with specialized horticulture. However, combining a new technology with new products also increases entrepreneurial uncertainty.

Aquaponics is especially useful for educators: even a small classroom system offers a wide range of possibilities for instruction at different educational levels, from primary school to university (see Chapter 15). Aquaponics can easily be integrated into all STEM (science, technology, engineering and mathematics) subjects, not only to demonstrate basic biological and ecological principles, but also chemistry, physics, and mathematics. A variety of competencies and skills can be gained by operating aquaponic systems, such as basic lab skills, team work, environmental ethics, to name but a few. The width of socio-economic aspects outlined here illustrates that aquaponics will only flourish with a broad collaboration between several additional key players beyond natural scientists and engineers. These could include, for example, (i) designers and architects to provide aesthetically pleasing designs; (ii) social scientists to help understand perceptions and acceptance of aquaponics among a wider audience; and (iii) health and nutritional scientists to explore how aquaponic products could be incorporated into diets as healthy and sustainably produced food. Feedback loops to system developers and plant and fish physiologists also need to be developed in order to improve systems with regard to consumer demand, sustainability, and the nutritional value of the products.

1.7 References

Bittsanszky, A., Uzinger, N., Gyulai, G., Mathis, A., Junge, R., Villarroel, M., Kotzen, B. & Komives, T. 2016a. Nutrient supply of plants in aquaponic systems. *Ecocycles* 2 (2), 17-20.

Bittsanszky, A., Gyulai, G., Junge R., Schmautz, Z. & Komives, T. 2016b Plant protection in ecocycle-based agricultural systems: Aquaponics as an example. In *Proceedings of the 28th International Plant Protection Congress (IPPC), Berlin, Germany, 24–27 August 2016.*

Bohl, M. 1977. Some initial aquaculture experiments in recirculating water systems. *Aquaculture* 11 (4), 323-328.

Buhmann, A. K., Waller, U., Wecker, B. & Papenbrock, J. 2015. Optimization of culturing conditions and selection of species for the use of halophytes as biofilter for nutrient-rich saline water. *Agricultural Water Management* 149, 102-114.

Connolly, K. & Trebic, T. 2010. *Optimization of a Backyard Aquaponic Food Production System*. Faculty of Agricultural and Environmental Sciences, Macdonald Campus, McGill University, BREE 495 Design 3.

Diver, S. 2006. *Aquaponics – Integration of Hydroponics with Aquaculture*. ATTRA – National Sustainable Agriculture Information Service.

Duncan, T. 2014. *World's largest aquaponics project, in China's third largest aquaculture lake*. Permaculture Research Institute.

Forchino, A.A., Lourguioui, H., Brigolin, D. & Pastres, R. 2017. Aquaponics and sustainability: the comparison of two different aquaponic techniques using the life cycle assessment (LCA). A*quacultural Engineering* 77, 80-88.

Gericke, W.F. 1937. Hydroponics — Crop production in liquid culture media. *Science* 85 (2198), 177-178.

Goddek, S., Espinal, C.A., Delaide, B., Jijakli, M.H., Schmautz, Z., Wuertz, S. & Keesman, K J. 2016a. Navigating towards decoupled aquaponic systems: A system dynamics design approach. *Water* 8 (7), 303.

Goddek, S., Schmautz, Z., Scott, B., Delaide, B., Keesman, K.J., Wuertz, S. & Junge, R. 2016b. The effect of anaerobic and aerobic fish sludge supernatant on hydroponic lettuce. *Agronomy* 6 (2), 37.

Goldman, J.C., Tenore, K.R., Ryther, J.H. & Corwin, N. 1974. Inorganic nitrogen removal in a combined tertiary treatment—marine aquaculture system—I. Removal efficiences. *Water Research* 8 (1), 45-54.

Graber, A. & Junge, R. 2009. Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination* 246 (1-3), 147-156.

Graber, A., Durno, M., Gaus, R., Mathis, A. & Junge, R. 2014a. UF001 LokDepot, Basel: The first commercial rooftop aquaponic farm in Switzerland. In *International Conference on Vertical Farming and Urban Agriculture (VFUA 2014), Nottingham, United Kingdom, 9–10 September 2014*.

Graber, A., Antenen, N. & Junge, R. 2014b. The multifunctional aquaponic system at ZHAW used as research and training lab. In Maček Jerala, M. & Maček, M.A. (eds). *Conference VIVUS: Transmission of Innovations, Knowledge and Practical Experience into Everyday Practice. Collection of Papers, Strahinj, 14–15 November 2014*, pp. 245-255.

Joly, A., Junge, R. & Bardocz, T. 2015. Aquaponics business in Europe: some legal obstacles and solutions. *Ecocycles* 1 (2), 3-5.

Junge, R., Wilhelm, S. & Hofstetter, U. 2014. Aquaponic in classrooms as a tool to promote system thinking. In Maček Jerala, M. & Maček, M.A. (eds.) *Conference VIVUS: Transmission of Innovations, Knowledge and Practical Experience into Everyday Practice. Collection of Papers, Strahinj, 14-15 November 2014*, pp. 234-244.

Junge, R., König, B., Villarroel, M., Komives, T. & Jijakli, M.H. 2017. Strategic points in aquaponics. *Water* 9 (3), 182.

Khandaker, M. & Kotzen, B. 2018. The potential for combining living wall and vertical farming systems with aquaponics with special emphasis on substrates. *Aquaculture Research* 49 (4), 1454-1468.

Klemenčič, A.K. & Bulc, T.G. 2015. The use of vertical constructed wetland and ultrasound in aquaponic systems. *Environmental Science and Pollution Research* 22 (2), 1420-1430.

Koohafkan, P. & Altieri, M.A. 2018. *Globally Important Agricultural Heritage Systems: A Legacy for the Future*. Food and Agriculture Organization of the United Nations, Rome.

Laidlaw, J. & Magee, L. 2016. Towards urban food sovereignty: the trials and tribulations of community-based aquaponics enterprises in Milwaukee and Melbourne. *Local Environment* 21 (5), 573-590.

Lennard, W.A. & Leonard, B.V. 2004. A comparison of reciprocating flow versus constant flow in an integrated, gravel bed, aquaponic test system. *Aquaculture International* 12 (6), 539-553.

Lennard, W.A. & Leonard, B.V. 2006. A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film technique) in an aquaponic test system. *Aquaculture International* 14 (6), 539-550.

Love, D.C., Fry, J.P., Genello, L., Hill, E.S., Frederick, J.A., Li, X. & Semmens, K. 2014. An international survey of aquaponics practitioners. *PLoS ONE* 9 (7), e102662.

Maucieri, C., Forchino, A.A., Nicoletto, C., Junge, R., Pastres, R., Sambo, P. & Borin, M. 2018. Life cycle assessment of a micro aquaponic system for educational purposes built using recovered material. *Journal of Cleaner Production* 172, 3119-3127.

McMurtry, M.R., Nelson, P.V., Sanders, D.C. & Hodges, L. 1990. Sand culture of vegetables using recirculated aquacultural effluents. *Applied Agricultural Research* 5 (4), 280-284.

Monsees, H., Kloas, W. & Wuertz, S. 2017. Decoupled systems on trial: Eliminating bottlenecks to improve aquaponic processes. *PloS ONE* 12 (9), e0183056.

Naegel, L.C. 1977. Combined production of fish and plants in recirculating water. *Aquaculture* 10 (1), 17-24.

Newman, G.E., Gorlin, M. & Dhar, R. 2014. When going green backfires: How firm intentions shape the evaluation of socially beneficial product enhancements. *Journal of Consumer Research* 41 (3), 823-839.

Nozzi, V., Parisi, G., Di Crescenzo, D., Giordano, M. & Carnevali, O. 2016. Evaluation of *Dicentrarchus labrax* meats and the vegetable quality of *Beta vulgaris var. cicla* farmed in freshwater and saltwater aquaponic systems. *Water* 8 (10), 423.

Nozzi, V., Graber, A., Schmautz, Z., Mathis, A. & Junge, R. 2018. Nutrient Management in Aquaponics: Comparison of Three Approaches for Cultivating Lettuce, Mint and Mushroom Herb. *Agronomy* 8 (3), 27.

Palm, H.W., Knaus, U., Appelbaum, S., Goddek, S., Strauch, S.M., Vermeulen, T., Jijakli, M.H. & Kotzen, B. 2018. Towards commercial aquaponics: A review of systems, designs, scales and nomenclature. *Aquaculture International* 26 (3), 813-842.

Podgrajsek, B., Schmautz, Z., Krivograd Klemencic, A., Jarni, K., Junge, R. & Griessler Bulc, T. 2014. Preliminarni monitoring akvaponicnega sistema v biotehniskem centru Naklo: Preliminary Monitoring of an Aquaponic System in Biotechnical Center Naklo. *Moje Podezelje* 5 (9), 10-11.

Rafiee, G. & Saad, C.R. 2010. The effect of natural zeolite (clinoptiolite) on aquaponic production of red tilapia (*Oreochromis* sp.) and lettuce (*Lactuca sativa* var. *longifolia*), and improvement of water quality. *Journal of Agricultural Science and Technology* 8, 313-322.

Rakocy, J.E., Schultz, R.C., Bailey, D.S. & Thoman, E.S. 2003. Aquaponic Production of Tilapia and Basil: Comparing a Batch and Staggered Cropping System. *Acta Horticulturae* 648, 63-70.

Rakocy, J.E., Bailey, D.S., Shultz, R.C. & Thoman, E.S. 2004. Update on tilapia and vegetable production in the UVI aquaponic system. In *New Dimensions on Farmed Tilapia: Proceedings of the Sixth International Symposium on Tilapia in Aquaculture*, pp. 12-16.

Rakocy, J.E., Masser, M.P. & Losordo, T.M. 2006. *Recirculating Aquaculture Tank Production Systems: Aquaponics — Integrating Fish and Plant Culture*. Southern Regional Aquaculture Center, SRAC Publication No. 454.

Roosta, H.R. & Afsharipoor, S. 2012. Effects of different cultivation media on vegetative growth, ecophysiological traits and nutrients concentration in strawberry under hydroponic and aquaponic cultivation systems. *Advances in Environmental Biology* 6 (2), 543-555.

Ryther, J.H., Goldman, J.C., Gifford, C.E., Huguenin, J.E., Wing, A.S., Clarner, J.P., Williams, L.D. & Lapointe, B.E. 1975. Physical models of integrated waste recycling-marine polyculture systems. *Aquaculture* 5 (2), 163-177.

Savidov, N. & Brooks, A.B. 2004. *Evaluation and Development of Aquaponics Production and Product Market Capabilities in Alberta*. Crop Diversification Centre South, Brooks, Alberta.

Schmautz, Z., Graber, A., Jaenicke, S., Goesmann, A., Junge, R. & Smits, T.H.M. 2016a. Microbial diversity in different compartments of an aquaponics system. *Archives of Microbiology* 199 (4), 613-620.

Schmautz, Z., Loeu, F., Liebisch, F., Graber, A., Mathis, A., Griessler Bulc, T. & Junge, R. 2016b. Tomato productivity and quality in aquaponics: comparison of three hydroponic methods. *Water* 8 (11), 533.

Schnitzler, W.H. 2013. Urban hydroponics for green and clean cities and for food security. *Acta Horticulturae* 1004, 13-26.

Smith, L. 2015. Aquaculture expert helps build one of the world's biggest fish farms in Middle East. *New South Wales Country Hour*.

Somerville et al. 2014. Introduction to aquaponics. Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. 2014. *Small-scale Aquaponic Food Production: Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 1-10.

Thorarinsdottir, R.I. (ed.) 2015. *Aquaponics Guidelines*. EU Lifelong Learning Programme, Reykjavik.

Trang, N.T.D. & Brix, H. 2014. Use of planted biofilters in integrated recirculating aquaculture-hydroponics systems in the Mekong Delta, Vietnam. *Aquaculture Research* 45 (3), 460-469.

Villarroel, M., Junge, R., Komives, T., König, B., Plaza, I., Bittsanszky, A., & Joly, A. 2016. Survey of aquaponics in Europe. *Water*, 8 (10), 468.

2. AQUACULTURE

2.1 Introduction to aquaculture

Aquaculture is the captive rearing and production of fish and other aquatic animal and plant species under controlled conditions (Somerville *et al.* 2014). Due to overfishing and the consequent decline of wild fish stocks, aquaculture has become increasingly important in the past few decades (Figure 1), and may become even more so in the future as wild fish stocks face immense pressure from climate change (Gibbens 2019).

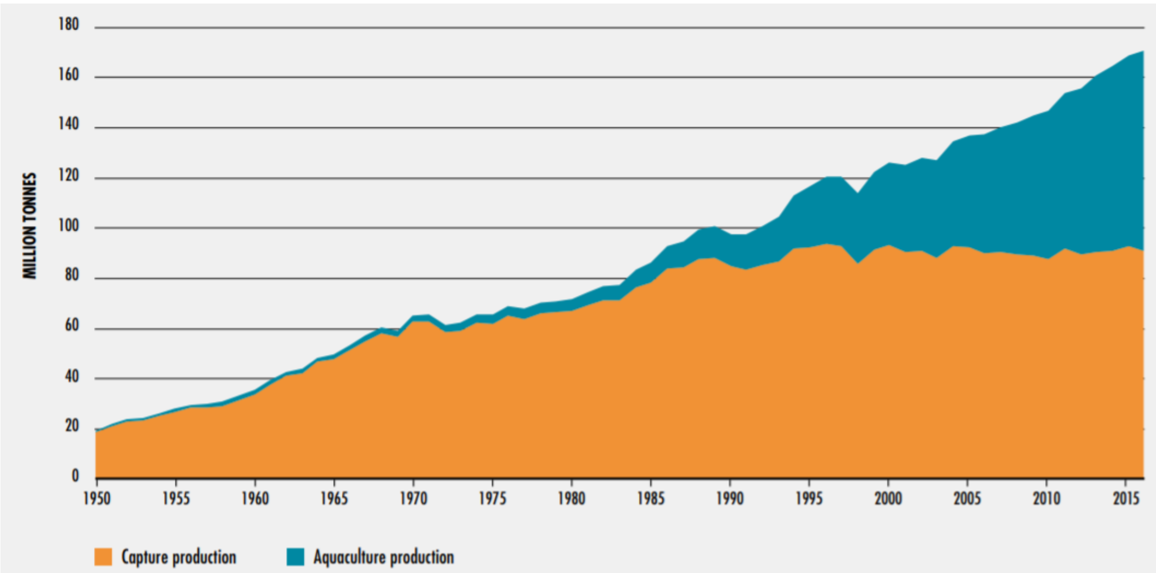

Figure 2: In 2016 aquaculture accounted for around 47% of total global fish production (FAO 2018)

The main goal of any aquaculture system is to produce, grow and sell fish or other aquatic animals and plants. The basic situation of fish rearing is shown in Figure 2. Fish living in a water body receive feed and oxygen. Their metabolism converts these into excreta and CO_2 which, if they accumulate in the water, are toxic for the fish. Different fish farming technologies cope with this problem using different strategies.

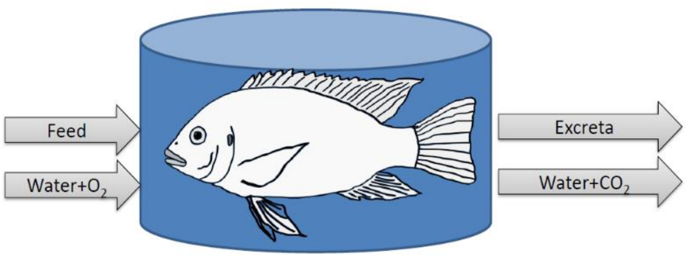

Figure 2: The basic principle of aquaculture from a water perspective. Fish living in water receive feed and oxygen. Their metabolism converts these into excreta and CO_2, which are toxic for the fish. The water becomes waste water

Aquaculture systems can be classified into four basic types: fish ponds, net-enclosures, flow-through, and recirculation systems (Figure 3). 'Open' aquaculture techniques such as net enclosures and flow-through systems release nutrient-rich wastewater into the environment, potentially causing eutrophication and oxygen deficiency in water bodies. In recirculating aquaculture systems (RAS) this waste water is treated and re-used within the system.

RAS has several advantages when compared to other aquaculture systems: it is a totally controlled system that is largerly independent of local conditions; it has very low water usage with low wastewater flows; and production can be planned and targeted year-round. However, there are also disadvantages, such as significant investment and operation costs, and high operation risk due to failure-prone technology. Species selection is therefore limited mostly to carnivores, which command a higher market price than herbivores, and the system is utterly dependent on artificial feeds (see Chapter 4). In this context, aquaponics can be viewed as a form of RAS or an extension of RAS. Therefore, in this chapter, the aquaculture part of a recirculating aquaponic system is presented in more detail.

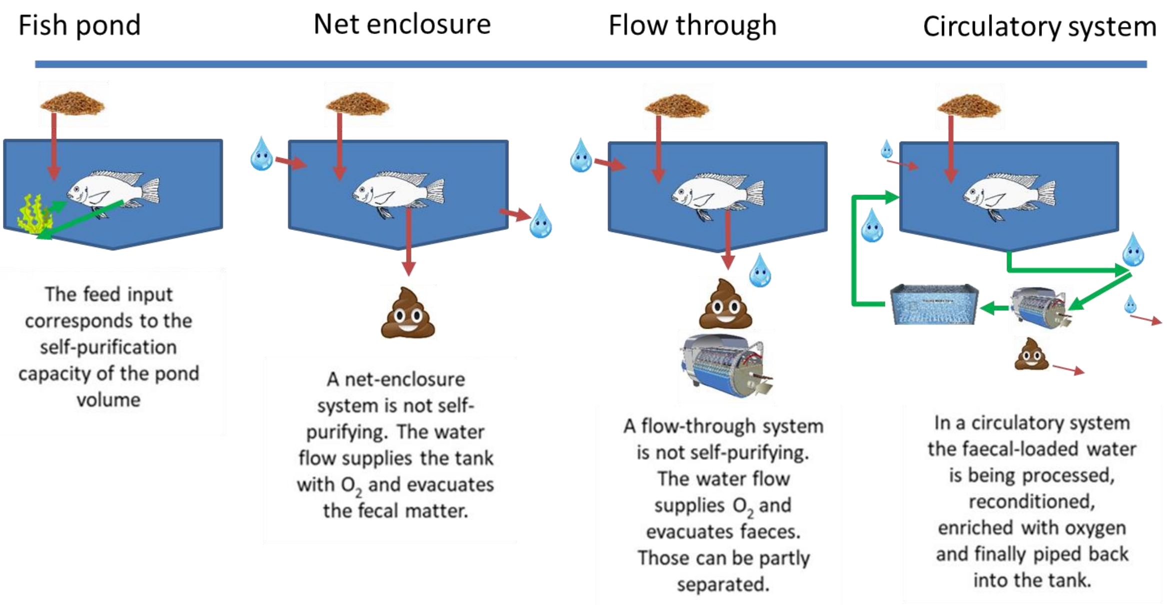

Figure 3: The main types of aquaculture systems

2.2 Recirculating aquaculture system (RAS) technology

A recirculating aquaculture system (RAS) consists of fish tanks and several filtration units which clean the water. In a classic RAS the water is thereby in constant flow from the fish tanks through the filtration system and then back to the fish tanks (Figure 4). Due to the metabolism of the fish, the water that leaves the tanks contains high concentrations of solids, nutrients, and carbon dioxide, whilst it is oxygen-poor compared to inflowing water. The goal of the filtration units is to decrease the solids, nutrients, toxins, and carbon dioxide concentrations, and increase the levels of dissolved oxygen in the water before it is returned to the fish tank.

The filtration system consists of several stages (Figure 4). The first treatment step after the outflow is the solids separation (Figure 4, Point 2) where the solids (feed remains, faeces and bacteria assemblages) are removed from the water. After this, the water is disinfected with UV (Figure 4, Point 6). This step is not always implemented in fish farms and can also be placed after the biofilter. The water then enters the biofilter (Figure 4, Point 3), where bacteria metabolise part of the organic load, and oxidize ammonia to nitrite and then to nitrate. All these bacterial metabolic reactions use dissolved oxygen (O_2) and, like the fish, release carbon dioxide (CO_2) into the water. Therefore, the CO_2 levels in water have to be lowered after biofiltration. This is done in the degassing unit in which the water to air surface area is increased so that the CO_2 enters the air phase (Figure 4, Point 4). As a last step, the oxygen concentration in the water has to be increased to a suitable level for the fish. This is done in the oxygenation unit (Figure 4, Point 5). The following sections describe these system components in more detail.

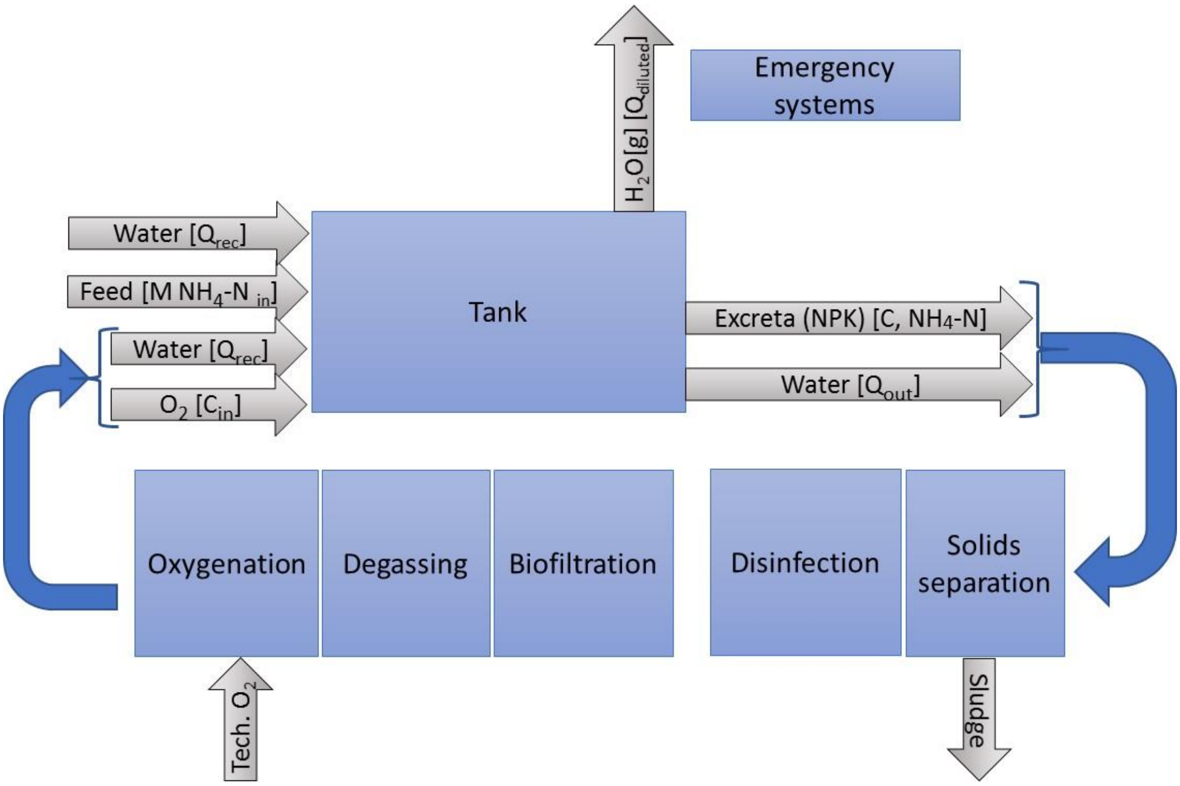

Figure 4: Main components of a recirculating aquaculture system (RAS)

2.2.1 The fish tank

The fish tank is the grow out area for the fish and therefore a core component of a RAS. The 'classic' tank designs are round tanks and square flow channels. One of the main aspects that makes round tanks favourable over square flow channels is the self-cleaning effect that can be achieved through a circular hydraulic pattern (Figure 5). The flow in the fish tanks has two functions: (i) uniform distribution of inflow water and fish feed; and (ii) transport of particles to the centre of the tank. Primary rotating flow is the flow from the inlet and then clockwise/anticlockwise around the tank. It transports settleable solids to the bottom. The primary rotating flow creates secondary radial flow and together they generate a self-cleaning tank.

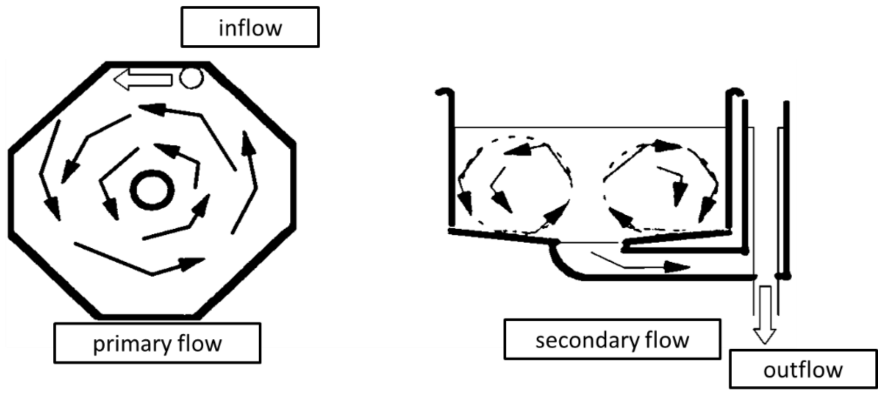

Figure 5: Role of primary and secondary flow patterns: the primary flow ensures good water distribution of the inlet water and the secondary flow contributes to effective solids removal (adapted after Timmons *et al.* 1999)

Although round tanks have numerous advantages over square tanks, their main disadvantage (low area efficiency) often makes them a suboptimal solution for a RAS farm. Therefore, numerous other forms of tanks have been developed and tested in the past decades (more details are presented in Chapter 12).

Since RAS has gained popularity and these systems are also planned as large-scale ventures (e.g. Nordic Aquafarms is planning to invest in a 500 Million USD RAS farm in Belfast, Maine, USA), large tank designs have become increasingly important. These large tanks are often (at least in theory) much more cost-efficient than the traditional smaller tanks (Figure 6).

Figure 6: A large round tank (6 m deep, 32.5 m in diameter) as part of a salmon RAS (Swiss Alpine Fish)

Flow conditions have an important impact on fish health. One can establish different water flows and thus structure the basins hydraulically by using panels. In this way the fish stay in the optimal part of the tank (Figure 7). It is important to know that swimmers need to swim, in other words they need a current. The speed of the current must be adapted to the fish species. Generally, smaller fish require a lower current speed, though it must be high enough to ensure that the solids separation still works. All this also has an impact on the quality of the fish flesh.

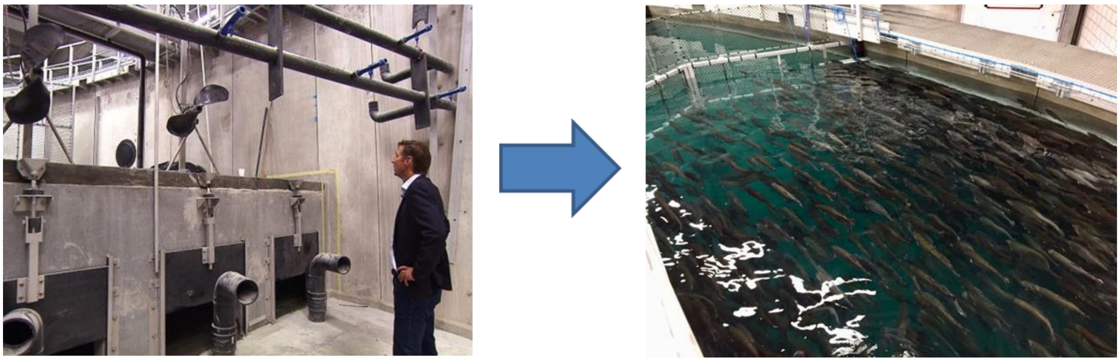

Figure 7: Flow system specially developed for farming salmon, Swiss Alpine Fish AG, Lostallo, Switzerland

2.2.2 Solids separation

There are several reasons for the removal of solids. Firstly, water quality is improved by reducing the organic solids which reduces mineralisation (aerobic respiration) and therefore also helps to stabilize the oxygen content. Secondly, the preservation of the water quality also benefits feed uptake and stock control. Furthermore, solids removal reduces the bacterial load, because it removes the food source for microorganisms. High bacterial activity in the water column leads to unnecessary consumption of oxygen.

Another benefit of solids removal is the prevention of clogging of the fish gills which may lead to slow growth or even fish death. However, this depends on the fish species. Filter feeding fish, like many carp species, may even rely on a certain amount of suspended compounds in their natural habitat and can therefore also withstand a higher amount of suspended solids in RAS than, for example, salmonids (Avnimelech 2014).

One of the most important technical reasons why solids need to be removed is the potential clogging of the biofilter (c.f. Chapter 9). Moreover, the effectiveness of germ reduction through disinfection (c.f. Chapter 9) is increased through the removal of solids. The solids in fish water have different sizes, and treatments to remove these solids vary mostly according to their size (Figure 8).

Wastewater treatment and sludge disposal are important cost factors of intensive RAS. A RAS requires 300-1000 l water exchange per kg of fish produced, and yields 100-200 g dry weight sludge. To minimize the volume of wastewater it is feasible to treat the sludge water that results from the solid separation. In this way even a low-tech filtration system can achieve a significant reduction of the final wastewater volume.

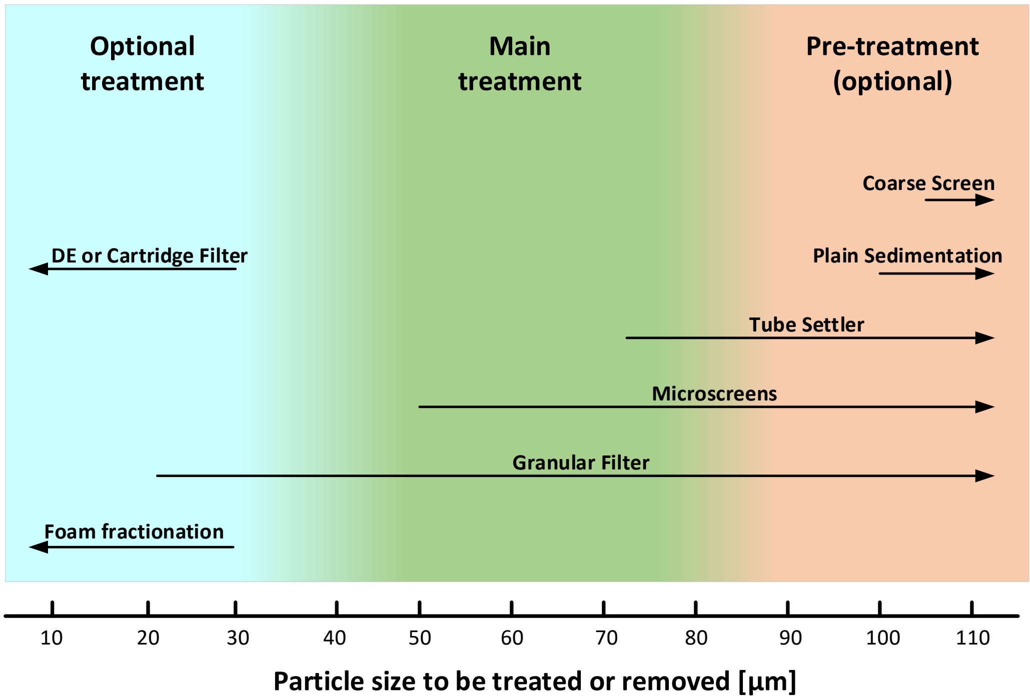

Figure 8: Solid removal processes and the particle size range (in µm) over which the processes are most effective (adapted after Timmons and Ebeling 2007)

2.2.3 Disinfection

Bacterial as well as viral diseases can pose serious problems in intensive RAS. Disinfection of the water using ozone or UV-irradiation are the most common methods. UV light at a certain intensity can destroy the DNA of bio-organisms such as pathogens and one-celled organisms. In RAS the UV light (Figure 9) is mostly encompassed in a short piece of pipe between the mechanical filtration unit (e.g. drum filter) and the biofilter. The intensity or dose of UV light can be expressed in $\mu Ws/cm^2$ (energy per area). In RAS the UV dose needed to kill (deactivate) around 90% of the organisms ranges between 2000-10,000 $\mu Ws/cm^2$. However, to kill all fungi and small parasites a dose of up to 200,000 $\mu Ws/cm^2$ may be necessary. For maximum efficiency it is important to place the UV light after the mechanical filtration system so that it is not blocked by the suspended solids.

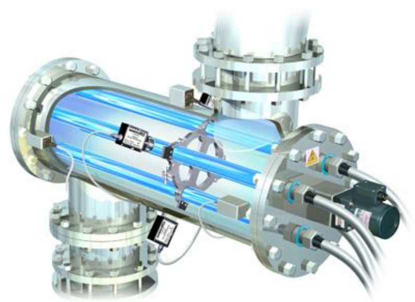

Figure 9: UV reactor (AKR UV Systems)

The addition of ozone (O_3) is another efficient method for reducing pathogens and other unwanted organisms in a RAS. In contact with water it splits into O_2 and a free oxygen radical O. This radical ‘attacks’ and oxidizes organic substances. This results in the degradation of suspended particles or some substances (clarification of water turbidity, colour formation by humic acids). Likewise, the biological cell walls of the organisms are also attacked by the radical O of the ozone molecule, killing off bacteria, floating, and filamentous algae. However, ozone is very reactive and can also harm the nitrifying bacteria in the biofilter and attack the fish gills if applied in too high amounts. The dosage therefore has to be monitored permanently. Chemical agents can be used for punctual treatments to reduce germ concentrations in the water. Hydrogen peroxide (H_2O_2) is commonly used, sometimes stabilized by peracetic acid (CH_3CO_3H). Overdosing can have severe effects on fish health and can damage the filter bacteria.

Table 1: Advantages and disadvantages of disinfection with UV, ozone, and hydrogen peroxide (H_2O_2) in RAS

	Disinfection agent		
	UV	**Ozone**	**H_2O_2**
Advantages	Works only locally in the UV reactor Can be applied without harming fish Simple management Cheap	Very effective in killing unwanted organisms like pathogens Breaks down complex molecules into small, biodegradable compounds Oxidizes nitrite to nitrate	Very effective in killing unwanted organisms like pathogens
Disadvantages	Sensitive to water turbidity, ineffective in water with high solids loading Bulbs need to be replaced (every year) If the radiation period is too short (i.e. the system has a too high flow rate) the UV-disinfection is ineffective	Complicated dosing Can harm fish and biofilter On-off of ozone system may lead to varying nitrite levels and decrease the amount of nitrifying bacteria in the biofilter Relatively expensive	Limited application, like disinfection of empty tanks and equipment or reduction of bacterial load in the fish tank Overdose is likely to severely damage the fish! Also damages the filter

2.2.4 Biofiltration

The nitrification process takes place in the biofilter to oxidise the toxic free ammonium into toxic nitrite and eventually to non-toxic nitrate. The nitrifying bacteria are the heart of the biofilter. These bacteria grow on the filter media surface. The media can be fixed (e.g. trickling filter) or moving (e.g. moving bed filter). The nitrifying bacteria are sensitive to water quality changes in the system (especially pH and temperature), and rapid changes should therefore be avoided or done in slow steps as otherwise large amounts of nitrifying bacteria may die off which would lead to ammonia and nitrite spikes in the system. Moreover, as the nitrifying bacteria are aerobic, the dissolved oxygen content in the biofilter should always be kept at a certain threshold (depending also on the water temperature). The chemical reactions taking place in the biofilter are explained in Chapter 5. More details about choosing the right biofiltration are provided in Chapter 12.

2.2.5 Degassing and aeration

Gas transfer between the liquid and the gas phase occurs when there is sub-saturation in one phase. Gas solubility is dependent on pressure, temperature, salinity, and gas partial pressure. The transfer takes place over the contact surfaces between gas and liquid. **Aeration** increases the oxygen content in the water. **Degassing** removes gases such as carbon dioxide from the water.

2.2.5.1 Degassing

Gases, especially carbon dioxide resulting from respiration of the fish and bacteria, accumulate in the system water. These can have harmful effects on the fish if concentrations become too high. Therefore, a degassing unit is usually added to intensive RAS. Gas outtake (degassing) is achieved by increasing the contact surface area between the water and the air, either by aeration of the water column, or by sprinkling water through the air. Different biofilters already have a high degassing effect: in a trickle filter the water passes through the air, while in a moving bed filter the air passes through the water. This may therefore make an additional degassing unit redundant.

2.2.5.2 Oxygenation

Dissolved oxygen (O_2) content is one of the most important water quality parameters in RAS and often the first constraint in emergency situations (e.g. in case of power cuts, pump failure etc.). There are numerous techniques to enrich dissolved oxygen in the water. Gas intake of water (aeration) can be enhanced by: (i) maximizing the oxygen/water contact area by using whirls or small bubbles; (ii) maximizing the oxygen/water contact period by using small bubble diameter and/or by a slow water flow; (iii) increasing the pressure (increases solubility) – water level, pressure vessel; and (iv) increasing partial pressure of O_2 (increases solubility) – pure oxygen.

High Efficiency Oxygen Input

In intensive RAS the oxygenation technologies depend on using pure oxygen rather than simple aeration which becomes impractical at certain fish densities. The oxygen is either produced on site with an oxygen generator or supplied by an external firm and stored in liquid oxygen tanks outside the aquaculture facility.

Low Efficiency Oxygen Input

In extensive fish ponds low efficiency oxygen input is usually sufficient. This is achieved by (i) keeping the water cool, as this dissolves more oxygen, and (ii) increasing the water movement. Different modes of aeration can support this (see Chapter 12).

2.2.6 Pumps and pumping pits

A pump is to RAS what the heart is to the human body. If it fails, then the result can be catastrophic. Therefore no expense should be spared when buying a pump. One can use speed controlled pumps to reduce the flow if needed. By using a parallel series of pumps with check valves, the chances of system failure can be reduced. Before buying a pump, the pressure losses in the pipes should be calculated, for example with the help of this online calculator: http://www.pressure-drop.com/Online-Calculator/.

2.3 Management of recirculating aquaculture system (RAS)

2.3.1 Stocking density

Stocking density is a very important factor that has to be decided in advance when designing a RAS. Stocking density can be defined in different ways (Table 2), and it is important to be aware when and why different definitions are being used.

Table 2: Stocking density definitions

Density of individuals		**Biomass density**	
per surface (#/m^2)	**per volume** (#/m^3)	**per surface** (kg/m^2)	**per volume** (kg/m^3)
Independent of tank depth. Relevant for bottom-dwelling fish	Is often high for small fishes even though the biomass density is higher	Independent of tank depth. Relevant for bottom-dwelling fish. It is often higher for bigger fish than for smaller species	Relevant for free swimming species

Different fish species have different possible stocking densities. Density is a central factor in determining fish welfare, although all the biological aspects are not clear yet. There are fish species that have different behaviour at different densities. For example, tilapia adopts schooling behaviour at high densities, and territorial behaviour at low densities. In order to prevent fish harming each other, they therefore have to be farmed at a certain density. To use space efficiently, and to prevent cannibalism, a fish tank should contain fish of approximately the same size. This means (a) that an aquaculture facility should have several tanks to house fish of different size classes, and (b) that the fish population has to be graded according to size occasionally, and redistributed into the tanks. Low and high stocking densities in aquaculture systems have several consequences for the management of a RAS (Table 3).

Table 3: Characteristics of high and low stocking density systems

Influencing factors for systems with the same annual production	**High Density**	**Low Density**
Change in water parameters	Fast change	Slow change
Response time (for example to a pump failure)	Is shorter. More stress for the fishes	Is longer. The system operation is safer
Capacity of the fish tanks for a given production volume	Less capacity needed for the same production volume	Higher capacity needed. This can be compensated partly by using deeper basins. However, these are more expensive and need a more expensive pipe and pumping system

Necessary circulation/displacement rate for a given production volume [m^3/h]	Same	Same. Due to the slowness of the system, there are softer peaks = smaller components = less expensive hardware for water reconditioning
Displacement volume relative to tank volume	High	Low
Tank dimensions	Smaller tanks with a high density of individuals are, depending on the species, more prone to stress	In larger tanks, easily scared fishes have a longer escape distance

2.3.2 Monitoring

Monitoring procedures should be defined according to the steps outlined in Figure 10. RAS or aquaponic systems are complicated, and consist of many parts. Many things can go wrong, so the operators have to remain permanently alert (Table 4, see also Chapter 9). The top priority of system mangement is the health of the fish and plants. Therefore, monitoring should be priorised according to the 'life support priorities' (Table 5). Table 6 lists important items that should be monitored on a daily basis.

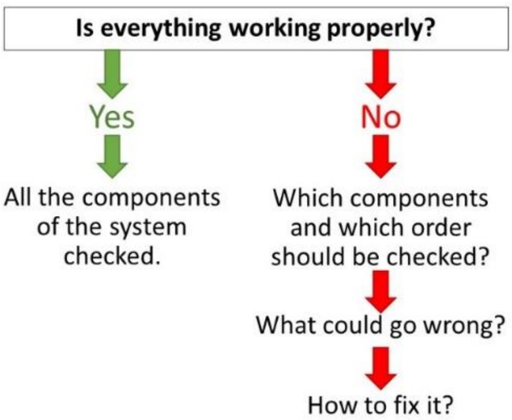

Figure 10: The logical steps of devising a monitoring procedure

Table 4: What can go wrong?

Type / System	Causes
Beyond your control	Floods, tornadoes, hurricanes, wind, snow, ice, storms, electrical outages, vandalism/theft
Staff errors	Operator errors, overlooked maintenance causing failure of backup systems or systems components, alarms deactivated
Tank water level	Drain valve left open, standpipe fallen or removed, leak in system, broken drain line, overflowing tank
Water flow	Valve shut or opened too far, pump failure, loss of suction head, intake screen blocked, pipe blocked, return pipe ruptures/breaks/glue failure

Water quality	Low dissolved oxygen, high CO_2, supersaturated water supply, high or low temperature, high ammonia, nitrite or nitrate, low alkalinity
Filters	Channeling/clogged filters, excessive head loss
Aeration system	Blower motor overheating because of excessive back pressure, drive belt loose or broken, diffusers blocked or disconnected, leaks in supply lines

Table 5: Priorisation of monitoring and response

		Parameter	Response time
Priority	High	- Electrical power - Water level - Dissolved oxygen	Very fast (minutes) Alarm needed!
	Medium	- Temperature - Carbon dioxide - pH	Moderate response time (hours)
	Low	- Nitrogen forms (ammonia, nitrite, nitrate) - Total suspended solids (TSS)	Slowly changing parameters (daily or weekly monitoring)

Table 6: Important items that should be monitored daily

Electrical power	Single and three phase supply, individual systems on life-saving GFCI outlets
Water level	Culture tank (high/low), supply sumps to pumps (high/low), filters (high/low)
Aeration system	Air oxygen pressure (high/low)
Water flow	Pumps, culture tanks, submerged filters, in-line heaters
Temperature	Culture tanks (high/low), heating/cooling systems (high/low)
Security	High temperature/smoke sensors, intruder alarms

2.3.2.1 Some advice for system design and safety

- Choose sensors carefully, label everything, and include expansion capability in all components
- Install the sensors and equipment where they are visible and easily accessible for servicing and calibration
- Remember that water and electricity make for a fatal combination, so use low voltages (5 VDC, 12 VDC or 24 VDC or AC) to protect yourself and the fish
- Clearly label the sensor's armed and unarmed modes, preferably with LEDs at each station to show sensor status.

2.3.2.2 Some advice for system maintenance

- Have a well prepared maintenance manual accessible for staff to read

- Maintain a weekly/monthly/yearly maintenance scheduling plan and keep files of major service records and equipment manuals
- Maintain daily/weekly/monthly instrument check lists
- Perform regular (and some unannounced) system checks, including triggering each sensor and checking the operation of the automatic backup systems and phone dialer
- Provide staff training on handling routine alarms
- Ensure that staff are familiar with the complete operating system, including water supply, aeration, and emergency backup systems.

2.3.2.3 When to monitor water quality?

Fish digest according to the time they are fed, and the amount of faeces depends on the amount of ingested feed. Thus, the highest levels of ammonium are to be expected after the last feed (in the evening) and the lowest value before the first feed (in the morning). Therefore, measurements of water quality have to be done at the end of the feed in order to catch ammonium peaks (Figure 11).

2.3.2.4 Automated monitoring and control systems

Automated monitoring is becoming increasingly affordable. There are several data acquisition and control systems commercially available for applications in RAS and/or aquaponics. A monitoring system includes (i) sensors to measure the desired variables, (ii) an interface to convert the electrical information into a form readable by a computer or microprocessor, (iii) a computer, (iv) software to run the system, and (v) displays. It is important to match the components, in order for the monitoring system to work.

One of the most important functions of a monitoring system is to provide alerts to the system operator in the event of malfunctions and problems. If critical variables are sensed to be outside of acceptable limits, alarms need to be sent out. It is important to design and test the monitoring and alarm system so that false alerts are not sent out too often. Too frequent false alarms make it less likely that the operator(s) will respond (Timmons *et al.* 1999). Alarms must be constructed and operated so that pertinent individuals are alerted. Visual and audible alarms can be placed in key areas within a facility to alert workers of problems. Outside normal working hours remote alarms (usually via SMS messages) need to be employed.

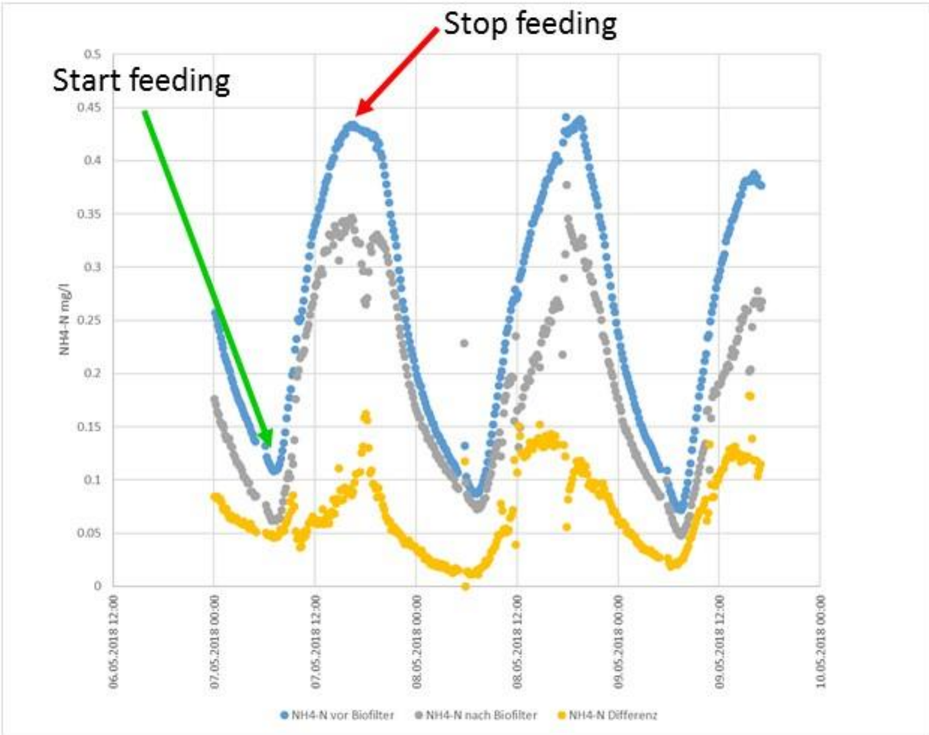

Figure 11: Daily time course of NH_4-N concentrations in RAS water. Blue = before biofilter; grey = after biofilter; yellow = difference between blue and grey

2.4 Planning the recirculating aquaculture part for an aquaponic system

In aquaponics, it is very important that the input and output of nutrients is in balance over the entire plant growing period. This balance can mainly be controlled using two different approaches:

- Approach 1: An existing recirculating aquaculture system (RAS) is used to dimension the corresponding hydroponic unit with plants (Figure 12). This approach is covered by the Exercise in Module 5 (nutrient water balance).
- Approach 2: The RAS is dimensioned based on the desired plant and fish production (Figure 13). This is covered by the in Exercise in Module 2.

The aim of dimensioning the RAS part of an aquaponic system is to adjust the different water treatment stages in order to achieve both good water quality for the fish, and sufficient nutrient supply for the plants. It is always an advantage if the system is as unaffected as possible by seasonal fluctuations (temperature, dissolved oxygen, ammonium, nitrite and nitrate). In general, it can be said that a large water volume and low stocking densities make systems more stable. It is important that the whole year is planned and that differences in the fish and plant species as well as the growth stages of all species are taken into account. As support for this planning, it is recommended that the 'Planning Basis for Dimensioning the Recirculating Aquaculture Part of an Aquaponic system model' is used (Tschudi 2018).

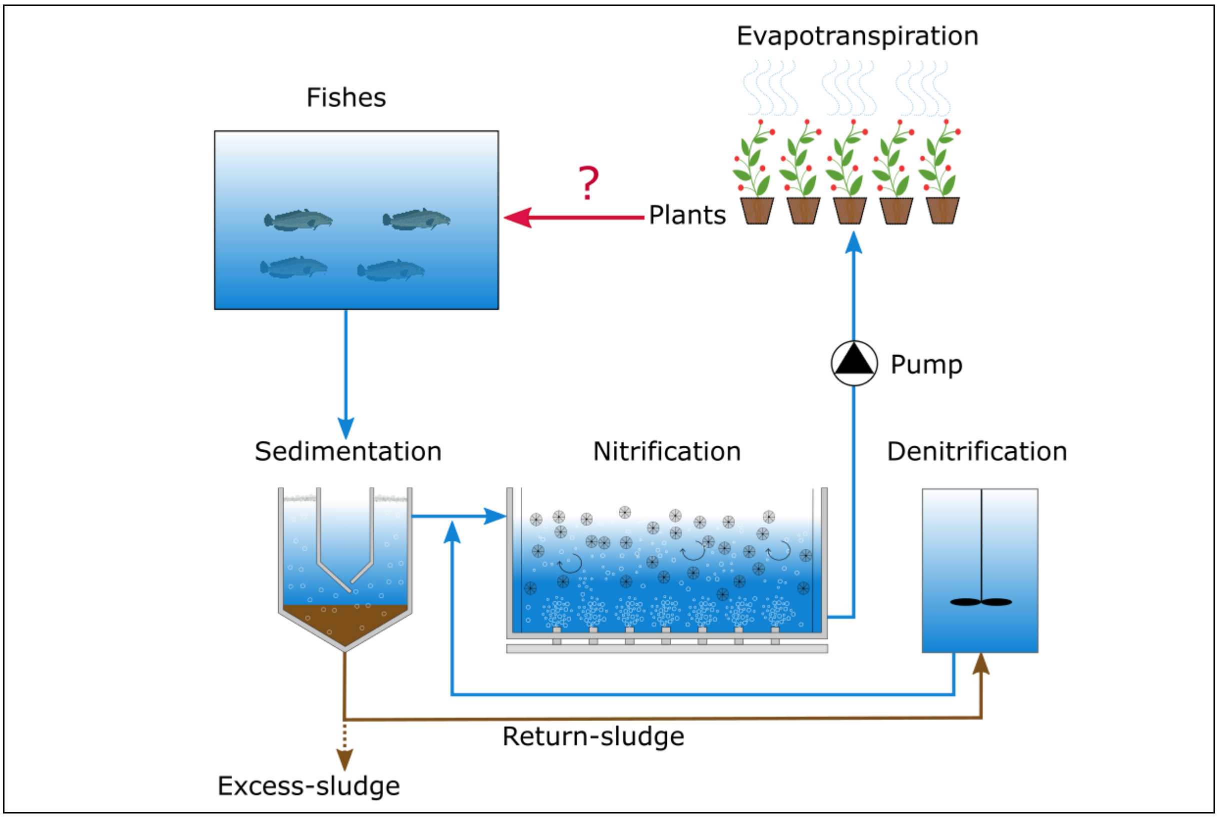

Figure 12: Dimensioning of the plant nutrient uptake based on existing RAS dimensions

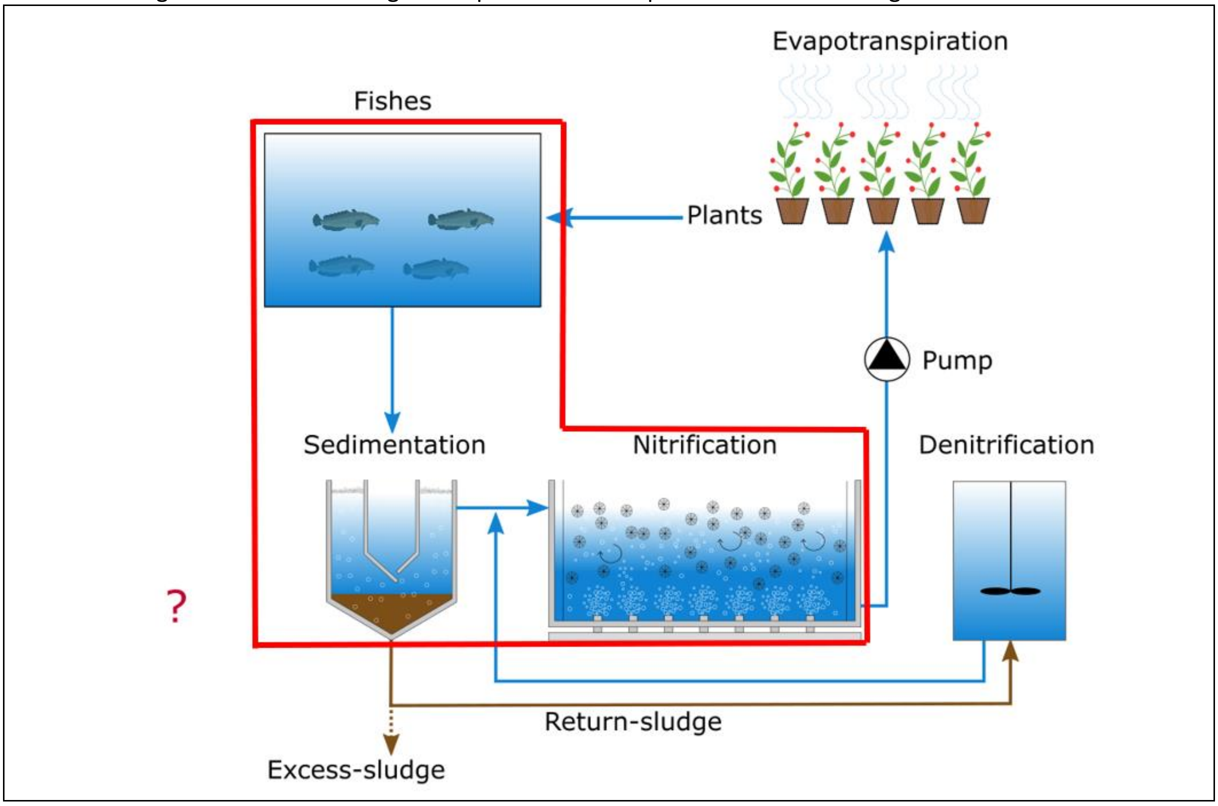

Figure 13: Desired plant and fish production and corresponding dimensioning of the RAS

2.5 References

Avnimelech, Y. 2014. Biofloc Technology – A Practical Guide Book (3rd edition). The World Aquaculture Society, Baton Rouge.

FAO 2018. *The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals*. Rome. Licence: CC BY-NC-SA 3.0 IGO.

Gibbens, S. 2019. Climate change is depleting our essential fisheries. *National Geographic* online. Retrieved 15. February 2019.

Somerville et al. 2014. Introduction to aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-scale Aquaponic Food Production: Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 1-10.

Timmons, M.B. & Ebeling, J.M. 2007. Recirculating Systems. Northeastern Regional Aquaculture Center, Ithaca, NY.

Timmons, M.B., Riley, J., Brune, D., and Lekang, O.-I. 1999. Facilities Design. In CIGR–The International Commission of Agricultural Engineering (eds.) *CIGR Handbook of Agricultural Engineering Volume II: Animal Production & Aquacultural Engineering*. American Society of Agricultural Engineers, USA. pp 245-280.

Tschudi, F. 2018. *Planning basis for dimensioning the aquaculture part of an aquaponic system.* Wädenswil: Zurich University of Applied Sciences, Research Group Aquaculture Systems, unpublished.

Morris Villarroel

3. FISH ANATOMY, HEALTH, AND WELFARE

3.1 General external anatomy

The main idea of this section is to introduce several important anatomical features of fish and to relate them to function and physiology. There are more than 20,000 species of freshwater and marine fish on our planet, each with specific requirements and ecological niches, which has led to specific body adaptations. However, many of the fish, especially teleosts (bony fish with a moveable pre-maxilla), share some common features. Although the number of species used in aquaculture is probably over 200, the number used in aquaponics is narrower, and mostly restricted to freshwater fish (Table 1).

Table 1: Summary of the species of fish used in aquaponics, including those cited in two international surveys on aquaponic practitioners (Love *et al.* 2014; Villarroel *et al.* 2016)

Common name	Species	Family	Order
Tilapia	*Oreochromis niloticus*	Cichlidae	Cichliformes
Catfish	*Pangasius pangasius*	Pangasiidae	Siluriformes
Koi	*Cyprinus carpio*	Cyprinidae	Cypriniformes
Trout	*Oncorhynchus mykiss*	Salmonidae	Salmoniformes
Bass	*Morone saxatilis*	Moronidae	Perciformes
Perch	*Sander lucioperca*	Percidae	Perciformes
Blue gill	*Lepomis macrochirus*	Centrarchidae	Perciformes

Most of the fish used in aquaponics follow a basic anatomical outline (Figure 1). Looked at longwise, there are three main regions of the body: the head, the trunk region, and the tail (Canada Department of Fisheries and Oceans 2004). In terms of possible abnormalities, veterinarians tend to focus on problems related to the eyes, fins and skin. Apart from those, there are other parts of the external anatomy that are important in terms of indirect measures of fish welfare, fish quality, and health problems, and one should be able to locate these. For example, blood sampling usually involves injecting a needle underneath the lateral line in the tail region to find the caudal vein. To tag individuals, passive integrated transponder tags (PIT tags) are normally injected into the muscle under the dorsal fin. Some other plastic paints can be injected on or near the mouth and eyes, but any type of exterior tags often cause problems since they affect the very delicate skin and can cause infections. If nothing else, basic knowledge of some species-specific anatomy can also help to avoid fish fraud when purchasing them commercially.

Eyes and nose

As opposed to some cartoon characters, real fish have no eyelids. Thus, not only are their eyes in direct contact with the surrounding water at all times, giving an idea of the importance of water quality, they are also quite light sensitive (they have no way of 'closing' their eyes). This is why many fish prefer to avoid direct sunlight and congregate in locations with shade. The Mexican cavefish

(*Astyanax mexicanus*) is one example of a blind fish, but most fish used in aquaponics can see very well. While alive, bilateral exophthalmia (the bulging of both eyes from their sockets) is often used as a general indicator of infection. Unilateral exophthalmia is probably the result of a contusion. After slaughter, the whiteness of the eye is used as a quality indicator (see Council Regulation (EC) 2406/96). For example, a high-grade fish will have a convex eye with a black and shiny pupil, while fish with a concave eye, grey pupil, and a 'milky' cornea should be discarded. Close to the eyes are two small openings (nares) which lead to an area with olfactory sensors which can be quite sensitive in many fish. For example, salmonids use their olfactory sensors during migration in order to return to their original breeding grounds. Technically, in order to be able to smell anything, a current has to be established in and out of the nares, normally while fish are swimming but, unlike in mammals, the holes do not lead to the throat.

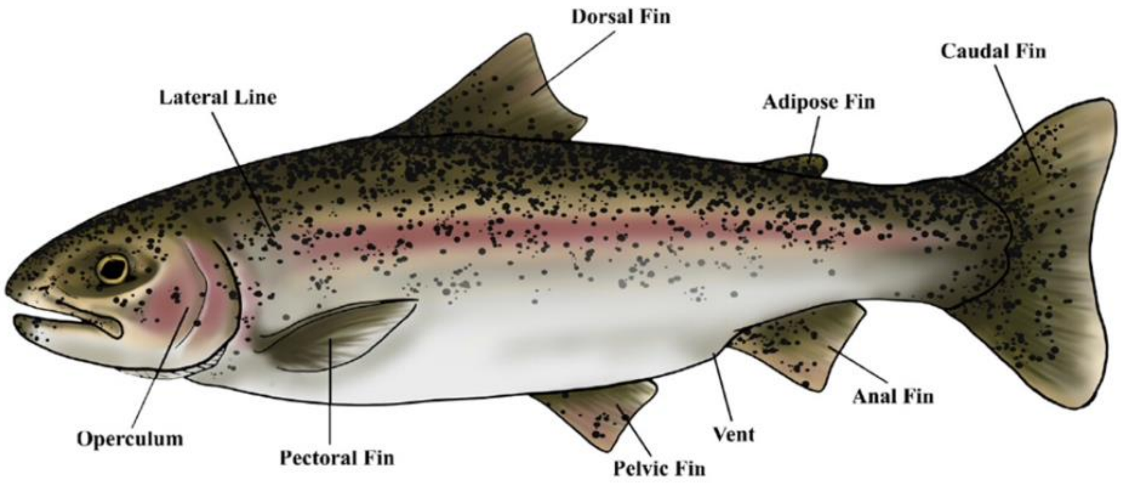

Figure 1: Basic external anatomy of a fish (from http://anatomyhumanbody.us)

Opercula and gills

The operculum is a bony cover that shields the gills, the lungs of the fish which capture the rather limited supply of oxygen dissolved in water. The opercular frequency, or the rate at which the opercula open and close over a period of time, can be used to verify whether fish are breathing correctly or may be overly stressed. In anesthetized or dead fish, veterinarians often 'check under the hood' by lifting up the opercula to examine the gills, which should be bright red and moist, and not covered in mucus, white, or smelly. External observation of the gills can also provide information about possible bacterial or parasitic infections. Compared to mammals, fish gills are thus more of an external organ than an internal one, again underlining the importance of water quality to protect this delicate and important organ (e.g. correct water pH). Finally, apart from oxygen absorption and CO_2 release, the gills are an important outlet for nitrogenous waste (Figure 2). Hoar & Randall (1984) calculated that more than 80% of ammonia (NH_3) is excreted via the gills, while only trace amounts are passed as urine.

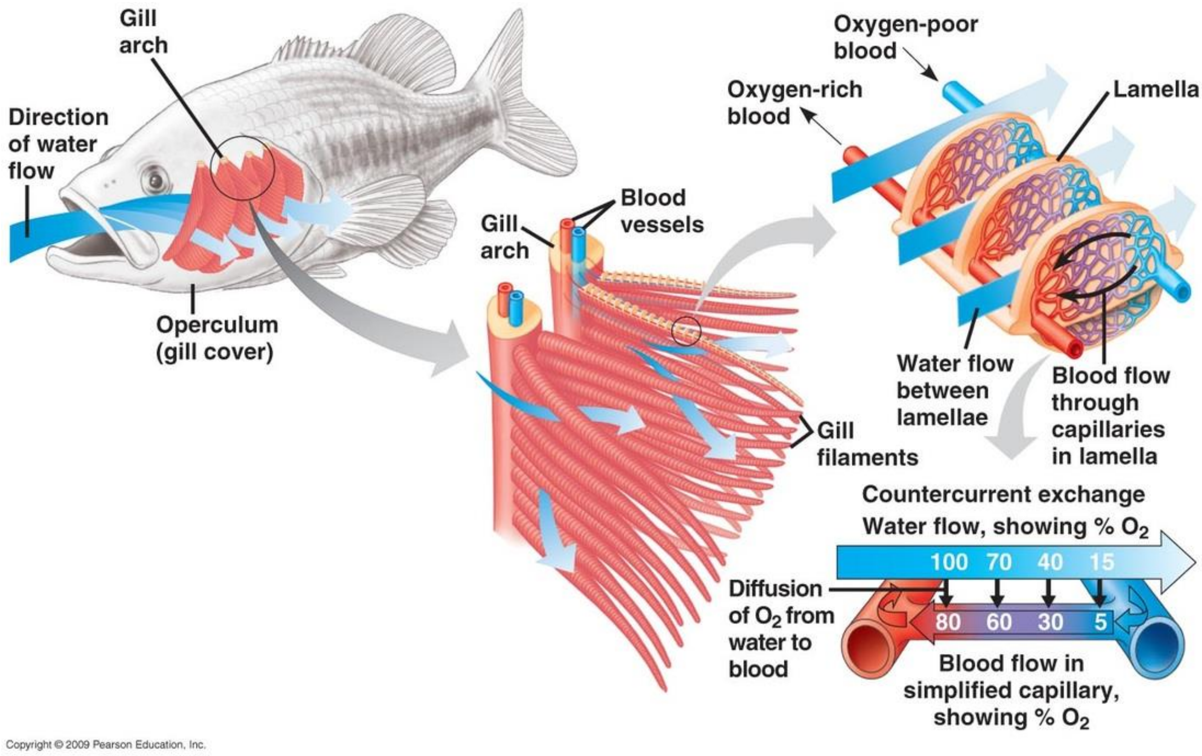

Figure 2: The gills work according to the counter flow principle: water and blood flow in opposite directions. The O_2 content in blood can therefore rise to the same concentration as that in the surrounding water (source https://338373gasexchange.weebly.com/fish.html)

Skin

The skin is one of the most important organs in fish. It has three basic components: the dermis (inner layer), the epidermis (outer layer), and the scales. The scales are embedded in the dermis, which is responsible for providing colour. Mucus is made by the epidermis and helps to protect the cells. It has anti-fungal and anti-bacterial properties and plays a role in immune function (Wainwright & Lauder 2017). Any type of skin lesion or scale loss can have serious consequences for fish, since healing in an aqueous environment can take a long time and wounds can get waterlogged. Just imagine, for example, trying to heal a paper cut on your finger by keeping it submerged in a glass of water for a week. The whole healing process would take much longer and you would be more exposed to bacterial infections. For all these reasons it is a good idea to use plastic gloves when handling live fish so as not to damage their skin.

The lateral line is part of the skin organ and consists of perforated scales with cilia (short microscopic hairs that can move) that are connected to the nervous system and provide information about water movement around the fish and pressure (constituting a sense organ not found in mammals). This allows fish to hunt at night or move in very opaque water by sensing the vibrations around them. The lateral line also has culinary importance, since cutting along this line in a cooked fish will separate the meaty upper section from the visceral section below.

Finally, as a curiosity, several recent studies have related skin colour to fish personality. For example, the colour of the dermis on the dorsal area of salmon (between the dorsal fin and the head) is darker or has more dark spots in fish that are more aggressive (Castanheira *et al.*, 2017)

Fins

Fins can be used as indirect indicators of fish health and welfare. We want to avoid fraying of the fins (when the skin comes apart between the rays), fin erosion (white colouring at the tips of the fins), necrosis (dead cells on the fins), or discoloured spots, the latter of which may indicate the presence of parasites.

Dorsal fin

Normally fish have one dorsal fin, but they can also have two (one after another, as in sea bass). The dorsal fin is mostly used to help maintain the fish in an upright position. It is supported by rays which are often erectile to allow the fish to 'open or close' it depending on signalling requirements. Tilapia has a large dorsal fin with pointed rays that can easily cut innocent hands that want to grab it out of the water. The number of rays per fin can also be used to identify the species of fish. For example, rainbow trout have between 10-12 rays on their dorsal fin while brown trout (not normally grown in aquaponics) have around 13-14.

Adipose fin

This is a rather short and fat fin which is common in salmonids, but whose function is unclear. It is full of fat and appears to have sensory neurons. Sometimes it is cut off in farmed salmon to differentiate them from wild salmon but Reimchen & Temple (2004) found that fish without an adipose fin have a higher tail beat amplitude, indicating that it has a role in natural swimming behaviour, and that cutting it off probably has a negative effect on welfare.

Caudal fin

This is the largest and most powerful fin and is directly connected to the spine. It is used to thrust the fish forward. Like the tail of piglets, it can also be nibbled by other fish or get eroded by being rubbed on different surfaces. The tail is also important for measurement purposes (Figure 3). Apart from weighing the fish, aquaculturists often measure the standard length (from mouth to the beginning of the tail) and fork length (from mouth to the fork at the tip of the tail).

Anal fin

This fin is posterior (behind) the anus and urogenital pore on the ventral side of fish. Sometimes referred to as the cloacal fin, it is also important in stabilizing fish when swimming, so that they do not roll over onto their sides.

Pectoral and ventral fins

Close to the operculum fish have pectoral fins, which roughly correspond with the arms of terrestrial mammals, and below them are the ventral or pelvic fins, which roughly correspond with 'legs'. In some fish, generally those considered to be 'less evolved' (i.e. those which have changed less over time compared to their ancestors), like salmonids, the ventral fins are further down the trunk region, while they are closer together in more modern fish (such as tilapia). The pectoral fins help fish to move up and down while the ventral fins are more important in stopping movement.

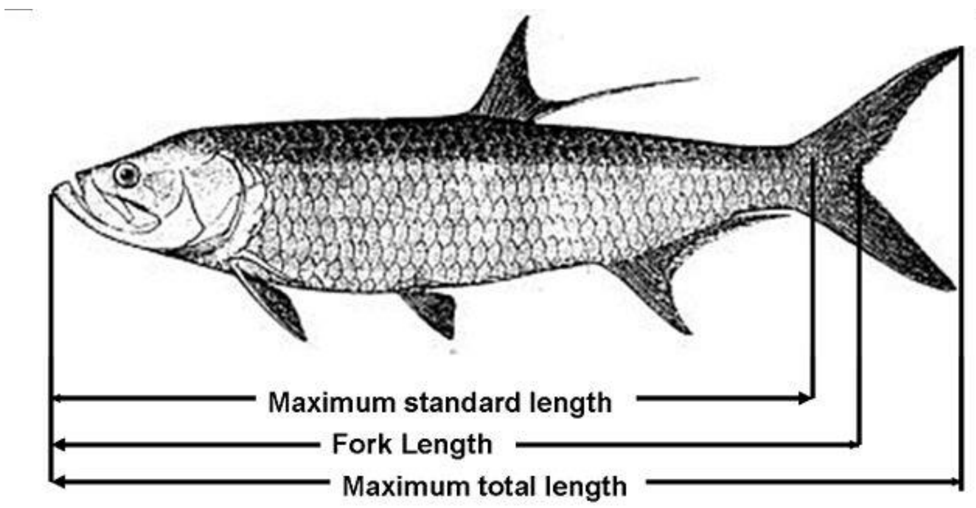

Figure 3: Example of fish length measurements for a tarpon fish. For standard weight equations, the total length is used, which includes the caudal fin (source http://www.nefsc.noaa.gov/lineart/tarpon.jpg)

3.2 General internal anatomy

In this section we will outline the most important internal organs of fish (Figure 4), underlining the main differences with mammals and some important facts that influence how fish should be maintained.

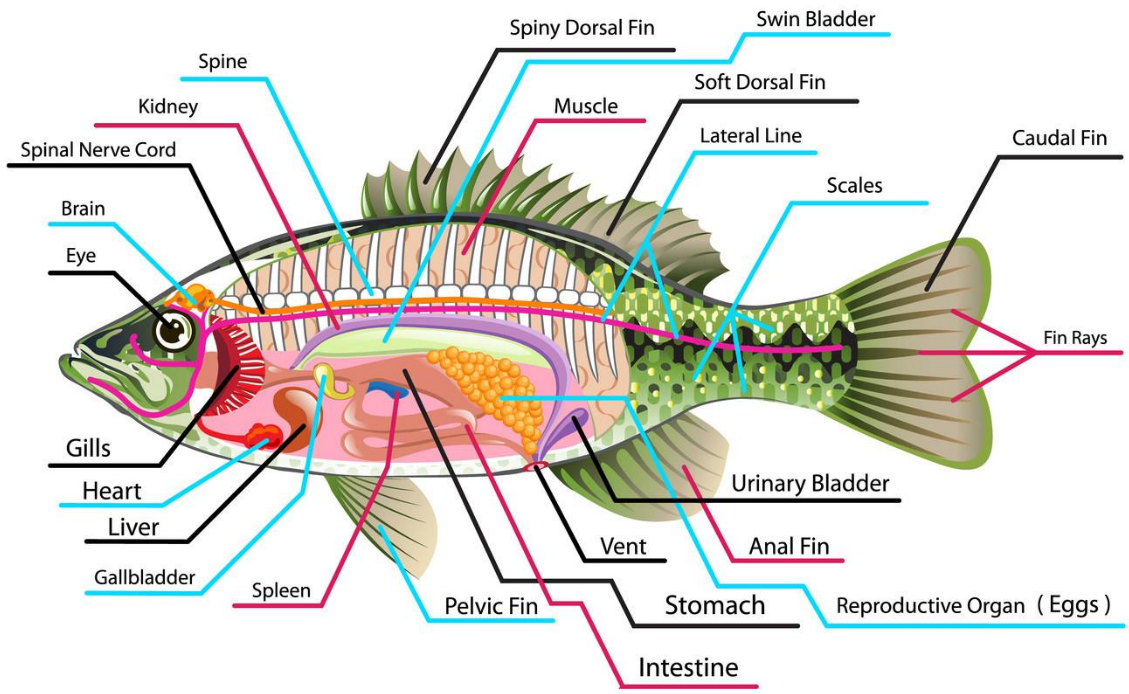

Figure 4: General internal fish anatomy (source http://www.animalsworlds.com/internal-anatomy.html)

Brain

Fish have small brains compared to terrestrial vertebrates. For example, the human brain weighs approximately 1.4 kg and represents around 2% of the total body mass, but fish brains only represent 0.15% of their body mass. Nonetheless, unlike many vertebrates, fish brains are quite adaptive and maintain the ability to grow and change throughout life (they maintain the ability to produce new neurons; Zupanc 2009). Fish brains have three main regions: the forebrain (with the olfactory lobes and telencephalon), the mid-brain (optical lobes), and the hind-brain (cerebellum). Fish do not have a neocortex, which some scientists think is necessary to be fully conscious of pain, but other important structures exist that suggest they can feel pain, such as the amygdala, the cerebellum, and the pallium (outer layer of the telencephalon; for more information see Braithwaite 2010).

Heart

The heart is located just underneath the gills. Like the brain, it is quite small and relatively simple compared to terrestrial vertebrates, normally only weighing a few grams. It has a contractile ability to collect blood from the body and send it to the gills in a one-loop system which will be commented on more below under the section on respiration. It is a simple circuit with one atrium, one ventricle, and a conus which leads directly to the gills. There is no double circuit as in mammals, where the blood sent to the lungs returns to the heart to get pumped back to the body. In fish the gills 'pump' the blood to the body without sending it back to the heart.

Digestive system

The general makeup of the digestive system in fish is similar to other vertebrates, with a mouth, oesophagus, stomach, small intestine, large intestine, and anus. However, there is little demarcation between the different sections of the small intestine, nor is there an ilea-caecal valve separating the small from the large intestine. Carnivorous fish (like salmon) have a simple and short stomach and shorter intestines than herbivores (such as carp or tench), which may lack a stomach altogether and have a longer intestine with more pyloric caeca. The caeca are derivations of the digestive tract, which help to increase the total surface area for digestion and extract essential nutrients.

Abdominal fat

An important difference between wild and cultured fish is the amount of abdominal fat that accumulates in the latter. For example, sea bream from aquaculture will typically accumulate more visceral fat than wild sea bream, while fish that are fasted for longer periods have less fat than fish fasted for less time (Mozanzadeh *et al.* 2017).

Spleen

The spleen is normally a dark red circular organ attached to the intestine. It helps to clean the blood, contains white blood cells, and is an important part of the immune system.

Liver and gall bladder

The liver is quite large and reddish, and beginners sometimes confuse it with the heart. It plays a vital role in detoxifying any organic or inorganic contaminants found in the food or water, as well as participating in protein synthesis, and fat and glycogen storage. Underneath the liver is the yellowish green gallbladder. Most fish do not have a distinguishable pancreas but rather Brockmann bodies, a collection of endocrine cells found along the digestive tract which can produce insulin.

Swim bladder

This organ is unique to fish. It can be filled or emptied to control buoyancy, and thus affects the amount of energy needed to swim. It can also be used to produce or receive sounds. Fish can be either physostomous (like trout), who can fill up their swim bladder via a pneumatic duct which is connected to the gut, or physoclistous (like bass), with no direct connection between the oesophagus and the entry to the swim bladder, so it must be filled up using a gas gland. Physostomous fish are better prepared for sudden changes in water height while it will take longer for physoclistous species. For all fish it is important to fill the swim bladder with air at an early stage of development, in order to assure proper growth and avoid spinal deformities (Davidson *et al.* 2011).

Kidneys

The kidneys are paired organs that are quite long and narrow, and dorsal to the swim bladder. They play an important role in blood homeostasis (i.e., maintaining appropriate levels of dissolved ions), which explains their substantial size. As in mammals, they are needed to 'clean' the blood, which is especially important in an aqueous medium where the concentration of different ions must be monitored continuously. It should be noted here that fish from fresh- and saltwater have adopted opposing methods to maintain appropriate levels of blood electrolytes. Freshwater fish have a higher concentration or ions in their blood than the surrounding water. Therefore, due to osmosis, the gills and kidneys of those fish must work to avoid absorbing too much water (H_2O) and losing too many ions (they drink little and 'urinate' a lot). In saltwater the opposite occurs: fish drink/ingest more water and urinate little since the concentration of ions in their blood is lower than the surrounding water. In aquaponic units, care should be taken to ensure that the nutrient solution for plants is not having a negative effect on the fish due to inappropriate ion levels. At the end of the kidney there is a bladder to store urine, but it is very small compared to mammals, mostly because little urine is produced in comparison (as mentioned above, much of the nitrogenous waste is excreted by the gills).

Testes and ovaries

Most of the fish used in aquaponics will be used as food and will not mature sexually (breeders are kept in a separate installation). However, it is useful to know that sexual reproductive organs in fish are internal and start to develop deep inside the dorsal region of the fish near the head kidney. As fish mature, the gonads grow in size drastically towards the urogenital pore near the anus. During breeding season semen or eggs will be expelled for external fertilization.

3.3 Respiration physiology

The air we breathe is mostly nitrogen (78%) and 21% oxygen. The water that fish 'breathe' also contains oxygen, but at a much lower concentration, less than 1%. In addition, since water is 840 times denser than air and 60 times more viscous, it takes more effort for fish to 'breathe' to extract oxygen, around 10% of their metabolic energy. In comparison, terrestrial animals only use about 2% of their metabolic energy to extract oxygen from air. For example, rainbow trout need to move approximately 600 ml of water past their gills per minute per kg weight while, in comparison, terrestrial reptiles such as turtles only need to move 50 ml air min^{-1} kg^{-1}. As a result, even though fish gills are quite efficient, obtaining enough oxygen from the surrounding water can be difficult and sometimes life threatening.

Fish capture oxygen using their gills which are in direct contact with the surrounding water and are easy prey for parasites and bacterial infections. The total surface area of the gills is approximately 10 times the surface area of the whole body. Gills are also important in ion exchange (maintaining the acid-base balance) and waste elimination, such as ammonia. Thus, fish basically urinate via their gills as well as breathe through them. To obtain oxygen, water is drawn into the mouth cavity and then the mouth is closed to force water out through the two opercula. This pumping movement creates a unidirectional flow of water, unlike the inhaling and exhaling through the same orifice in terrestrial mammals. Some fish, such as sharks, can keep their mouth open while swimming, which apparently provides enough flow of water over the gills to breathe normally. If your tanks allow it, you can try to measure the heart frequency of your fish indirectly by counting the opercular frequency – the times that the opercula open and close during one minute. This measurement can be used as an indirect indicator of animal welfare since stressed fish have high opercular frequencies.

Most fish have four gill arches on each side of their body (Figure 2). Each arch consists of a white bony rod which runs from top to bottom (ventral-dorsal) from which stem the V-shaped primary filaments in a caudal direction. The primary filaments or primary lamellae are red since they are full of blood. Each primary lamella has secondary lamellae which cross it perpendicularly and carry individual blood cells to facilitate gas exchange (release CO_2 and capture O_2 using the haemoglobin in the red blood cells). The flow of the blood runs against the flow of water, which increases its efficiency. In addition, fish can open or close the set of primary filaments to expose more secondary lamellae to the water, effectively taking deeper breaths. After filling up with oxygen the blood cells continue to move through the body via arteries.

3.4 Fish welfare

3.4.1 Introduction

Aquaculture is one of the few types of animal farming that has grown continuously over recent decades, by about 10% annually on an international level (Moffitt & Cajas-Cano 2014). However, as production increases and new methods appear, such as aquaponics, we have been witness to more problems related with fish health and welfare. Although it may seem surprising, more than 1300 scientific articles have been published on fish welfare since 1990 (see Table 2). Not all those studies deal with commercially produced species, but in general the number for all fish is comparable to or higher than some other species like sheep, horses or poultry.

Table 2: Summary of publications on animal welfare for different species of farm animals (based on a search in the *Web of Science* for the years 1990-2017)

Species	Papers
Fish	1295
Trout	550
Sheep	1149
Cattle	2417
Pig	2638
Horse	926
Poultry	1078

One of the first scientific reviews of fish welfare was by Conte (2004) from the University of California at Davis, followed a few years later by two groups from the United Kingdom (Huntingford *et al.* 2006 and Ashley 2007). In his review, Conte (2004) underlines that fish farmers already know that welfare is important and that stress must be minimized since fish have specific requirements in terms of handling and environment outside of which they will not thrive or survive. That is to say, compared to terrestrial animals, fish are more demanding in terms of growing conditions and can be stressed easily, so much so that they can also die easily. Huntingford *et al.* (2006) summarize the main arguments for believing that fish can feel pain. Fish are complex beings that develop sophisticated behaviour, so the authors believe they can probably suffer, although it may be different in degree and type than for humans. That review ends up identifying four main critical areas when considering fish welfare: assuring that fish are not kept without water or food; assuring that producers provide good water quality and equipment; that their movements or behaviour are not restricted; and that mental and physical suffering be avoided. In his review, Ashley (2007) starts with a description of the industry and the critical points that may compromise fish welfare, including fish density in cages and problems with aggression. For example, some species, like tilapia, are more aggressive when kept at low densities than at higher densities. Importantly, Ashley (2007) provides a table of the main welfare problems in fish which is 7 pages long. In conclusion, there is a lot of scientific literature about fish welfare and several critical areas have been identified. However, regarding aquaponics, there are very few studies about the welfare of fish bred together with plants, but we can learn from other studies about the welfare of fish kept in small-scale recirculation systems.

3.4.2 Legislation in the EU

In Europe, any animal kept for the purpose of farming must comply with Directive 98/58/EC, which is a law that sets down several minimum conditions for adequate animal welfare for vertebrates. Although fish are technically included in that Directive, they are practically exempt due to our lack of knowledge about fish welfare, so there are no specific requirements for minimum conditions for fish used in aquaculture. Since 2006, several reports have been published in Europe, for example by the European Council of the European Food Safety Authority (EFSA), which give scientific recommendations for the most common species used in aquaculture. Overall, at least in Europe, there seems to be general agreement that fish undergo stress when oxygen levels are low and when they are taken out of water, and that chronic stress in fish compromises the immune system and can make them more vulnerable to disease.

3.4.3 Specific measures to evaluate welfare

Studies on fish welfare began later than for other farm animal species, in part because aquaculture is a younger animal production science and also since it was unclear to many whether fish can feel pain. Until recently, fish were not considered to be sensitive animals, but that situation has been changing. Sneddon (2003) was one of the first to prove that trout have pain receptors (nociceptors) on their face and jaw. She proved that those receptors respond to stimuli which are potentially damaging and send nervous signals to the spinal cord and brain. In addition, it appears that trout are aware of pain since they change complex behaviour when given a noxious substance, but revert to normal behaviour when given morphine (which essentially eliminates the pain). Those findings have also been confirmed in other species such as goldfish, where anxiety and fear decrease when they are given doses of morphine (Nordgreen *et al.* 2009). On the other hand, other scientists like Rose (2002) argue that fish cannot feel pain like humans since they lack a neocortex. Thus, they are probably not conscious about their pain in the same way as we are, although they react to pain in a similar manner. Whatever the case may be, both sides agree that fish can be stressed and that they have evolved a complex physiological response to stressors. Dawkins also makes the important point that everyone should worry about animal welfare whether or not they are conscious, simply because poor animal welfare leads to diseased and unhealthy fish, which has negative effects on farmers and consumers (Dawkins 2017).

3.4.4 The HPI axis and the stress response

The cascade of neuroendocrine activities that are released in fish after they become aware of a stressor is very similar to the responses seen in other vertebrates. As in mammals, the immediate neuroendocrine response is called the primary response and consists of nerve signals which release adrenaline and noradrenaline from chromaffin cells (at the head kidney), whose equivalent in mammals is the adrenal medulla (Figure 5). After the primary response, there is a slower secondary response which takes 2-15 minutes to activate the hypothalamo-pituitary-interrenal axis, or HPI axis (Sumpter *et al.* 1991), which in mammals is called the hypothalamo-pituitary-adrenal axis or HPA.

The hypothalamus produces corticotropin releasing hormone (CRH) which stimulates the production of adrenocorticotropic hormone (ACTH) by the anterior pituitary, also called the adenohypophysis. ACTH is released into the blood stream and simulates the production of cortisol by the interrenal tissue (also associated with the kidneys in fish), which corresponds with the adrenal cortex in mammals (Okawara *et al.* 1992). The secondary response includes an increase in heart frequency, greater oxygen uptake by the gills, and an increase in glucose concentration in plasma via glucogenolysis (Pickering & Pottinger 1995). Both the primary and secondary response systems help to maintain homeostasis after a stress by providing energy and increased levels of oxygen to the brain so that the body can adjust and return to normal or basal metabolic function.

Although there is no simple relationship between stress and welfare, we know that they are related and that the response to a stressor can be used to give an idea about the degree of the challenge.

With that in mind, it is always preferable to consider several indicators at the same time, including growth indices, immune system response, and other physiological indicators.

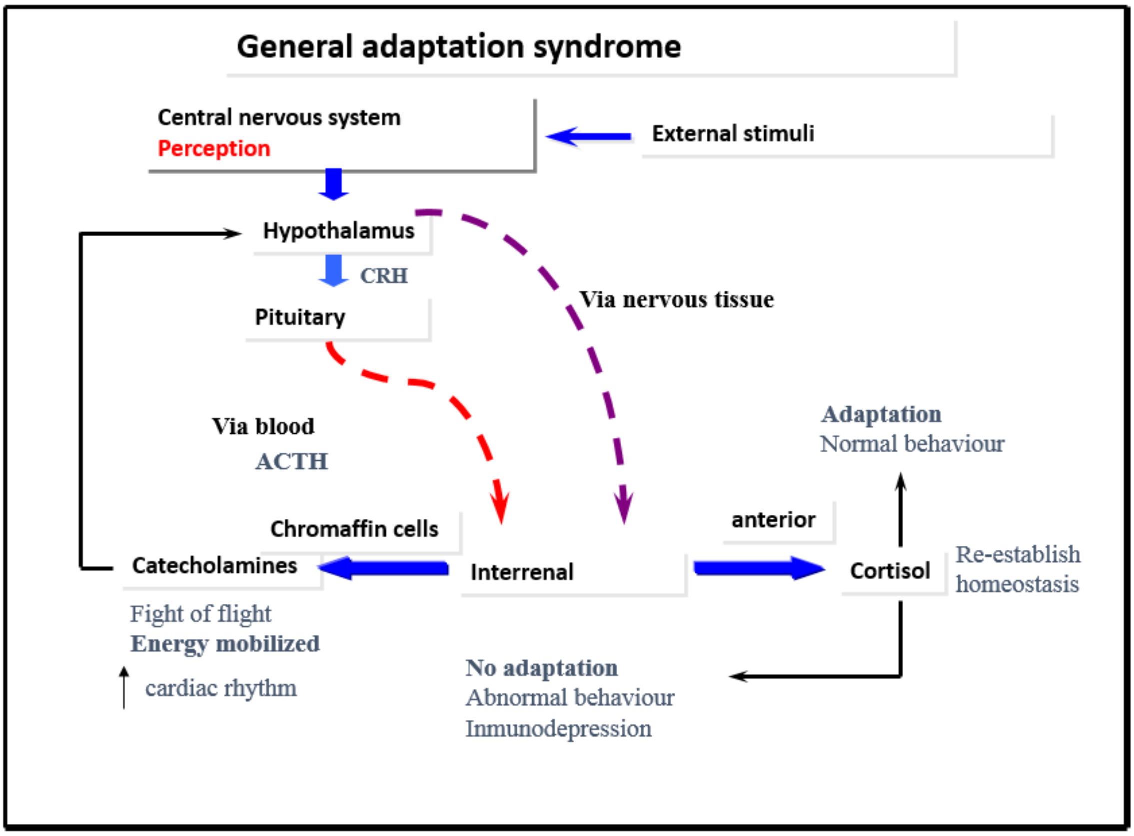

Figure 5: The HPI axis in fish and the cascade of responses to a stressor (source M. Villarroel) (CRH = corticotropin releasing hormone, ACTH = adrenocorticotropic hormone)

3.4.5 Operational welfare indicators

On an industrial level, a new approach is being developed to analyse fish that involves interactions between scientists studying animal welfare and companies that strive to be more efficient. Together they are developing operational welfare indicators (OWI). A good example for salmon is the manual presented by Noble *et al.* (2018) that tells farmers how to evaluate on a commercial level the immediate environment, different groups of fish, and individual fish. As mentioned above, many scientific articles have been published on fish welfare, most of which are based on observations made in the lab. OWI are practical indicators that are used on the farm and can be easily explained and repeated. OWI can be separated into two large groups: those more related to the environment; and those related to the fish. The latter can be applied to groups of fish, or individually. Finally, individual indicators can include laboratory analyses which are less operational per se but can provide useful information in the short term (see Figure 6). OWI can provide an idea of the current status of production in terms of the needs of the fish and their welfare. In parallel, they can be used to help develop good practice and to identify critical points that can have a negative effect.

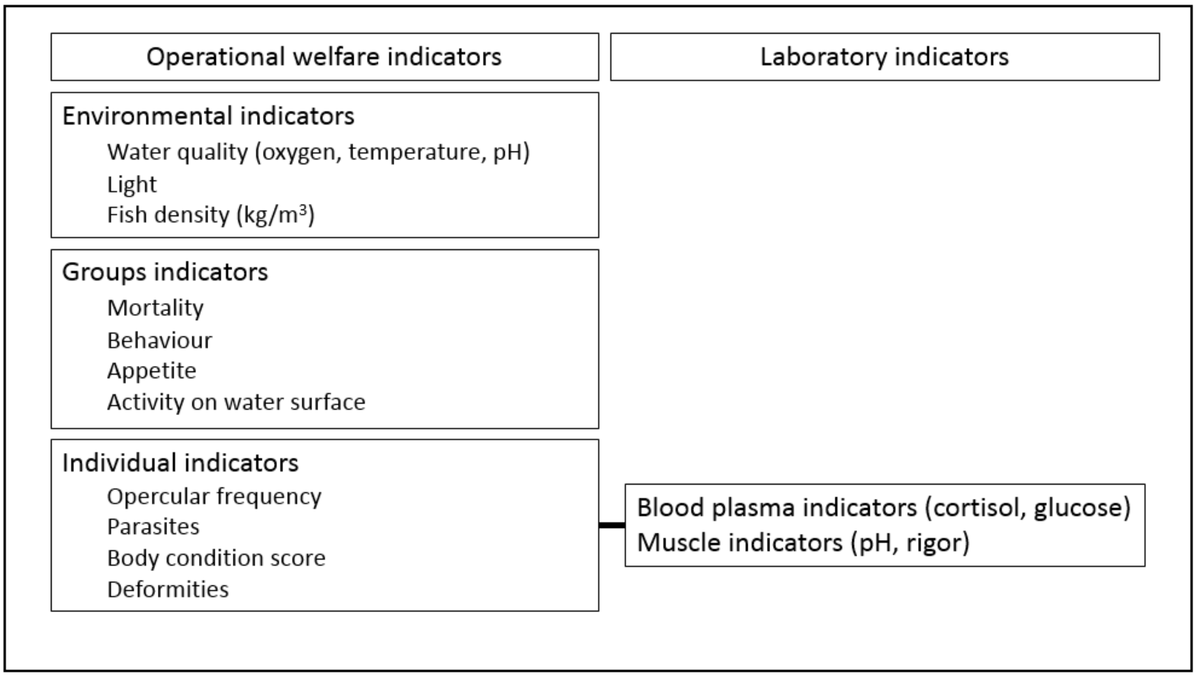

Figure 6: Summary of the operational indicators used on fish farms, including indicators that vary with the environment and the animal. The animal-based indicators can be based on groups of fish or on individuals, and individual indicators can include laboratory analyses

In general, aquaculturists use feeding as an indirect indicator of welfare. That is, one approaches the tank and provides food, and the fish respond by going to the surface and eating, which is a good sign. If the fish do not come to eat, they have lost their appetite for some reason and more information is needed. Although there is plenty of equipment that can be purchased to feed fish automatically, it is recommended to feed fish at least once a day by hand in order to get an idea about how they are doing. If the fish do not eat, that will affect their weight gain, which is also relatively easy to measure. Another operational indicator that is common in fish farms is the coefficient of condition in live weight (the live weight in grams divided by the cube of the fork length in centimetres cm^3). It indicates nutritional status (Bavčević *et al.* 2010), and gives an idea about the amount of intraperitoneal fat. The hepato-somatic index (HSI) is defined as the ratio between the weight of the liver and the live weight. During periods of fasting, the needs for energy are met mostly by mobilising glycogen reserves from the liver, while the fat reserves are left more or less untouched during the first few days (Peres *et al.* 2014). Thus, HSI can be used to indicate energy reserves since the liver is an important regulator of nutrient use in fish (Christiansen & Klungsøyr 1987).

3.5 References

Ashley, P.J. 2007. Fish welfare: current issues in aquaculture. *Applied Animal Behaviour Science* 104 (3-4), 199-235.

Bavčević, L., Klanjšček, T., Karamarko, V., Aničić, I. & Legović, T. 2010. Compensatory growth in gilthead sea bream (*Sparus aurata*) compensates weight, but not length. *Aquaculture* 301 (1-4), 57-63.

Braithwaite, V. 2010. *Do Fish Feel Pain?* Oxford University Press, Oxford.

Canada Department of Fisheries and Oceans 2004. *Animal User Training Template. 1.0. Anatomy and Physiology of Salmonids.*

Castanheira, M.F., Conceicão, L.E., Millot, S., Rey, S., Bégout, M.L., Damsgård, B., Kristiansen, T., Höglund, E., Øverli, Ø. & Martins, C.I.M. 2017. Coping styles in farmed fish: consequences for aquaculture. *Reviews in Aquaculture* 9, 23-41.

Christiansen, D.C. & Klungsøyr, L. 1987. Metabolic utilization of nutrients and the effects of insulin in fish. *Comparative Biochemistry and Physiology Part B: Comparative Biochemistry* 88 (3), 701-711.

Conte, F.S. 2004. Stress and the welfare of cultured fish. *Applied Animal Behaviour Science* 86 (3-4), 205-23.

Council Regulation (EC) No 2406/96 of 26 November 1996 laying down common marketing standards for certain fishery products.

Davidson, J., Good, C., Welsh, C. & Summerfelt, S.T. 2011. Abnormal swimming behavior and increased deformities in rainbow trout *Oncorhynchus mykiss* cultured in low exchange water recirculating aquaculture systems. *Aquacultural Engineering* 45 (3), 109-117.

Dawkins, M.S. 2017. Animal welfare with and without consciousness. *Journal of Zoology*, 301 (1), 1-10.

Hoar, W.S. & Randall, D.J. 1984. *Fish Physiology: Gills: Part B – Ion and Water Transfer*. Academic Press, Cambridge MA.

Huntingford, F.A., Adams, C., Braithwaite, V.A., Kadri, S., Pottinger, T.G., Sandøe, P. & Turnbull, J.F. 2006. Current issues in fish welfare. *Journal of Fish Biology* 68 (2), 332-72.

Love, D.C., Fry, J.P., Genello, L., Hill, E.S., Frederick, J.A., Li, X. & Semmens K. 2014. An international survey of aquaponics practitioners. *PloS One* 9, e102662.

Moffitt, C.M. & Cajas-Cano, L. 2014. Blue Growth: the 2014 FAO state of world fisheries and aquaculture. *Fisheries* 39 (11), 552-553.

Mozanzadeh, M., Marammazi, J.G., Yaghoubi, M., Yavari, V., Agh, N. & Gisbert, E. 2017. Somatic and physiological responses to cyclic fasting and re-feeding periods in sobaity sea bream (*Sparidentex hasta*, Valenciennes 1830). *Aquaculture Nutrition* 23, 181-191.

Noble, C., Gismervik, K., Iversen, M.H., Kolarevic, J., Nilsson, J., Stien, L.H. & Turnbull, J.F. (eds.) 2018. *Welfare indicators for farmed Atlantic salmon: tools for assessing fish welfare*.

Nordgreen, J., Garner, J.P., Janczak, A.M., Ranheim, B., Muir, W.M. & Horsberg, T.E. 2009. Thermonociception in fish: effects of two different doses of morphine on thermal threshold and post-test behaviour in goldfish (*Carassius auratus*). *Applied Animal Behaviour Science* 119 (1-2), 101-107.

Okawara, Y., Ko, D., Morley, S.D., Richter, D. & Lederis, K.P. 1992. In situ hybridization of corticotropin-releasing factor-encoding messenger RNA in the hypothalamus of the white sucker, *Catostomus commersoni*. *Cell and Tissue Research* 267 (3), 545-549.

Peres, H., Santos, S. & Oliva-Teles, A. 2014. Blood chemistry profile as indicator of nutritional status in European seabass (*Dicentrarchus labrax*). *Fish Physiology and Biochemistry* 40 (5), 1339-1347.

Pickering, A. & Pottinger, T. 1995. Biochemical effects of stress. *Biochemistry and Molecular Biology of Fishes* 5, 349-379.

Reimchen, T.E. & Temple, N.F. 2004. Hydrodynamic and phylogenetic aspects of the adipose fin in fishes. *Canadian Journal of Zoology* 82, 910-916.

Rose, J.D. 2002. The neurobehavioral nature of fishes and the question of awareness and pain. *Reviews in Fisheries Science* 10 (1), 1-38.

Sneddon, L.U. 2003. The evidence for pain in fish: the use of morphine as an analgesic. *Applied Animal Behaviour Science* 83 (2), 153-162.

Sumpter, J., Le Bail, P., Pickering, A., Pottinger, T. & Carragher, J. 1991. The effect of starvation on growth and plasma growth hormone concentrations of rainbow trout, *Oncorhynchus mykiss*. *General and Comparative Endocrinology* 83 (1), 94-102.

Villarroel, M., Junge, R., Komives, T., König, B., Plaza, I., Bittsánszky, A., & Joly, A. 2016. Survey of aquaponics in Europe. *Water* 8 (10), 468.

Wainwright, D.K. & Lauder, G.V. 2017. Mucus matters: The slippery and complex surfaces of fish. In Gorb, S.N. & Gorb, E.V. (eds.) *Functional Surfaces in Biology III: Diversity of the Physical Phenomena*, pp. 223-246. Springer, New York.

Zupanc, G.K. 2009. Towards brain repair: insights from teleost fish. *Seminars in Cell and Developmental Biology* 20 (6), 683-690.

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4. FISH FEEDING AND GROWTH

4.1 General introduction to fish feeding

Feeding and fish nutrition are fundamental aspects of aquaculture, both in terms of fish growth and in economic terms. Proper feeding depends on the development of quality feeds and on choosing appropriate methods to distribute the feed to the fish in the tanks. Apart from affecting growth, feeding can also affect fish health and welfare, which depends in turn on how much we know about the requirements of each species. Each species has its own natural history and well defined stages of growth, which should be understood in order to provide optimal care.

The candidate fish species for aquaponics (see Chapter 3, Table 1) occupy well defined ecological niches in their natural habitat. For that reason we need to provide adequate conditions for proper development, including housing conditions, which means defining the correct temperature, salinity, water quality, and speed of water flow. Normally the most demanding phases are the maintenance of breeders and the fertilization/incubation of ova or eggs, but aquaponic production will normally be dealing with later stages, usually called 'on-growing'. As the scale of aquaculture and aquaponic farms increases, it becomes more complex to maintain a large number of production phases in the same installation, so companies become specialized in one or two stages, such as breeding or on-growing. In the case of aquaponics, where fish are maintained in recirculating aquaculture systems (RAS), we normally use juveniles which are grown to adults, aiming to simplify the fish production part of the system with only one or two phases, if possible.

In general terms, feeding in aquaculture differs in some fundamental aspects compared to terrestrial mammals. Livestock on land normally self-feed using what are known as *ad libitum* feeders (each animal can choose when to approach the feeder and how much to eat at any given time of the day). In that case it is relatively easy for the farmer to detect the ration that was really ingested. In the case of aquaculture and aquaponics, fish can also use self-feeders but it is much more difficult to judge how much feed they actually consume. The danger is that any extra feed that falls into the water and is not ingested becomes waste that 'pollutes' the system. Efforts need to be made, therefore, to estimate the feed to be distributed and the precise ration that the fish need.

One way to distribute the feed is by hand from outside the tanks, spread over the whole surface area of the water, observing the behaviour of the fish until they seem to be satiated, and then feeding is stopped. Since the fish are feeding underwater, it is not that easy to know when they stop feeding or how much they ate, or even if some fish ate more than others. The more we know about a species, the more we know about their feeding habits. For example, Nile tilapia in the wild are omnivorous when young (juveniles), eating both zooplankton and phytoplankton, while they become more herbivorous as they get older (> 6 cm long) (FAO 2018). Trout, on the other hand, are mostly carnivorous throughout their lives, with a diet almost exclusively based on insects and any smaller fish they can manage to catch. In any case, the perception and knowledge of the people who are in charge of feeding is very important, especially if feeding is done manually. For more information on the feeding habits of different species, see the Aquaculture Feed and Fertilizer

Resources Information System, run by the Food and Agriculture Organization of the United Nations (FAO 2018).

Another way is to use automatic feeders instead of manual feeding. Here we might depend on technological developments such as underwater cameras to detect when the fish are no longer eating. All the feed that goes into the tank becomes a part of the system, whether it is eaten or not. Indeed, fish feed is the main external element of any aquaponic system and should be carefully controlled. Non-ingested feed remains in the tank and causes two problems, one associated with its cost and another associated with its elimination. These two problems underlie the need for adequate designs.

The hydraulics of the system should facilitate the removal of the uneaten feed. Normally this involves tapering the tanks so that the bottom part is narrower than the top, and promoting a swirling motion or current so that faeces settle on the bottom and can be removed efficiently. If the design is deficient, cleaning will be more complex and the fish may be bothered by the frequency of maintenance routines. Any decrease in the sanitary conditions of the tanks will have immediate consequences on the welfare of the fish, and on the profitability of the farm. So, even if we know the nutritional needs of the species, a poorly designed installation will make it difficult to provide adequate requirements for good fish welfare, and feed will be wasted.

4.2 Energy requirements

As with all living animals, fish require energy, and that energy is provided by the oxidation of the organic components in feed. Fish require energy to carry out their daily activities, such as breathing and swimming, and to transform, restore, and grow their body tissues. The energy requirements of fish depend on their physiological state and on the environmental conditions. In general fish make a more efficient use of the energy ingested compared to terrestrial mammals, due to the following reasons:

1. Aquatic species are poikilotherms, which means that their body temperature is the same as the surrounding water, so they do not need to spend energy heating up their body or keeping it at a constant temperature, as occurs with terrestrial livestock;

2. Since they live in water, fish do not require a strong body skeleton to support their weight under the full pressure of gravity, as in terrestrial livestock, nor do they require the costly metabolic processes required to maintain that skeleton;

3. Nitrogenous waste in fish is eliminated as ammonia directly from the gills which consumes less energy than having to make urea or uric acid and then eliminate it, as is done by mammals and birds.

Figure 1 provides an overview of the balance of nutrients and energy in fish. If we assume that it has ingested all the feed provided, the energy is distributed percentage-wise among different physiological processes, within ranges. If maintained under stressful conditions (poor lighting, low water quality, inadequate stocking densities), where the fish are alive but not comfortable, about 40% of the feed energy will be consumed just to cope with the stress, leaving only 30% for growth. On the other hand, under optimal conditions, fish will use up to 40% for growth. Obviously, the economic viability of an aquaponic system will depend on the optimal use of the energy provided. To do that we have to ensure that they ingest all of the feed, and that we provide optimal housing conditions so that the fish are not overly stressed.

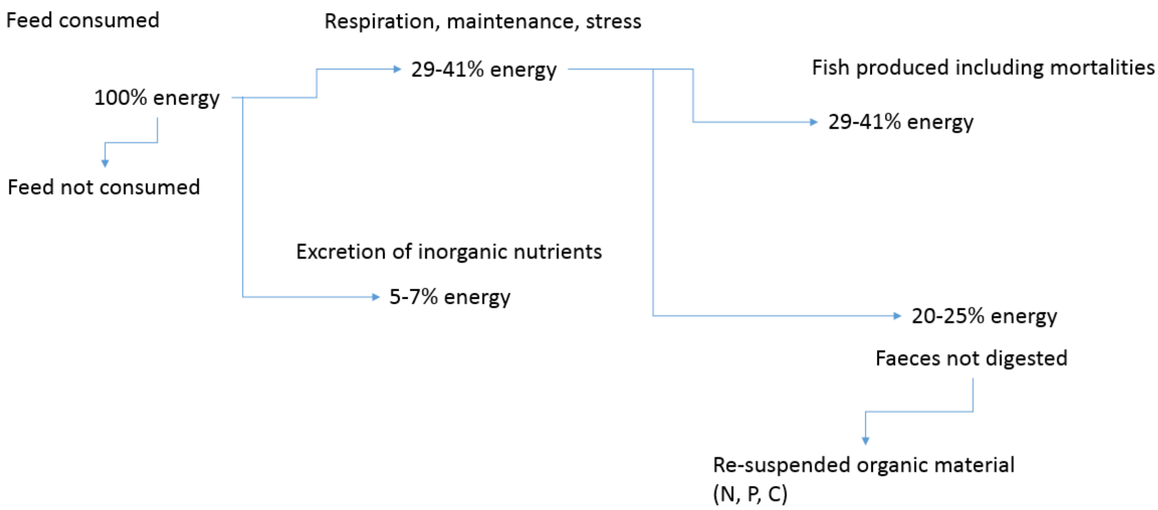

Figure 1: Balance of nutrients and energy for fish kept in recirculating systems

4.3 Main interactions between ingestion and environmental factors

As commented above, we should be able to house each species according to its requirements. For that we first need a profound knowledge of the species that we are going to work with before we begin to grow the fish or start the installation. Once we have this information, we should be able to maintain the adequate housing conditions in our system, which in this case is related to aquaponic systems.

4.3.1 Abiotic factors

The main environmental aspects to consider and that have a direct effect on production are the following:

1. Physico-chemical parameters of the source water, which are independent of the aquaculture activity itself:
    a. Water temperature, which regulates all metabolic processes
    b. Water salinity or conductivity
    c. Turbidity and total suspended solids
    d. Any potentially toxic compounds in the source water. The initial quality of the water is one of the basic success factors in the installation

2. Physico-chemical parameters of the tank water:
    a. Dissolved gases: fundamentally oxygen, which should be monitored continuously and is required by fish for normal function. In parallel, carbon dioxide is produced by fish respiration, and other gases are present in the circuit, such as nitrogen (that can appear during the over-saturation of pumped water), or hydrogen sulphide or methane from the anaerobic decomposition of sediments
    b. Dissolved micro- or macronutrients, which are related to the feed, including several elements vital for the development of the fish, such as phosphorus, iron, and especially the nitrogenated substances excreted by the fish

4.3.2 Biotic factors

Different species of fish are extraordinarily diverse in terms of their social requirements, such as stocking density. Historically, fish chosen for aquaculture are robust under different conditions, which makes it easier to choose adequate management. That includes carrying out daily tasks on the farm without generating many sanitary complications in the fish. This is also the case for aquaponics, where the most popular fish is tilapia, well known for its hardiness.

However, in the beginning, we first had to domesticate wild species, which were normally difficult to manage, reproduce, and grow, but had a high economic value. That high value covered the costs of production of delicate species. A clear example is rainbow trout, which in the beginning was a very complex species, hard to produce and manage, even though now it seems relatively simple. Any poor management and inadequate movement of the fish produced stress and even loss of scales, which led to infections that brought on or facilitated disease and other common problems of fish that are stressed. Examples of species that are currently being domesticated, and have not reached their full potential in aquaculture, are burbot (*Lota lota*) and grayling (*Thymallus thymallus*). Technological development and accumulated knowledge have drastically improved the techniques used in the routine operations on farms, such as sampling of the fish, counting the fish, movement of live fish, etc. The main aspects that will influence the welfare of the fish in the tanks include:

1. Social structure: depending on the species, some are quite territorial, and we must manage these characteristics in the tanks. For example, we know that trout are quite territorial, and that they require frequent size grading during the initial phases of growth in order to avoid the appearance of dominant fish that will damage the smaller fish. In that case it is better to keep the fish within a narrow size range in separate tanks in order to improve production. We also know that tilapia and *Clarias* species show two different modes of behaviour: territorial if at low densities, and swarming/schooling if at high densities. Thus, low densities are not always better for all fish species.

2. Fish density: each species has a minimum and maximum stocking density below or above which problems may arise and fish welfare will be jeopardized. Density is normally measured in kg/m^3 and varies depending on the system. Some high output industrial RAS systems grow tilapia above 60 kg/m^3 but normally aquaponic systems use lower densities, around 20

kg/m^3 (see for example the Aquaponic Gardening Rules of Thumb), although values can range widely depending on fish size and RAS system.

3. Human disturbance: this depends on the species. Tench (*Tinca tinca*), for example, are quite flighty, and can hurt themselves by bumping into the tank walls when disturbed or even when they notice human shadows. One solution is to put curtains around the tanks to avoid being seen, or to set tanks on rubber supports to minimize vibrations from human steps or machines.

4. Prey or feed: the size of the feed should be appropriate for the size of the fish, and distributed throughout the tank so as not to promote dominant fish. Otherwise less proactive fish will not gain weight and tanks will need to be size sorted more often, which is stressful.

5. Predators. The presence of predators, such as cats, dogs or birds close to the tanks, can stress the fish a lot, and contact needs to be avoided by using artificial boundaries such as fences.

6. Loud noises, such as music (especially a strong bass sound) can be stressful for fish as well.

4.4 Proximate composition of fish feeds and essential nutrients

When research began on fish feeds more than 50 years ago, scientists first analysed the natural diets of the species in question. Trout, as an example of a carnivorous fish, had a natural diet that consisted of 50% protein, 15% fat, 8% fibre, and 10% ash, which is high in protein compared to terrestrial mammals. Ever since then researchers have been trying to find the right balance of protein, carbohydrates, fats, fibre, vitamins and minerals for fish used in aquaculture (Bhilave *et al.* 2014).

One of the most important components of any fish feed is protein. All proteins are composed of amino acids in different proportions. Thus, modern nutritionists tend to look at protein requirements in terms of amino acid requirements and aim to identify the ideal levels of the most important ones. This makes the whole system more efficient since fish are not getting any extra amino acids (that are then wasted), and have enough of the essential amino acids to grow healthily. Usually the level of protein is the first and most important question to ask when designing a diet. This is also a key issue in aquaponics since the protein in feed is the source of all the nitrogen waste that will later be used by plants (see Chapter 5).

Carbohydrates are composed of glucose, the main energy source for animals. In fish feed the most commonly found carbohydrate is starch, which helps to hold feed pellets together and provides an inexpensive source of energy. Although typically found in low amounts in fish feed, recent developments have led to an increase in its use. Now, in an effort to spare protein, that is, to reduce the amount of amino acids that are broken down to make energy, fish nutritionists are supplying more carbohydrates, with the advantage that the latter are also cheaper than protein (e.g., Lazzarotto *et al.* 2018). The only drawback is that this approach effectively makes many carnivorous fish more herbivorous, or vegetarian, since the extra carbohydrates are mostly of plant origin. Many studies in the past 5 years have been analysing how this can affect fish growth and welfare, and the results are promising.

Fats are made up of triglycerides or fatty acids which, like carbohydrates, provide energy to fish and, unlike carbohydrates, can be stored in different organs. Many fish, especially from colder waters, rely on high levels of fat in their diet (less than 15%), including omega-3 and omega-6 fatty acids. Fatty acids are also needed to transport fat-soluble vitamins. The relatively high levels of fat in most fish diets means that anti-oxidants are required to maintain their stability, avoiding degradation during processing and storage of the feed (Harper & Wolf 2009).

Crude fibre is the indigestible or difficult to digest part of feed that helps to promote gut motility (peristalsis). Ash represents the minerals in feed, such as potassium, phosphorus, copper and zinc. Exceeding the minerals that can be assimilated by the fish means that the extra minerals will be dissolved in the water. This is also important in aquaponics since we can design feeds that provide excess minerals that will end up being excreted by the fish and will therefore be available for the plants. However, it is usually a good idea to optimize feed for fish first.

An important concept in fish nutrition is the digestible protein to digestible energy ratio, often abbreviated as DP/DE. If the diet given to the fish is healthy and balanced, they will stop eating when they 'feel' their energy budget is reached. Energy can come from fat, carbohydrates or protein. As seen above, the most accessible source of energy is carbohydrate, followed by fat, and lastly protein. If the diet is high in protein compared to easily accessible energy (a high DP/DE), fish will have to eat more protein than they need to grow. Thus, that extra protein will not turn into muscle but will be broken down and used for other metabolic purposes, or simply wasted. On the other hand, if the DP/DE is low, then the fish will stop eating before then have enough to grow properly, and will be debilitated (Oliva-Teles 2012).

Table 2: Summary of feed composition (as percentage of dry weight) for a carnivore (trout) and a herbivore (tilapia). The remaining 10% includes ash with vitamins and minerals

	Trout[1]	Tilapia[2]
Protein	50	30
Carbohydrates	17	46
Fat	15	9
Fibre	8	5

[1]FAO 2018; [2]Tran-Ngoc *et al.* 2016

In summary, Table 2 provides the general composition of a diet for adult trout (carnivore) and adult tilapia (herbivore), the latter being the most commonly used fish in aquaponics. The amount of vitamins and minerals is low compared to the other main components, and depends on the vitamin/mineral mix used by the feed producer. For example, the aquaponic system at the Arizona State University that is used to grow tilapia uses feed with 5 mg/kg of folic acid and 66 mg/kg of vitamin E in terms of vitamins, and 7 mg/kg of phosphorus and 0.5 mg/kg of magnesium in terms of minerals (see Fitzimmons 2018), among others.

4.5 Types of feeds

In Europe, intensive aquaculture began at the end of the 19th century, when governments decided to breed fish to obtain fingerlings which were used to restock lakes and rivers (Polanco & Bjorndal 2018). Those fish represented an important source of protein for river communities, and helped to alleviate hunger. Efforts were made to promote the most appreciated species, such as salmonids, which are carnivorous. As production increased and fish were kept under intensive care for longer periods, farmers began to formulate feeds. In the beginning they captured macroinvertebrates in nearby water bodies, but that was seasonal and in limited supply. Later, fish were fed using waste products from slaughterhouses, which were chopped up into small pieces and thrown in the water directly. As a result, many salmon farms were established close to slaughterhouses.

Fish farms near ports used discarded fish from the fisheries but the supply was not always constant and was more difficult to organize as production increased. So farmers began making a paste with discarded fish that was blended together to make fish meal, to which they sometimes added plant protein. The paste could also be shaped into pellets, which facilitated spreading over many tanks, but since it was quite humid it could not be kept for very long periods before going bad. As time went on, fish nutritionists started to develop granulated feeds around the middle of 20th century. They were drier and were easier to formulate to the nutritional requirements of each species, and were much easier and cheaper to store.

Those first granulated or compound dry feeds facilitated the expansion of fish farms. Since then there has been intense research on the most appropriate and economically profitable raw materials to use in feed formulas. The whole process was improved by introducing the technique of extrusion, which applies high pressure to the feed paste during short intervals, increasing the temperature, making the granule lighter (allowing it to float in the water for longer periods) and allowing the incorporation of more fish oil. It also improved the compactness of the granules so that they did not dissolve immediately upon contact with water.

More recently efforts have been made to produce feeds that are more sustainable and organic. As mentioned above, for carnivores that means reducing the amount of fish meal in fish feed (and replacing it with plant protein like soya meal) and fish oil. For tilapia is also means reducing or eliminating any fish meal or fish oil, while maintain flesh quality. Recent research has focused on alternative protein sources for many types of fish, including the use of algae or insect meal.

4.6 Feeding strategies

Apart from using adequate feeds, we need to ensure that the pellets provided are the right size for the mouth of the fish. For small fish this usually means a fine powder and for larger fish a round pellet that can be several mm in diameter. For example, Aquaponics USA suggests using powder for tilapia from hatching to 3 weeks old, and then a fingerling crumble (1/32 inch or 0.9 mm) until they grow to about 2 cm in length, fingerling pellet (1/16 inch or 1.6 mm) until about 4 cm in length, and grow out pellet (3/16 inch or 4.8 mm) after about 6 cm in length.

It is also necessary to distribute the feed adequately. Normally feed is thrown onto the surface of the tank and personnel perceive how the fish react – whether they move to the surface and begin to eat (generally a good sign), or whether they remain on the bottom of the tank (generally a bad sign). However, in neither case is it obvious whether they are eating properly, how much ends up in their mouths, and how much is wasted. Due to these problems it is quite easy to overfeed.

In general, feed is distributed to the fish according to feeding tables that are prepared by the feed producer in terms of water temperature and growth stage. But the perception of the feeder, the personnel giving out the food, is very important since he/she can tell how hungry the fish are, and that is related to health and welfare. More and more efforts are being made to automate the process, and systems have improved considerably, but we cannot underestimate the importance of observing the fish, which is probably the best and most direct method of understanding their status. While much research has been performed to optimize feeding for maximum growth, it is obvious that if we provide less feed than they need, they will grow less, and the producer will lose money.

In order to understand the feeding process we need to define some concepts, based on Figure 2, which was developed by Skretting, an important feed company. We need to define the concept of maximum ration, which is the theoretically ideal ration to be given to the fish. However, it is specific to each farm since it depends on external conditions such as water quality and temperature, as well as tank design. The main concepts and indices used commercially include the following:

1. Feed conversion rate (FCR): this is the ratio between the amount of feed ingested (in kilograms or grams) divided by the live weight increase (in kg or g). On a commercial level we sometimes use an 'industrial FCR' which is an approximate figure based on all the feed provided over a period of time divided by the tonnes of fish produced during that same period. In that case, if there was mortality, we do not subtract the feed consumed by the fish before their death. This industrial FCR provides an idea of the real production costs. Another similar index is the biological conversion factor (BCF), which is the kg of feed really consumed by the fish divided by kg gained. It is harder to calculate the BCF at an industrial level since the fish have to be handled and the feed put down their throats, but is useful when we want to know the maximum efficiency of newly developed feeds. FCR describes the amount of feed needed for one kg weight gain by the fish:

$$FCR = \frac{Food\ fed\ to\ the\ fish\ [kg]}{Live\ weight\ gain\ [kg]}$$

This ratio reflects the nutritional and economic value of a feed. An FCR of 1 means that you have a live weight gain of 1 kg if you feed 1 kg of feed. The higher the FCR is, the higher your feed expenses are. Young fishes have a lower FCR (between 0.4 – 0.8), while adult fishes have an FCR between 0.9 – 2. The FCR depends on fish species and feed manufacturer. Sometimes you get more economic value with high quality food and the related better growth of the fish, in comparison to cheaper feed with a lower FCR.

2. Specific growth rate (SGR): this represents the percentage daily growth of fish. It is specific for each species and related to fish size and water temperature. Like the FCR it is dimensionless (no units) and is useful for comparing data between farms or species. The SGR shows the daily average growth of a fish in percentage of its bodyweight:

$$SGR\left[\frac{\%}{d}\right] = \left(\frac{lnW_2 - lnW_1}{T_2 - T_1}\right) * 100$$

where W_1 and W_2 denote the weight of fish at the beginning and at the end of the growth period, respectively, and (T_2-T_1) denote the duration of growth period in days.

3. The daily feed rate (DFR): the percentage of feed provided expressed as a percentage of fish weight (% fish weight per day). Normally this percentage is higher for younger fish (around 10%) and lower for older fish (around 1-2%).

4. Ration consumed: the ration really consumed by the fish.

5. Maintenance ration: the precise ration needed in order to maintain the fish at a constant weight without growth.

6. Maximum ration: the ration needed in order to obtain the maximum possible growth.

In Figure 2 we can visualize the concept of the maximum ration, which provides maximum growth of the species under culture. This maximum ration will be specific to each farm, and depends on local conditions. As we get nearer to the maximum ration, growth will increase, but if we go over the limit, we are wasting feed. However, in general terms it is advisable to feed small fish more than the maximum ration, since the waste will be small due to the small existing biomass, and we will tend to maximize growth. But in the case of final growth, we tend to be more prudent, since there is a large biomass in the water, and any extra feed that is lost will be costly and will increase the negative environmental impact, making it necessary to clean it up.

Following Figure 2, with a small ration the fish will use all the energy for their daily activities and may even lose weight (where the FCR will be infinite). If we increase the ration, the fish will improve their growth as well as the FCR. At the point of maximum growth, any feed provided in excess will be an economic and environmental problem, with no benefits for production. For that reason, we have to adjust the feed ration to the growth of the fish to a point that is close to the maximal ration, but being careful not to go past that point.

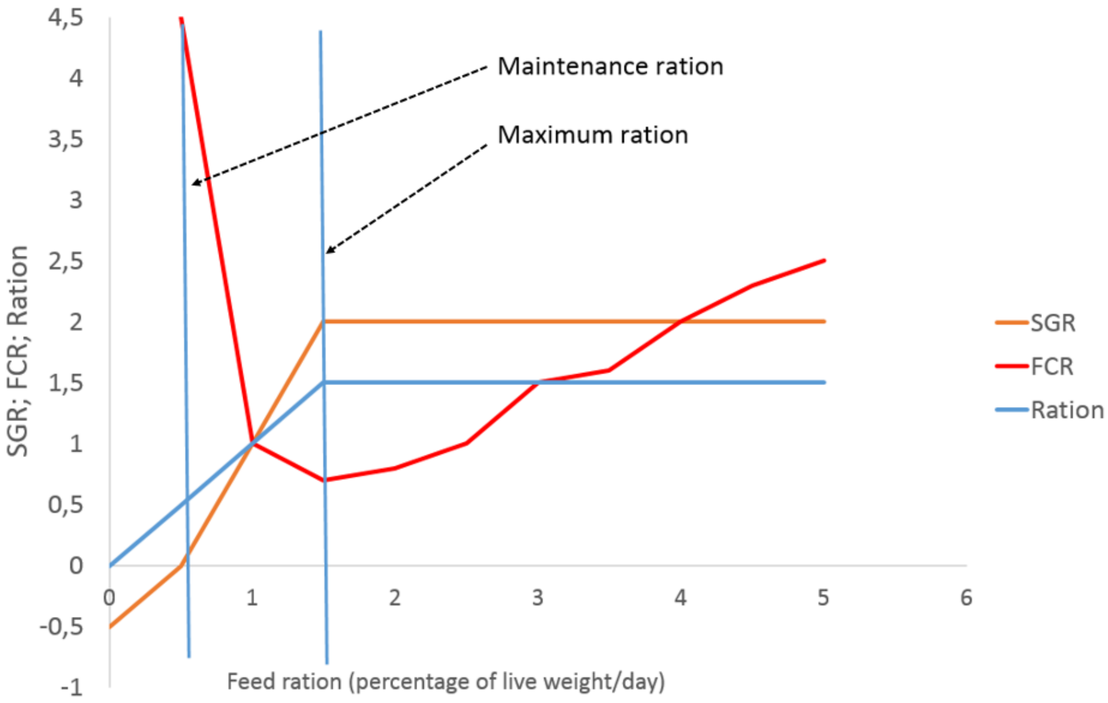

Figure 2: Evolution of specific growth rate (SGR), feed conversion rate (FCR) and ration of feed provided to the fish in terms of the percentage of feed per live-weight of the fish per day

As mentioned above, the control of biological processes involved in aquaculture requires supervision in order to anticipate possible problems. It is important to be able to fix problems as far in advance as possible, which implies detecting very mild symptoms at the outset. All that will help reduce production costs and improve efficiency. As a result, the aquaculture sector understands that it needs to train personnel adequately and continuously, especially those in charge of feeding.

Even in modernised aquaculture systems such as RAS, which are increasingly computerized and automated, personnel need to be aware of the sophisticated biological processes occurring within the unit. Technological developments are increasing but should be accompanied by adequate training in the use of available techniques to improve production on all levels. Those concepts are a foundation for success. Indeed, the continuous training of personnel involved in feeding is a very important tool in farm operations. The supervisor of feeding determines, to a large degree, the profitability of the farm, since he/she provides the energy for the fish to grow. Any changes in feeding habits, however small, can be a symptom of problems in the system which, if uncorrected, can become serious sanitary problems.

4.7 Automatic feeders

The automation of feeding requires knowledge about the feeding habits of the species in question. We also need to know technical details, such as the number of fish in each tank and their sizes. Manual feeding has advantages, as mentioned above, and is still used to ‘keep in touch’ with the fish. Nonetheless, technological developments can facilitate this labour. Nowadays there are many types of automatic feeders, especially for large-scale projects with a large biomass. Here we focus on the different types of automatic feeders used in RAS.

Normally the feed to be distributed is dry and pelleted, and placed directly into the tank where it may float for a time, but eventually it will tend to sink to the bottom. Most fish eat the feed on the surface or on its way down the water column, before it reaches the floor of the tank. Many species used in aquaponics are predators in the natural habitat and show aggressive behaviour when eating, which can lead to problems. Most modern automatic feeders take this fact into consideration, since poor feeding with inadequate feeders can lead to populations with dominant individuals who eat in excess, while the more submissive individuals go without. The immediate consequence is a higher variety of sizes in the tank (more intraspecific diversity in live weight), which makes it necessary to classify it more often, in order to break the social hierarchy and increase feed efficiency. Automatic feeders can be divided into two large groups, related to the biomass of fish and the quantity of feed to be distributed:

1. Feeders for juveniles: these distribute small rations at a high frequency (5-10 times a day). The pellet is very small and feed can be stored directly on the feeder and refilled by hand.

2. Feeders for on-growing: these distribute large quantities of feed at a relatively low frequency (1-3 times a day). Pellets are large and feeders are refilled by hand or automatically.

The cost of manually feeding fish is quite high in terms of time dedication needed to distribute it. The following company web sites provide details of feeder designs available for different species and aquaculture farms (www.acuitec.es; www.akvagroup.com; www.aquacultur.de). The basic parts of on-growing feeders are:

1. Storage or deposits for different types of pellets which originate from feed bags or silos delivered by truck.

2. Distribution of feed from the deposit onto the distribution site at the tank. Tubing runs from the storage site to the automatic feeder, which in turn has a small deposit. At this stage pellets are moved using mechanical systems or compressors and air injection. This equipment is quite specialized in order to ensure correct supply and adequate hygiene. Examples of the degree of sophistication of the feeding systems used in intensive aquaculture can be found at AKVA group. Some companies also use feeding robots for fingerlings in RAS, which is an automated way to fill up deposits near the tank. The robots move throughout the building using guides or rails that hang from the ceiling (see for example Crystalvision).

3. Distribution site
   This is the final part of the automatic feeding system. Here the feed has to be spread out on the surface of the tank all at the same time, thereby allowing all the fish to feed

simultaneously, which is better than placing the pellets in one small location. Thus, the distribution site is important for keeping the tank population more or less homogeneous.

4. Monitoring feed actually consumed
Recent technological developments allow one to detect when fish stop eating, which sends a signal to the automatic feeders to stop providing feed. These systems work with subaquatic cameras or acoustic and laser detectors, which let the feeder know when the appetite of the fish is waning.

4.8 Production plan and monitoring the evolution of the farm

All aquaponic farms need well defined production goals and a plan to fulfil those goals. Specifically, it is helpful to define the following aspects well in advance:

1. The species to be used
2. The size of fingerlings needed initially and the target size of the adults to be sold at the end. This will help to define the productive cycles on the farm (types of tanks, etc.)
3. The optimal densities and housing conditions for each stage of growth. This will help to define the maximum load of live biomass in the installation, and annual production
4. The health management to be used to maintain optimal conditions for the fish
5. The level of training of the personnel involved

The welfare of the fish and the economic viability of the installation will depend on compliance with the objectives that are budgeted in the project. We need to know whether fish are reaching their expected growth and transforming feed adequately, and whether mortality is higher than expected. We should know the expected growth curve in relation to the water temperature. That, along with the duration of the production system, will help to design a production plan that will be the basis for the operating costs. Once production has begun, it should be monitored adequately.

There should be clear traceability back to the source of the fish. We need to know the number of fish and their initial size on the first day that they were housed. On a daily basis we register each of the production activities that were carried out, such as the daily source of feed, the cleaning mode, and measures of physical and chemical parameters. In Figure 3 we present an example of the control sheet. These data are collected daily for each of the tanks and should be stored in the monthly report and processed in order to be able to determine the evolution of farm production. Periodically we should weigh a sample of fish to estimate growth in each tank. We should capture enough fish to represent the tank, normally at least 10-15 individuals per 100 fish. Feeding is then adjusted periodically according to that average fish weight.

Daily Control Sheet per Tank									
Tank number:				Treatment:					
Number of fish:				Average weight:			Density:		
Source tank:				Destination tank:					
Day	**Temperature (ºC)**	**Oxygen (mg/l)**	**Flow inlet (l/s)**	**Cleaning (partial/complete)**	**Mortality (number dead)**	**Feed (g)**	**Treatments (medical)**	**Marks**	**Observations (treatments, movements, incidents)**
1									
2									
3									
.									
.									
28									
29									
30									
31									

Figure 3: Data sheet to note details about the tanks and the fish on a daily basis

There are many software control programs on the market, such as those made by the Norwegian company AKVA GROUP, which are used to manage feed. They provide two programs. *Fishtalk* covers most aspects of control and planning on the farm, as well as production costs. The reports generated and the analysis of the evolution of production are the basis for the decisions to be taken by the manger, both in the short and long terms. *AKVAconnect* is related to the platform software provided by AKVA GROUP and controls the automation and optimal adjustments of processes and activities on the farm. It offers complete control, with permanent vigilance of the interaction between machines, sensors, and other processes.

Other examples of the information produced and processed during fish production is STEINSVIK for salmon production. In Figure 4 we can see a control screen for the production unit, with physical conditions and growth, fish appetite, fish inventory, the daily rhythm of feeding, etc. For other examples see www.aqua-manager.com.

Finally, as part of the production plan, it is important to maintain feeds under proper storage. Usually feeds are in the form of dry pellets made by extrusion, and hence are relatively easy to store. The quality of the pellets is high and they are quite compact, with limited losses in water since they will not break down easily. To maintain the quality of the dry feeds it is important to store them in silos or in a dry storage area that is insulated from excess heat. If the feed gets humid it can become contaminated with fungi, which in turn produce mycotoxins that can harm fish.

Figure 4: Control screen for the Steinsvik automation program for aquaculture farms.

4.9 Designing feeds for aquaponics

Fish feeds for aquaponics can be home-made or bought from specialized feed companies that formulate specific diets depending on the species and age of the fish. Normally commercial producers use specialized feeds since they are guaranteed to meet all the nutritional needs of the fish, and tend to be more cost effective compared to making and formulating one's own feed. However, formulated feeds are not always perfect and may have varying effects on the quality of the water where fish live and excrete waste. Only recently have scientists and engineers begun to look at specific diets for fish in recirculation systems and in aquaponic units. Theoretically it seems possible to provide fish with pelleted feed, which will help them to grow quickly, while providing enough nutrients for the plants that will later 'feed' on this water. In practice, however, things are more difficult, and depend on many complex parameters such as the temperature and pH of the recycled water, as well as microbiota in fish intestines and in biofilters. An aquaponics practitioner should know the basics of feed composition in order to have some way to judge which feed would be best to start off with. Although it may not be necessary to design feeds from scratch, students should be able to choose the best feed for this system after reading the following sections.

Fish growth and nitrogen retention

The nitrogen that will eventually be eliminated as ammonia by the fish comes from the protein in the feed. Although there is some nitrogen in other components of feed, almost all of the nitrogen absorbed by fish and eliminated as waste is from amino acids since, as their name suggests, they all contain nitrogen in the chemical makeup.

If we know the percentage of nitrogen in the feed, we can then calculate the approximate amount that will be excreted as ammonia into the water by a process similar to that of urination. That ammonia will later be turned into nitrate which will be provided to the plants. It should be noted here, however, that fish do not really urinate but, as opposed to most mammals, they eliminate nitrogenous waste through their branchia (similar to our lungs). In the following sections we will follow the source and fate of nitrogen in an aquaponic system, based on Seawright *et al.* (1998), who were one of the first groups to publish studies on nutrient cycling in aquaponic systems, several decades ago. In their paper they provide an equation for calculating the nitrogen balance in the system, which we will use as a guide. After calculating the nitrogen present in the feed, we calculate how much is retained in the fish, lost as uneaten feed, and lost in faeces, to end up with the concentration of ammonia in the surrounding water.

Nitrogen source

Feed is the main nitrogen source in our aquaponic system. In order to calculate the total amount of nitrogen placed into the tank via the feed we first need to know the exact amount of feed used, in grams or kilograms. Next we need to know the percentage of protein in the feed. This is normally shown on the feed label or available from the feed producer. As mentioned in previous sections, fish feeds have high proportions of protein, normally between 25% and 50%. Once we know the protein percentage we can calculate the percentage of nitrogen by dividing it by 6.25. We use that number since nutritionists assume that 1/6.25 or approximately 16% of all protein is nitrogen. Thus, for a feed for tilapia with 35% protein we know it has 35% * 16% = 5.6% nitrogen. If we added, for example, 120 grams of feed to the tank in one day, we are adding 120 * 5.6% = 6.72 g of nitrogen.

Nitrogen absorption by the fish

The fish will absorb nitrogen into its protein deposits, which is mostly its muscle. However, most of the fish body weight is water, so that weight has to be discounted since the nitrogen is only present in what can be called the 'dry weight of the muscle'. In general, and based on results in our lab and findings from the literature (e.g., Seawright *et al.* 1998), the dry weight of tilapia is about 27% of its body weight or, put another way, 73% of tilapia muscle is water.

Next we need to know the feed conversion rate (FCR). The FCR is the ratio between the feed provided divided by the weight gained. The inverse of the FCR is called the feed efficiency, or the weight gain divided by the feed ingested. The FCR is typically around 1-2 in fish. The feed efficiency, on the other hand, can be viewed as 1 divided by the FCR. That is, for a conversion index of 1.5, the feed efficiency is 1/1.5 = 66.73%. To put it another way, about two thirds of the feed eaten by the fish will be absorbed by the muscle of fish and counted as growth.

Of course it would be better to have a high feed efficiency (close to 100%); the higher it is, the more economically advantageous it is. However, fish have a maximum limit for how much muscle they can accrue over time. As muscle grows, the amount of protein will grow (as well as the amount of total nitrogen in the muscle), but the proportion of protein in the muscle will stay more or less stable. The total percentage of nitrogen with respect to body weight is around 8.8% in tilapia. This may vary among species, but is a good approximate number.

So, depending on the feed provided, we can estimate how much nitrogen will be retained in the fish. If we provide 120 g of feed using the values suggested above, then the nitrogen retained in fish will be found by multiplying the feed by the dry weight, by the feed efficiency and by the percentage of nitrogen in fish muscle, i.e., 120g * 27% * 66.73% * 8.8% = 1.90 grams of nitrogen from the feed will stay in the fish.

Nitrogen lost in solids

Apart from being lost as urine, nitrogen waste can be lost via faeces. We can measure the protein or nitrogen content of faeces since it accumulates in the solids filter of our system, or we can siphon it up daily and store it. The solid waste could also contain feed that was not ingested but, as mentioned above, it is difficult to measure exactly how much feed was not consumed by the fish, so we lump together faeces and feed not consumed as solid waste. Before analysis, the solid waste is dried in order to calculate the dry weight, and then the nitrogen content is measured. In a RAS system the total amount of solids is around 10%, i.e., 10% of the feed provided to the fish ends up as solid waste (including fish faeces and pellets that are not ingested). When analysed we found that the nitrogen content of the faeces was 4.8%.

As we explained earlier, protein is 16% nitrogen, or that is what nutritionists estimate. Thus, if we only have a measure of nitrogen, to obtain the amount of protein it came from originally we need to 'back-calculate' by dividing the amount of nitrogen by 16%, which is the same as multiplying it by 6.25% (1/16 = 0.0625 or 6.25%). So in the case where the nitrogen content of the faeces was 4.8%, the amount of protein would be 4.8% * 6.25% = 30%.

Finally, to calculate the total grams of nitrogen lost in solids per the amount of feed we provide to the tank, we need to multiply the amount of feed (120 g) by the percentage of feed that is lost in solids (faeces and feed not eaten), and the percentage of nitrogen in the solids (4.8%). Say that the percentage of feed lost in solids is 10%, the nitrogen lost in solids in that case would be: 120g * 10% * 4.8% = 0.576 g of nitrogen in the feed is lost as solids. Again, this is only an example, and that percentage can vary depending on the system and other conditions.

Nitrogen dissolved in water as ammonia

Next we can use the above calculations to quantify the nitrogen dissolved in the water, which is essentially lost as ammonia waste. First we add the nitrogen absorbed by the fish and lost in faeces, and then subtract it from the nitrogen applied via the feed. The remaining nitrogen is the amount lost or dissolved in the water. In the case above, 6.72 – (1.90 + 0.576) = 4.24 g NH_3. That is, 63.1% (4.24/6.72) of the nitrogen from the feed is converted into NH_3. It is excreted by the branchia as NH_3 but, depending on the water pH, it is converted into NH_4. The term TAN denotes total ammonia nitrogen, or the combination of NH_3 + NH_4. In Figure 6 we provide an example of results from our lab where the total nitrogen was calculated in feed, and then measured in the fish, faeces, and water.

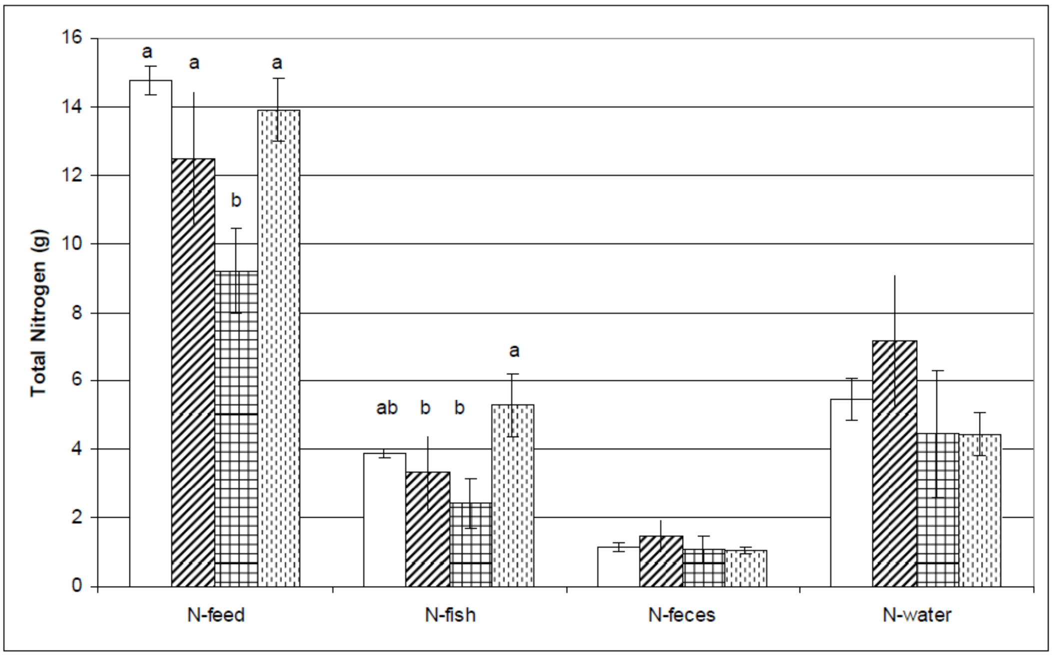

Figure 5: Example of a nitrogen cycle analysis in tilapia using four different feeds based on different protein sources (fish meal, soy, corn gluten, and pea concentrate)

4.10 References

Bhilave, M.P., Nadaf, S.B. & Deshpande, Y.V. 2014. Proximate analysis of formulated feed. Originally published in 2010 in *All About Feed* 1(9).

FAO 2018. Aquaculture Feed and Fertilizer Resources Information System. Rainbow trout. Food and Agriculture Organization of the United Nations.

Fitzimmons, K. 2018. Introduction to tilapia nutrition. University of Arizona.

Harper, C. & Wolf, J.C. 2009. Morphologic effects of the stress response in fish. *ILAR* 50 (4), 387-396.

Lazzarotto, V., Médale, F., Larroquet, L., & Corraze, G. 2018. Long-term dietary replacement of fishmeal and fish oil in diets for rainbow trout (Oncorhynchus mykiss): Effects on growth, whole body fatty acids and intestinal and hepatic gene expression. *PloS One*, 13(1), e0190730.

Oliva-Teles, A. 2012. Nutrition and health of aquaculture fish. *Journal of Fish Diseases* 35 (2), 83-108.

Polanco, J. F. & Bjorndal, T. 2018. Paper 2 Aquaculture diversification in Europe: the kingdom of Spain and the kingdom of Norway. In *Planning for aquaculture diversification: the importance of climate change and other drivers: FAO Technical Workshop 23–25 June 2016, Rome Italy* (p. 37). Food & Agriculture Org.

Seawright, D.E., Stickney, R.R. & Walker, R.B. 1998. Nutrient dynamics in integrated aquaculture-hydroponics systems. *Aquaculture* 160, 215-237.

Tran-Ngoc, K. T., Dinh, N. T., Nguyen, T. H., Roem, A. J., Schrama, J. W., & Verreth, J. A. 2016. Interaction between dissolved oxygen concentration and diet composition on growth, digestibility and intestinal health of Nile tilapia (*Oreochromis niloticus*). *Aquaculture* 462, 101-108.

Ranka Junge

5. NUTRIENT WATER BALANCE

5.1 Macro- and micronutrients

5.1.1 The elements of the universe

There are 92 naturally occurring elements on the Earth. Some are very well studied, some not at all: for example astatine (Bryson 2003). The problem is that some elements are very rare. For example, only 24.5 grams of francium occur at any time in the whole of the Earth's crust. Only about 30 of the naturally occurring elements are widespread on Earth, and very few are important for life (Figure 1). In the solar system, stars in general, and probably the universe as a whole, the most abundant elements are the lighter elements: over 75% hydrogen (H), 25 % helium (He), about 1% everything else. In the 'everything else' category even numbered elements are more abundant than odd numbered elements. Abundance tends to fall rapidly with increasing atomic number. However, carbon (C), oxygen (O), magnesium (Mg), silicon (Si), and iron (Fe) are anomalously high relative to these general trends, while lithium (Li), beryllium (Be), and boron (B) are anomalously low. In the Earth's crust the order of abundance is O (< 50%), Si (> 20%), Al, Fe, Mg, Ca, Na, and K. These are all the sorts of elements that rocks are mostly made out of. In the Earth as a whole, because of the core and the mantle, Fe, Ni, and Mg, become more common, while O, Si, Al remain major overall constituents (Table 1). Concerning life, elements have different functions (Table 2). We have evolved to utilize or tolerate the elements, but we live within narrow ranges of acceptance. As a rule, our tolerance for elements is directly proportionate to their abundance in the Earth's crust (Bryson 2003).

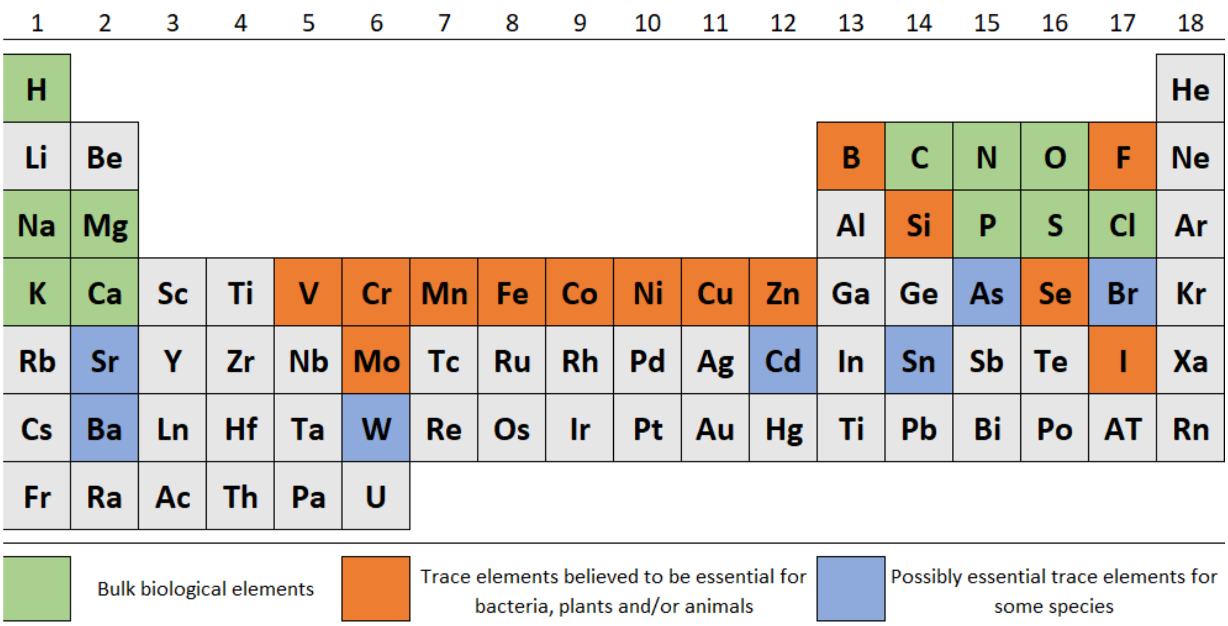

Figure 1: The distribution of naturally occurring elements known or believed to be essential for life in the periodic table. The understanding of the ecological importance of C, N, and P is much more advanced than it is for the other elements (redrawn after Da Silva & Williams 2001)

Table 1: The occurrence of elements in % dry weight of the Earth crust, green algae and animals (data from different sources) in comparison with lettuce grown in a hydroponic system, and fish feed (Schmautz, unpublished data). Note that the frequency (and with that the availability) of elements in the Earth crust does not match the frequency in living beings

Element	Symbol	Earth crust (%)	Diatoms (green algae)	Animals	Lettuce	Fish feed
Oxygen	O	47.4	44.4	18.6	59.9	69.2
Carbon	C	0.048	22.5	48.4	33.1	46
Hydrogen	H	0.15	4.6	8.7	4.9	6.8
Nitrogen	N	0.0025	3.8	8.7	4.7	7.6
Calcium	Ca	4.1	0.8	8.5	2.8	2.3
Phosphorous	P	0.1	0.425	4.3	1.2	1.3
Sulphur	S	0.026	0.6	0.54	0.6	0.8
Potassium	K	2.1	?	0.75	9.1	1.3
Sodium	Na	2.3	0.6	0.73	0.9	1.4
Magnesium	Mg	2.3	0.32	0.1	1.0	0.27
Silicium	Si	27.7	20	0.012	0.43	0.1
Aluminium	Al	8.2	0.1	0.0003	0.16	0.02
Iron	Fe	4.1	0.35	0.016	0.13	0.03

5.1.2 Macro- and micronutrients and their roles in organisms

Chemical elements have different roles and are mainly involved in different functions in an organism (Table 2). Organisms do not require all these elements in the same quantities. Some elements are required in large quantities, while others are required in minute quantities. This is illustrated nicely by the tentative stoichiometric formula for a living human being (Sterner & Elser 2002):

$$H_{375,000,000}O_{132,000,000}C_{85,700,000}N_{6,430,000}Ca_{1,500,000}P_{1,020,000}S_{206,000}Na_{183,000}K_{177,000}$$
$$Cl_{127,000}Mg_{40,000}Si_{38,600}Fe_{2,680}Zn_{2,110}Cu_{76}I_{14}Mn_{13}\ F_{13}Cr_{7}Se_{4}Mo_{3}Co_{1}$$

This means that for every cobalt (Co) atom in our body, there are 132 million oxygen (O) atoms. The major nutritional requirements of plants and animals, without which they are unable to complete a normal life cycle, are outlined in Figure 2. Macronutrients are required in larger quantities. Micronutrients are required in minute quantities.

Table 2: Primary functions and the chemical elements (or associated ions) involved in performing them for organisms (modified from Sterner & Elser 2002). Elements with a relatively minor role are indicated in parentheses

Function	Elements	Chemical form	Examples
Structural (biological polymers and support materials)	H, O, C, N, P, S, Si, B, F, Ca, (Mg), (Zn)	Involved in chemical compounds or sparingly soluble inorganic compounds	• biological molecules (proteins, DNA, fats, carbohyxdrates) • tissues (muscle, lung, leaves…) • skeletons; shells; teeth • plant support tissues (lignine, cellulose)
Electrochemical	H, Na, K, Cl, HPO_4^{2-}, (Mg), (Ca)	Free ions	• message transmission in nerves • cellular signalling • energy metabolism
Mechanical	Ca, HPO_4^{2-}, (Mg)	Free ions exchanging with bound ions	• Muscle contraction
Catalytic (acid-base)	Zn, (Ni), (Fe), (Mn)	Complexed with enzymes	• Digestion (Zn). Zinc oxidises alcohol. • Hydrolysis of urea (Ni) • PO_4 removal in acid media (Fe, Mn)
Catalytic (redox)	Fe, Cu, Mn, Mo, Se, (Co), (Ni), (V)		• Reactions with O_2 (Fe, Cu) • nitrogen fixation (Mo) • reduction of nucleotides (Co) • Co is necessary for the creation of Vitamin B_{12}

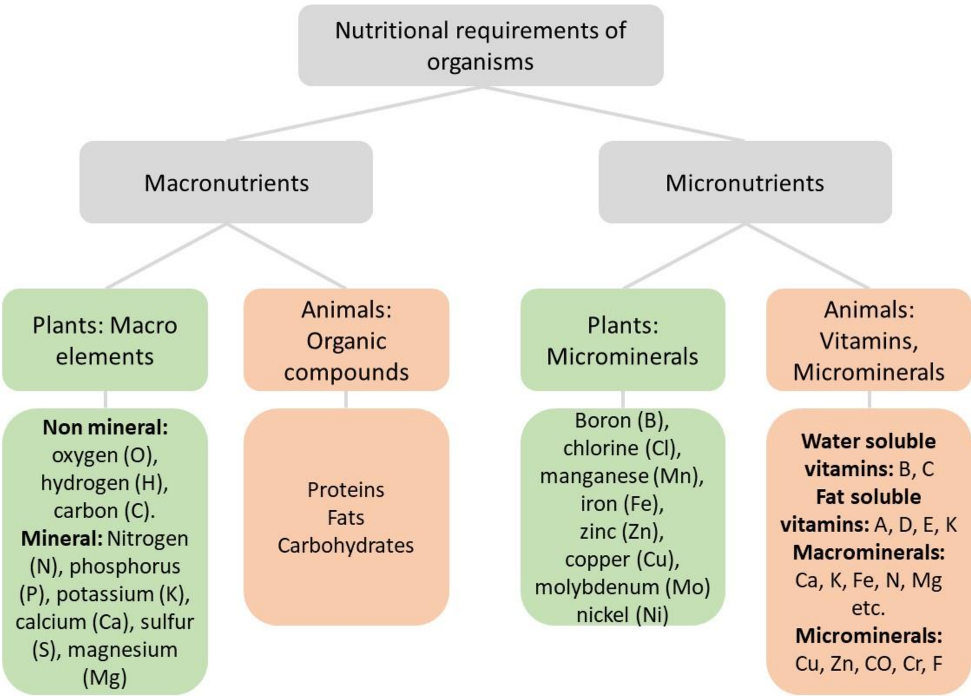

Figure 2: Nutritional requirements of plants and animals. Note that water (needed by all living beings) is not included in the chart. Animals obtain their nutrients from food and drink. Plants, with the exception of parasitic and carnivorous ones, absorb the essential nutrient elements from their environment (air, soil solution, nutrient solution)

5.2 The biogeochemical cycles of major nutrients in aquaponics

5.2.1 The nitrogen cycle

Nitrogen is an essential element for all living organisms and is the main nutrient of concern in aquaponics. It occurs in amino acids (parts of proteins), nucleic acids (DNA and RNA), and in the energy transfer molecule adenosine triphosphate (Pratt & Cornely 2014). As nitrogen occurs in many chemical forms, the nitrogen cycle is very complex (Figure 3).

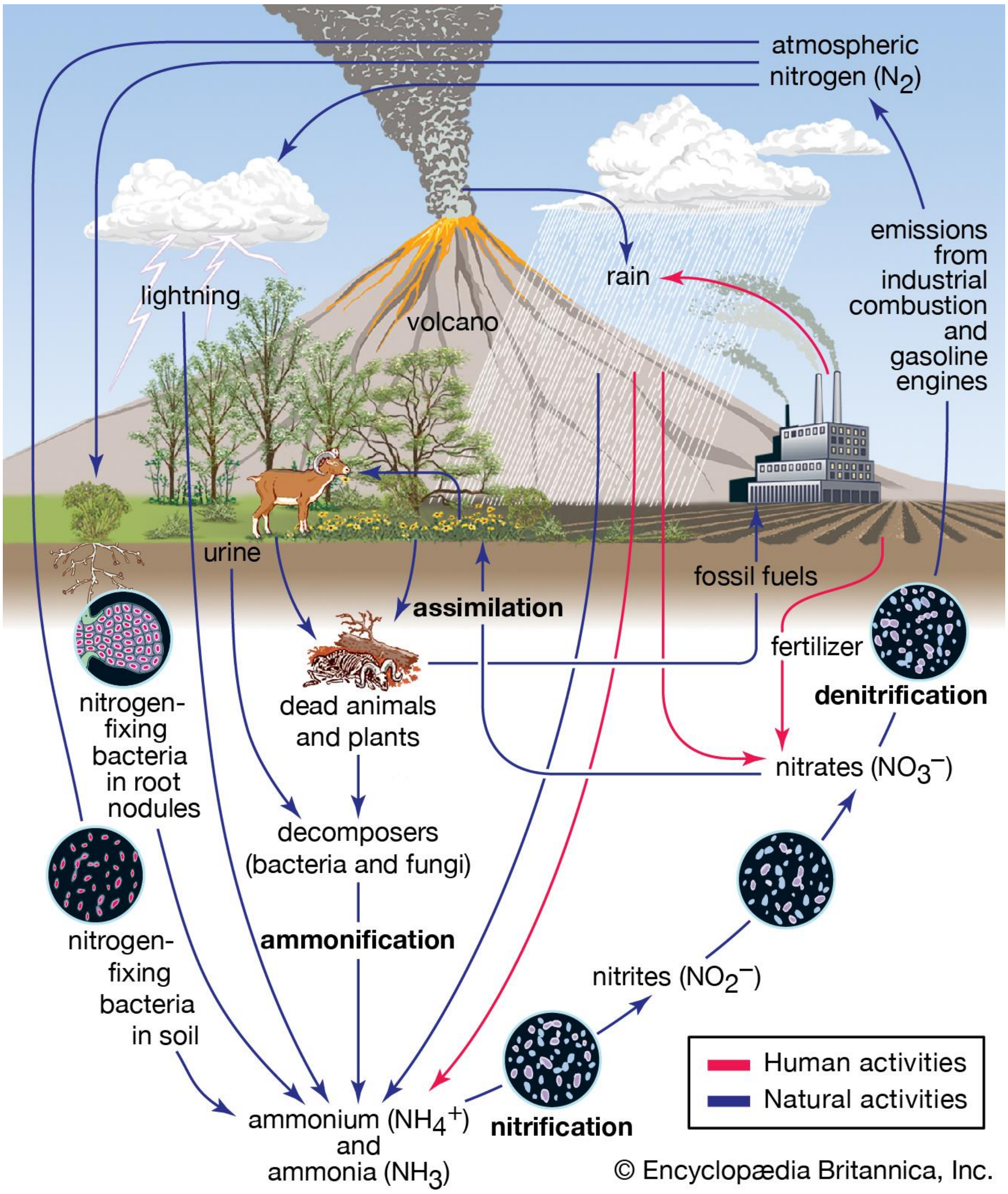

Figure 3: The general form of nitrogen cycle (Encyclopaedia Britannica)

The majority of Earth's atmosphere (78%) is atmospheric nitrogen gas, which is molecular dinitrogen (N_2). Nitrogen gas is very nonreactive and of no use for most organisms. Nitrogen fixation are all processes that convert atmospheric nitrogen gas into compounds that can be termed reactive nitrogen (Nr). Nr includes all biologically active, photochemically reactive, and radiatively active N compounds in the atmosphere and biosphere. It includes inorganic reduced forms of N (e.g., NH_3 and NH_4^+), inorganic oxidized forms (e.g., NO_x, HNO_3, N_2O, and NO_3^-), and organic compounds (e.g., urea, amines, and proteins) (Galloway *et al*. 2008).

Nitrogen fixation can occur naturally by lightning, as the very hot air breaks the bonds of N2 starting the formation of nitrous acid. It can be performed chemically in a reaction called the Haber-Bosch process. Biological nitrogen fixation occurs when N_2 is converted to ammonia by an enzyme called a nitrogenase. Microorganisms that fix N_2 are mostly anaerobic. Most legumes (beans, peas etc) have nodules in their root systems that contain symbiotic bacteria called rhizobia that help the plant to grow and compete with other plants. When the plant dies, the fixed nitrogen is released, making it available to other plants.

Figure 4 shows the nitrogen cycle as it occurs in aquaponics. In aquaponics two parts of the food chain (primary producers and consumers) which usually occur together are spatially separated into the aquaculture and hydroponic compartments. The synergistic effects that allow for efficient nutrient utilisation are mediated by microorganisms.

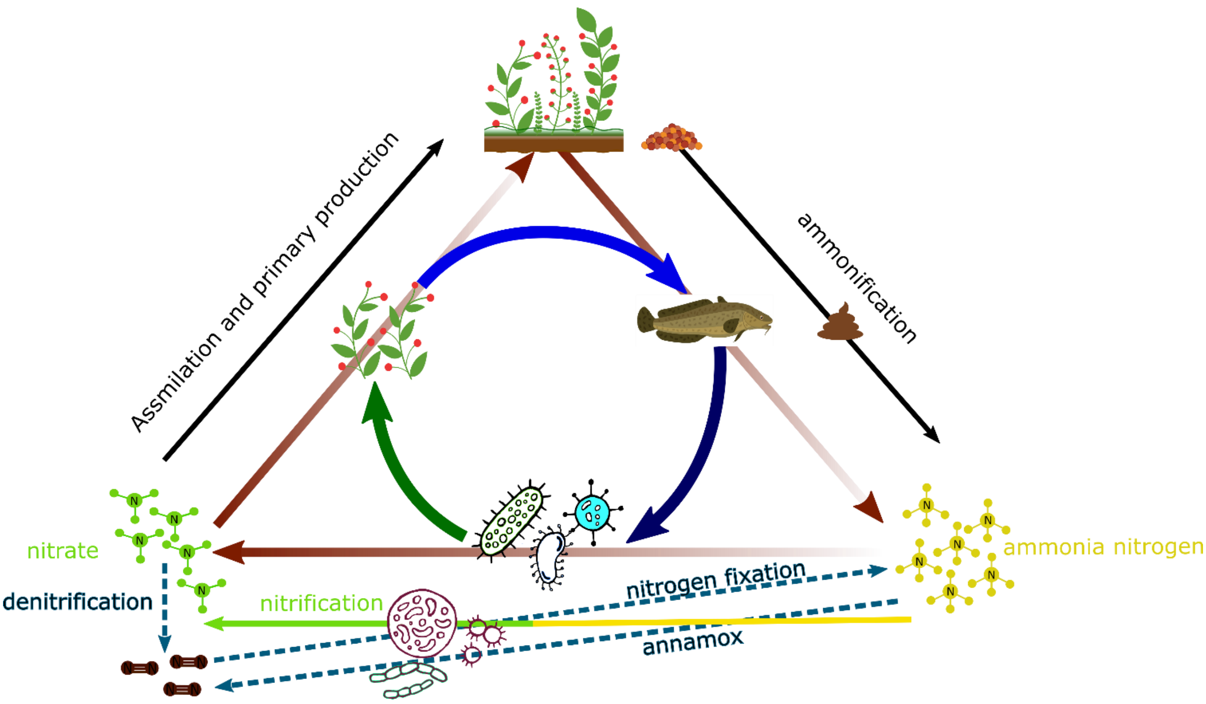

Figure 4: The nitrogen cycle in aquaponics.

Nitrogen enters the aquaponic system via fish feed, which is ingested by fish and later excreted as total ammonia nitrogen (TAN, ammonia - NH_3 and ammonium – NH_4^+) (Wongkiew *et al.* 2017). The nitrogen is converted to either ammonium (NH4 +) under acidic or neutral pH conditions, or ammonia (NH3) at higher pH levels. The ammonia concentration is dependent on the ammonium content, pH and temperature (Figure 5, Table 3). Ammonia is less soluble in water than NH4 +; therefore, NH_3 is rapidly converted to a gaseous form and emitted from the water (Gay & Knowlton 2009).

Whilst ammonium (NH_4^+) is not toxic, ammonia (NH_3) is. Therefore, TAN ought to be removed from the system water and ideally converted to nitrate for two reasons: (i) ammonia and nitrite, a secondary product of nitrification, are both harmful to fish, while nitrate is tolerated by the fish up to 150-300 mg/L (Graber & Junge 2009); (ii) TAN is not optimal for plants, which require predominantly nitrates or a mix of ammonium and nitrate for growth (Hu *et al.* 2015). This process of biological oxidation of ammonia or ammonium to nitrite followed by the oxidation of the nitrite to nitrate is called **nitrification** and mostly takes place in the biofilter of aquaponic systems (Table 4). Nitrification is an aerobic process performed by small groups of autotrophic bacteria and archaea and was discovered by the Russian microbiologist Sergei Winogradsky (1892).

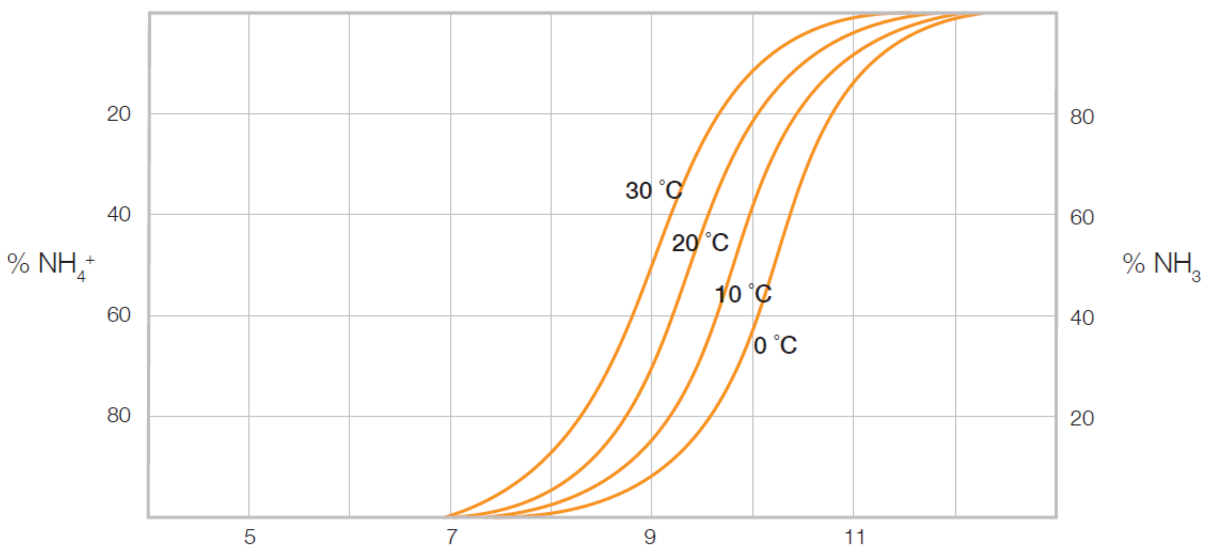

Figure 5: Ammonia-ammonium equilibrium as a function of different temperatures and pH
(from Cofie *et al.,* 2016)

Table 3: Percentage (%) of un-ionized ammonia in aqueous solution at different pH values and temperatures. To calculate the amount of un-ionized ammonia present, the Total Ammonia Nitrogen (TAN) concentration must be multiplied by the appropriate factor selected from this table using the pH and temperature from your water sample and divided by 100. If the resulting concentration is larger than 0.05 mg/L the ammonia is harming the fish (adapted after Francis-Floyd *et al.* 2009)

	pH																
T (°C)	**7.0**	**7.2**	**7.4**	**7.6**	**7.8**	**8.0**	**8.2**	**8.4**	**8.6**	**8.8**	**9.0**	**9.2**	**9.4**	**9.6**	**9.8**	**10.0**	**10.2**
6	0.13	0.21	0.34	0.53	0.84	1.33	2.10	3.28	5.10	7.85	11.90	17.63	25.33	34.96	46.00	57.45	68.15
8	0.16	0.25	0.40	0.63	0.99	1.56	2.45	3.83	5.93	9.09	13.68	20.08	28.47	38.68	50.00	61.31	71.52
10	0.18	0.29	0.46	0.73	1.16	1.82	2.86	4.45	6.88	10.48	15.65	22.73	31.80	42.49	53.94	64.98	74.63
12	0.22	0.34	0.54	0.86	1.35	2.12	3.32	5.17	7.95	12.04	17.82	25.58	35.26	46.33	57.78	68.44	77.46
14	0.25	0.40	0.63	1.00	1.57	2.47	3.85	5.97	9.14	13.76	20.18	28.61	38.84	50.16	61.47	71.66	80.03
16	0.29	0.46	0.73	1.16	1.82	2.86	4.45	6.88	10.48	15.66	22.73	31.80	42.49	53.94	64.99	74.63	82.34
18	0.34	0.54	0.85	1.34	2.11	3.30	5.14	7.90	11.97	17.73	25.46	35.12	46.18	57.62	68.31	77.35	84.41
20	0.39	0.62	0.98	1.55	2.44	3.81	5.90	9.04	13.61	19.98	28.39	38.55	49.85	61.17	71.40	79.83	86.25
22	0.46	0.72	1.14	1.79	2.81	4.38	6.76	10.31	15.41	22.41	31.40	42.04	53.48	64.56	74.28	82.07	87.88
24	0.52	0.83	1.31	2.06	3.22	5.02	7.72	11.71	17.37	25.00	34.56	45.57	57.02	67.77	76.92	84.08	89.33
26	0.60	0.96	1.50	2.36	3.70	5.74	8.80	13.26	19.50	27.74	37.83	49.09	60.45	70.78	79.33	85.88	90.60
28	0.69	1.10	1.73	2.71	4.23	6.54	9.98	14.95	21.78	30.68	41.16	52.58	63.73	73.58	81.53	87.49	91.73
30	0.80	1.26	1.98	3.10	4.82	7.43	11.29	16.78	24.22	33.62	44.53	55.99	66.85	76.17	83.51	88.92	92.71
32	0.93	1.50	2.36	3.69	5.72	8.77	13.22	19.48	27.68	37.76	49.02	60.38	70.72	79.29	85.85	90.58	93.89

Table 4: Chemical equations of nitrification. Nitrification is usually a two-step process, performed by a specialised group of bacteria, called nitrifiers

Equation	**Involved bacteria**
$NH_4^+ + 1.5\,O_2 \rightarrow NO_2^- + 2\,H^+ + H_2O + energy$	nitritation; ammonia oxidizing bacteria (AOB)
$NO_2^- + 0.5\,O_2 \rightarrow NO_3^- + energy$	nitratation; nitrite oxidizing bacteria (NOB)
$NH_4^+ + 2.0\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O + energy$	nitrifiers

The transformation of ammonia to nitrite is usually the rate limiting step of nitrification. This is because AOB (bacteria of the genus *Nitrosomonas, Nitrosospira, Nitrosovibrio* sp., etc.) and NOB (bacteria of the genus *Nitrobacter, Nitrospira, Nitrococcus,* etc.) have different growth rates, causing partial nitrification, especially during the start-up period, leading to NO_2^- accumulation until nitrifiers are fully established, which can take up to 4 weeks (Figure 6).

Denitrification (Table 5) is conversion of nitrate (NO_3-) to nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O) and finally to nitrogen gas (N_2) under anoxic and anaerobic conditions (very low or zero levels of dissolved oxygen). Denitrification is carried out by dentrifiers, who belong to taxonomically different groups of archaea and facultative heterotrophic bacteria. As N_2O is a more potent greenhouse gas than CO_2, its production has to be reduced to a minimum (Zou *et al.* 2016) in order to maximize the rates of incorporation of N into plant biomass.

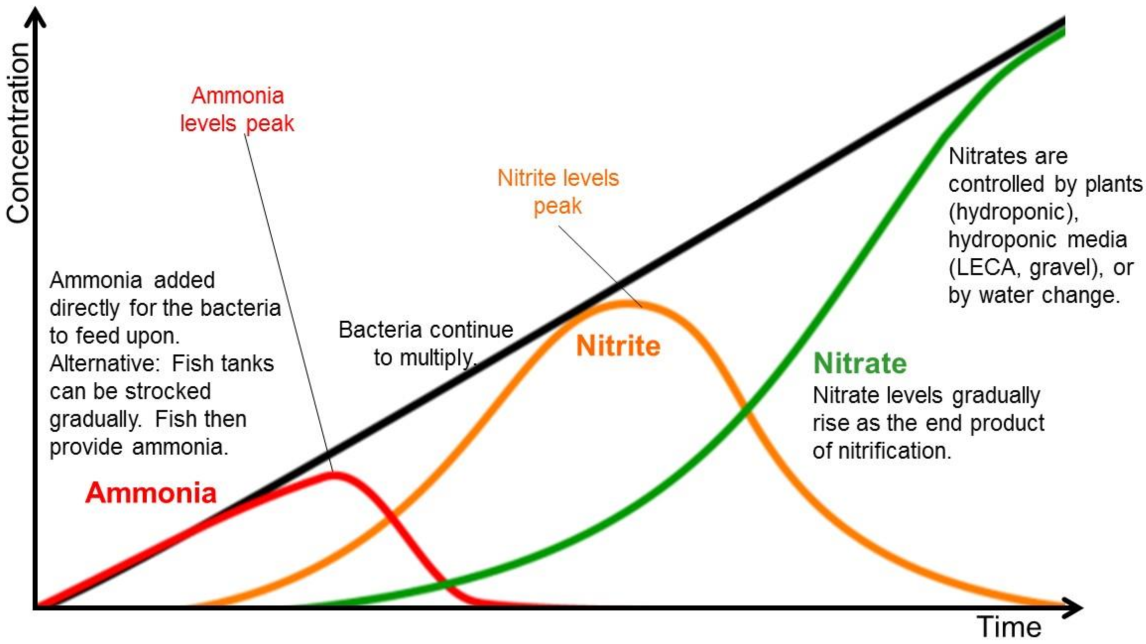

Figure 6: Starting the biofilter: development of ammonia, nitrite, and nitrate concentrations over time. (LECA denotes Light Expanded Clay Aggregate, a medium often used in hydroponics)

Table 5: Chemical equations of denitrification reactions. Denitrification generally proceeds through some combination of the following half reactions, with the enzyme catalysing the reaction in parentheses

Equations	Enzyme catalysing the reaction
$NO_3^- + 2\,H^+ + 2\,e^- \rightarrow NO_2^- + H_2O$	Nitrate reductase
$NO_2^- + 2\,H^+ + e^- \rightarrow NO + H_2O$	Nitrite reductase
$2\,NO + 2\,H^+ + 2\,e^- \rightarrow N_2O + H_2O$	Nitric oxide reductase
$N_2O + 2\,H^+ + 2\,e^- \rightarrow N_2 + H_2O$	Nitrous oxide reductase
$2\,NO_3^- + 12\,H^+ + 10\,e^- \rightarrow N_2 + 6\,H_2O$	The complete process can be expressed as a net balanced redox reaction

Anaerobic ammonium oxidation (anammox). The bacteria mediating this process were identified in 1999 (Strous *et al.* 1999). Anammox could exist in aquaponic systems because the water characteristics are similar to those in aquaculture systems, where the anammox process has been shown to occur (Wongkiew *et al.* 2017). However, the anammox rate is 10-fold slower than the nitrification rate. The anammox process has been reported to contribute to nitrogen loss in different ecosystems (Burgin & Hamilton 2007, Hu *et al.* 2010). Since ammonia and nitrite are available in aquaponic systems, nitrogen gas could be formed via the anammox process under anoxic conditions in the biofilter (Table 6).

Table 6: Chemical equation of annamox reaction

Equation	Involved bacteria
$NH_4^+ + NO_2^- \rightarrow N_2 + 2\,H_2O \quad + energy$	anammox bacteria

5.2.2 Phosphorus cycle

Phosphorus (P) is the second most important macronutrient for plant growth and it is required in relatively large amounts. It plays a role in respiration and cellular division and is used in the synthesis of energy compounds. P enters the aquaponic system by the way of fish feed, tap water, and fertilizer additions (if applicable). The chemical form in which P is present in the nutrient solution depends on the pH. The pKs (quantitative measure of acidity) for the dissociation of H_3PO_4 into $H_2PO_4^-$ and then into HPO_4^{2-} are 2.1 and 7.2 respectively (Schachtman *et al.* 1998, cited in da Silva Cerozi & Fitzsimmons 2016). Therefore, in the pH range maintained in aquaponic systems, P is mostly present in the form $H_2PO_4^-$, and less as H_3PO_4 or HPO_4^{2-}. Plants can only absorb P as the free orthophosphate ions $H_2PO_4^-$ and HPO_4^{2-}. Experimental and simulation studies have shown that P availability decreases with increasing pH of aquaponic water due to precipitation (Figure 7).

If the pH in aquaponic nutrient solution increases, P binds to several cations, so that fewer free P ions (PO_4) are available in solution, but there are more insoluble calcium phosphate species, which precipitate from the solution. These insoluble complexes can accumulate either in the fish sludge (Schneider *et al.* 2005) or in the sediments and periphyton on the walls and piping of the aquaponic system. Yogev *et al.* (2016) estimated that this loss can be up to 85%. One option to prevent this massive loss of P via sludge is to add a digestion compartment to the aquaponic system. During aerobic or anaerobic digestion, the P is released into the digestate and can be re-introduced into the circulating water (Goddek *et al.* 2016). da Silva Cerozi & Fitzsimmons (2016) also demonstrated the importance of organic matter and alkalinity in keeping free phosphate ions in solution at high pH ranges. It is recommended though that pH in aquaponic systems is maintained at a range of 5.5–7.2 for optimal availability and uptake by plants.

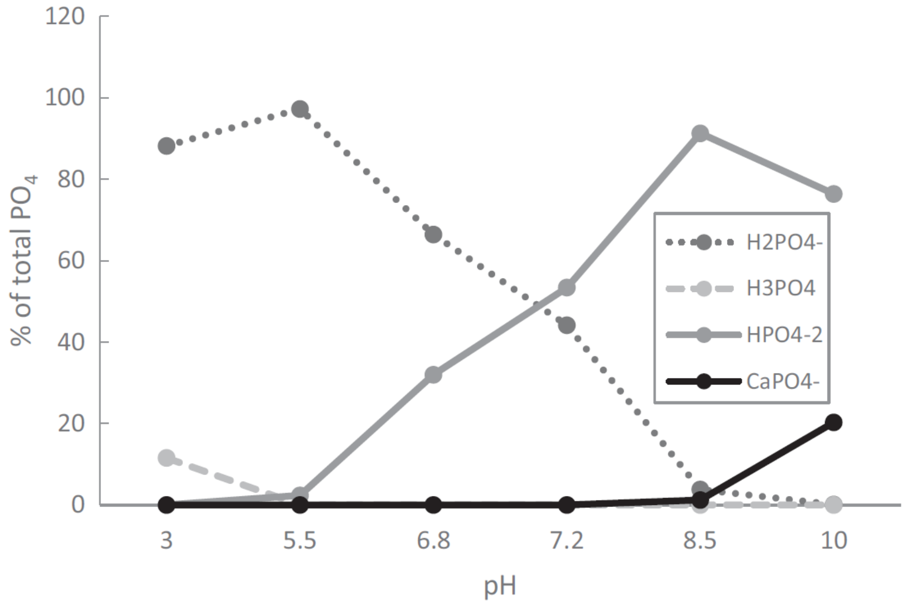

Figure 7: Speciation of the major forms of P in aquaponic solution as a function of pH as simulated in Visual MINTEQ. Note that not all PO_4 species are described in the chart (from da Silva Cerozi & Fitzsimmons 2016)

The precise dynamics of phosphorus in aquaponics is still not understood. The main input of phosphorus in the system is the fish feed, and in un-supplemented systems phosphorus tends to be limiting (Graber & Junge 2009; Seawright *et al.* 1998). This is also the reason why up to 100% of phosphorus present in the fish water can be recycled in the plant biomass, depending on the design of the system (Graber & Junge 2009).

5.3 Plant nutrition

5.3.1 Essential nutrient elements

Plants require 16 (Resh 2013) or according to other sources 17 (Bittszansky *et al.* 2016) essential nutrient elements without which they are unable to complete a normal life cycle. Plants require essential nutrients for normal functioning and growth. A plant's sufficiency range is the range of nutrient amount necessary to meet the plant's nutritional needs and maximize growth. The width of this range depends on individual plant species and the particular nutrient. Nutrient levels outside of a plant's sufficiency range cause overall crop growth and health to decline due to either a deficiency or toxicity.

Plants normally obtain their water and mineral needs from the soil. In hydroponics they still need to be supplied with water and minerals. In aquaponics, the situation is complicated by the fact, that the system water contains a highly complex mixture of organic and inorganic compounds originating from fish waste and fish food. There are two major categories of nutrients: macronutrients and micronutrients (Figure 8). Both types are essential, but in differing amounts. Much larger quantities of the six macronutrients are needed compared with the micronutrients, which are only needed in trace amounts (Jones & Olson-Rutz 2016).

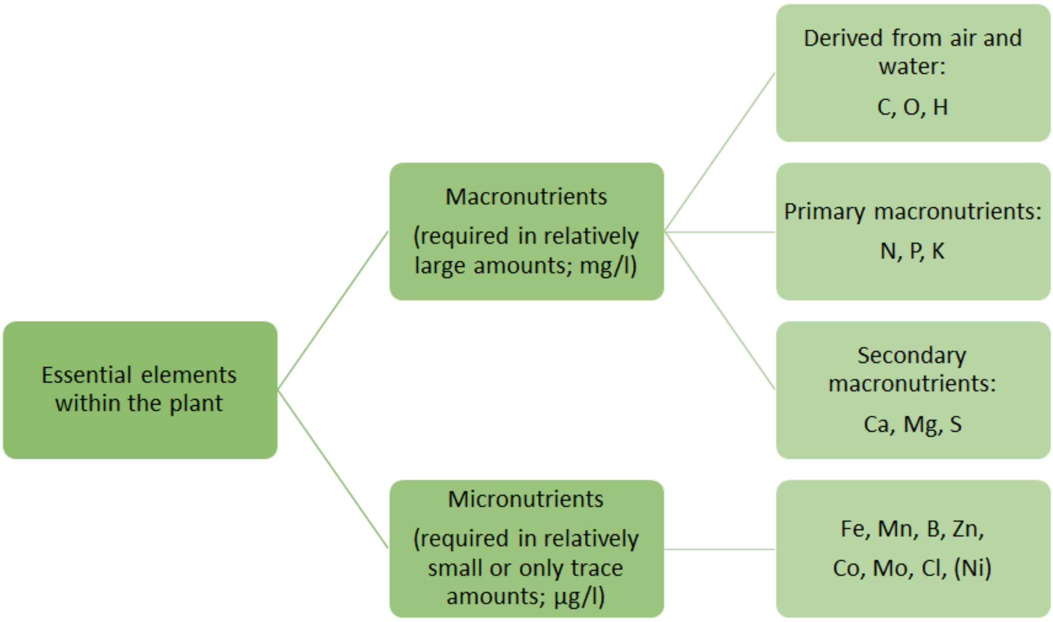

Figure 8: Classification of essential elements (nutrients) that are needed for the plant growth

Macronutrients are divided into three groups. The terms 'primary' and 'secondary' refer to the quantity, and not to the importance of a nutrient. A lack of a secondary nutrient is just as detrimental to plant growth as a deficiency of any one of the three primary nutrients, or a deficiency of micronutrients. A basic understanding of the function of each nutrient is important in order to appreciate how they affect plant growth (Table 6). A good orientation of how much of particular nutrient is required gives the elemental composition of plant material (Figure 9). If nutrient deficiencies occur, it is important to be able to identify which element is lacking in the system and adjust it accordingly by adding supplemental fertilizer or increasing mineralization (see also Chapters 6 and 9).

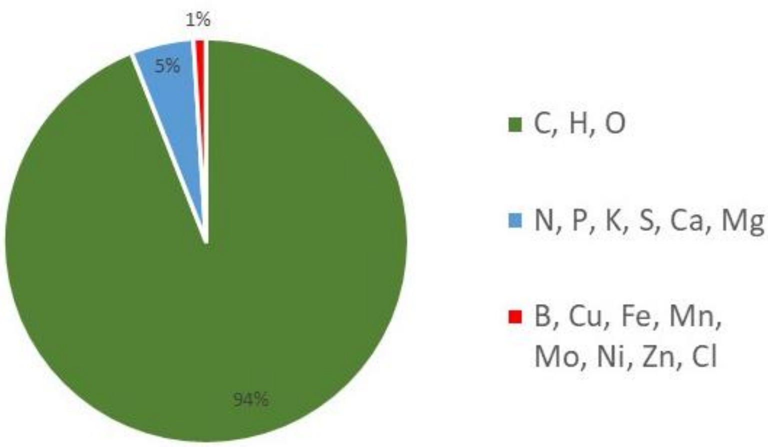

Figure 9: Representation of nutrient amounts in dried plant material

Table 6: Essential elements and their role in plants (adapted after Resh 2013)

Element	Role
Carbon (C)	C forms the backbone of most biomolecules, including proteins, starches and cellulose. Photosynthesis converts CO_2 from the air or water into carbohydrates which are used to store and transport energy within the plant.
Hydrogen (H)	H is constituent of all organic compounds of which carbon is a constituent. It is obtained almost entirely from water. It is important in cation exchange in plant–soil relations. H^+ ions are required to drive the electron transport chain in photosynthesis and in respiration.
Oxygen (O)	O is a component of many organic and inorganic compounds in plants. Only a few organic compounds, such as carotene, do not contain O. It can be acquired in many forms: O_2 and CO_2, H_2O, NO_3^-, $H_2PO_4^-$ and SO_4^{2-}. It is also involved in anion exchange between roots and the external medium. Plants produce O_2 during photosynthesis but then require O_2 to undergo aerobic respiration and break down this glucose to produce ATP.
Nitrogen (N)	N is part of a large number of organic compounds, including amino acids, proteins, coenzymes, nucleic acids, and chlorophyll. It is essential for photosynthesis, cell growth, and metabolic processes. Usually, dissolved N is in the form of nitrate, but plants can utilize moderate quantities of ammonia and even free amino acids.
Phosphorus (P)	P is part of the phospholipid backbone of nucleic acids (such as DNA, deoxyribonucleic acid), and adenosine triphosphate (ATP, the molecule that stores energy in the cells), and is contained in certain coenzymes. It is essential for photosynthesis, as well as the formation of oils and sugars, and encourages germination and root development in seedlings. As young tissues require more energy, it is particularly important for juveniles.
Potassium (K)	K acts as a coenzyme or activator for many enzymes. Protein synthesis requires high potassium levels. It is used for cell signalling via controlled ion flow through membranes. K also controls the opening of the stomata, and is involved in the development of flowers and fruit. It is also involved in the production and transportation of sugars, water uptake, disease resistance, and the ripening of fruits. K does not form a stable structural part of any molecules inside plant cells.
Calcium (Ca)	Ca is found in cell walls as calcium pectate, which cements together primary walls of adjacent cells. It is involved in strengthening stems, and contributes to root development. Required to maintain membrane integrity and is part of the enzyme α-amylase. It precipitates as crystals of calcium oxalate in vacuoles. Sometimes interferes with the ability of magnesium to activate enzymes.
Magnesium (Mg)	Mg is an essential part of the chlorophyll molecule. Without Mg, chlorophyll cannot capture the solar energy needed for photosynthesis. Mg is also required for activation of many enzymes needed for growth. It is essential to maintain ribosome structure, thus contributing to protein synthesis.
Sulphur (S)	S is incorporated into several organic compounds including amino acids (methionine and cysteine) and proteins (like photosynthetic enzymes). Coenzyme A and the vitamins

	thiamine and biotin also contain S.
Boron (B)	B is one of the less understood nutrients. It is used with Ca in cell wall synthesis and is essential for cell division. B increases the rate of transport of sugars from mature plant leaves to actively growing regions (growing point, roots, root nodules in legumes) and also to developing fruits. B requirements are much higher for reproductive growth as it helps with pollination, and fruit and seed development. Other functions include N metabolism, formation of certain proteins, regulation of hormone levels and transportation of K to stomata (which helps regulate internal water balance).
Chlorine (Cl)	Cl is classified as a micronutrient however plants may take up as much Cl as they do secondary elements such as S. Cl is important in the opening and closing of stomata. It is required for photosynthesis, where it acts as an enzyme activator during the production of oxygen from water. It functions in cation balance and transport within the plant. It is involved in disease resistance and tolerance. Cl competes with nitrate uptake, tending to promote the use of ammonium nitrogen. Lowering nitrate uptake may be a factor in chlorine's role in disease suppression, since high plant nitrates have been associated with disease severity.
Copper (Cu)	Cu activates some enzymes which are involved in lignin synthesis and it is essential in several enzyme systems. It is also required in photosynthesis, plant respiration, and assists in plant metabolism of carbohydrates and proteins. Cu also serves to intensify flavour and colour in vegetables, and colour in flowers.
Iron (Fe)	Fe is required for the synthesis of chlorophyll and some other pigments and is an essential part of ferredoxins. Ferredoxins are small proteins containing Fe and S atoms that act as electron carriers in photosynthesis and respiration. Fe is also part of the nitrate reductase and activates certain other enzymes.
Manganese (Mn)	Mn activates one or more enzymes in fatty acid synthesis, the enzymes responsible for DNA and RNA formation, and the enzymes involved in respiration. It participates directly in the photosynthetic production of O_2 from H_2O and is involved in chloroplast formation, nitrogen assimilation and synthesis of some enzymes. It plays role in pollen germination, pollen tube growth, root cell elongation, and resistance to root pathogens.
Molybdenum (Mo)	Mo acts as an electron carrier in the conversion of nitrate to ammonium before it is used to synthesize amino acids within the plant. It is essential for nitrogen fixation. Within the plant, Mo is used in conversion of inorganic phosphorus into organic forms.
Nickel (Ni)	Ni is the metal cofactor of urease-enzymes: without it they are inactive (Polacco *et al.* 2013). Ureases are present in bacteria, fungi, algae, and plants - but they are absent from fish and other animals. Urease enzymes are responsible for the catabolic detoxification of urea, potentially phytotoxic waste excreted by the fish.
Zinc (Zn)	Zn activates a series of enzymes that are responsible for the synthesis of certain proteins, including some important enzymes like alcohol dehydrogenase, lactic acid dehydrogenase etc. It is used in the formation of chlorophyll and some carbohydrates, conversion of starches to sugars and its presence in plant tissue helps the plant to withstand cold temperatures. Zn is required for the formation of auxins, which are hormones which help with growth regulation and stem elongation.

5.3.2 Nutrient availability and pH

Nutrients exist both as complex, insoluble compounds and as simple forms that are usually water soluble and readily available to plants. The insoluble forms must be broken down to available forms in order to benefit the plant. These available forms are summarized in Table 7.

Table 7: Absorbed nutrient forms and approximate concentrations in dry plant tissue (adapted from Jones & Olson-Rutz 2016)

Element	Form absorbed	Concentration range in dry plant tissue (%)
Nitrogen (N)	NO_3^- (nitrate) / NH_4^+ (ammonium)	1 - 5
Phosphorus (P)	$H_2PO_4^-$, HPO_4^{2-} (phosphate)	0.1 – 0.5
Potassium (K)	K^+	0.5 – 0.8
Calcium (Ca)	Ca^{2+}	0.2 - 1.0
Magnesium (Mg)	Mg^{2+}	0.1 – 0.4
Sulphur (S)	SO_4^{2-} (sulfate)	0.1 – 0.4
Boron (B)	H_3BO_3 (boric acid) / $H_2BO_3^-$ (borate)	0.0006 – 0.006
Chlorine (Cl)	Cl^- (chloride)	0.1 – 1.0
Copper (Cu)	Cu^{2+}	0.0005 – 0.002
Iron (Fe)	Fe^{2+}, Fe^{3+}	0.005 – 0.025
Manganese (Mn)	Mn^{2+}	0.002 – 0.02
Molybdenum (Mo)	MoO_4^{2-} (molybdate)	0.000005 - 0.00002
Nickel (Ni)	Ni^{2+}	0.00001 – 0.0001
Zinc (Zn)	Zn^{2+}	0.0025 – 0.015

The pH of the solution determines the availability of the various elements to the plant (Figure 10). The pH value is a measure of acidity. A solution is acidic if the pH is less than 7, neutral if the pH is at 7, and alkaline if the pH is above 7. Since pH is a logarithmic function, a one-unit change in pH means a 10-fold change in H^+ concentration. Therefore, any small change in pH can have a large effect on the ion availability to plants. Most plants prefer a pH between 6.0 and 7.0 for optimum nutrient uptake.

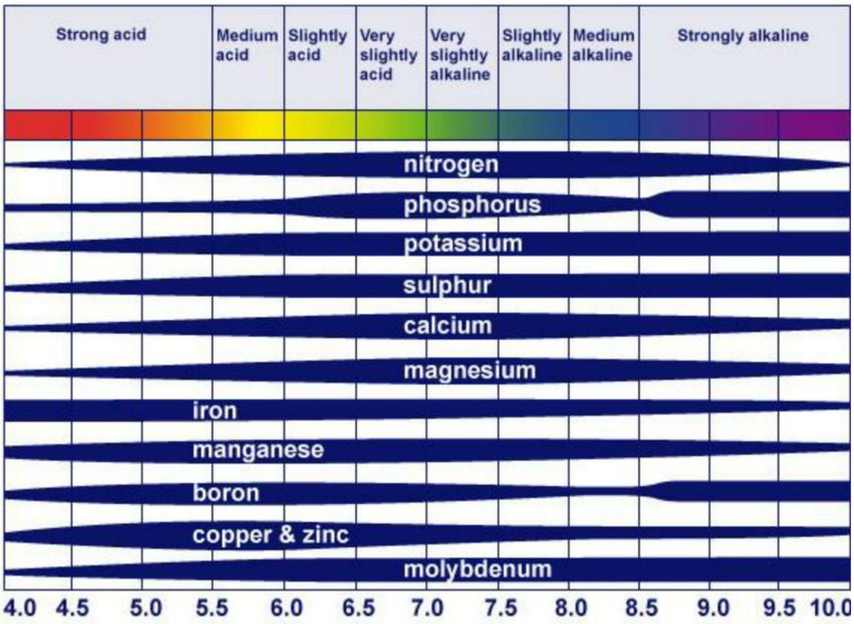

Figure 10: The effect of pH on the availability of plant nutrients (from Roques *et al.* 2013)

5.3.3 Nutritional disorders in plants

A nutritional disorder is caused by either excess or deficiency of a certain nutrient (Resh 2013). It is important to detect nutritional disorders as soon as possible, to prevent spreading of the symptoms and eventual death of the plant. However, the precise diagnosis of nutrient disorders is not easy, because many deficiencies have overlapping symptoms. To make things more complicated, there are also plant diseases that can cause similar symptoms. The only way to be able to distinguish these symptoms from one another is to acquire knowledge through practice. Observe your plants, note the different symptoms, and relate these to the results of the water quality analysis. Also, a beginner should always consult an expert.

One aspect of the diagnosis is the distinction between **mobile (Mg, P, K, Zn, N)** and **immobile elements (Ca, Fe, S, B, Cu, Mn)**. All nutrients move relatively easily from the root to the growing portion of the plant through the xylem. However, mobile elements can also be repositioned from older leaves to the actively growing region of the plant (younger leaves), when the deficiency occurs. As a result, the deficiency symptoms first appear on the older leaves. Conversely, immobile elements, once incorporated into the various structures, cannot be disassembled from these structures and re-transported through the plant. Deficiency symptoms first appear on the upper young leaves of the plant. Other aspects of diagnosis and their terminology are summarized in Table 8. Descriptions of deficiency and toxicity symptoms for essential elements are presented in Table 9.

Table 8: Terminology used for the description of symptoms of nutritional disorders (adapted from Resh 2013)

Term	Description
Generalized	Symptoms spread over entire plant or leaf
Localized	Symptoms limited to one area of plant or leaf
Drying	Necrosis—scorched, dry, papery appearance
Marginal	Chlorosis or necrosis—on margins of leaves; usually spreads inward as symptom progresses
Interveinal chlorosis	Chlorosis (yellowing) between veins of leaves
Mottling	Irregular blotchy pattern of indistinct light (chlorosis) and dark areas; often associated with virus diseases
Spots	Discoloured area with distinct boundaries adjacent to normal tissue
Colour of leaf undersides	Often a particular coloration occurs on the lower surface of the leaves, for example, phosphorus deficiency—purple coloration of leaf undersides
Cupping	Leaf margins or tips may cup or bend upward or downward
Checkered (reticulate)	Pattern of small veins of leaves remaining green while interveinal tissue yellows— manganese deficiency
Brittle tissue	Leaves, petioles, stems may lack flexibility, break off easily when touched—calcium or boron deficiency
Soft tissue	Leaves very soft, easily damaged—nitrogen excess
Dieback	Leaves or growing point dies rapidly and dries out—boron or calcium deficiencies
Stunting	Plant shorter than normal
Spindly	Growth of stem and leaf petioles very thin and succulent

Table 9: Deficiency and toxicity symptoms for essential elements (adapted from Resh 2013)

Element	Deficiency	Toxicity
Nitrogen (N)	Reduction in protein results in stunted growth and dormant lateral buds. Stems, petioles, and lower leaf surfaces of corn and tomato can turn purple. The chlorophyll content of leaves is reduced, resulting in general pale yellow colour, especially older leaves. Flowering, fruiting, protein and starch contents are reduced.	Plants usually dark green in colour with abundant foliage but usually with a restricted root system. Can cause difficulties in flower and fruit set.
Phosphorus (P)	Poor root development, stunted growth. Reddening of the leaves. Dark green leaves (may be confused with excessive N supply, as it also leads to darker green leaves). Delayed maturity. The tips of plant leaves may also appear burnt. Deficiency symptoms occur first in mature leaves.	No primary symptoms yet noted. Sometimes Cu and Zn deficiencies occur in the presence of excess P.
Potassium (K)	Deficiency will cause lower water uptake and will impair disease resistance. Symptoms first visible on older leaves. Margins of leaves curl inward. In dicots, these leaves are initially chlorotic but soon scattered burnt spots (dead areas) develop. In monocots, the tips and margins of the leaves die first.	Usually not excessively absorbed by plants. Excess K may lead to Mg, and possibly Mn, Zn or Fe deficiency.
Calcium (Ca)	Signs of deficiencies include tip burn on leafy plants and roots, blossom end rot on fruity plants, and improper growth of tomatoes. Young leaves are affected before old leaves.	No consistent visible symptoms.
Magnesium (Mg)	Without sufficient amounts of Mg, plants begin to degrade the chlorophyll in the old leaves. This causes interveinal chlorosis, the main symptom of Mg deficiency. Later, necrotic spots may occur in the chlorotic tissue. Growth is reduced.	No information.
Sulphur (S)	Not often encountered. S deficiency can be easily confused with lack of N. Symptoms, like delayed and stunted growth, are similar. However, general chlorosis occurs on younger leaves first, whereas N deficiency symptoms are first visible on older foliage.	Reduction in growth and leaf size. Sometimes interveinal yellowing or leaf burning.
Boron (B)	Symptoms vary with species and first appear on new leaves and the growing points (which often die. The branches and the roots are often short and swollen. Leaves show mottled chlorosis, thickening, brittleness, curling, wilting. Internal tissues sometimes disintegrate or discolour. Since B helps	Yellowing of leaf tip followed by progressive necrosis starting on the leaf margin and progressing toward midrib. Unlike most nutrient deficiencies that typically exhibit symptoms

	transport sugars, its deficiency causes a reduction of exudates and sugars from plant roots, which can reduce the attraction and colonization of mycorrhizal fungi.	uniformly across the crop, B symptoms can appear randomly within a crop (Mattson & Krug 2015).
Chlorine (Cl)	Wilting of leaves, often with stubby tips. Leaf mottling and leaflet blade tip wilting with chlorosis and necrosis. Roots become stunted and thickened near tips. Chlorine deficiency in cabbage is marked by an absence of the typical cabbage odour.	Excessive Cl can be as a major component of salinity stress and toxic to plants (Chen *et al.* 2010). Symptoms include scorched leaf margins, bronzing, yellowing, excessive abscission, reduced leaf size, lower growth rate. Cl accumulation is higher in older tissue.
Copper (Cu)	Natural deficiency is rare. Typically, the symptoms start as cupping of young leaves, with small necrotic spots on the leaf margins. As the symptoms progress, the newest leaves are smaller in size, lose their sheen and may wilt. The growth points (apical meristems) may become necrotic and die. Plants typically have a compact appearance as the stem length between the leaves shortens. Excess K, P or other micronutrients can indirectly cause Cu deficiency.	Reduced growth followed by symptoms of iron chlorosis, stunting, reduced branching, thickening, and abnormal darkening of rootlets.
Iron (Fe)	Pronounced interveinal chlorosis. Similar to Mg deficiency, but here chlorosis will start at the tips of younger leaves and will work its way to older leaves. Other signs, always be coupled with the leaf chlorosis, can include poor growth and leaf loss.	Not often evident in natural conditions. Has been observed after the application of sprays where it appears as necrotic spots.
Manganese (Mn)	Leaves turn yellow and there is also interveinal chlorosis, first on young leaves. Necrotic lesions and leaf shedding can develop later. Disorganization of chloroplast lamellae. Mn may be unavailable to plants where pH is high. This is why it often occurs together with Fe deficiency, and also has similar symptoms. The symptoms of Mn deficiency are also similar to Mg because Mn is also involved in photosynthesis.	Sometimes chlorosis, uneven chlorophyll distribution. Reduction in growth.
Molybdenum (Mo)	As Mo is closely linked to N, its deficiency can easily resemble N deficiency. Deficiency symptoms start on older or midstem leaves: interveinal chlorosis, in some crops the whole leaf turns pale; leaf marginal necrosis or cupping. Leaves can be misshapen. Crops that are most sensitive to Mo deficiency are crucifers (broccoli, cauliflower, cabbage), legumes (beans, peas, clovers), poinsettias and primula.	Rarely observed. Tomato leaves turn golden yellow.

Nickel (Ni)	Ni is part of enzymes that detoxify urea. Although urea is an excellent source of nitrogen for plants (Yang *et al.* 2015), at higher concentrations it is strongly toxic to plant tissues. Typical symptoms of urea toxicity, and potentially also of Ni deficiency, are leaf burn and chlorosis (Khemira *et al.* 2000).	Ni is strongly phytotoxic at higher concentration. In induces change in activity of antioxidant enzymes, and has a negative effect on photosynthesis and respiration. Excess Ni causes are chlorosis, necrosis and wilting. Cell division and plant growth are inhibited. High uptake of Ni induces a decrease in water content, which can act as an indicator for Ni toxicity in plants (Bhalerao *et al.* 2015).
Zinc (Zn)	Stunted growth, with shortened internodes and smaller leaves. Leaf margins are often distorted or puckered. Sometimes interveinal chlorosis.	Excess Zn commonly produces iron chlorosis in plants.

5.4 Nutrient supply in aquaponics

The chemical composition of system water in aquaponics is very complex. Besides a large array of dissolved ions, it contains organic substances resulting from the release of products of fish metabolism and feed digestion, as well as substances excreted by the plants. These substances are largely unknown, and their interactions can further influence the chemical composition and pH of aquaponic nutrient solutions. All this can exert manifold, but mostly yet unknown, effects on the nutrient uptake by plants, on fish health, and on microbial activity.

Nutrients enter an aquaponic system via added water and fish feed (Schmautz *et al.* 2016). In terms of elemental composition, fish feed contains about 7.5 % nitrogen, 1.3% phosphorus and 46% carbon (Schmautz, unpublished data). In terms of organic compounds, fish feed contains proteins (fishmeal or plant based), fats (fish oil, plant oils) and carbohydrates (Boyd 2015). Herbivorous fish (like Tilapia) need only about 25% protein in their feed, compared to carnivorous fish which require around 55% protein (Boyd 2015). Both fishmeal and soya are unsustainable (for different reasons), so there is intense research towards finding suitable fishmeal replacements and plant-based diets (Boyd 2015; Davidson *et al.* 2013; Tacon & Metian 2008).

If the feeding ratios are calculated correctly, all the feeds added to the system are eaten, and only whatever is not used for growth and metabolism is excreted (Figure 11). The proportion of excreted nutrients also depends on the quality and digestibility of the diet (Buzby & Lin 2014). The digestibility of the fish feed, the size of the faeces, and the settling ratio are all very important for the system operation (Yavuzcan Yildiz *et al.* 2017). Therefore, the nutrient composition of aquaponic system water, resulting from the quality of the added water, the added fish feeds, and the entire metabolic reactions in the system, is extremely complex and does not always match the plant requirements. However, the welfare of fish should be of central concern, and fish feed should be chosen to fit the fish species at each development stage. The availability of nutrients that can be assimilated by plants has to be regulated in a second step.

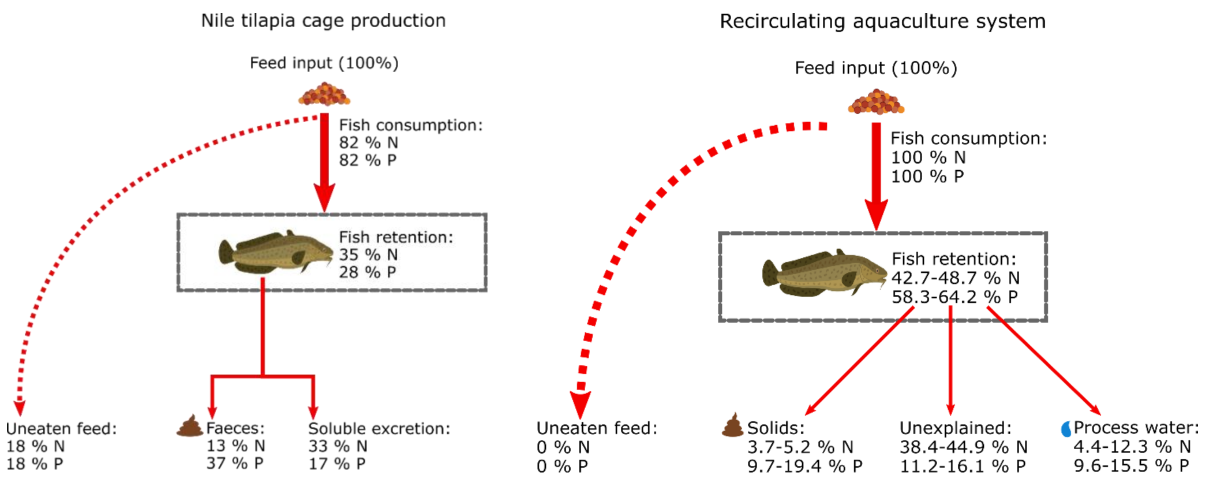

Figure 11: Environmental flow of nitrogen and phosphorus (in %) for (a) Nile Tilapia cage production (after Montanhini Neto & Ostrensky 2015); (b) RAS production (data from Strauch *et al*. 2018). 'Unexplained' denotes the fraction of N and P that could not be attributed to any category

The data in Table 10 show that most plant nutrients, but especially P and Fe, were at significantly lower concentrations in the investigated aquaponic system as compared with the standard hydroponic solutions. This seems to be a typical situation in aquaponic operation; however, the growth rates of aquaponic crops are nevertheless in most cases satisfactory (Schmautz, unpublished data). Let us have a closer look at this phenomenon.

Unfortunately, interpretation of these data is very difficult. The reason is that very recently in plant nutrition the nearly two-century-old 'Liebig's law' (plant growth is controlled by the scarcest resource) has been superseded by complicated mathematical models that take the interactions between the individual nutrient elements, compounds, and ions into account (Baxter 2015). These methods do not allow a simple evaluation of the effects of changes in nutrient levels in a hydroponic or aquaponic system. Also, we must bear in mind that a perfect formulation of nutritional requirements for a particular crop does not exist. The nutritional requirements vary with variety, life cycle stage, day length, and weather conditions (Bittszansky *et al.* 2016; Resh 2013; Sonneveld & Voogt 2009).

Very generally, for good plant growth in **hydroponics**, nitrogen concentration should stay above 165 mg/l N, phosphorus above 50 mg/l, and potassium above 210 mg/l (Resh 2013). In aquaponics, such high concentrations are difficult to achieve for several relevant elements because of three reasons:

1. The higher the concentrations in the water, the higher is the loss of nutrients through water exchange or sludge. However, even in closed system, a certain level of water exchange is

required, in order to compensate for evapotranspiration losses and to reduce accumulation of unwanted components.

2. With the elevated concentration of nutrients in the water, components like salt or toxins accumulate in the system as well.

3. Phosphorus reacts with calcium if this is present in higher concentrations and precipitates as calcium phosphate.

Plants growing in the hydroponic compartment have specific requirements which depend on the plant variety and the growth stage (Resh 2013). Nutrients can be supplemented either via the system water (Schmautz *et al.* 2016) or via foliar application (Roosta & Hamidpour 2011).

Table 10: Comparison of concentrations of nutrients in standard hydroponic solution and in water from a closed aquaponic system (Schmautz, unpublished data)

		Concentration [mg/l]		
		Aquaponics (Schmautz, unpublished)	**Hydroponics** (optimized for lettuce, Resh 2013)	**Concentration ratio** (hydroponic/aquaponic)
Macronutrients				
N	(as NO_3^-)	147	165	1.1
N	(as NH_4^+)	2.8	15	5.4
P	(as PO_4^{3-})	5.1	50	10
K	(as K^+)	84	210	2.5
Mg	(as Mg^{2+})	18	45	2.5
Ca	(as Ca^{2+})	180	190	1.1
S	(as SO_4^{2-})	21	65	3.1
Micronutrients				
Fe	(as Fe^{2+})	0.2	4	20
Zn	(Zn^{2+})	0.2	0.1	0.5
B	(as $B[OH_4]^-$)	0.1	0.5	5
Mn	(as Mn^{2+})	1.4	0.5	0.4
Cu	(as Cu^{2+})	0.1	0.1	1
Mo	(as MoO_4^{2-})	0.002	0.05	25

Usually, with appropriate fish stocking rates the levels of **nitrogen (N, as nitrate)** are sufficient for good plant growth, whereas the levels of several other nutrients, notably **iron (Fe), phosphorus (P),**

potassium (K) and magnesium (Mg) are generally insufficient for maximum plant growth. As seen in the table, other micronutrients could be limiting too. In aquaponic, it is especially important to monitor pH, because at a pH above 7 several nutrients (see Figure 10) may precipitate from water and become thus unavailable for plants.

Potassium (K) is not necessary for fish which leads to a low potassium composition of the fish feed and to even lower levels of potassium available for the plants (Seawright *et al.* 1998). To supply potassium, KOH pH buffer is often used, as the pH often decreases in aquaponics due to nitrification (Graber & Junge 2009). This has the added benefit of raising the potassium levels, although it can be toxic to fish. The LC50 value of acute fish toxicity was reported to be in the order of 80 mg/l. In aquaponic systems planted with tomato, potassium accumulated mainly in the fruits (Schmautz *et al.* 2016).

Iron (Fe) is also often a limiting factor in aquaponics, therefore it can be added as a preventive measure before the deficiencies become apparent. High concentrations of iron will not harm an aquaponic system, although it may give a slight red colour to the water. In order to ensure easy uptake by plants, iron has to be added as chelated iron, otherwise known as sequestered iron. There are different types of iron chelates: Fe-EDTA, Fe-DTPA, and Fe-EDDHA. Iron can be added into the system water (for example 2 mg L^{-1} once every two weeks) or sprayed directly on the leaves (foliar application) of 0.5 g L^{-1}) (Roosta & Hamidpour 2011).

The main source of **calcium (Ca), magnesium (Mg),** and **sulphur (S)** is tap water, which facilitates the absorption by the plants as the nutrients are already available (Delaide *et al.* 2017). Nevertheless, these elements are often at low levels in aquaponic systems (Graber & Junge 2009; Seawright *et al.* 1998, Schmautz, unpublished data). Especially **Ca** is often a limiting factor in aquaponics, as it can only be transported through active xylem transpiration. When conditions are too humid, calcium can be available but locked out because the plants are not transpiring. Increasing air flow with vents or fans can prevent this problem. Otherwise, calcium carbonate ($CaCO_3$) or calcium hydroxide ($Ca(OH)_2$) ought to be supplemented.

Zinc (Zn) is used as part of the galvanisation process of some metal parts, which may be used in construction of AP (fish tanks, bolts etc.), and it is found in fish waste. While zinc deficiencies are rare, zinc toxicity can pose a problem in aquaponics, because while plants can tolerate an excess, fish cannot. Levels of zinc should be kept between 0.03 - 0.05 mg/l. Most fish will be stressed at 0.1 to 1 mg/l, and will start dying at 4-8 mg/l. The best way to keep zinc levels within harmless range is to avoid galvanised equipment (Storey 2018). Nevertheless, in some systems zinc deficiencies might occur. Zinc deficiency can be alleviated by foliar application of chelated zinc (Treadwell *et al.* 2010).

The question thus arises whether it is necessary and effective to add nutrients to aquaponic systems (Nozzi *et al.* 2018). Provided that the system is stocked with enough fish, and the pH is within correct level it is not necessary to add nutrients for plants with a short cropping cycle which do not produce fruits (e.g. leafy greens such as lettuce, Nozzi *et al.* 2018). In contrast, fruiting vegetables (e.g.

tomatoes, aubergines) require nutrient supplementation. The amount of required mineral fertilizers can be calculating by using the HydroBuddy software (Fernandez 2016) (See also the exercise in Module 6). In addition to our experience in supplementing mineral nutrients, in the future commercially available organic hydroponic fertilizers should be tested in order to define which ones do not harm fish life. Recently, the treatment of the fish sludge in a digester, and re-introduction of this digestate into the water system, has been suggested to increase nutrient supply to the plants (Goddek *et al.* 2016). Another possible benefit of supplying the aquaponic system with organic, instead of mineral, nutrients could be a positive effect on the microbial population.

5.5 References

Baxter, I. 2015. Should we treat the ionome as a combination of individual elements, or should we be deriving novel combined traits? *Journal of Experimental Botany* 66 (8), 2127-2131.

Bhalerao, S.A., Sharma, A.S. & Poojari, A.C. 2015. Toxicity of nickel in plants. *International Journal of Pure and Applied Biosciences* 3 (2), 345-355.

Bittsanszky, A., Uzinger, N., Gyulai, G., Mathis, A., Junge, R., Villarroel, M., Kotzen B. & Kőmíves, T. 2016. Nutrient supply of plants in aquaponic systems. *Ecocycles* 2 (2), 17-20.

Boyd, C.E. 2015. Overview of aquaculture feeds: Global impacts of ingredient use. In D.A. Davis (ed.) *Feed and Feeding Practices in Aquaculture*, pp. 3-25. Woodhead Publishing Series in Food Science, Technology and Nutrition, Sawston.

Bryson, B. 2003. *A Short History of Nearly Everything.* Doubleday, London.

Burgin, A.J. and Hamilton, S.K. 2007. Have we overemphasized the role of denitrification in aquatic ecosystems? A review of nitrate removal pathways. *Frontiers in Ecology and the Environment* 5 (2), 89-96.

Buzby, K.M. & Lin, L.S. 2014. Scaling aquaponic systems: Balancing plant uptake with fish output. *Aquacultural Engineering* 63, 39-44.

Chen, W., He, Z.L., Yang, X.E., Mishra, S. & Stoffella, P.J. 2010. Chlorine nutrition of higher plants: progress and perspectives. *Journal of Plant Nutrition* 33 (7), 943-952.

Cofie, O., Nikiema, J., Impraim, R., Adamtey, N., Paul, J. and Koné, D. 2016. Co-composting of Solid Waste and Fecal Sludge for Nutrient and Organic Matter Recovery. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE). 47p. (Resource Recovery and Reuse Systems Series 3).

da Silva Cerozi, B. & Fitzsimmons, K. 2016. The effect of pH on phosphorus availability and speciation in an aquaponics nutrient solution. *Bioresource Technology* 219, 778-781.

Da Silva, J.F. & Williams, R.J.P. 2001. *The Biological Chemistry of the Elements: The Inorganic Chemistry of Life*. Oxford University Press, Oxford.

Davidson, J., Good, C., Barrows, F.T., Welsh, C., Kenney, P.B. & Summerfelt, S.T. 2013. Comparing the effects of feeding a grain-or a fish meal-based diet on water quality, waste production, and rainbow trout *Oncorhynchus mykiss* performance within low exchange water recirculating aquaculture systems. *Aquacultural Engineering* 52, 45-57.

Delaide, B., Delhaye, G., Dermience, M., Gott, J., Soyeurt, H. & Jijakli, M.H. 2017. Plant and fish production performance, nutrient mass balances, energy and water use of the PAFF Box, a small-scale aquaponic system. *Aquacultural Engineering* 78, 130-139.

Fernandez, D. 2016. *HydroBuddy v1.62: The First Free Open Source Hydroponic Nutrient Calculator Program Available Online*.

Francis-Floyd, R., Watson, C., Petty, D. & Pouder, D.B. 2009. *Ammonia in Aquatic Systems*. University of Florida, IFAS Extension. Publication #FA 16.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P. & Sutton, M.A. 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science* 320 (5878), 889-892.

Gay, S.W. & Knowlton, K.F. 2009. *Ammonia Emissions and Animal Agriculture*. Virginia Cooperative Extension (VCE) Publications, No. 442-110.

Goddek, S., Schmautz, Z., Scott, B., Delaide, B., Keesman, K.J., Wuertz, S. & Junge, R. 2016. The effect of anaerobic and aerobic fish sludge supernatant on hydroponic lettuce. *Agronomy* 6 (2), 37.

Graber, A., & Junge, R. 2009. Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination* 246 (1-3), 147-156.

Hu, B.L., Zheng, P., Tang, C.J., Chen, J.W., van der Biezen, E., Zhang, L., Ni, B.J., Jetten, M.S., Yan, J., Yu, H.Q. & Kartal, B. 2010. Identification and quantification of anammox bacteria in eight nitrogen removal reactors. *Water Research* 44 (17), 5014-5020.

Hu, Z., Lee, J.W., Chandran, K., Kim, S., Brotto, A.C. & Khanal, S.K. 2015. Effect of plant species on nitrogen recovery in aquaponics. *Bioresource Technology* 188, 92-98.

Jones, C. & Olson-Rutz, K. 2016. *Plant nutrition and soil fertility*. Montana State University Extension, Nutrient Management Module No. 2.

Khemira, H., Sanchez, E., Righetti, T.L. & Azarenko, A.N. 2000. Phytotoxicity of urea and biuret sprays to apple foliage. *Journal of Plant Nutrition* 23 (1), 35-40.

Mattson, N. & Krug, B. 2015. *Identifying Boron Deficiency and Corrective/Preventative Actions*. Cornell University Cooperative Extension/University of New Hampshire Cooperative Extension.

Montanhini Neto, R. & Ostrensky, A. 2015. Nutrient load estimation in the waste of Nile tilapia *Oreochromis niloticus* (L.) reared in cages in tropical climate conditions. *Aquaculture Research* 46 (6), 1309-1322.

Nozzi, V., Graber, A., Mathis, A., Schmautz, Z. & Junge, R. 2018. Nutrient management in aquaponics: comparison of three approaches on lettuce, mint and mushroom herbs. *Agronomy* 8 (3), 27.

Polacco, J.C., Mazzafera, P. & Tezotto, T. 2013. Opinion–nickel and urease in plants: still many knowledge gaps. *Plant Science* 199, 79-90.

Pratt, C.W. & Cornely, K. 2014. *Essential Biochemistry* (3rd edition). John Wiley and Sons Inc., MA.

Resh, H.M. 2013. *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower*. CRC Press, Boca Raton.

Roosta, H.R. & Hamidpour, M. 2011. Effects of foliar application of some macro-and micro-nutrients on tomato plants in aquaponic and hydroponic systems. *Scientia Horticulturae* 129 (3), 396-402.

Roques, S., Kendall, S., Smith, K., Newell Price, P. & Berry, P. 2013. *A review of the non-NPKS nutrient requirements of UK cereals and oilseed rape*. Research Review No. 78. HGCA, Kenilworth.

Schachtman, D.P., Reid, R.J. & Ayling, S.M. 1998. Phosphorus uptake by plants: from soil to cell. *Plant Physiology* 116 (2), 447-453.

Schmautz, Z., Loeu, F., Liebisch, F., Graber, A., Mathis, A., Bulc, T.G. & Junge, R. 2016. Tomato productivity and quality in aquaponics: Comparison of three hydroponic methods. *Water* 8 (11), 533.

Schneider, O., Sereti, V., Eding, E.H. & Verreth, J.A.J. 2005. Analysis of nutrient flows in integrated intensive aquaculture systems. *Aquacultural Engineering* 32 (3-4), 379-401.

Seawright, D.E., Stickney, R.R. & Walker, R.B. 1998. Nutrient dynamics in integrated aquaculture–hydroponics systems. *Aquaculture* 160, 215–237.

Sonneveld, C. & Voogt, W. 2009. *Plant Nutrition of Greenhouse Crops*. Springer, Springer Netherlands.

Sterner, R.W. & Elser, J.J. 2002. *Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere*. Princeton University Press.

Storey, N. 2018. Why You Need to Be Careful About Zinc in Aquaponics. Upstart University.

Strauch, S., Wenzel, L., Bischoff, A., Dellwig, O., Klein, J., Schüch, A., Wasenitz, B. and Palm, H. 2018. Commercial African catfish (*Clarias gariepinus*) recirculating aquaculture systems: Assessment of element and energy pathways with special focus on the phosphorus cycle. *Sustainability* 10 (6), 1805.

Strous, M., Fuerst, J.A., Kramer, E.H., Logemann, S., Muyzer, G., van de Pas-Schoonen, K.T., Webb, R., Kuenen, J.G. & Jetten, M.S. 1999. Missing lithotroph identified as new planctomycete. *Nature* 400 (6743), 446.

Tacon, A.G. & Metian, M. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture* 285 (1-4), 146-158.

Treadwell, D., Taber, S., Tyson, R. & Simonne, E. 2010. *Foliar-applied micronutrients in aquaponics: A guide to use and sourcing*. University of Florida IFAS Extension, HS1163.

Winogradsky, S. 1892. Contributions à la morphologie des organismes de la nitrification. *Arch. Sci. Biol*. 1, 87–137.

Wongkiew, S., Hu, Z., Chandran, K., Lee, J.W. & Khanal, S.K. 2017. Nitrogen transformations in aquaponic systems: A review. *Aquacultural Engineering* 76, 9-19.

Yang, H., Menz, J., Häussermann, I., Benz, M., Fujiwara, T. & Ludewig, U. 2015. High and low affinity urea root uptake: involvement of NIP5; 1. *Plant and Cell Physiology* 56 (8), 1588-1597.

Yavuzcan Yildiz, H., Robaina, L., Pirhonen, J., Mente, E., Domínguez, D. & Parisi, G. 2017. Fish welfare in aquaponic systems: its relation to water quality with an emphasis on feed and faeces—a review. *Water* 9 (1), 13.

Yogev, U., Barnes, A. & Gross, A. 2016. Nutrients and energy balance analysis for a conceptual model of a three loops off grid, aquaponics. *Water* 8 (12), 589.

Zou, Y., Hu, Z., Zhang, J., Xie, H., Liang, S., Wang, J. & Yan, R. 2016. Attempts to improve nitrogen utilization efficiency of aquaponics through nitrifies addition and filler gradation. *Environmental Science and Pollution Research* 23 (7), 6671-6679.

Sarah Milliken, Ranka Junge

6. HYDROPONICS

6.1 Introduction to hydroponics

6.1.1 The principles of hydroponics

Hydroponics is a method for growing crops without the use of soil, and with nutrients added to the irrigation water (so called fertigation) (Figure 1). The main differences between traditional in-ground growing techniques and soil-less techniques concern the relative use of water and fertilizer, and overall productivity. Soil-less agriculture is also typically less labour-intensive, supports monocultures better than in-ground agriculture, and can be used on non-arable land (Somerville *et al.* 2014c).

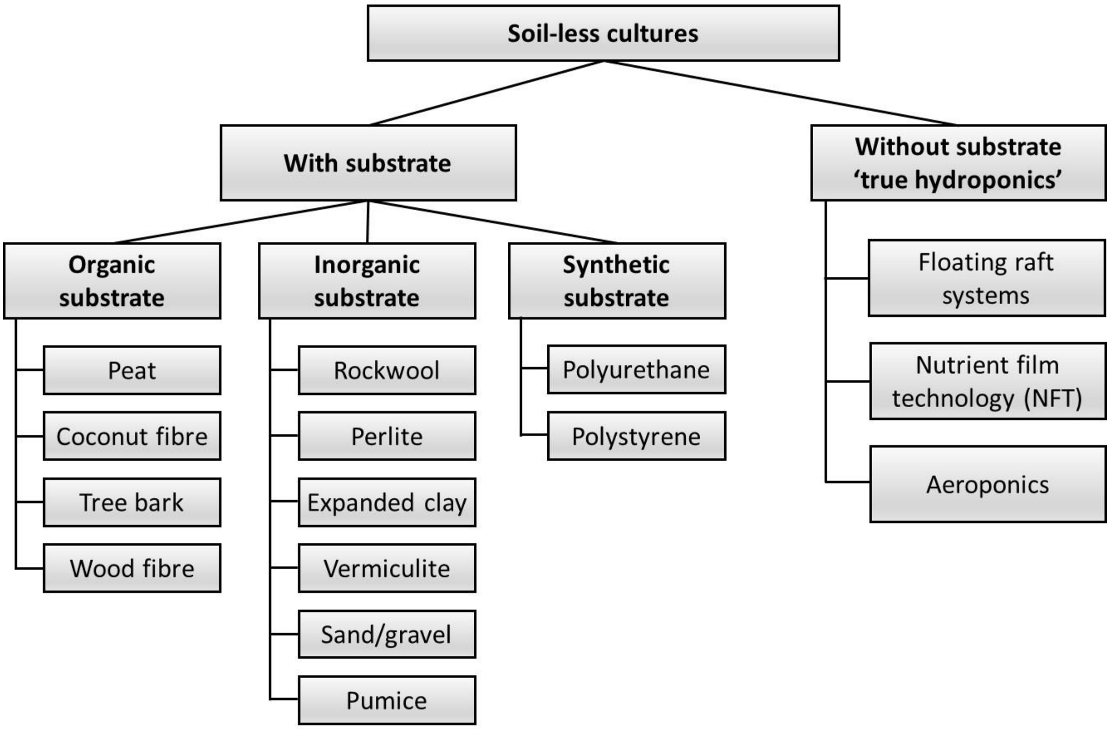

Figure 1: Classification of soil-less cultures according to the use of substrate or growing medium. The main role of substrate (if used at all) is to act as a support for the plants, and to provide moisture and aeration

6.1.2 Advantages of hydroponics

Hydroponics allows the farmer to monitor, maintain and adjust the growing conditions of the plants, ensuring optimal real-time nutrient balances, water delivery, pH and temperature. In addition, there is no competition from weeds, and the plants benefit from higher control of pests and diseases. It is said that a plant grown using hydroponics uses 90% less water than would be used to grow the same plant in soil (Somerville *et al.* 2014c). In hydroponics the water used is the minimum needed for plant growth, while in-ground agriculture loses water through evaporation from the surface, percolation into the subsoil, runoff, and weed growth. Hydroponics therefore offers great potential for crop production in areas where water is scarce or expensive. Since the nutrients necessary for plant growth are in a solution that is delivered directly to the roots, the solution can be tailored to the plant's needs at a particular growth stage. With in-ground agriculture, on the other hand, farmers cannot fully control the delivery of nutrients to the plants because of the complex processes occurring in the soil, and some fertilizer may be lost to runoff, which not only decreases efficiency, but also causes environmental concerns. Because hydroponically grown plants dip their roots directly into the nutrient solution, they obtain what they need much more easily than plants grown in soil, so they usually have smaller root systems and can divert more energy into leaf and stem growth. As a result, hydroponic culture can achieve between 5 and 25% higher yields than soil-based culture (Somerville *et al.* 2014c).

6.1.3 Disadvantages of hydroponics

However, there are also some limitations to hydroponic systems. The main problem is the high initial setup cost. They are also vulnerable to power outages, as the electrical-driven devices in the systems cannot supply the nutrient solution without power. In addition, when phytopathogens (microorganisms such as *Verticillium*, *Pythium*, and *Fusarium*) contaminate solutions or crops, waterborne diseases can rapidly spread throughout the entire system. Hydroponic system operators need specialized skills and knowledge to produce high yields of crops; they must learn the proper amounts of nutrients and lighting, manage complex nutritional problems, maintain pest control, and prevent the formation of biofilms in the water tubing system. Finally, although nutrient-rich hydroponic solutions and plastic materials can be reused, hydroponic systems still generate a large amount of waste that can have negative impacts on the environment (Lee & Lee 2015).

6.2 Hydroponic systems

There are three main types of hydroponic systems (see also Module 1). In media bed hydroponics the plants grow in a substrate. In nutrient film technique (NFT) systems the plants grow with their roots in wide pipes supplied with a trickle of water. In deep water culture (DWC) or floating raft systems the plants are suspended above a tank of water using a floating raft. Each type has its advantages and disadvantages which are discussed in more detail below. The evidence is somewhat contradictory in terms of their relative efficiency for crop production in aquaponic systems. Lennard and Leonard (2006) compared the three hydroponic sub-systems for lettuce production and found the highest production in gravel media beds, followed by DWC and NFT. However, subsequent studies by Pantanella *et al.* 2012 found that NFT performed as well as DWC, while media bed consistently underperformed in terms of yield.

As for the role of the design of the hydroponic component on the overall performance and water consumption of aquaponic systems, a literature review by Maucieri *et al.* 2018 found that NFT is less efficient than media bed or DWC hydroponics, although the results were not unequivocal. The hydroponic component directly influences water quality, which is essential for fish rearing, and is also the main source of water loss by plant evapotranspiration. The design of the hydroponic component therefore influences the sustainability of the entire process, either directly in terms of water consumption and/or indirectly in terms of system management costs. The choice of the hydroponic component for an aquaponic system will also influence the design of the entire system. For example, in media bed systems the substrate usually provides enough surface area for bacteria growth and filtration, while in NFT channels the surface area is insufficient, and additional biofilters will need to be installed (Maucieri *et al.* 2018).

6.2.1 Media bed hydroponics

In media bed hydroponics, a soil-less growing medium or substrate is used to help the roots support the weight of the plant. The media bed also serves as a biological and physical filter. Of the hydroponic sub-systems, media beds have the most efficient biological filtration because of the large surface area where biofilm, containing nitrifying and other bacteria, can colonize. The substrate also captures the solid and suspended fish waste and other floating organic particles, although the effectiveness of this physical filter will depend on the particle and grain size of the substrate, and the water flow rate. Over time, the organic particles are slowly broken down by biological and physical processes into simple molecules and ions that are available for the plants to absorb (Somerville *et al.* 2014b).

The substrate may be organic, inorganic, natural, or synthetic (Figure 1), and is housed in grow containers of different forms. It needs to have an adequate surface area while remaining permeable for water and air, thus allowing bacteria to grow, water to flow, and the plant roots to breathe. It must be non-toxic, have a neutral pH so as not to affect the water quality, and be resistant to mould growth. It must also not be so lightweight that it floats. Water retention, aeration and pH balance are all aspects that vary depending on the substrate. Water is retained on the surface of the particles and within the pore space, so water retention is determined by particle size, shape, and porosity. The smaller the particles, the closer they pack, the greater the surface area and pore space, and hence the greater the water retention. Irregular-shaped particles have a greater surface area and hence higher water retention than smooth, round particles. Porous materials can store water within the particles themselves; therefore, water retention is high. While the substrate must be capable of good water retention, it must also be capable of good drainage. Therefore, excessively fine materials must be avoided so as to prevent excessive water retention and lack of oxygen movement within the substrate. All substrates need to be cleaned periodically (Resh 2013).

Substrates can also be classified as either granular or fibrous. Granular substrates include light expanded clay aggregate, gravel, vermiculite, perlite, and pumice. Fibrous substrates include rockwool and coconut fibre. Water is mainly held in the micropore space of a substrate, while rapid drainage and air entry is facilitated by the macropores (Drzal *et al.* 1999). An adequate combination of large and small pores is therefore essential (Raviv *et al.* 2002). Granular substrates have high macroporosity (air availability) but comparatively low microporosity (water availability), while fibrous substrates have high microporosity but comparatively low macroporosity.

Light expanded clay aggregate (LECA) is very lightweight compared with other substrates, which makes it ideal for rooftop aquaponics. It comes in a variety of sizes; the larger sizes with diameters of 8-20 mm are recommended for aquaponics (Somerville *et al.* 2014). Larger pore spaces (macroporosity) mean better percolation of solution through the substrate and better air supply, even when biofilms cover the surfaces. However, LECA has small micropores, and thus does not have good water holding capacity.

Volcanic gravel (tuff) has a very high surface area to volume ratio which provides ample space for bacteria to colonize, and it is almost chemically inert, except for small releases of microelements such as iron and magnesium and the absorption of phosphate and potassium ions within the first few months. The recommended size of volcanic gravel is 8-20 mm in diameter. Smaller gravel is likely to clog with solid waste, while larger gravel does not offer the required surface area or plant support (Somerville *et al*. 2014b).

Limestone gravel is not recommended as a substrate, although it is sometimes used. Limestone has a lower surface-to-volume ratio than volcanic gravel, it is comparatively heavy, and it is not inert. Limestone is composed primarily of calcium carbonate ($CaCO_3$), which dissolves in water. This will increase the pH, and it should therefore only be used where water sources are very low in alkalinity or acidic. Nevertheless, a small addition of limestone can help to counterbalance the acidifying effect of nitrifying bacteria, which can offset the need for regular water buffering in well-balanced aquaponic systems (Somerville *et al.* 2014b).

Vermiculite is a micaceous mineral which expands when heated above 1000 ^{o}C. The water turns to steam, forming small, porous, sponge-like kernels. Vermiculite is very light in weight and can absorb large quantities of water. Chemically, it is a hydrated magnesium-aluminium-iron silicate. It is neutral in reaction with good buffering properties, and has a relatively high cation exchange capacity and thus can hold nutrients in reserve and later release them. It also contains some magnesium and potassium, which is available to plants (Resh 2013).

Perlite is a siliceous material of volcanic origin, mined from lava flows. It is heated to 760 ^{o}C, which turns the small amount of water into steam, thereby expanding the particles to small, sponge-like kernels. Perlite is very lightweight and will hold three to four times its weight of water. It is essentially neutral, with a pH of 6.0–8.0, but with no buffering capacity; unlike vermiculite, it has no cation exchange capacity and contains no minor nutrients. It should not to be used on its own, but rather mixed with another substrate in order to improve drainage and aeration and thereby prevent nutrient build-up and subsequent toxicity issues while providing an oxygen-rich environment for the roots to thrive in (Resh 2013).

Pumice, like perlite, is a siliceous material of volcanic origin and has essentially the same properties. However, it is the crude ore after crushing and screening, without any heating process, and therefore it is heavier and does not absorb water as readily, since it has not been hydrated (Resh 2013).

Rockwool is made from basalt rock that is molten in furnaces at a temperature of 1500 ^{0}C. The liquid basalt is then spun into threads and compressed into wool packets which are cut into slabs, blocks, or plugs. Most of the rapid expansion of the greenhouse industry over the past two decades has been with rockwool culture. However, in recent years concerns have been raised about its disposal, as it does not break down in landfills. Now many growers are turning to a more sustainable substrate – coconut fibre (Resh 2013).

Coconut fibre (or coir) is an organic substrate derived from frayed and ground coconut husks. It is close to pH neutral and retains water while allowing for a good amount of oxygen for the roots (Resh 2013).

Table 1: Characteristics of different growing media (after Somerville *et al.* 2014b)

Substrate	Surface area (m^2/m^3)	pH	Cost	Weight	Lifespan	Water retention	Plant support
Limestone gravel	150-200	Basic	Low	Heavy	Long	Poor	Excellent
Volcanic gravel	300-400	Neutral	Medium	Medium	Long	Medium-Poor	Excellent
Pumice	200-300	Neutral	Medium-High	Light	Long	Medium	Medium-Poor
LECA	250-300	Neutral	High	Light	Long	Medium-Poor	Medium
Coir	200-400 (variable)	Neutral	Low-Medium	Light	Short	High	Medium

Depending on the type of substrate, it will occupy roughly 30-60 percent of the total media bed volume. The depth of the media bed is important because it controls the amount of root space volume in the unit, which in turn determines the types of vegetables that can be grown. Large fruiting vegetables such as tomatoes, okra and cabbage will need a substrate depth of 30 cm to allow sufficient root space and to prevent root matting and nutrient deficiencies. Small leafy green vegetables only require 15-20 cm of substrate depth (Somerville *et al.* 2014b).

Figure 2: Tomato transplants growing in a media bed container system with drip irrigation and LECA substrate
https://commons.wikimedia.org/wiki/Category:Hydroponics#/media/File:Hydroponic_Farming.jpg

There are different techniques for delivering nutrient-enriched water to media beds. It can be simply trickled from drippers attached to pipes uniformly distributed on the medium (see Figure 2). Alternatively, a method called flood-and-drain (or ebb-and-flow) causes the media beds to be periodically flooded with water which then drains back to a reservoir. The alternation between flooding and draining ensures that the plants have fresh nutrients and adequate air flow in the root zone, which replenishes the oxygen levels. It also ensures that enough moisture is in the bed at all times so the bacteria can thrive in their optimal conditions. The nature of a flood-and-drain media bed creates three separate zones which are differentiated by their water and oxygen content (Somerville *et al.* 2014b):

- The top 2-5 cm is the dry zone, which functions as a light barrier, minimizing evaporation and preventing the light from directly hitting the water which can lead to algal growth. It also prevents the growth of fungus and harmful bacteria at the base of the plant stem, which can cause collar rot and other diseases.
- The dry/wet zone has both moisture and high gas exchange. This is the 10-20 cm zone where the media bed intermittently floods and drains. If not using flood-and-drain techniques, this zone will be the path along which the water flows through the medium. Most of the biological activity occurs in this zone.
- The wet zone is the bottom 3-5 cm of the bed which remains permanently wet. The small particulate solid wastes accumulate in this zone, and therefore the organisms that are most active in mineralization are also located here, including heterotrophic bacteria and other micro-organisms which break down the waste into smaller fractions and molecules that can be absorbed by the plants through the process of mineralization (Somerville *et al.* 2014b).

6.2.2 Nutrient Film Technique (NFT)

NFT is a system of solution culture where a thin film (two to three millimetres depth) continually flows along the base of small channels in which the root systems sit. With NFT, the objective is that part of the developing root mat is in the nutrient flow, but the other roots are suspended above this in the moist air, accessing oxygen without being submerged (Somerville *et al.* 2014b).

Figure 3: NFT round pipe system
https://commons.wikimedia.org/wiki/File:Hydroponics_(33185459271).jpg

Figure 4: NFT rectangular pipe system
https://commons.wikimedia.org/wiki/File:Hydroponics_(33185459271).jpg

The channels are often in the form of pipes (Figure 3). Pipes with a rectangular section (Figure 4) are best, with a width larger than the height, as this means that a larger volume of water hits the roots, thereby increasing nutrient uptake and plant growth. Larger fruiting vegetables and polycultures (growing different types of vegetables) require larger pipes than those needed for fast-growing leafy greens and small vegetables with small root masses. The length of the pipe can vary, but it is worth bearing in mind that nutrient deficiencies can occur in plants towards the end of very long pipes because the first plants have already stripped the nutrients (Figure 5). White pipes should be used as the colour reflects the sun's rays, thereby keeping the inside of the pipes cool. The channels must be positioned on a slope (Figure 5) so that the nutrient solution flows at a good flow rate, which for most systems is around one litre/minute (Somerville *et al.* 2014a).

Figure 5: Sloping NFT channels. The NFT channel is 12.5 m long and was fed with water from the adjacent fish tank. No nutrients were supplemented. One can observe the increasing nutrient limitation along the channel

NFT systems are mostly used for producing rapid-turnover crops such as lettuce, herbs, strawberries, green vegetables, fodder, and microgreens.

6.2.3 Deep water culture (DWC)

DWC or floating raft system is a type of hydroponic system in which the plants are suspended above a tank using a floating raft, and the roots are submerged in nutrient solution and aerated via an air pump. However, unlike in NFT systems, where the nutrients in the small film of water flowing at root level quickly become depleted, the large volume of water contained in the DWC canals allows for considerable amounts of nutrients to be used by the plants. The length of the canals is therefore not an issue, and they can range from one to ten metres. The recommended depth is 30 cm to allow for adequate plant root space, although small leafy greens such as lettuce only require a depth of 10 cm or even less. The flow rate of the water entering each canal is relatively low, and generally each canal has a retention time (the amount of time it takes to replace all the water in a container) of 1-4 hours. This allows for adequate replenishment of nutrients in each canal, although the volume of water and the amount of nutrients in deep canals is sufficient to nourish the plants over longer periods (Somerville *et al.* 2014b). On the other hand, additional aeration might be required, because the flow rates are not high enough to provide sufficient oxygen.

Some plants, such as lettuce, thrive in water and are commonly grown using deep water culture. DWC is the most common method for large commercial operations growing one specific crop (typically lettuce, salad leaves or basil), and is more suitable for mechanization.

Figure 6: Basil and other plants growing in the DWC system in the CDC South Aquaponics greenhouse in Brooks, Alberta (https://commons.wikimedia.org/wiki/File:CDC_South_Aquaponics_Raft_Tank_1_2010-07.jpg)

6.2.4 Aeroponics

In aeroponic systems the plants are grown and nourished by suspending their root structures in air and regularly spraying them with a nutrient solution. There are two main types of aeroponic systems: high pressure aeroponics and low pressure aeroponics, the main difference being the droplet size of the mist used in each case. Low-pressure aeroponics uses low-pressure, high-flow pumps, whereas high-pressure aeroponics uses high-pressure (around 120 PSI), low-flow pumps to atomize water and create water droplets of 50 microns or less. In the case of extremely fine mist that resembles fog, the term ‘fogponics’ is used to denote a third type of aeroponic system. Plants grown using an aeroponic system tend to grow faster than those grown in other types of hydroponic system because of their ample exposure to increased oxygen (Li *et al.* 2018).

6.3 Plant anatomy, physiology and growing requirements

6.3.1 Plant anatomy

Plant anatomy describes the structure and organization of the cells, tissues and organs of plants in relation to their development and function. Flowering plants are composed of three vegetative organs: (i) roots, which function mainly to provide anchorage, water, and nutrients, and to store sugars and starch; (ii) stems, which provide support; and (iii) leaves, which produce organic substances via photosynthesis. The roots grow down in response to gravity. In general, a seedling produces a primary root that grows straight down and gives rise to secondary lateral roots. These may produce tertiary roots, which in turn may branch, with the process continuing almost indefinitely. Growth occurs at the root tip or apex, which is protected by a root cap. Roots grow and branch continually, in their search for minerals and water. The efficiency of the root as an absorbing organ depends on its absorptive surface area relative to its volume, which is created by the root hairs and the complex system of branches.

Figure 7 illustrates the basic anatomy of a plant. The hypocotyl is the portion of the stem which at its base links with the root. At the other end of the stem is the terminal bud, or apical bud, which is the growing point. The stem is normally divided into nodes and internodes. The nodes hold one or more leaves, which are attached to the stem by petioles, as well as buds which can grow into branches with leaves or flowers. The internodes distance one node from another. The stem and its branches allow leaves to be arranged to maximize exposure to sunlight, and flowers to be arranged to best attract pollinators. Branching arises from the activity of apical and axillary buds. Apical dominance occurs when the shoot apex inhibits the growth of lateral buds so that the plant may grow vertically. The shoots, which bear the leaves, flowers and fruit, grow towards a light source. The leaves usually contain pigments and are the sites of photosynthesis (see 4.3.2.1). The leaves also contain stomata, pores through which water exits and through which gas exchange occurs (carbon dioxide in and oxygen out).

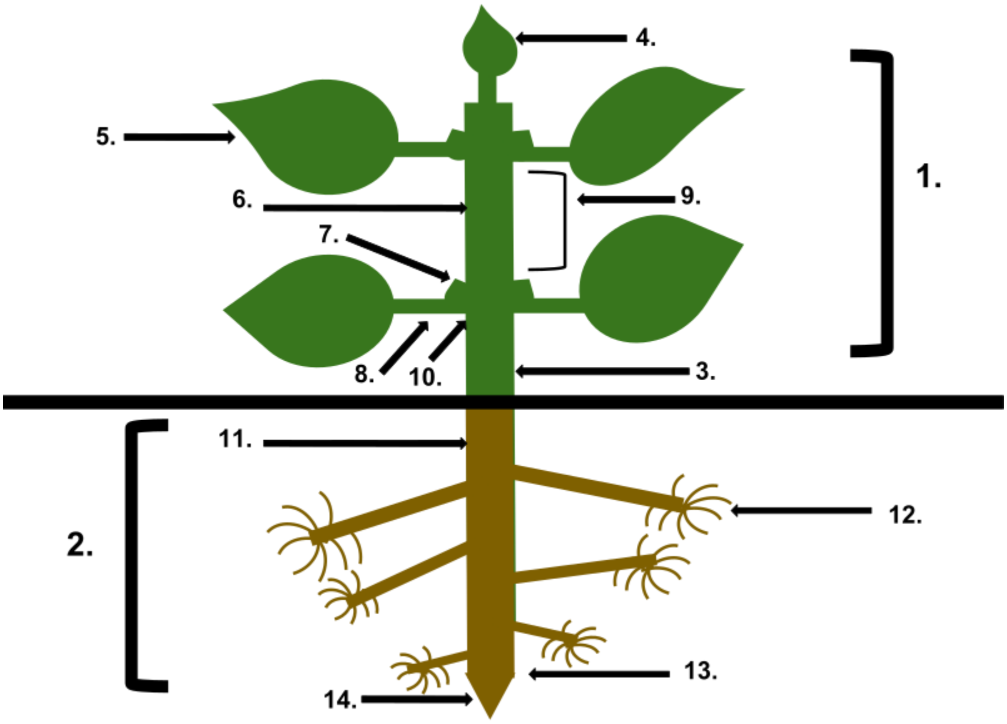

Figure 7: The anatomy of a plant

1. The Shoot System. 2. The Root System. 3. Hypocotyl. 4. Terminal Bud. 5. Leaf Blade. 6. The Internode. 7. Axillary Bud. 8. Node. 9. Stem. 10. Petiole. 11. Tap Root. 12. Root Hairs. 13. Root Tip. 14. Root Cap

https://en.wikipedia.org/wiki/Plant_anatomy#/media/File:Plant_Anatomy.svg

6.3.2 Plant physiology

Plant physiology is a vast subject, covering fundamental processes such as photosynthesis, respiration, plant nutrition, plant hormone functions, tropisms, photoperiodism, photomorphogenesis, circadian rhythms, environmental stress physiology, seed germination, dormancy, stomata function, and transpiration. Here we will focus on the most important physiological processes and how they are affected by growing conditions.

Photosynthesis

All green plants generate their own food using photosynthesis. Photosynthesis is the process by which plants are able to use light to produce energy and carbohydrates through the fixation of CO_2:

$$6\,CO_2 + 6\,H_2O \rightarrow C_6H_{12}O_6 + 6\,O_2$$

Although photosynthesis occurs in all green parts of a plant, the main site for this process is the leaf. Small organelles called chloroplasts contain chlorophyll, a pigment that uses energy from sunlight to create high-energy sugar molecules such as glucose. Once created, the sugar molecules are transported throughout the plant where they are used for all the physiological processes such as growth, reproduction, and metabolism. Photosynthesis requires light, carbon dioxide, and water.

Respiration

The process of respiration in plants involves using the sugars produced during photosynthesis plus oxygen to produce energy for plant growth:

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + energy$$

While photosynthesis takes place in the leaves and stems only, respiration occurs in all parts of the plant. Plants obtain oxygen from the air through the stomata, and respiration takes place in the mitochondria of the cell in the presence of oxygen. Plant respiration occurs 24 hours per day, but night respiration is more evident since the photosynthesis process ceases. During the night, it is very important that the temperature is cooler than during the day because this reduces the rate of respiration, and thus allows plants to accumulate glucose and synthesise other substances from it that are needed for the growth of the plant. High night temperatures cause high respiration rates, which could result in flower damage and poor plant growth.

Osmosis and plasmolysis

Osmosis is the process by which water enters the plant's roots and moves to its leaves (Figure 8). In most soils, small quantities of salts are dissolved in large quantities of water. Conversely, the plant cells contain lesser amounts of water in which salts, sugars and other substances are concentrated. During osmosis, water molecules attempt to equalize their concentration on both sides of cell membranes. Thus, when water moves from the soil, where it is most abundant, it 'seeks' to dilute the solution in the cells. Water entering a cell is stored in a large, central vacuole. When a cell becomes turgid (fully inflated) the rate of water uptake is slowed. Cell turgor gives firmness to water-filled tissues. The difference between crisp and wilted lettuce leaves illustrates the nature of turgid and non-turgid (flaccid) cells. Most plant species wilt in soils where significant quantities of salts have accumulated, even when adequate water is present. Such saline soils have a lower water content than the root cells, so the roots lose water as the direction of osmotic flow is reversed. This process is called plasmolysis. A cell starts to shrink without adequate internal water. After prolonged water loss, the cell begins to collapse without any internal water for support. Complete cellular collapse is rarely reversible. When the cells start to collapse from water loss, the plant is usually doomed because its cells die.

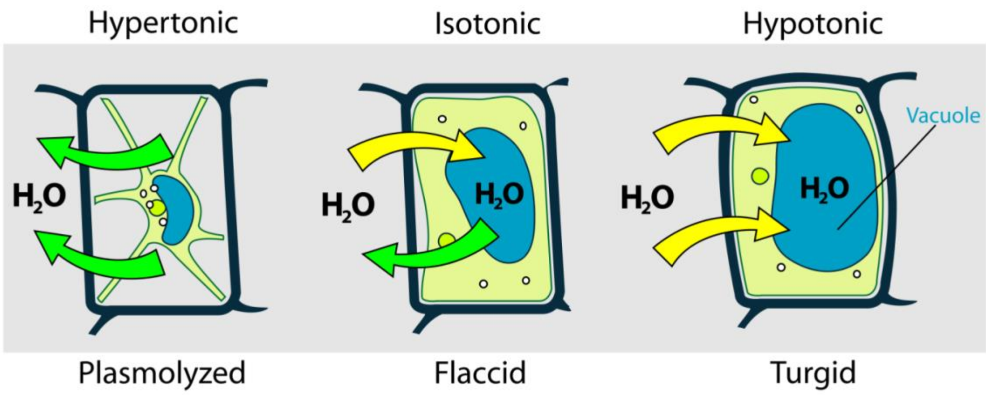

Figure 8: Turgor pressure on plant cells
https://commons.wikimedia.org/wiki/File:Turgor_pressure_on_plant_cells_diagram.svg

Transpiration

Transpiration is the loss of water from a plant in the form of water vapour. This water is replaced by additional absorption of water through the roots, leading to a continuous column of water inside the plant. The process of transpiration provides the plant with evaporative cooling, nutrients, carbon dioxide entry, and water to provide plant structure. When a plant is transpiring, its stomata are open, allowing gas exchange between the atmosphere and the leaf. Open stomata allow water vapour to leave the leaf but also allow carbon dioxide (CO_2), which is needed for photosynthesis, to enter. Temperature greatly influences transpiration rate. As air temperature increases, the water holding capacity of that air increases sharply. Warmer air will therefore increase the driving force for transpiration, while cooler air will decrease it.

Phototropism

Phototropism is a directional response that allows plants to grow towards, or in some cases away from, a source of light. Positive phototropism is growth towards a light source; negative phototropism is growth away from light. Shoots, or above-ground parts of plants, generally display positive phototropism. This response helps the green parts of the plant to get closer to a source of light energy, which can then be used for photosynthesis. Roots, on the other hand, will tend to grow away from light. The hormone controlling phototropism is auxin. Its principal function is to stimulate increase in cell length, especially near stem and root tips. In stems illuminated from above, cells undergo equal rates of elongation, resulting in vertical growth. But when lit from one side, stems change direction because auxin accumulates in the shaded side, causing the cells there to grow faster than those toward the light. Phototropism can therefore cause plants to grow tall and thin as they stretch and bend to find an adequate light source.

Photoperiodism

Photoperiodism is the regulation of physiology or development in response to day length, which allows some plant species to flower – switch to reproductive mode – only at certain times of the year. Plants generally fall into three photoperiod categories: long-day plants, short-day plants, and day-neutral plants. The effect of photoperiodism in plants is not limited to when they will flower. It can also affect the growth of roots and stems, and the loss of leaves (abscission) during different seasons. Long-day plants generally flower during the summer months when nights are short. Examples of long-day plants are cabbages, lettuces, onions and spinach. On the other hand, short-day plants flower during seasons that have longer periods of night. They require a continuous amount of darkness before flower development can begin. Strawberries are short-day plants. The flowering of some plants, referred to as day-neutral plants, is not connected to a particular photoperiod. These include chillies, cucumbers and tomatoes. Commercial growers can take advantage of knowledge about a plant's photoperiod by manipulating it into flowering before it would naturally do so. For example, plants can be forced to flower by exposing or restricting their access to light, and can then be manipulated to produce fruit or seeds outside of their usual season (Rauscher 2017).

6.3.3 Growing requirements

The primary environmental factors that affect plant growth are: light, water, carbon dioxide, nutrients (see Chapter 5), temperature, and relative humidity. These affect the plant's growth hormones, making the plant grow more quickly or more slowly.

Light

Light transmission, of the appropriate quantity and quality, is crucial for optimal photosynthesis, growth, and yield. The sun produces photons with a wide range of wavelengths (Figure 9): UVC 100-280 nanometres (nm), UVB 280-315 nm, UVA 315-400 nm, visible or photosynthetically active radiation (PAR) 400-700 nm, far-red 700-800 nm, and infrared 800-4000 nm. Within the visible range of the spectrum the wavebands can be further divided into colours: blue 400-500 nm, green 500-600 nm, and red 600-700 nm.

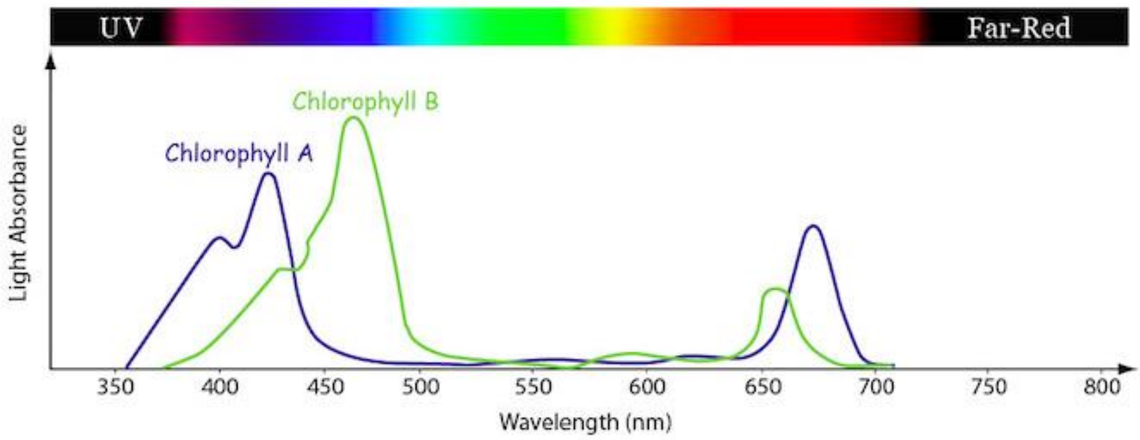

Figure 9: Chlorophyll absorption spectrum
https://www.flickr.com/photos/145301455@N07/29979758460

There are two different types of chlorophyll – chlorophyll a and chlorophyll b. Chlorophyll a is the most common photosynthetic pigment and absorbs blue, red and violet wavelengths in the visible spectrum. It participates mainly in oxygenic photosynthesis in which oxygen is the main by-product of the process. Chlorophyll b primarily absorbs blue light and is used to complement the absorption spectrum of chlorophyll a by extending the range of light wavelengths a photosynthetic organism is able to absorb. Both of these types of chlorophyll work in concert to allow maximum absorption of light in the blue to red spectrum.

Plant light responses have evolved to help plants acclimatise to a wide variety of light conditions. All plants respond differently to high and low light conditions, but some species are adapted to perform optimally under full sun, while others prefer more shade. In darkness, plants respire and produce CO_2. As the light intensity increases, the photosynthetic rate also increases, and at a certain light intensity (the light compensation point), the rate of respiration is equal to the rate of photosynthesis (no net uptake or loss of CO_2). In addition to light intensity, the colour of light also influences the rate of photosynthesis. Plants are able to use wavelengths between 400 nm and 700 nm for photosynthesis. This waveband is called photosynthetically active radiation (PAR) (Davis 2015).

The amount of light available for plants is highly variable across the globe and through the seasons. For example, at low solar elevations the light must pass through a larger volume of atmosphere before it reaches the earth's surface, which causes changes in the spectrum, as the atmosphere filters proportionately more of the shorter wavelength of light, so it filters more UV than blue, and more blue than green or red. Changes in spectral composition with season and location influence plant light responses (Davis 2015).

Water

The availability of many nutrients depends on the pH of the water. In general, the tolerance range for most plants is pH 5.5-7.5. If the pH goes outside of this range, plants experience nutrient lockout, which means that although the nutrients are present in the water, the plants are unable to use them. This is especially true for iron, calcium and magnesium. However, there is evidence that nutrient lockout is less common in mature aquaponic systems than in hydroponics, because aquaponics is an entire ecosystem, while hydroponics is a semi-sterile undertaking. Consequently, in aquaponic systems there are biological interactions occurring between the plant roots, bacteria and fungi that may allow nutrient uptake even at higher levels than pH 7.5. However, the best course of action is to attempt to maintain slightly acidic pH (6–7), but understand that higher pH (7–8) may also function (Somerville *et al.* 2014c).

Most plants need high levels (> 3mg/L) of dissolved oxygen (DO) within the water. This oxygen makes it easier for the plant to transport nutrients across its root surfaces and internalise them. Without it, the plants can experience root rot, where the roots die and fungus grows. Also, many plant root pathogens operate at low dissolved oxygen levels, so if the water is low in oxygen it can give these pathogens the chance they need to attack the roots (Pantanella 2012).

The ideal water temperature range for most vegetables is 14-22 ^{o}C, though the optimal growing temperatures varies between different plant species (see Chapter 7). Generally, it is the water temperature that has the greatest effect on the plants, rather than the air temperature. The bacteria and other micro-organisms that inhabit aquaponic systems also have a preferred temperature range. For example, the nitrification bacteria that convert ammonia to nitrate prefer an average temperature of approximately 20 ^{o}C (Pantanella 2012; Somerville *et al.* 2014c).

Carbon dioxide (CO_2)

During photosynthesis, plants use CO_2 to make food, and release oxygen as a result. Increased concentrations of CO_2 increase photosynthesis, spurring plant growth. Fresh air contains CO_2 at about 0.037%, but in a tightly enclosed greenhouse or growroom, ambient CO_2 can get used up quickly. For example, in a plastic greenhouse, CO_2 levels can be reduced to less than 0.02 % just 1-2 hours after sunrise. At levels below 0.02%, plant growth will be greatly limited, and at levels below 0.01%, plants will stop growing altogether. By increasing CO_2 levels to 0.075-0.15%, growers can expect a 30-50% increase in yields over ambient CO_2 levels, and time to fruiting and flowering can be reduced by 7-10 days. However, excessive levels of CO_2 enrichment can have adverse effects. Levels above 0.15% are considered wasteful, while levels above 0.5% are harmful. Excessive levels will cause the stomata on plant leaves to close, temporarily stopping photosynthesis, and since plants are no longer able to transpire water vapour adequately when the stomata are closed, leaves can become scorched.

Temperature

Temperature is the major environmental factor that influences the vegetative growth processes in plants from the initial stages of development to flower formation. Each plant species has its own optimal temperature range. Plants 'seek' to reach their optimal temperature, and a balance between air temperature, relative humidity and light is important in this. If light levels are high, the plant will heat up, resulting in a difference between plant temperature and air temperature. To cool down, the plant's transpiration rate must increase. Very low or high temperatures in the growth environment may be detrimental to various metabolic processes such as nutrient uptake, chlorophyll formation, and photosynthesis. Generally, an increase or decrease in temperature above or below the optimal level is known to alter several physiological processes in plants and damage the plant cells, thus altering growth.

Relative humidity

Relative humidity (RH) is the amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature. Relative humidity directly influences the water relations of a plant, and indirectly affects leaf growth, photosynthesis, and the occurrence of diseases. Under high RH the transpiration rate is reduced, turgor pressure is high, and plant cells grow. When RH is low, transpiration increases, causing water deficits in the plant which may result in plant wilt. The water deficits cause partial or full closure of the stomata, thereby blocking entry of carbon dioxide and inhibiting photosynthesis. The incidence of insect pests and diseases is high under high humidity conditions, and high RH also favours easy germination of fungal spores on plant leaves.

6.4 General cultivation practices

Staggered planting allows for continual harvest and transplant of vegetables. It is best to have an excess of plants ready to go into the system, as waiting for seedlings to be ready for transplanting is a source of production delay. Crop scheduling is covered in more detail in Chapter 7.

6.4.1 Transplants from seeds

Collecting seeds from growing plants is an important cost-saving and sustainable strategy, except when F1 hybrid plants are being grown (see below). Seed should only be collected from mature plants, as young plant seeds will not germinate, and old plants will have already dispersed their seeds. Collecting seeds from a number of different plants will help to retain genetic diversity and healthy plants. There are two major categories of seeds: dry seed pods and wet seed pods. Dry seed pods include basil, lettuce and broccoli. Seeds from basil can be harvested throughout the growing season, while lettuce and broccoli can only be harvested after the plant is fully mature and no longer usable as a vegetable. The seed heads should be cut from the plant and stored in a large paper bag for 3–5 days in a cool, dark place, and then lightly shaken to release the seeds. After passing the contents of the bag through a sieve, the seeds should be placed in a paper bag for storage (Somerville *et al.* 2014a).

Wet seed pods include cucumbers, tomatoes and peppers. The seeds develop inside the fruit, usually coated in a gel sac which prohibits seed germination. When the fruits are ready to harvest, which is usually indicated by a strong and vibrant colour, the fruit should be removed from the plant and the seeds collected using a spoon. Once the gel has been washed off using water and a smooth cloth, the seeds should be laid out to dry in the shade, and turned occasionally, before being stored in a paper bag (Somerville *et al.* 2014a).

Most commercial vegetable transplants are produced from F1 hybrid seeds, which are created by means of controlled pollination of two genetically distinct parent plants. F1 seed is preferred because most of the plants will have the same characteristics and produce the same quality and quantity of fruit. F1 seeds also produce plants with larger and more vigorous flowers and fruit. Hybrids are therefore more robust and better able to overcome adverse growing conditions. Seeds saved from F1 hybrid plants, however, will not produce plants that are true to the parent type (Rorabaugh 2015).

Seeds can be planted in polystyrene propagation trays filled with growing media such as rockwool, vermiculite or perlite. For commercial growing, seeds are usually started in rockwool or coir germination blocks, which are two and a half centimetre starter cubes with a small hole in the top of each cube into which the seed is placed. The starter cubes can then be transplanted into larger blocks that have a 2.5 cm hole for the starter cube to fit into, thereby minimising root disturbance (Rorabaugh 2015).

The propagation trays need to allow adequate distance between the seedlings in order to favour good growth without competition for light. The trays should be put in a shaded area and the seedlings should be watered each day. Too much water increases the threat of fungal infections. After germination and sprouting, and when the first leaves appear, the seedlings can be hardened off by placing them in increasingly intense sunlight for a few hours each day. The seedlings need to be grown on for at least two weeks after the appearance of the first leaf in order to ensure adequate root growth. They can be fertilized once a week with a gentle organic fertilizer high in phosphorous in order to strengthen their roots (Somerville *et al.* 2014c).

The seedlings should be transplanted into the system when adequate growth has been achieved and the plants are sufficiently strong. Transplanting seedlings in the middle of the day should be avoided, because plant roots are extremely sensitive to direct sunlight, and the leaves can face water stress due to the new growing conditions. It is recommended to plant at dusk so that the young seedlings have a night to acclimatize to their new environment (Somerville *et al.* 2014c).

Figure 10: Seedlings germinating in rockwool starter cubes
https://commons.wikimedia.org/wiki/Category:Hydroponics#/media/File:Hydroponic_Farming.jpg

The transplants need to be supported in a net cup containing 3-4 centimetres of gravel or growing medium, and the rest of the net cup should be filled with a mixture of gravel and moisture-retaining medium. The medium helps to retain water because the young plant roots only barely touch the water flow in the grow pipe. After one week, the roots should have extended out through the net cup and into the pipe, and will have full access to the water flowing along the bottom. The planting holes in the grow pipe should match the size of the net cups, and there should be adequate space between the centre of each plant hole to accommodate the cultivated plants (Somerville *et al.* 2014b).

Figure 11: Net cup used for planting in an NFT system
https://commons.wikimedia.org/wiki/Category:Hydroponics#/media/File:2009-03-30_Lettuce_roots.jpg

Figure 12: Transplanting onion plugs to a DWC system
https://commons.wikimedia.org/wiki/Category:Hydroponics#/media/File:Hydroponic_onions_nasa.jpg

6.4.2 Transplants from cuttings

Cuttings are portions of the stem, root, leaf or leaf bud removed from a 'parent plant'. These portions are then induced to form roots and shoots by chemical, mechanical and/or environmental means. The resulting plants will be clones of the parent plant with exactly the same genetic makeup. For example, tomato plant suckers can be removed, the severed ends placed in water, and roots will form within a few days to a week. The parent plant stock material must be free of disease and pests, and the material selected for cuttings needs to be in the proper physiological state so that roots and shoots develop readily. Transplants from cuttings can be grown by using an aggregate medium in plug trays. Rockwool is also a suitable medium for rooting cuttings. All but the uppermost 4-5 leaves should be removed to reduce water loss. Because the cuttings initially have no roots, misting is typically used in greenhouses to maintain a humid environment and reduce water loss while the roots are forming (Rorabaugh 2015).

In some species, root development is promoted by the auxin hormone being naturally present in the cutting. Other species need to be treated with a rooting compound – a preparation of synthetic auxin. The use of 'bottom heat' provided by means of electric cables, electric mats, or hot water tubes running beneath the beds or trays containing the cuttings, will also hasten the development of roots. No nutrients are added to the water until the roots have formed. Cutting production of vegetable crops is very labour-intensive, which is why seeds are usually used instead (Rorabaugh 2015).

6.4.3 Transplants using grafting

Grafting is a technique for connecting two previously separate plant parts such that the resulting plant will live and grow as one. The 'stock' is the lower part of the graft including the roots, while the 'scion' is the upper part of the graft including the shoot and dormant buds from which new stems, leaves, etc., will grow. Grafting is widely used in commercial tomato transplant production. While it is very labour intensive, there are several reasons for using it, such as maintaining clones that cannot be easily maintained by other asexual methods, and creating specialized growth forms. Professional hydroponic vegetable growers are also now using grafted plants, not just for pathogen protection, but also to increase yields of many greenhouse vegetable crops, including tomatoes, with high-powered, vegetative root stocks that can support two heads. The root stock and scion must be compatible (usually the same family or genus), and both must be in the proper physiological stage to promote the fusion of the two parts into one (Rorabaugh 2015).

6.5 Fertigation

Fertigation is the use of fertilizers in the appropriate combination, concentration and pH. Mineral nutrition is critical for optimal plant growth. Optimal nutritional conditions can vary between different plant species, for the same plant species at different times of its life cycle, for the same plant species at different times of the year, and for the same plant species under different environmental conditions. Even balanced aquaponic systems can experience nutrient deficiencies. Fish feeds do not necessarily have the right quantities of nutrients for plants, and generally have low iron, calcium and potassium values (see Chapter 5). Thus supplementary plant fertilizers may be necessary, particularly when growing fruiting vegetables or those with high nutrient demands. Synthetic fertilizers are often too harsh for aquaponics and can upset the balanced ecosystem. In general, iron is added as chelated iron to reach concentrations of about 2 mg/litre. Calcium and potassium are added when buffering the water to the correct pH. These are added as calcium hydroxide or potassium hydroxide, or as calcium carbonate and potassium carbonate. The choice of the buffer depends on the plant type being cultivated: leafy vegetables may need more calcium, while fruiting plants may need more potassium (Somerville *et al.* 2014c).

Any hydroponic nutrient solution begins with the water, and therefore it is essential to begin with laboratory analysis of a sample. The three main things to note are the alkalinity, the electrical conductivity (EC), and the concentration of specific elements. Alkalinity, which is a measure of water's ability to neutralize acid, is usually reported in terms of mg/L of calcium carbonate equivalents ($CaCO_3$). Alkalinity values may range from near 0 (in very pure or reverse osmosis-treated water) to more than 300 mg/L $CaCO_3$. The greater the alkalinity of the water, the more the pH will tend to rise in the nutrient solution. Water source alkalinity is a much more important number to look at than its pH: the pH is simply a one-time snapshot of how acidic or basic the water is, while alkalinity is a measure of its long-lasting pH effect. Only once the water alkalinity is known will it be possible to select an appropriate fertilizer strategy. Depending on the alkalinity, it may be necessary to choose a formulation with a greater proportion of acidic nitrogen forms (ammonium or urea) or to add acid to neutralize the alkalinity and counter the pH rise (Mattson & Peters 2014).

EC is a measure of the total dissolved salts, including both essential elements and unwanted contaminants (such as sodium). EC is therefore a rough measure of water source purity. EC should ideally be less than 0.25 mS/cm for closed systems. The laboratory water analysis will also indicate which specific essential elements and contaminants are in the water. The concentration of essential elements should be taken into account when preparing a nutrient solution recipe (see below). Tap water can often contain significant levels of Ca, Mg, S and P. Sodium and chloride (table salt) are common contaminants in some waters; ideally these should be less than 50 and 70 mg/L, respectively (Mattson & Peters 2014).

Mineral nutrients are available in the form of liquids or as powder concentrates that are then diluted with water. Nutrients are available in different formulas that, when mixed together, provide all the essential elements. Usually, the calcium containing compounds are kept separate from the phosphate and sulphate compounds, because in high concentrations the calcium will combine with the phosphates and sulphates to form insoluble precipitates. A typical nutrient solution will be divided into 3 tanks: a calcium/iron tank, the macro/micro tank containing all the other nutrients, and an acid tank which is kept separate so that pH can be adjusted individually (Rorabaugh 2015).

A grower will start with a nutrient solution recipe – a list of inorganic compounds and their final concentrations in mg/L (milligram per litre) or mMol (millimole). The recipe needs to take into account the plant you want to grow, the regional location and environmental conditions, and the time of year. Table 3 shows a nutrient solution recipe for growing tomatoes in Las Vegas during winter. In weeks 0-6 the recipe is higher in nitrogen, calcium and magnesium to ensure good structure and vegetative growth. In weeks 6-12 the nitrogen is reduced and the potassium increased to enhance flowering (reproduction). From week 12 onwards the recipe is designed to maintain a balance between vegetative and reproductive growth (Rorabaugh 2015).

Table 3: Example of a nutrient solution recipe used by Sunco Ltd., Las Vegas NV, for tomatoes during winter (from Rorabaugh 2015)

Nutrient (mg/L)	Week 0-6	Week 6-12	Week 12+
N	224	189	189
P	47	47	39
K	281	351	341
Ca	212	190	170
Mg	65	60	48
Fe	2.0	2.0	2.0
Mn	0.55	0.55	0.55
Zn	0.33	0.33	0.33
Cu	0.05	0.05	0.05
B	0.28	0.28	0.28
Mo	0.05	0.05	0.05

HydroBuddy is an open source program for the calculation of nutrient solutions for hydroponics. The programme enables one to find the amount of salt weights necessary for the preparation of nutrient solution with a given composition or, conversely, to determine nutrient concentrations within a solution based on a given fixed weight of salts. While the database contains pre-defined formulations, the programme can be customised to allow the addition of other preparations.

6.6 Greenhouse control systems

Control systems include those for lighting, heating, cooling, relative humidity, and carbon dioxide enrichment. Whilst it is helpful to have a fully controlled environment, aquaponic cultivation can also thrive without it, or with only some of the parameters being controlled.

6.6.1 Light

Maximum light transmission, of the appropriate quantity and quality (PAR, 400-700 nm), is crucial for optimal photosynthesis, growth and yield. If there is too much light in the summer, shade paint or white wash can be sprayed on the outside of the greenhouse. This will either wear off by the end of the growing season, or it can be washed off. External fabric shade cloths made of varying degrees of mesh size to exclude specific amounts of light (e.g. 30%, 40%, 50% shade) can be placed on the outside of the greenhouse or hung inside it. If there is too little light during the winter, white reflective ground covers can significantly increase light levels to the plant canopy (Rorabaugh 2015).

Artificial lights can be used to extend the winter growing season. Various different light technologies are used in greenhouses, but the most common type is light emitting diodes (LEDs). Unlike all other artificial lighting systems, LEDs contain no glass or gaseous components: all the components are solid state. They are therefore less fragile than other types of lamp, and can be located in places where other lamps may become damaged and pose a health and safety risk. However, one potential negative impact of using LED lighting in greenhouses is the lack of radiative heat that they produce, which reduces the overall energy saving as there is greater heating demand (Davis 2015).

LEDs are now available with almost any wavelength between 200 and 4000 nm. The advantages of LEDs are (i) their high efficiency (light energy output/electrical energy) compared to other lighting sources; (ii) that the light emitted is directional, which reduces the amount of stray light and ensures that the maximum amount of light reaches the crop; and (iii) that the overall spectrum can be modified for different applications by changing the number and colours of LEDs installed in a lighting unit. LEDs thus provide the potential for optimisation of light treatments that allow the enhancement of specific plant qualities or control over plant morphology and flowering time. To produce healthy plants, both red and blue light are required. Red light is most effectively used to drive photosynthesis, but plants are generally found to grow more effectively when some blue light is contained within the light spectrum, because it helps promote the stomata-promoting CO_2 uptake. Stomatal responses to light do, however, differ between species, so not all species will benefit equally following the addition of blue light. In lettuce, for example, growth rates have been found to decrease as blue light was increased (Davis 2015).

There are instances where additional colours of light may provide additional benefits. The inclusion of green light has been shown to increase fresh and dry weight biomass accumulation in lettuce plants when the green light replaces some of the blue or red light in the mixture. Green light can also penetrate deeper into the plant canopy, and therefore drive more photosynthesis. Far-red light is important for plant development and performance throughout the life of a crop. While it can inhibit the germination of lettuce seeds, it can nevertheless increase leaf area, potentially allowing greater light capture and growth rates. During the later stages of crop development, on the other hand, it will cause stretching and bolting. The area where far-red light can perhaps be used to greatest effect is for controlling flowering time (Davis 2015).

LEDs also provide the opportunity to light crops in non-traditional ways. LEDs are cool light sources and, as such, can be placed close to crops or within a canopy to light leaves that would normally receive little natural or supplemental light. By adding light to leaves normally in the shaded region of the canopy, plants are able to use the light more efficiently. This means that ‘interlighting’ has the potential to increase yields more than the same amount of light added on top of the canopy. Interlighting blue light has been found to have mixed results in yields of cucumber plants and tomatoes (Davis 2015).

Spectral manipulation can also be used to improve pigmentation. Blue light is important for driving the synthesis of anthocyanin, which is one of the types of compounds that causes red pigmentation. Light is also important in regulating the biosynthesis of many of the compounds that function to directly alter the flavour and aroma of leaves, fruits and flowers. UVB light exposure has been linked to increased oil and volatile contents in a range of herb species, including lemon balm and basil (Davis 2015).

In the majority of research, the influence of light quality on crop quality is considered during the period of crop growth, but more recently the effect of post-harvest light treatments has also been considered. Post-harvest crop treatments provide the potential to enhance crop qualities during transport to delay the onset of senescence, thus extending shelf life. Exposure to two hours of low intensity red light was found to delay senescence of basil leaves for two days during storage at 20 ^{o}C in the dark (Davis 2015).

The reaction of plants to various colours of the light spectrum can therefore be used to manipulate plants to satisfy different needs, including the following:

- Ultraviolet light can be used to shorten the internodes
- Blue and ultraviolet light can be used to increase plant stress tolerance before transplanting
- Blue light can be used to stimulate vegetative growth and prevent shorter-day plants from flowering during their propagation stages
- Red light can be used to induce flowering and lengthen the internodes to produce plants with longer stems and bigger flowers
- Far-red light can be used to control the photoperiodism of plants

Lux meters are widely used in horticulture to measure the intensity of high-pressure sodium lamps (HPS). Lux meters have been designed to have the same sensitivity to different regions of the electromagnetic spectrum as the human eye, which is most sensitive to green light. However, for many of the horticultural LED lamps, especially those with predominantly red and blue LEDs, the emission spectra fall in regions where the lux meters are relatively insensitive, and provide very low estimates even when the actual intensity of these spectra is high. The most suitable light measurement for use with plants is PAR photon irradiance (also called photosynthetic photon flux density, PDFD). PAR photo irradiance indicates the number of photons that are incident on a surface measured in micromoles per metre squared per second (μmol m^{-2} s^{-1}). Because photosynthesis is measured in similar units (μmol [CO_2] m^{-2} s^{-1}), use of PAR photon irradiance allows direct comparisons between the amount of light and the amount of photosynthesis to be made (Davis 2015).

Figure 13: Growing under UV light
https://commons.wikimedia.org/wiki/Category:Aquaponics#/media/File:Light_on_Aquaponics.jpg

6.6.2 Temperature and humidity

Heating devices will maintain the temperature within the optimal range during periods of cold weather. Insulating material (cloth or film curtains) can be positioned above the crop or near the roof to retain heat near the crop. The insulating material used during the night can be the same as the material used for shading during the day (Rorabaugh 2015).

High temperatures can be detrimental to plant growth, especially is there is low light availability. High temperatures can cause problems such as thin, weak stems, reduced flower size, delayed flowering and/or poor pollination/fertilization and fruit set, and flower and bud/fruit abortion. Passive ventilation systems include shade cloths or shade paint/white wash which, besides regulating the light intensity, can also help to cool the greenhouse. Ridge vents in the roof of a greenhouse allow hot, interior air to escape. The area of the vents should be 25% of the floor area. Roll-up side walls can be used in flexible glazing (polyethylene film) greenhouses to allow a natural horizontal flow of air over the plants. As with ridge vents, the area of the side wall vents should be 25% of the floor area. Water cooled pads at the top of cooling towers can be used to cool the surrounding air which then drops, thereby displacing warmer air below. Recent greenhouse designs can include a roof that retracts completely for natural ventilation. This allows greenhouse grown plants to adapt to outside conditions (Rorabaugh 2015).

Active cooling systems involve fan and pad 'evaporative cooling' where air from the outside is pulled through porous, wet pads (usually cellulose paper). Heat from the incoming air evaporates water from the pads, thereby cooling the air. Evaporative cooling will also help to increase the relative humidity in the greenhouse. Alternatively, fogging systems also use evaporative cooling, but incorporate a dispersion of water droplets that evaporate and extract heat from the air. This system gives better uniformity since the fogging is distributed throughout the greenhouse, and not just near one pad end as with the fan and pad system. The smaller the droplet size, the faster each droplet evaporates, and therefore the faster the rate of cooling. Relative humidity can be increased by running the cooling pads or by fogging, and can be decreased by running heaters or simply by venting (Rorabaugh 2015).

6.6.3 Carbon dioxide (CO_2)

The rate of photosynthesis is dependent upon the availability of carbon dioxide. Ventilating may provide sufficient CO_2 during the spring, summer and autumn, but in winter, or anytime in cold climates, it will result in cold air being brought into the greenhouse. Heating will then be needed to maintain the proper temperature, which may become uneconomical. CO_2 generation is therefore an effective way to increase levels in the greenhouse during the winter or in cold climates. CO_2 generators can burn various types of fuel, including natural gas (most economical) or propane. Open-flame generators also produce heat and water vapour as by-products. Therefore, hydroponic growers sometimes use CO_2 generators in the winter, when the extra heat production is welcome, and bottled CO_2 and dosers in the summer, since they produce no extra heat or humidity. Since CO_2 is released by plants through respiration at night, it is not uncommon for levels to build up to between 0.045% and 0.070% in the growroom by morning. Setting the timer to begin dosing CO_2 one hour after the lights come on, with the last dose one hour before the lights go off, is the most economical way to provide supplemental CO_2. To keep CO_2 at optimal levels, it is best to dose for short periods of time at higher volumes than to dose for longer periods of time at low volumes. (Rorabaugh 2015). In aquaponics, the fish tanks are often in the same room as the hydroponic component. The fish respiration raises the CO_2 levels of the system water, and CO_2 also enters the atmosphere. Therefore, additional CO_2 inputs are either not required, or are very low (Körner *et al.* 2014).

6.6.4 Air circulation

One reason for having a greenhouse is to create a 'controlled environment' for all of the plants. However, especially during times when the heating and cooling systems are not in operation, pockets of high or low temperature, relative humidity or carbon dioxide may develop which can be less than optimal for plant growth or flower/fruit development. Horizontal air flow (HAF) fans can be placed in the rafters of the greenhouse to circulate air above the crop. This helps to minimize pockets of warm or cold air and high or low humidity or carbon dioxide. HAF fans can be used in conjunction with hot air heating systems to circulate warm air throughout the greenhouse (Rorabaugh 2015).

6.6.5 Environmental control systems

Environmental control systems can be very simple or very complex. The simplest systems involve manually rolling up a side vent, opening a roof vent or door, or turning on a heater or cooler. Simple controllers operate from a thermostat in the greenhouse and will automatically set day and night temperature ranges, open and close vents, and turn heaters and coolers on or off. Step controllers will also automatically control 1 or 2 heating stages, depending on the number of heaters, and control several cooling stages using cooling fans and pump(s) to wet the pads. The most complex environmental control systems use sophisticated computers which operate from a temperature sensor in the greenhouse and automatically set day and night temperature ranges, control heating equipment including boilers, root zone heating, heat retention curtains, etc., control other equipment including HAF fans, exhaust fans, vents, pad pumps, fogger systems, etc., control relative humidity, and control shade curtains and artificial lighting depending on light requirements. Sophisticated computers can also monitor an external weather station and use the data collected (light, temperature, relative humidity, rain, and wind) to control internal conditions in the greenhouse. They can also operate the fertigator system by automatically using light quantity (e.g. X ml of solution/Y amount of light), and controlling the timing of watering, duration of watering, nutrient solution pH and EC, and misting (Rorabaugh 2015).

6.7 References

Davis, P. 2015. *Lighting: The Principles*. Agriculture and Horticulture Development Board Technical Guide.

Drzal, M.S., Keith Cassel, D. & Fonteno, W.C. 1999. Pore fraction analysis: A new tool for substrate testing. *Acta Horticulturae* 481, 43-54.

Körner, O., Gutzmann, E. & Kledal, P.R. 2014, Modelling the symbiotic effects in aquaponics. European Aquaculture Society conference, Donastia/San Sebastian, Spain, October 2014.

Lee, S. & Lee, J. 2015. Beneficial bacteria and fungi in hydroponic systems: Types and characteristics of food production methods. *Scientia Horticulturae* 195, 206-215.

Lennard, W.A. & Leonard, B.V. 2006. A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film texhnique) in an aquaponics test system. *Aquaculture International* 14 (6), 539-550.

Li, Q., Li, X., Tang, B. & Gu, M. 2018. Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate culture. *Horticulturae* 4 (4), 35.

Mattson, N. & Peters, C. 2014. *A Recipe for Hydroponic Success*. Inside Grower.

Maucieri, C., Nicoletto, C., Junge, R., Schmautz, Z., Sambo, P. & Borin, M. 2018. Hydroponic systems and water management in aquaponics: A review. *Italian Journal of Agronomy* 13: 1012.

Pantanella, E. 2012. *Aquaponic System Design Parameters: Basic System Water Chemistry.* Aquaponic Solutions.

Pantanella, E., Cardarelli, M. & Colla, G. 2012. Yields and nutrient uptake from three aquaponics sub-systems (floating, NFT and substrate) under two different protein diets. World Aquaculture Society Meeting, Prague, 1-5 Sept 2012.

Raviv, M., Wallach, R., Silber, A. & Bar-Tal, A. 2002. Substrates and their analysis. In Passam, H. & Savvas, D. (eds.) *Hydroponic Production of Vegetables and Ornamentals.* Embryo Publications, Athens, pp. 25-105.

Resh, H.M. 2013. *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower* (7th edition). Newconcept Press, Mahwah, SA.

Rorabaugh, P.A. 2015. *Introduction to Controlled Environment Agriculture and Hydroponics*. Controlled Environment Agriculture Center, University of Arizona, Tucson.

Somerville et al. 2014b. Design of aquaponics units. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant*

Farming. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 35-74.

Somerville et al. 2014c. Plants in aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 83-102.

Somerville et al. 2015a. Additional topics on aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 141-155.

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7. PLANT VARIETIES

7.1 Introduction

More than 150 different vegetables, herbs, and flowers have been grown successfully in aquaponic systems. Plants suited to aquaponic systems are typically fast growing, have shallow root systems, and a low nutrient demand, such as leafy greens and herbs. Fruiting vegetables, such as tomatoes, cucumbers and peppers, also do well but they have higher nutrient demands and are more appropriate for established systems with adequate fish stocks. But there are some plants that don't grow well, some that don't make sense in terms of economics, and some that probably won't work well due to space restrictions. Root crops, such as potatoes, sweet potatoes, turnips, onions, garlic, and carrots, typically do better in traditional culture, though they can be grown successfully in deep media beds (Somerville *et al.* 2014a).

There are some crops that require a larger investment, and if the intention is to grow a marketable crop for profit, then these crops are not cost-effective to grow. Radishes fall into this category, given their relatively low market price, as do some lettuces and leafy greens when their soil-grown counterparts are in season. However, there may well be niche markets that will pay higher-than-average prices for out-of-season vegetables, for crops not easily grown in the area, or for the novelty of hydroponically grown vegetables.

Aquaponic systems are finite spaces. This usually rules out growing fruit and nut trees, as well as most shrub-type plants, although bananas and papayas have been grown successfully at the Zurich University of Applied Sciences. Not only would the system require an enormous reservoir or tank to house the root system, but the amount of space needed to accommodate the plant itself would also need to be very large. Squashes and melons fall into this category, as can vine tomatoes which need trellising or some other structure for their cultivation. While there are hundreds of successful hydroponic operations growing tomatoes, these are typically in large greenhouse settings. Similarly, cucumbers can do reasonably well, but most heirloom species do not because they require a trellis system for their heavy fruits and many square metres of space per plant for their vines and foliage. Other vining crops that can outgrow their space and can be a nutrient drain include peas, pole beans, nasturtiums, and hops. While they all can be grown in a hydroculture system, they require a lot of work. The height of the grow lights must be regularly adjusted, the nutrient levels need to be adjusted according to the stage of plant growth, the trellising needs constant inspection and the provision of additional supports, and frequent pruning needs to be performed to successfully grow vining crops in a hydroponic set-up. On average, plants can be grown at the following density (Somerville *et al.* 2014b):

- Leafy greens – 20-25 plants/m^2
- Fruiting vegetables – 4 plants/m^2

These figures are only averages, and many variables exist depending on plant type, and therefore should only be used as a guideline.

When building a new farm, crop choice impacts sales, space, and technique. There are two types of cropping system: monocrop (or monoculture) is a system with a single plant type or variety; polycrop (or polyculture) is a system with different plant types and varieties. The choice between a variety of crops or a single plant type must be made with an eye on logistics, sales, experience, and pest control. The biggest advantage in favour of monocropping is simplicity. It can beat polycropping in terms of ease of sales, and is easier for new farmers when it comes to logistical overheads. If you're growing a single crop, you'll only ever need to prepare and ship your product in a single fashion. However, monocropping opens up the possibility of exhausting demand and, if combined with poor pest control, runs the risk of losing the entire yield at once. Polycropping gives farmers the possibility to meet a variety of demand, and is inherently more robust and resistant to pest outbreaks as there is a lower chance of the *entire* operation being compromised. However, members of the same family should be avoided, as these tend to be susceptible to the same bacterial, fungal and viral diseases, and to share common pests. Tomatoes, bell peppers and aubergines, for example, belong to the same family (Solanaceae), as do cabbages, pak choi, mustard greens and kale (Cruciferae or Brassicaceae). A crop set for polyculture requires crops with overlapping pH and temperature preferences.

Polycropping may also involve the use of companion plants. Companion planting is a small-scale intercropping method that is very common in organic and biodynamic horticulture, and is based on the observation that the association of different plants can have a mechanical, repellent or dissusasive effect against pests. The degree of success depends on the level of pest infestation, the crop density, the ratio between the crops and the beneficial plants, and the specific planting times. Companion planting can therefore be used in combination with other strategies within an integrated plant and pest management protocol (see Chapter 8) to obtain healthier plants in an aquaponic system (Somerville *et al.* 2014a). Some plants are also incompatible with others. For example, members of the cabbage family benefit from a number of companions, including aromatic herbs, spinach and herbs, but they are incompatible with strawberries and tomatoes.

Annual plant production rates in aquaponic systems vary depending on the species grown. Lettuce has been grown at different densities (16 to 44 plants/m^2) and crop lengths (21-28 days), mainly on floating raft systems, resulting in yields ranging from 1.4 to 6.5 kg/m^2. Basil is another widely tested crop, with densities of 8-36 plants/m^2 producing yields of 1.4 to 4.4 kg/m^2 for crop cycles of 28 days. Warm temperature crops have also proved to be very productive, such as water spinach which produced yields of 33-37 kg/m^2 in 28 days at a density of 100 plants/m^2, while okra produced yields of 2.5 and 2.8 kg/m^2 in less than three months at densities of 2.7 and 4 plants/m^2 respectively. Speciality and culinary herbs such as samphire (*Salicornia*) and saltwort (*Salsola*) gave yields of 7 kg m^2 in 110 days and 5 kg m^2 in 28 days respectively (Thorarinsdottir 2015).

Vegetables fall into three categories based on their overall nutrient demand. Low nutrient demand plants include leafy greens and herbs, such as lettuce, chard, rocket, basil, mint, parsley, coriander, chives, pak choi and watercress, and legumes such as peas and beans. At the other end of the spectrum are plants with high nutrient demand, sometimes referred to as 'nutrient hungry'. These include the botanical fruits, such as tomatoes, aubergines, cucumbers, courgettes, strawberries and peppers. Plants with medium nutrient demand are members of the cabbage family, such as kale, cauliflower, broccoli, and kohlrabi (Somerville *et al.* 2014a).

Aquaponic systems need to be balanced. The fish (and thus the fish feed) need to supply adequate nutrients for the plants, and the plants need to filter the water for the fish. Fruiting vegetables require about one-third more nutrients than leafy greens to support flower and fruit development (Somerville *et al.* 2014b):

- Leafy greens – 40-50 g of fish feed/m^2/day
- Fruiting vegetables – 50-80 g of fish feed/m^2/day

7.2 Plant selection

This section covers some of the plant species most commonly grown in aquaponic systems. Details are provided on the ideal growing conditions, the length of the growing cycle, common pests and diseases, and recommendations for harvesting and storage. Many varieties of vegetables are available from seed houses. While both field and greenhouse varieties can be grown in a greenhouse, it is advantageous to use greenhouse varieties whenever possible, since they have often been bred to yield very heavily under controlled environmental conditions (Resh 2013).

7.2.1 Leafy greens

7.2.1.1 Lettuce

Lettuce (*Lactuca sativa*) takes up relatively little space, and has a short growing cycle when it is healthy: 5-6 weeks from transplant, or 9-11 weeks from seed. It can be grown in media bed, NFT and DWC systems with 20-25 heads/m^2. Many varieties can be grown in aquaponic systems, including iceberg lettuce which is ideal for cooler conditions, Romaine lettuce which is slow to bolt, and loose leaf lettuce which has no head and can be sown directly onto media beds and harvested by picking single leaves without collecting the whole plant. The most common pests and diseases affecting lettuce are aphids, leaf miners, and powdery mildew.

Ideal growing conditions for lettuce:

- Temperature: 15-22^{o}C
- pH: 5.8-7.0

The seeds take between 3 and 7 days to germinate at 13-21^{o}C. Supplemental fertilization with phosphorus during the second and third week of growth favours good root growth and reduces stress at transplant. Plant hardening, through exposing the seedlings to colder temperatures and direct sunlight for 3-5 days before transplanting, also results in higher survival rates. The seedlings can be transplanted into the hydroponic unit after 3 weeks, when the plants have 2-3 true leaves.

When transplanting lettuce in warm weather, place light sunshade over the plants for 2-3 days to avoid water stress (Somerville *et al.* 2014c).

For head growth, the air temperature should be 3-12ºC during the night, with a day temperature of 17-28ºC. The generative growth is affected by photoperiod and temperature: extended daylight and warm conditions (>18ºC) at night cause bolting. Water temperatures above 26ºC may also cause bolting and leaf bitterness. Some varieties are more tolerant of heat than others. When air and water temperatures increase during the season, use bolt-resistant (summer) varieties. If growing in media beds, plant new lettuces where they will be partially shaded by taller plants. To achieve crisp, sweet lettuce, grow plants at a fast rate by maintaining high nitrate levels. The plant has low nutrient demand, though higher calcium concentrations in the water help to prevent tip burn in the summer. While the ideal pH is 5.8-6.2, lettuce still grows well with a pH as high as 7, although some iron deficiencies might appear owing to reduced bio-availability of this nutrient above neutrality (Somerville *et al.* 2014c).

Figure 1: Hydroponic production of different lettuce cultivars
https://www.maxpixel.net/Natural-Lettuce-Fresh-Healthy-Raw-Food-Green-1239155

Harvesting can begin as soon as the heads or leaves are large enough to eat. Lettuce should be harvested early in the morning when the leaves are crisp and full of moisture, and quickly chilled. Gentle harvests and cold, consistent temperatures extend shelf life. Harvesting techniques can affect shelf life if the lettuce is handled roughly, bruised or crushed during the process. This makes the produce much more vulnerable to post-harvest decay and diseases (Storey 2016f).

Lettuce can be harvested quickly as a batch by taking the whole head, using a harvesting knife to cut each head where it meets the surface of the system. Some growers harvest the entire plant, including the roots, which can extend shelf life. With so much transpiration and moisture, lettuce can be difficult to store for more than a few days before it starts to wilt and decay. It can stay fresh for up to three weeks if it is stored at just above $0^{o}C$, but it should not be allowed to freeze, as this will cause the leaf epidermis to separate from the other tissues, and the leaf will decay rapidly. Lettuce requires humidity to keep it from drying out, but condensation or heavy moisture on the leaves is detrimental. The best thing that producers can do to avoid condensation is to keep temperatures very consistent (Storey 2016f).

Figure 2: Hydroponic production of lettuces using NFT channels
https://www.maxpixel.net/Organic-Greenhouse-Farming-Hydroponic-Cucumber-2139526

Processing should be kept to a minimum. The only absolutely necessary task is to trim the leaves that are dried out, diseased, or which affect the aesthetics of the crop. Preferably do not wash the lettuce before delivery, although some growers use a cold water dunk in the belief that it extends shelf life by closing the stomata (Storey 2016f).

7.2.1.2 Chard

Chard (*Beta vulgaris* subsp. *vulgaris*) is easy to grow in media beds, NFT channels and DWC systems. It is a fairly tough crop, occasionally susceptible to aphids and powdery mildew problem, and although high or low temperatures will affect the taste, the crop is overall very tolerant of stressful conditions.

Ideal growing conditions for chard:

- Temperature: 16-24^{o}C and frost tolerant
- pH: 6.0-7.5

Chard is a moderate nitrate feeder, and requires lower concentrations of potassium and phosphorus than fruiting vegetables. Owing to its high market value, its fast growth rate and its nutritional content, chard is frequently grown in commercial aquaponic systems. Although traditionally a late winter/spring crop, it also grows well in full sun during mild summer seasons, though a shading net is recommended when temperatures exceed 26^{o}C (Somerville *et al.* 2014c).

Chard is easiest to grow from seed, and germinates within 4-5 days at 25-30^{o}C. The seeds produce more than one seedling, so thinning is required as the seedlings begin to grow. The seedlings can be transplanted at 15-20 plants/m^2. As plants become senescent during the season, the older leaves can be removed to encourage newer growth (Somerville *et al.* 2014c). Chard can be harvested 4-5 weeks after being transplanted, and yields well. Growers should only harvest partially, leaving 30% of the foliage for the plant to photosynthesize for the next crop. The largest leaves should be clipped as close to the base of the plant as possible. Harvesting in the morning or evening can help keep chard fresh, and will keep for over a week without beginning to wilt if treated correctly. Chard lasts longest when stored without washing in sealed containers or bags at cool temperatures, which dramatically reduce respiration and decay (Storey 2016b).

7.2.1.3 Kale

Growing kale (*Brassica oleracea*) in aquaponic systems can be a simple and profitable option. The crop grows relatively quickly with a six-week cycle from transplant to harvest, or can be harvested partially, leaving 30% to regrow for the next crop.

Ideal growing conditions for kale:

- Temperature: 8-29^{o}C
- pH: 6.0-7.5

Kale is a cool weather crop, and many growers even apply cooler temperatures (down to 5^{o}C) purposefully to draw out a smoother, improved flavour. Fortunately, kale is another crop which, when grown indoors, is targeted by only a few pests such as aphids and some powdery mildew (Storey 2016p).

7.2.1.4 Pak choi

Pak choi (*Brassica chinensis*), also known as bok choy or Chinese cabbage, comes in a range of sizes, including large varieties like Joi Choi and smaller varieties like Shanghai Green Pak Choy, which offer more compact, tender heads with a delicate flavour. Tatsoi (*Brassica narinosa*, also called broadbeaked mustard) has the same thick leaves and light veins as pak choi and can be grown in similar conditions. Napa cabbage (*Brassica rapa pekinensis*) is another brassica member which, while it looks different to pak choi and tatsoi, shares the same pH and EC range of pak choi, and tastes better when grown at cooler temperatures (Storey 2016i).

Ideal growing conditions for pak choi:

- Temperature: 13-23^{o}C
- pH: 6.0-7.5

Although pak choi is typically milder in cool temperatures, it is fairly temperature tolerant, which makes it an easy fit in many hydroponic and aquaponic systems. Deficiencies in pak choi can be difficult to identify, as the more obvious symptoms like interveinal chlorosis, burning, or bronzing are not common. Deficiencies are marked by stunted growth, cupping, and some yellowing. Plant pak choi from seed and transplant as soon as there are true leaves on the plant; this will typically occur in about four weeks. Though the highest yields occur at six weeks from transplant, pak choi may be grown in shorter rotations of four weeks (Storey 2016i).

Figure 3: Pak choi growing in the NFT system at Lufa Farms
https://commons.wikimedia.org/w/index.php?curid=27515408

7.2.1.5 Cabbage

Cabbage (comprising several cultivars of *Brassica oleracea*) is a fairly hands-off crop to grow. General pest control measures using an IPM plan usually keep pests at bay, and cabbage needs no extra pruning or training. The heads grow large (3.5 kg is not uncommon), so farmers can get a fairly large crop from a small space.

Ideal growing conditions for cabbage:

- Temperature: 15-20^{o}C (but frost tolerant)
- pH: 6.0-7.2

Cabbage is vulnerable to common pests such as aphids, as well as bacterial diseases such as blackleg and black rot. The latter are usually due to the crown of the plant being kept moist. Other than pests and diseases, the most common problem with cabbage cultivation is splitting, when the head cracks and splits. This looks unappealing to consumers and can catch dirt and disease. Splitting can be avoided by keeping growing conditions consistent, and harvesting at the right time (Storey 2016k).

Cabbages grow best in media beds because they reach significant dimensions and may be too large and heavy for rafts or grow pipes. As a nutrient-demanding plant, it is not suitable for newly established aquaponics units (less than four months old). Nevertheless, owing to the large space required (4-8 plants m^2), cabbage crops take up fewer nutrients per square metre than other leafy vegetables (lettuce, spinach, rocket etc.). Cabbage likes full sun and grows best when the heads mature in cooler temperatures, so they should be harvested before daytime temperatures reach 23-25^oC. High concentrations of phosphorus and potassium are essential when the heads begin to grow. Integration with organic fertilizers delivered either on the leaves or substrates may be necessary in order to supply the plants with adequate levels of nutrients (Somerville *et al.* 2014c).

For best germination rates, seedlings should be kept a little warmer than mature crops (18-29^oC). Scarification of seeds can also increase germination rate. After being planted, seeds will germinate in 4-7 days, and the seedlings will be ready to transplant 4-6 weeks later when they have 4-6 leaves and a height of 15 cm. It is important to leave enough room for each head to grow to the desired size. In the event of day temperatures higher than 25^oC, a 20 percent light shading net should be used to prevent the plant from bolting. Depending on the type of cabbage and the size of head desired, the crop will be ready for harvest 45-70 days after transplanting. It should be harvested when the head is firm and big enough for the market, by cutting the head from the stem with a sharp knife, and discarding the outer leaves (Somerville *et al.* 2014c).

7.2.1.6 Mustard greens

Mustard greens (Brassica juncea) are another member of the brassica family (a relative of kale and cabbage).

Ideal growing conditions for mustard greens:

- Temperature: 10-23^oC
- pH: 6.0-7.5

Mustard greens can be managed in a similar way to kale – grown from seeds, which take 4-7 days to germinate, the seedlings will be ready to transplant at 2-3 weeks later (3-4 weeks from the seed planting). After 4-6 weeks growing, the plants should be harvested partially, taking only 30% of the plant and leaving the rest to continue to grow (Storey 2016g).

7.2.1.7 Nasturtium

Nasturtium (*Tropaeolaceae tropaeolum*) is a tender plant native to South America. Unlike many crop plants, both the leaves and flowers are edible and have a sharp peppery taste similar to mustard or watercress. Nasturtiums are easy to grow in hydroponic systems for their leaves. However, if growers are optimizing for flower production they may need to adjust nutrient ratios and light to cue flowering. It may also be necessary to control the ratio of nitrogen to potassium to cue the vegetative and fruiting stage, and to switch the system from a greens mix to a strawberry mix when they are about half of their mature size in order to start flowers. This gives the crop a chance to establish roots and photosynthesizing tissue, so that when they flower they are able to produce more. Nasturtium suffers from typical pests like aphids and spider mites. It can be sourced as two different varieties: a vining variety and a bush variety (Storey 2017b).

Ideal growing conditions for nasturtium:

- Temperature: 13-23^{o}C
- pH: 6.1-7.8

Nasturtiums are light-lovers but do best with low heat stress. Seeds can be germinated at 13-18^{o}C, and adult plants do best at about 21^{o}C. The flowering crop does well in low EC systems like those optimized for leafy greens or strawberries. Nasturtium seeds take 7-10 days to germinate in the right conditions and are ready to transplant as soon as true leaves appear, which is usually 2-3 weeks from germination. Plants will produce flowers 5-6 weeks later, but if the grower is only interested in the leaves, these can be harvested earlier. Some growers prefer to grow nasturtiums at a high density and harvest the leaves while they are still very young (Storey 2017b).

7.2.2 Herbs

Herbs are usually more profitable than leafy greens. Different herbs have different needs, and lack of understanding of this can reduce shelf life or even ruin produce before it can be used. Tips to keep herbs fresh after harvest include (Storey 2016o):

- Keep it cool, but not too cool
  Respiration rates slow down when produce is kept cool, as the stomata close and gas exchange decreases. Harvesting during a cool part of the day will also help. Some herbs, such as basil, are sensitive to chilling and can become damaged. Basil should not be kept below 13^{o}C, for example, but can attain a shelf life of 12 days at 15^{o}C.

- Be consistent
  Temperature and moisture fluctuations are largely responsible for disease and decay issues. These can be avoided by reducing the number of times that produce is moved from one place to another, and by keeping the the temperature of coolers and transport vehicles steady.

- Decrease plant damage
  The production of ethylene is increased by wounds, and accelerates the rate of deterioration. The use of clippers when harvesting herbs, rather than tearing, will help to avoid this.

- One size does not fit all
  Harvesting and packaging practices should be specific to the herb and its age, since needs vary widely. Most of the herbs commonly used differ in their origin, needs, and life cycles. This means that each herb should be treated differently to increase shelf life.

- Packaging should balance water loss with decay
  Tender herbs such as basil or chives lose less water when packaged in plastic bags, but condensation increases decay rates.

- Control light exposure
  Whether stored under light or in the dark may influence the decay rate, depending on the herb.

7.2.2.1 Coriander

While coriander (*Coriantrum sativum*) is an easy crop for soil gardeners, indoor and hydroponic growers may not get the highest space use efficiency from this crop, as it has a comparatively long growing cycle and limited yield. On the other hand, it is low-maintenance, and if growers are sure that they can get a good price, then coriander can still be a good crop. Since it is small-statured, coriander can be grown in almost any hydroponic system, so long as pH and EC ranges are appropriate (Storey 2017a).

Ideal growing conditions for coriander:

- Temperature: 5-23^{o}C
- pH: 6.5-6.7

Coriander can be a tricky crop to grow since it bolts very easily, especially in hot conditions. It prefers cooler temperatures (5-23^{o}C) and low salts. The preference for cool temperatures extends to germination as well; temperatures of 15-20^{o}C will result in the best germination rates. If bolting is triggered, which makes the flavour of the herb more bitter, the bolts should be trimmed and the environmental conditions adjusted. Growers can purchase slow bolting seeds to minimize the potential for crop failure. Two of the most common diseases of coriander in hydroponics are bacterial leaf spot and powdery mildew. Coriander is also vulnerable to Pythium, which can become problematic in systems with inadequate aeration around the roots (Storey 2017a).

Coriander seeds germinate in 7-10 days, with leaves ready to harvest 40-48 days later. From seed to harvest, coriander takes 50-55 days. Coriander can be harvested fully or partially, requiring very little maintenance like trimming. If using a partial harvest, the first harvest will take place at about 5 weeks after transplant and the second at about 8 weeks after transplant. The second harvest will be lower than the first. Coriander may be packaged in various ways depending on the farmer and, even more importantly, market preference (Storey 2017a).

7.2.2.2 Mint

There are dozens of types of mint, but the main varieties are spearmint (*Mentha spicata*), peppermint (*Mentha x piperita*), and pennyroyal mint (*Mentha pulegium*); some of the other mints like lemon mint (*Monarda citriodora*) are actually not mint at all. Mint is one of the the easiest crops to grow. It is easy to plant, grows quickly, and easy to harvest.

Ideal growing conditions for mint:

- Temperature: 19-21^{o}C
- pH: 6.5-7.0

Mint is tolerant of low EC and some temperature variation, although it doesn't do well when heat spikes above 26^{o}C. It struggles less with pests than many of the herbs, although verticillium wilt and powdery mildew can become problematic. Mint can be grown from seed, but using cuttings or rootstock is much quicker, especially on a commercial scale. Stem cuttings can be made by removing healthy green sprigs and setting them in water. Roots will form and the plants will grow to maturity within a few weeks. Mint can be harvested by cutting about 5 centimetres from the surface of the system. A second harvest will be ready in only 2-3 weeks, once it has grown out to about 20 centimetres (Storey 2016m).

7.2.2.3 Basil

Owing to the higher nitrogen uptake, basil (*Ocimum basilicum*) is an ideal plant for aquaponics, and it can be grown in media beds, NFT and DWC systems. However, if mint is one of the easiest herbs to grow, then woody herbs like basil are at the other end of the scale. Although basil isn't needy in terms of water and pH, it does require pruning (see below) to achieve full yields, and grows best in high temperatures which can be tough to match with other crops, so it may be best to grow it as a monocrop. Many cultivars of basil have been tried and tested in aquaponic systems, including Genovese basil (sweet basil), lemon basil, and purple passion basil.

Ideal growing conditions for basil:

- Temperature: 18-30^{o}C, optimal 20-25^{o}C
- pH: 5.5-6.5

Basil seeds need a reasonably high and stable temperature to initiate germination (20-25^{o}C), and should germinate within 6 to 7 days. The seedlings should be transplanted to the aquaponic system when they have 4-5 true leaves. Once transplanted, basil grows best in warm to very warm conditions, with full exposure to the sun. However, better quality leaves are obtained through using slight shading. If temperatures exceed 27^{o}C the plants will need to be ventilated or covered with shading nets (20%) to prevent tip burn. Basil can be affected by various fungal diseases, including *Fusarium* wilt, grey mould, and black spot, particularly under suboptimal temperatures and high humidity conditions. Air ventilation and water temperatures higher than 21^{o}C help to reduce plant stress and incidence of diseases (Somerville *et al.* 2014c).

The shape of basil leaves causes them to catch water and hold it, so controlling condensation is very important. Humidity in the greenhouse should be kept between 40-60%. Basil is very sensitive, so it requires good air flow but not a draught. It grows well with 10-12 hours of light, but supplementing light will increase yield. Dying leaves should be removed, as they tend to stick to the other leaves and damage them, or grow fungus. Plants that are end- or top-heavy should be pruned using sharp shears rather than pinching, as this risks damaging or pulling off a whole stem. If the growth on the end of the stem is too heavy, it will split from the main root base and become bitter. The bitterness in basil can be eliminated by harvesting before bolting to flower, throwing out any old/tough growth, and removing broken stems (Storey 2016e).

Figure 4: Basil growing in an NFT system
https://www.goodfreephotos.com/public-domain-images/plants-in-the-green-house.jpg.php

Basil has been bred to be a single-stemmed plant growing upward (apical growth). For most growers, a bushier plant is better. A pruned plant looks better, yields more, and can be easier to transport depending on the growing method. To change the way that basil grows, growers can trigger a secondary type of growth that moves outward and up instead of straight up (lateral growth). A young basil plant (12-25 centimetres tall) has lateral buds on the side of the stem that will only grow if the main stalk gets badly damaged or removed. This means that if growers clip the stem right above those lateral buds (1 centimetre or so), the buds will be triggered to grow out. By pruning basil this way, growers can increase the production of that branch and control the shape of the plant. The plant should be cut above the second pair of buds so that the growth fans out and doesn't stop airflow or light penetration. Correct pruning will result in increased yield in each of the first three harvests (around weeks 5, 8, and 11) (Storey 2016e).

The harvest of leaves starts when plants reach 15 cm in height and continues for 30-50 days. Basil needs to be handledl gently, as bruising can increase the rate of deterioration. It should not be stored in a chiller, where the temperature is usually kept at 5-7^{o}C, as it is a warm weather crop and does not have the cellular machinery to deal with those temperatures, and will decay rapidly. To extend its shelf life, it should be stored above 13^{o}C (preferably at a temperature of 16^{o}C). At this temperature, it can attain a shelf life of 12 days. If growers package basil in bags or cartons that reduce moisture loss (plastic with little or no air exchange), the storage temperature will need to be kept steady to avoid condensation (Storey 2016e).

7.2.2.4 Chives

Chives (*Allium schoenoprasum*) are a tough crop that will survive a wide range of temperatures and can even go without water for a while without it impacting quality. Chives are also fairly pest-resistant, rarely infected with diseases and rarely being targeted by insect pests. The most common issues in hydroponic systems are viruses and fungus gnats (Storey 2016n).

Ideal growing conditions for chives:

- Temperature: 18-26^{o}C
- pH: 6.1 to 6.8

Chives propagate rapidly from roots, and can be planted by division. Rarely will growers need to use seeds to grow chive seedlings, unless mature chive plants are nowhere to be found. If chives are grown from seed, seedlings will be ready to transplant about 4 weeks later, and ready to harvest 3-4 weeks later. When planted from root, chives will be established within 2-3 weeks and will grow thicker with every harvest. Chives should be harvested every two to three weeks by trimming back to about 2.5-5 centimetres above the crown (Storey 2016n).

7.2.2.5 Parsley

Parsley (*Petroselinum crispum*) grows well in media beds, NFT and DWC systems, and is common in commercial aquaponics units due to its high market value. Large leaf varieties like Italian flat leaf (*P. crispum* var. *neapolitanum*) grow particularly well. Pests on parsley are rare, but growers might see aphids or thrips.

Ideal growing conditions for parsley:

- Temperature: 15-25^{o}C; very cold hardy
- pH: 6.0-7.0

Parsley is a biennial herb that is traditionally grown as an annual. Most varieties will grow over a two-year period if the winter season is mild with minimal to moderate frost. In the first year the plants produce leaves while in the second they will send up flower stalks for seed production. Parsley enjoys full sun for up to eight hours a day. Partial shading is required when temperatures exceed 25^{o}C (Somerville *et al.* 2014c).

Parsley comes as an affordable seed and germinates within 8-10 days with good moisture and a temperature of 20-25^{o}C. If the seeds are not fresh, germination can take as long as 5 weeks. To accelerate germination, seeds can be soaked in warm water (20-23^{o}C) for 24-48 hours to soften the seed husks. Emerging seedlings will have the appearance of grass, with two narrow seed leaves opposite each other. Seedlings are ready to transplant after 5-6 weeks when they display their true leaves. They can be planted at 10-15 plants/m^2. The first harvest typically happens 20-30 days after transplant, once the individual stalks of the plants are at least 15 cm long. Harvest the outer stems first as this will encourage growth throughout the season (Somerville *et al.* 2014c). Alternatively, parsley can be harvested multiple times, by using shears or a harvesting knife to cut the crop down to 5 centimetres from the surface of the system. Another harvest may be taken about 3 weeks later. A new cycle should be started after the second harvest (Storey 2016a).

7.2.2.6 Fennel

Fennel (*Foeniculum vulgare*) rarely struggles with pests if it is kept healthy, although aphid infestations could affect the crop.

Ideal growing conditions for fennel:

- Temperature: 16-21^{o}C
- pH: 6.4-6.8

Fennel prefers a lower EC and moderate pH. Although it often proves to be both, heat, and cold tolerant, it is not frost tolerant. Fennel has a wider range of germination rates, from about 60% to 90%. Seeds take 1-2 weeks to germinate and are typically ready to transplant 3-5 weeks later. From transplanting it takes about 6-8 weeks to reach harvesting size. The bulbs can be harvested as soon as the grower wants, but 250 g to 500 g bulbs are standard at most markets. Fennel can be harvested twice (once just for the greens, once for the bulb and greens together) if there is a market for the greens. As with chard and kale, only 70% of the greens should be removed in the first harvest (Storey 2016d).

7.2.3 Fruiting crops

Pruning is important for fruiting crops grown in aquaponic systems. Without regular pruning, excessive growth can occur, which is very hard to manage. The root systems of aquaponic plants are not as strong as plants growing in soil because the roots do not have to spread out in search of nutrients, and plants in aquaponic systems are not able to support heavy loads due to poor anchorage of the roots. Pruning is also important for greenhouse production because, due to higher cost per square foot, growers need to use the area very efficiently. Therefore, pruning allows high density planting and better quality products.

7.2.3.1 Tomatoes

Tomatoes (*Solanum lycopersicum*) typically grow in one of two patterns, depending on the variety. Bush varieties (determinate – seasonal production) are especially common in heirlooms and can be more difficult to manage. Bush tomatoes tend to sprawl along a greenhouse floor, making trellising difficult or even impossible. As a result, growers can have trouble reaching the fruit, pruning plants, and navigating the greenhouse. Vining varieties (indeterminate – continuous production of floral branches) are preferable to most growers since the plants can be pruned to a single ‘leader’ and trellised. This makes plants more accessible and much faster to harvest and prune. A typical Bato bucket and tomato setup (see 9.2.4) includes two plants per bucket, with buckets 60-90 centimetres apart. If grown as single plants (such as in a slab system), tomatoes can be pruned to two leaders per plant. Tomatoes are prone to many pests and diseases, the most common being *Verticillium* wilt, *Fusarium*, nematodes, spider mites, aphids, damping off, and mosaic virus. When purchasing tomatoes or seeds, look for the 'VFN' label which indicates resistance to *Verticillium*, *Fusarium*, and nematodes (Storey 2017c).

Ideal growing conditions for tomatoes:

- Temperature: 13-26°C
- pH: 5.5-6.5

Tomatoes, as a fruiting crop, are nutrient greedy (see Table 1). They like heat, and will grow well in the same environment as crops like okra or basil. A downside of tomatoes is that their taste is particularly influenced by the medium in which they grow. It is therefore necessary to ensure that the growing medium is at a properly maintained ratio. Because tomatoes are such a commonly grown crop, there is an abundance of data on troubleshooting and deficiencies. Common deficiencies for tomato plants are phosphorus and magnesium (Storey 2017c).

Table 1: Recommended nutrient solution compositions matched to the growth phase of tomatoes in soilless culture (from Raviv & Lieth 2007)

Growth phase	N	P	K	Ca	Mg
			(mg L^{-1})		
Transplanting	80-90	30-40	120-140	180-220	40-50
Blooming and anthesis[1]	120-150	30-40	180-220	230-250	40-50
Fruit ripening and harvesting	180-200	30-40	230-250	180-220	40-50
Fruit harvesting	120-150	30-40	180-220	180-220	40-50

Seeds will germinate in 4-6 days at 20-30°C. Stakes or plant supports should be set before transplanting to prevent root damage. Seedlings can be transplanted to the aquaponics system 3-6 weeks after germination when the seedlings are 10-15 cm high and when night time temperatures are constantly above 10°C. Tomatoes can be grown in media beds, avoiding waterlogged conditions around the plant collar to reduce any risks of diseases. Given their high nutrient demand, especially for potassium, the number of plants per unit should be planned according to the fish biomass in order to avoid nutrient deficiencies. Tomatoes prefer warm temperatures, with full sun exposure. The optimal daytime temperature is 22-26°C, while night time temperatures of 13-16°C encourage fruit set (Somerville *et al.* 2014c).

Pruning is crucial for tomato production, as it ensures proper utilization of energy for the growth of fruits and the main stem. Once the tomato plants are around 60 cm tall, the growing method (bush or single stem) can be determined by pruning the unnecessary upper branches. Bush varieties can be left to grow as bushes by leaving 3-4 main branches and removing all the auxiliary suckers in order to

[1] Anthesis is the flowering period of a plant, from the opening of the flower bud

divert nutrient to the fruits. Vining tomatoes can grow up to a height of 4 metres, while 2 metres is a normal height. Pruning is required for vining tomatoes, as 50 percent of tomato yield is reduced without pruning and trellising. Both bush and vining varieties should be grown with a single stem (double in case of high plant vigour) by removing all the auxiliary suckers. Hand removal of suckers 2 to 2.5 mm in length once a week is the best method. At this size, the suckers can be easily broken off without injuring the main stem. In bush varieties, the apical tip of the single stem has to be cut as soon as the plant reaches 7-8 floral branches in order to favour fruiting. Tomatoes rely on supports that can either be made of stakes (bush varieties) or bound to vertical plastic/nylon strings that are attached to iron wires pulled horizontally above the plant units (vining varieties). It is also important to remove the leaves from the lower 30 cm of the main stem to favour a better air circulation and reduce fungal infection. The best way to remove them is to bend them upward first and then pull down in order to prevent peeling of the skin on the stem. Remove the leaves covering each fruit branch soon before ripening to favour nutrition flow to the fruits and to accelerate maturation (Singh & Dunn 2017; Somerville *et al.* 2014c).

Tomatoes are normally wind pollinated or pollinated by bees when grown outside. In greenhouses, however, air movement is insufficient for flowers to pollinate themselves. Pollination can either be carried out manually, or by using bumble bees (*Bombus* sp.). It is important to maintain the correct population levels of bumble bees, as overpopulation may result in the bees overworking the tomato flowers. For manual pollination, vibration of the tomato flower clusters is essential. This can be done by tapping the flowers with a stick, fingers, or an electric vibrator such as an electric toothbrush. Pollination must be done while the flowers are in a receptive state, which is indicated by their petals curling back. Plants should be pollinated at least every other day, since blossoms remain receptive for about 2 days. Pollinating should be done between 11:00 am and 3:00 pm under sunny conditions for best results. If pollination has been done correctly, small beadlike fruit will develop within a week or so. This is called fruit set. When young plants produce their first trusses, pollinate each day until fruit set is visible. It is important to get the fruit set on these first trusses, as it throws the plant into a reproductive state, which favours greater flower and fruit production as the plant ages. After the first few trusses have set, pollinating can be done every other day. Research has shown that a relative humidity of 70% is optimum for pollination, fruit set, and fruit development (Resh 2013).

The growth time is 50-70 days until the first harvest, and fruiting continues for 90-120 days in bush varieties and up to 8-10 months for vining varieties. For best flavour, harvest tomatoes when they are firm and fully coloured. Fruits will continue to ripen if picked half ripe and brought indoors. Fruits can be easily maintained for 2-4 weeks at 5-7^{o}C under 85-90 percent relative humidity (Somerville *et al*. 2014c).

7.2.3.2 Bell peppers

Bell peppers (*Capsicum anuum*) prefer warm conditions and full sun exposure. As with other fruiting plants, nitrate supports the original vegetative growth (optimum range 20-120 mg/litre), but higher concentrations of potassium and phosphorus are needed for flowering and fruiting (Somerville *et al.* 2014c).

Ideal growing conditions for bell peppers:

- Temperature: 19-23°C
- pH: 5.5-6.5

Table 2: Recommended nutrient solution compositions matched to the growth phase of bell peppers in soilless culture (from Raviv & Lieth 2007)

Growth phase	N	P	K
		(mg L^{-1})	
Transplanting to blooming	50-60	50-60	75-80
Anthesis to fruit growth	80-100	80-100	100-120
Fruit ripening and harvesting	100-120	100-120	140-160
Fruit harvesting	130-150	130-150	180-200

Seeds will germinate in 8-12 days at 22-30°C. The seedlings can be transplanted as soon as the night time temperature settles above 10°C, and when they have 6-8 true leaves. Bushy, heavy yielding plants need to be supported with stakes or vertical strings hanging from iron wires pulled horizontally above the buckets. The first few flowers that appear on the plant should be picked in order to encourage further plant growth, and the number of flowers should be reduced in the event of excessive fruit setting to favour the growing of fruits to reach adequate size (Somerville *et al.* 2014c).

Because of a pepper's unique growth patterns, pruning is essential in ensuring a successful crop. Pruning will reduce production cost, increase yield and reduce disease susceptibility. Sweet pepper pruning is different from tomato pruning because peppers do not produce side shoots like tomatoes. After pinching (removal of the plant tip), the top two nodes start to grow. The main objective of sweet pepper pruning is to develop a strong vegetative frame for supporting fruit growth and weight during production. Here are the steps for sweet pepper pruning (Singh & Dunn 2017):

1. Remove the growth point or stem tip after the first 40 centimetres
2. Treat each of the two stems as an individual and alternate between removing the inner and outer side shoot from each main stem
3. Remove the side shoot when it is 50 mm long
4. On each individual stem, remove alternate flower clusters. Heavy fruit load on a plant may lead to lower fruit quality and may cause physiological disorders like blossom end rot
5. Completely remove any yellow leaves from the greenhouse

The growth time is 60-95 days. Like tomatoes, peppers also need to be pollinated either manually or by introducing a bumble bee hive to the greenhouse. For sweet red peppers, the green fruits should be left on the plant until they ripen and turn red. Harvesting should begin when the peppers reach marketable size, and continue throughout the season to favour blossoming, fruit setting and growth. Peppers can be easily stored fresh for 10 days at 10°C with 90-95 percent humidity (Somerville *et al.* 2014c).

7.2.3.3 Cucumbers

Cucumber (*Cucumis sativus*) comes in three sexual breeds: a half-and-half mix of male and female flowers (monoecious); a seventy-thirty mix of female to male flowers (gynoecious); and entirely female flowering plants (parthenocarpic). Planting only female flowering plants will ensure a flowering fruit with each plant, and therefore a crop that can fruit without pollination. However, the pollen transmitted by bees and other pollinators can corrupt parthenocarpic plants, so it will be necessary to keep potential pollinators out of the greenhouse (Valdez 2017a). Cucumbers can be grown in media bed units as they have a large root surface, and on DWC floating rafts, although in grow pipes there could be a risk of clogging owing to excessive root growth (Somerville *et al.* 2014c).

Ideal growing conditions for cucumbers:

- Temperature: 24-27^{o}C
- pH: 5.5-6.5

Cucumbers require large quantities of nitrogen and potassium, so the decision on the number of plants to grow should take into account the nutrients available in the water and the fish stocking biomass. They grow best with long, hot and humid days, with ample sunshine and warm nights. Optimal growth temperatures are 24-27^{o}C during the day, with 70-90 percent relative humidity, and a night time temperature of 18-20^{o}C. They are highly susceptible to frost. Full sunlight and a temperature of the substrate of about 21^{o}C are also optimal for production. A higher potassium concentration will favour higher fruit settings and yield (Somerville *et al.* 2014c).

Seeds will germinate after 3 to 7 days at a temperature of 20-30^{o}C. The seedlings can be transplanted at 2-3 weeks when they have developed 4-5 leaves. Once transplanted, cucumbers can start producing fruit after 2-3 weeks. In optimal conditions, plants can be harvested 10-15 times. Harvesting every few days will prevent the fruits from becoming overly large, and favour the growth of the following ones. Cucumber plants grow very quickly and it is good practice to limit their vegetative vigour and divert nutrients to the fruits by cutting their apical tips when the stem is two metres long; removing the lateral branches also favours ventilation. Further plant elongation can be achieved by leaving only the two furthest buds coming out from the main stem. Plants are encouraged to further production by regular harvesting of fruits of marketable size. Cucumber plants need support for their growth, which will also provide them with adequate aeration to prevent foliar diseases like powdery mildew and grey mould. Owing to the high incidence of pests in cucumber plants, it is important to implement appropriate IPM strategies (see Chapter 8) and to intercrop the plant units that are less affected by the treatments used (Somerville *et al.* 2014c).

7.2.3.4 Aubergine

Aubergine (*Solanum melongena*) is a greedy crop, thriving at high temperatures and requiring a lot of space between each plant. It may be difficult to regulate temperatures to keep the aubergines happy while growing other crops in the same environment, so they are best grown as a monocrop to avoid juggling climate control (Valdez 2017a).

Ideal growing conditions for aubergine:

- Temperature: 22-26°C
- pH: 5.5-7.0

Aubergine has high nitrogen and potassium requirements, so careful management choices are required regarding the number of plants to grow in order to avoid nutrient imbalances. It enjoys warm temperatures with full sun exposure, and a relative humidity of 60-70 percent. Ideal night time temperatures are 15-18°C. Aubergine plants are highly susceptible to frost (Somerville *et al.* 2014c).

The seeds will germinate in 8-10 days in warm temperatures (26-30°C) and the seedlings can be transplanted in springtime, when temperatures are rising, when they have 4-5 leaves. Towards the end of summer, new blossoms should be pinched off to favour the ripening of existing fruit. At the end of the season, plants can be drastically pruned at 20-30 cm by leaving just three branches. This method interrupts the crop without removing the plants during the winter, and lets the plant restart production afterwards. Plants can be grown without pruning, and management of the branches can be facilitated with stakes or vertical strings. The growth time is 90-120 days. Like tomatoes and peppers, aubergines also need to be pollinated either manually or by introducing a bumble bee hive to the greenhouse. Harvesting should begin when the fruits are 10-15 cm long, using a sharp knife to cut the fruit from the plant, leaving at least 3 cm of stem attached to the fruit. The skin should be shiny; dull and yellow skin is a sign that the fruit is overripe. Delayed harvest makes the fruits unmarketable owing to the presence of seeds inside. Plants can produce 10-15 fruits for a total yield of 3-7 kilos (Somerville *et al.* 2014c).

7.2.3.5 Strawberries

The garden strawberry (or simply strawberry; *Fragaria × ananassa*) is a widely grown hybrid species of the genus *Fragaria*, collectively known as strawberries. Strawberries are different from other crops. They live for a long time, but they are also susceptible to many diseases. Crown or heart rot is a fungal disease that is especially common for strawberries. The crown of the plant is the region where the roots become the stem, so is important to make sure that the crown is kept out of the wet zone. Mites can also be a problem. Different varieties have different environmental preferences and different bearing timelines: one variety may take a month to start bearing fruit after planting, while another may need several months. Some varieties also only bear fruit for part of the year, even indoors. Ever-bearing or day-neutral varieties are best for indoor growers (Storey 2016l).

Ideal growing conditions for strawberries:

- Temperature: 18-20°C
- pH: 5.5 to 6.0

Table 3: Recommended nutrient solution compositions matched to the growth phase of strawberries in soilless culture (from Raviv & Lieth 2007)

Growth phase	N	P	K	Ca	Mg
			(mg L^{-1})		
Transplanting	55-60	20-25	45-60	60-70	35-40
Anthesis and first fruit wave	70-85	20-25	70-90	100	45
Second fruit wave	80-85	25-30	80-90	100	45
Third fruit wave	80-85	25-30	80-90	100	45
Fourth fruit wave	55-60	20-25	55-60	80	35

Grow strawberries from rootstock rather than seed. Vegetative growth (runners) tends to be much faster that sexual reproduction (seeds), so you can cut the time from planting to production by months or years by using rootstock. In a healthy system, strawberry rootstock will have new growth sprouting up in less than a week, with the first flowers at about two weeks, but it is important to pinch back the buds for 4-6 weeks to keep the plant's resources directed towards vegetative growth, which will give the plant the ability for higher yields later on. If flowers are allowed to develop, fruit forms and ripens in about 2 weeks, though this will vary depending on the variety and growing environment. Outdoors, producers can rely on natural pollinators such bees, flies, and birds to spread pollen from the male parts to the female parts of the strawberry plants. Indoors, growers will either have to host a hive, or hand pollinate. Hand pollination can be done with a paintbrush. By lightly disturbing the centre of the flowers, one after the other, this will spread pollen from flower to flower. Hand pollination can take 10-30 seconds per plant, which can be time consuming on a large scale, so it may be more economical to use bees instead (Storey 2016l).

Strawberry pruning consists of leaf, flower, and crown pruning, and runner removal. Leaf pruning involves the removal of old leaves that start turning yellow. These leaves also prevent air circulation and light interception into the canopy, thereby enhancing the chance of disease development. Growth of runners during the production period is unnecessary and a waste of carbohydrates, which can be used for flower production. Therefore, runner pruning is also important for good quality fruit production. Flower pruning in strawberry is done to promote vegetative growth or to promote production of large fruits. When plants are started from runners, plants need to establish a large crown. For crown development, the flowers developed during early growth are removed, so that sugars produced by photosynthesis are allocated to vegetative growth. The size of fruit is inversely proportional to the number of flowers. If there are a large number of small flowers produced, small fruit production is likely, so flower pruning is necessary for good quality fruit production. Crown pruning is also important for flower bud induction in strawberry when plants are overly vegetative. During winter production, crown pruning is necessary for maintaining proper crown density in greenhouse strawberry production (Singh & Dunn 2017).

Figure 5: Strawberries growing in NFT channels
https://www.maxpixel.net/Produce-Strawberries-Hydroponic-Farming-Growing-621914

7.2.4 Crop selection for different systems

The style of grow bed influences the choice of plants. In media-based units, provided that they are of the right depth (at least 30 cm), it is common practice to grow a polyculture of leafy greens, herbs and fruiting vegetables at the same time. Polyculture on small surfaces can also take advantage of companion planting for pest and disease control, and better space management, because shade-tolerant species can grow underneath taller plants. Monoculture practices are more prevalent in commercial NFT and DWC units, because the grower is restricted by the number of holes in the pipes and rafts in which to plant vegetables. Using NFT units, it might be possible to grow the larger fruiting vegetables, such as tomatoes, but these plants need to have access to copious amounts of water to secure sufficient supply of nutrients and to avoid water stress. Wilting in fruiting plants can occur almost immediately if the flow is disrupted, with devastating effects for the whole crop. Fruiting plants also need to be planted in larger grow pipes, ideally with flat bottoms, and be positioned over a larger distance than leafy vegetables. This is because fruiting plants grow larger and need more light to ripen their fruits, and also because there is limited root space in the pipes. On the other hand, large bulb and/or root crops, such as kohlrabi, carrots and turnips, are more likely to be grown in media beds because DWC and NFT units do not provide a good growing environment and adequate support for the plants (Somerville *et al.* 2014a).

Selecting plants for deep water cultivation (DWC) or raft systems requires consideration of a number of important factors (Valdez 2017b):

1) Weight – Rafts are usually quite durable and affordable, but they can only support so much weight. The best crops for deep water cultivation are small and lightweight. Lettuce, for example, is a popular DWC crop and the perfect size to fit on rafts. Larger crops like tomatoes grow top-heavy. Without the root anchoring provided by a dense media, top-heavy plants can fall over or break at the stems.

2) Footprint (volume) – DWC systems function on a single horizontal plane since they are typically too heavy to stack. This means that there is a 1:1 volume to growing area ratio, so it is necessary to fill the horizontal plane efficiently by choosing plants that can be grown at higher planting densities (ie. leafy greens).

3) Water-friendly – Drought loving plants and herbs like oregano and rosemary that prefer 'dry feet' don't do well in DWC systems. On the other hand, thirsty plants like lettuce will thrive in deep water cultivation systems.

Bato buckets (or 'Dutch' buckets) are a variation of the media bed technique that uses a series of small media beds in buckets. A Bato bucket system is typically set up with buckets staggered on a bench or on the floor, with the feed line running water to the buckets from above, and the drain line (or return line) running water away from below. The three most common media used in Bato bucket systems are perlite, expanded clay, and coconut coir**.** These can be used by themselves or together in different ratios (Valdez 2017a).

The most popular crops for Bato buckets are large and/or vining crops like tomatoes, cucumbers, peppers, and aubergine. Vining crops grow in 'leaders' that vine upward or outward depending on the trellising. Many of these crops can therefore be trellised and trained upward, creating rows of tall towering plants which are easy to access and monitor. Selecting crops for a Bato system requires the following considerations (Valdez 2017a):

1) Disease resistance – Bato buckets can save a lot of space but cluster together crops, creating a vulnerability to disease. Tougher plants mean less risk and disappointment.

2) Footprint and plant style – The plants chosen for growing in Bato buckets will have an influence space, maintenance, and harvest strategies. Since Bato buckets are set up on horizontal planes, on benches or set on the floor, it is important for growers to take advantage of the volume of space above the buckets as much as possible. Vining crops allow growers to do that.

Figure 6: Bato buckets (on the right) being used to grow strawberries at the University of District of Columbia urban farm in Beltsville (https://www.flickr.com/photos/usdagov/32245870463)

The best plants for Bato buckets are:

- Tomatoes – allow 60-90 centimetres between buckets. Two plants per Bato bucket will give maximum produce for material invested. The vining crop can grow to six or even twelve metres tall in a greenhouse setting.
- Bell peppers – allow 30-50 centimetres between buckets
- Cucumbers – allow 60-80 centimetres between buckets
- Aubergine – allow 20-40 centimetres between buckets

7.3 Crop scheduling

Planting all the crops on a farm at the same time results in production waves instead of continuous production. Continuous production is what farmers need in order to satisfy weekly or even bi-weekly demand, by always having mature crops in the farm. A planting and harvesting schedule that accounts for the life cycles of each crop is a useful tool to achieve this (Storey 2016c):

- Leafy greens like chard, lettuce, and cabbage have a 4-6 week cycle from transplant to harvest
- Quick herbs like chives and mint have a 3-4 week cycle between harvests
- Coriander, parsley, and basil have a 5 week cycle when conditions are right
- Fruiting crops such as strawberries and tomatoes produce continually. They can therefore all be planted at the same time

It is also important to consider the effect of harvesting the plants on the entire ecosystem of the aquaponic unit. If all of the plants were to be harvested at once, the result would be an unbalanced system without enough plants to clean the water, resulting in nutrient spikes. Some farmers use this technique, but it must correspond with a large fish harvest or a reduction of the feed ration. However, it is recommended to use a staggered harvesting and replanting cycle. The presence of too many plants growing synchronously would result in the systems being deficient in some nutrients towards the harvest period, when the uptake is at a maximum. By having plants at different growth stages – some seedlings and some mature plants – the overall nutrient demand will always be the same. This will ensure more stable water chemistry, and also provides a more regular production (Somerville *et al.* 2014a).

While indoor growers enjoy the benefit of year-round harvests, they can still lose precious time when their system is empty between crop cycles (downtime). In order to minimize downtime, seedlings need to be ready to transplant to the aquaponic system when the previous crop is ready for harvest. This can be done by calculating the number of days in advance that you should germinate new seeds so that they are ready to go into the system on the day you are ready to plant. Use a calendar or Gantt chart and follow these steps (Godfrey 2018):

1 – Mark harvest day

2 – Add together your crop's germination time and propagation time. This will give you the number of days prior to harvesting that you should start germinating seeds for the next crop cycle. Count back on the calendar, and mark the day you should germinate your seeds and the day you should move them to propagation. The day you transplant into the system should fall on the day immediately after the harvest of the previous cycle. Depending on the size of your system, you may be able to harvest and transplant on the same day. If you have a large farm, it may take you a few days to harvest.

Environmental conditions and crop variety will all influence crop timing. Figure 7 shows a hypothetical crop schedule for a lettuce variety where the whole plant is harvested (as opposed to a cut-and-come-again variety). The five day germination time is followed by a 16 day propagation time, at which point the seedlings are ready to transplant into the aquaponic unit. After a further nine days of growth, the lettuces are ready to harvest. The second crop cycle is timed so that the seedlings are ready to transplant into the aquaponic unit on the same day that the first cycle is harvested, thereby minimizing downtime.

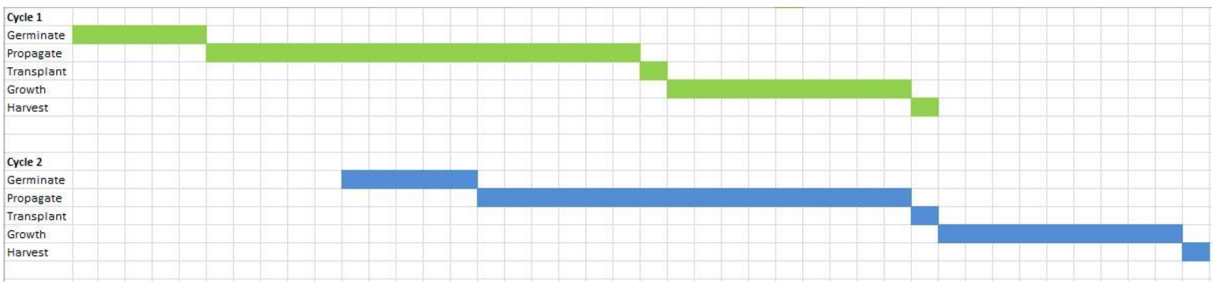

Figure 7: A hypothetical crop schedule for lettuce

Using overlapping crop cycles, as in the example above, produces a small harvest each week, rather than a large one every five weeks. This is an obvious strategy to use for a farmer with a contract that states that they promise to deliver a certain amount of produce every week. The steps for creating an effective scheduling plan are as follows (Godfrey 2018):

1. Make a labour plan for harvest – If you will be harvesting by yourself, make sure that you have enough time to harvest everything you need to in order to have it ready on time for the sale

2. Know your varieties – Each crop has different cycle timing, so make sure you read up on the unique requirements of the crop. This will inform all of your decisions, from germination to harvest to delivery. In addition, consider what type of harvest the plant will require. For example, lettuce will probably be fully harvested, which will mean that you would need to replant sooner than if you grew something like basil where you could harvest the same crop cycle multiple times

3. Choose your harvest technique – How you harvest should be determined by your crop type; some crops allow you to use cut-and-come-again harvest while others are more suited for a full harvest. A cut-and-come-again-style harvest will probably take longer than a full harvest technique, because you will be cutting the same plant multiple times rather than taking the whole thing in one go

4. Factor in the size of your farm – The bigger the system, the longer it will take to harvest. That is a general rule, even if you have employees working for you. Labour is one of the largest costs of running indoor farms, and because things just take a long time. Ensure that when you are planning for your timing, you take into account how big your system is; take notes on how long on average it takes to do your harvests, and factor it into your crop timing calculations. This will also inform your decision of what sized sections of your farm you'll designate for each overlapping crop cycle

5. Think about your customers – If your market doesn't want it, don't grow it. If your market does want it, and you can grow it well, then budget plenty of time and resources to get them what they want when they want it.

7.4 References

Godfrey, M. 2018. *How to Minimize Downtime Between Hydroponic Crop Cycles*. Upstart University.

Raviv, M. & Lieth, J.H. 2007. *Soilless Culture: Theory and Practice*. Elsevier.

Resh, H.M. 2013. *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower* (7th edition). Newconcept Press, Mahwah, SA.

Singh, H. & Dunn, B. 2017. *Pruning Hydroponic Crops*. Oklahoma Cooperative Extension Service.

Somerville, C. et al. 2014a. Plants in aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 83-102.

Somerville, C. et al. 2014b Management and troubleshooting. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish* *and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 123-139.

Somerville et al. 2014c. Appendix 1 – Vegetable production guidelines for 12 common aquaponics plants. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 169-181.

Storey, A. 2016a. *Best Conditions and Methods for Growing Parsley in Hydroponics*. Upstart University.

Storey, A. 2016b. *Everything You Need to Know About Growing Chard Without Soil.* Upstart University.

Storey, A. 2016c. *Farmer Tip #1 – How to Make a Planting Schedule*. Upstart University.

Storey, A. 2016d. *Get the Scoop on How to Grow Fennel in Hydroponics*. Upstart University.

Storey, A. 2016e. *Growing or Selling Basil? Read this First.* Upstart University.

Storey, A. 2016f. *Harvesting and Handling Lettuce for a Longer Shelf Life*. Upstart University.

Storey, A. 2016g. *Get the Tips and Guidelines on Growing Mustard Greens*. Upstart University.

Storey, A. 2016h. *Growing Oregano in Hydroponics? Read This First!* Upstart University.

Storey, A. 2016i. *Here's What You Need to Know About Growing Bok Choy in Hydroponics.* Upstart University.

Storey, A. 2016j. *How to Grow Classic Rosemary in Hydroponics.* Upstart University.

Storey, A. 2016k. *How to Grow Hydroponic Cabbage: The Beginner's Guide.* Upstart University.

Storey, A. 2016l. *How to Grow Hydroponic Strawberries*. Upstart University.

Storey, A. 2016m. *How to Grow Mint in Hydroponics – All You Need to Know.* Upstart University.

Storey, A. 2016n. *So You Want to Grow Chives? Read this First!* Upstart University.

Storey, A. 2016o. *10 Tips for Farmers on the Post-harvest Care of Herbs*. Bright Agrotech.

Storey, A. 2016p. *The Beginner's Guide to Growing Kale in Hydroponics*. Upstart University.

Storey, A. 2017a. *Are You Growing Cilantro in Hydroponics? Read This First!* Upstart University.

Storey, A. 2017b. *Everything You Need to Know About Growing Nasturtiums in Hydroponics*. Upstart University.

Storey, A. 2017c. *The Beginner's Guide to Hydroponic Tomatoes*. Upstart University.

Thorarinsdottir, R. (ed.) 2015. *Aquaponic Guidelines*. EU Lifelong Learning Programme.

Valdez, J. 2017a. *The Best Plants for Bato Buckets.* Upstart University.

Valdez, J. 2017b. *The Best Plants for Raft Systems (DWC).* Upstart University.

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8. INTEGRATED PEST MANAGEMENT

8.1 The concept of integrated pest management (IPM)

Many national and intergovernmental bodies have firmly decided that the officially endorsed paradigm for crop protection is 'integrated pest management' (IPM). For example, a European Union (EU) Directive (The European Parliament and the Council of Europe 2009) has obliged all professional plant growers within the Union to apply the general principles of IPM since 2014. IPM is an ecosystem-based strategy that focuses on the long-term prevention of pests or their damage through a combination of techniques such as biological control, habitat manipulation, modification of cultural practices, and the use of resistant varieties (Tang *et al.* 2005). Although aquaponics is understood to be more resilient against pathogens when compared with conventional hydroponic production (Gravel *et al.* 2015), it is nevertheless impossible to avoid pests and diseases. Healthy crops are first and foremost the consequence of good growth conditions and choosing an appropriate plant variety, which allow plants to achieve their high productive potential, and not the result of chemical and biological plant protection. A higher microbial diversity improves plant resistance in the rhizosphere against root diseases as well as greater nutrient uptake by the crop. Therefore, optimal plant nutrition, proper environmental conditions in the cultivation system, and intelligent cultivation techniques are essential. The management of pests and pathogens ought to minimize the application of biological and chemical products.

According to Food and Agriculture Organization (FAO), Integrated Pest Management (IPM) is defined as '*A pest management system that in the context of the associated environment and the population dynamics of the pest species utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest populations at levels below those causing economic injury*' (FAO 2018). Integrated crop protection and pest management (IPM) encompasses preventive measures, use of barrier-based approaches (e.g. agrotextiles), biotechnology-based methods (e.g. plant breeding), biological pest control using natural enemies, and controlled application of chemical products that are allowed in organic farming. IPM is therefore a cost-effective, environmentally sound, and socially acceptable way to manage pests and diseases.

Both in conventional hydroponics and in aquaponics, cultivation managers have to deal with different kind of biological threats. Insect pests are not only problematic because of the direct damage they cause to the plant, but also because they often act as carriers (vectors) for bacterial or viral diseases. Both insects and diseases benefit from controlled climate conditions in greenhouses: they are sheltered from rain, wind, and strong temperature fluctuations. However, these environmental conditions also allow an effective use of beneficial organisms against insects. Different management strategies should contribute to minimize pesticide use and to improve plant health. While biological pest control is part of Integrated Pest Management (IPM), there are some differences between the general concept of IPM and biological pest control (BPC) (Table 1).

Table 1: Integrated pest management (IPM) versus organic farming

	Integrated pest management (IPM)	Organic farming guidelines
Preventive methods	• crop hygiene (weed removal, room disinfection etc.) • physical barriers against pests (nets etc.) • use of strong and resistant seedlings • hygiene measures at the entrance • restricting visitor numbers	
Use of beneficial insects against pests (Biological pest control (BPC))	• Ladybird larva against aphids • Fly parasitoid (*Encarsia formosa*) against whitefly • Gall midges (*Aphidoletes aphidimyza*) against aphids • Enthomopathogenic nematodes • Enthomopathogenic bacteria and fungi	
Chemical control	Use of synthetic pesticides not toxic to fish* could be used under controlled conditions but only as a last resort, such as • Pymetrozine against aphids, whitefly • Clofentezine against mites • Fosetyl-aluminium against downy mildew Use of natural pesticides listed under BPC is possible too. * TER (Toxicity Exposure Ratio) = acute LC50 (mg agent/liter)/PEC (Predicted Environmental Concentration) > 100 for fish, and > 10 for aquatic invertebrates.	Use of natural pesticides, such as • Oils* (fennel oil against powdery mildew) • Potassium bicarbonate* against powdery mildew (*Oidium, Leveillula, Sphaerotheca)* • Sulphur* against powdery mildew (*Oidium, Leveillula, Sphaerotheca)* • Lecithin* against powdery mildew (*Erysiphe*)

Source: FiBL – Betriebsmittelliste 2019 für den biologischen Landbau in der Schweiz

Check the fish safety before using any kind of phytopharmaceuticals, biological control agents or plant-based insecticides and fungicides

In contrast to conventional hydroponics, aquaponic systems are independent ecosystems with different zones (or compartments). Besides the target crops (fish and plants), the system also hosts a wide array of distinct microorganism communities (Schmautz *et al.* 2017), and small insects and spiders with either a beneficial, neutral or harmful effect on the crop. Aquaponic systems also usually feature a high density of fish and plants in one location, which facilitates the rapid spread of disease or pests throughout the whole system. In contrast to conventional cultivation systems, where the use of chemical pesticides is part of the daily routine, such methods are not suitable for aquaponics (Bittsánszky *et al.* 2015). The consequences of severe disease infection or of pest infestation are compounded, as losses or removal of either plants or fish will upset the balance between the fish, plants and water chemistry. The use of chemical products should be considered very carefully. The input of organic or inorganic chemicals could be fatal for aquatic animals as well as for the microbiological balance in the system. Therefore it is better to abstain from chemical products than to risk fatal consequences for the whole aquaculture system.

The IPM response to disease and/or pests in aquaponics is therefore constrained by: (i) the combination of fish, plants and bacteria, since fish may be sensitive to plant treatments and vice-versa, and bacteria may be sensitive to both fish and plant treatments; and (ii) the desire to maintain chemical free or organic status.

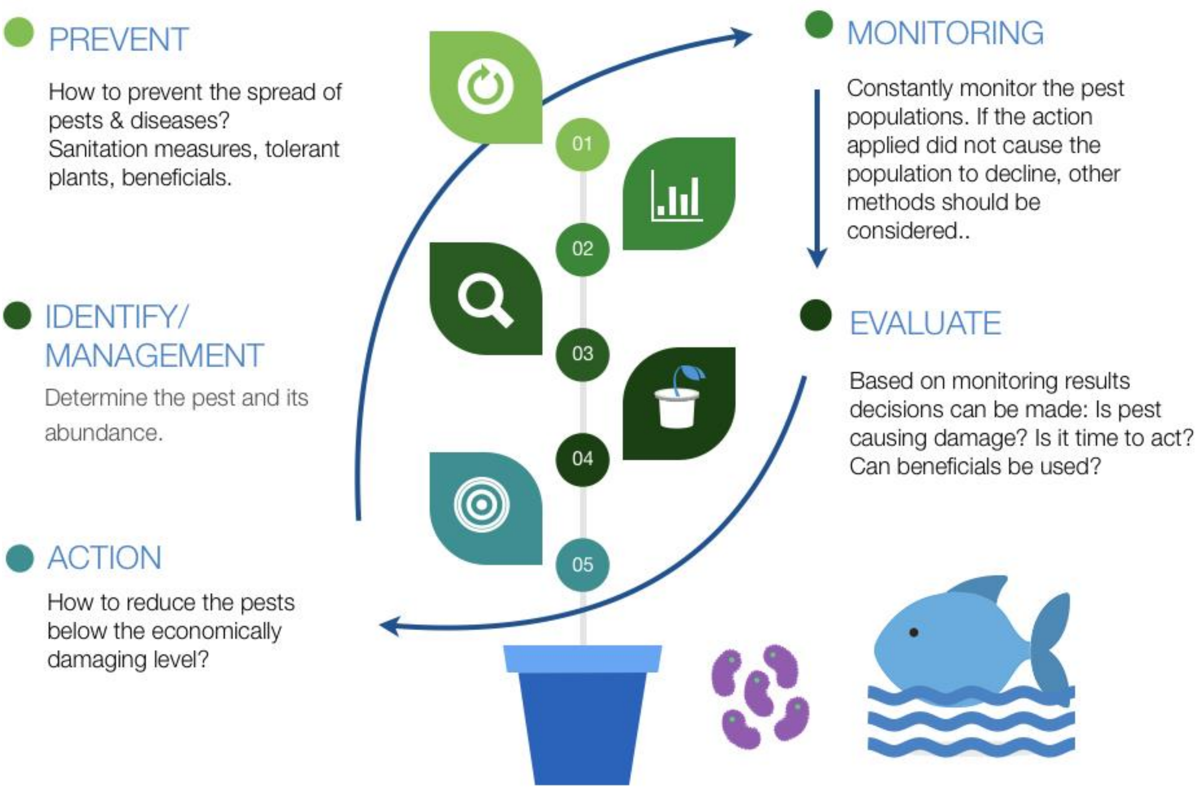


Figure 1: The five-step IPM program in aquaponics

8.2 Prevention methods in integrated pest management

Good plant health is not only the absence of diseases and pests. Good cultivation techniques with adequate nutrition, water quality, climate conditions and production hygiene are required for healthy growth. To achieve sustainable plant protection management, it is essential to understand how to minimize the risk of plant diseases and pests. Prevention is the most important part of integrated pest management (Table 2).

Table 2: Plant disease prevention measures in aquaponics

Control measure	Examples of actions
Hygiene of cultivating conditions	Respecting sanitation rules, specific clothes, separate room for plant germination, avoiding algae development
Physical water treatment	UV treatments Heat treatment
Physical barriers against insect vectors	- Netting - Trapping
Respect of good agricultural practices	- Use of tolerant and resistant crop varieties - Adequate supply of nutrients - Correct plant spacing - Regular monitoring
Management of environmental conditions	The regulation of humidity and temperature is central to the prevention of fungal and bacterial diseases in covered crops. Manipulate the heating, the ventilation, the shading, the supplement of lights, the cooling and the fogging to find the optimal conditions allowing both plant production and disease control
Support the natural community of disease suppressing organisms	- Beneficial microorganisms - Beneficial insects - Compost extracts

8.2.1 Hygiene of cultivation conditions

Before starting aquaponics (or any other cultivation) in a greenhouse it is necessary to clean and disinfect the interior and all the tools. First, all plant material, slabs, floor covers etc. should be removed. Greenhouse plastic cover films older than 3-4 years tend to be dirty and less translucent, and therefore suboptimal for plant growth. Every year the exterior of the greenhouse should be washed to improve the light level for the crops. Before disinfecting a greenhouse, all surfaces need to be clean and free from organic matter. Sustainable disinfectants are water, water damp, alcohol (70%), peroxide, organic acids etc. It is also recommended that working tools such as knives be disinfected. A clean greenhouse provides the best starting conditions for healthy and strong seedlings. Disinfection before entering a greenhouse, such as using hand-washing techniques and disinfection of shoes with disinfectant foot mats, is indispensable. Cleaning empty greenhouses, irrigation systems, plant containers and harvesting equipment with a sanitizing solution are also important factors to ensure food safety. Protective clothing and shoe covers should also be used.

8.2.2 Tolerant and resistant crop varieties

Plant resistance to insects is one of several cultural control methods. Cultural control methods involve the use of agronomic practices to reduce insect pest abundance and damage below that which would have occurred if the practice had not been used. In IPM, plant resistance to insects refers to the use of resistant crop varieties to suppress insect pest damage. Plant resistance is intended to be used in conjunction with other direct control tactics. The development of tolerant and resistant crop varieties is remarkable, and seed catalogues should be studied carefully in order to choose varieties that are resistant against diseases. In some crops, like tomatoes, cucumbers, peppers or aubergines (Figure 3 and 4), grafting allows for very good results. With some practice, it is possible to do grafting by oneself. Manuals, such as Kleinhenz *et al.* (2011), and tutorials describing the grafting technique, are available on the internet.

Figure 3: Grafted tomato seedlings
(Photo ZHAW)

Figure 4: *Botrytis* infection on lettuce stem
(Photo ZHAW)

8.2.3 Appropriate plant spacing

Appropriate plant spacing is a challenge in any greenhouse cultivation, for all crops start very small and grow and develop extensively. High planting density increases competition for light, weakens plant vigour, and invites pest and diseases to settle. Periodic pruning is essential.

8.2.4. Adequate supply of nutrients

Different crops require different fertilisation regimes. A famous example is the tomato crop in conventional hydroponics with more than five different nutrition recipes (Raviv & Lieth 2007); however, this cannot be done in aquaponics, because of recirculation. On the other hand, crops with short cultivation periods and less dependence on vegetative and generative phases usually receive a uniform supply of nutrients during the entire growth cycle. Incorrect nutrient supply encourages pest infestation and disease. For example, too high nitrogen levels make plant tissues more succulent, and easier for pests to penetrate. There are two main ways of regulating the nutrient levels in aquaponics:

- adding soluble fertilizer according to the nutrient requirements of the crop (Resh 2013, see also Chapters 5, 6, and 9)
- regulating the nutrition according to the salt concentration in the water (EC level). This method assumes that the ratio between different nutrients (salts) is stable.

EC levels between 0.5 – 1.5 mS/cm are usually applied in aquaponics (Vermeulen & Kamstra 2012). If the salt concentration exceeds 2.5 mS/cm, fresh water should be added. Too high salt concentrations in the water cause physiological disorders, resulting in necrosis on the leaf surface or the leaf margins. Such damage creates access for secondary plant diseases. More information is included in Chapters 5 and 6.

8.2.5 Monitoring

IPM programs work to monitor for pests and diseases and identify them accurately, so that appropriate control decisions can be made in conjunction with action thresholds. Monitoring and identification remove the possibility that pesticides will be used when they are not really needed, or that the wrong kind of pesticide will be used. Regular monitoring of pest and diseases is therefore fundamental. Any discolouring or deformations of leaves and the occurrence of mould fungus on the leaves or fruit should be recorded (see also below). As it is challenging to diagnose fungal diseases or pests, we recommend contacting plant protection consultants.

8.2.6 Physical defence

Plant health can benefit greatly from preventing or limiting injury by arthropod pests from the start. Physical control strategies include methods for excluding pests or limiting their access to crops, disrupting pest behavior, or causing direct mortality (Vincent *et al*. 2009). Physical control methods can be categorized as active and passive (Vincent *et al.* 2009). Active methods involve the removal of individual pests by hand, pruning out infested plant tissues, and removing heavily infested plants. Passive methods usually include the use of a device or tool for excluding or removing pests from a crop. Typically, these devices serve as barriers between the plants and the insect pests, thus protecting plants from injury and damage. Other passive tools include repellents and traps. While traps are often used for monitoring pest abundance and distribution, many are designed as ‘attract and kill’ technologies, which attract insect pests through colour, light, shape, texture or scent, or a combination of these.

8.2.6.1 Netting

Use of netting is a simple way of preventing pests from coming into contact with the crop. The mesh size depends on the pest targeted:

- 0.15 mm against thrips
- 0.35 mm to exclude whitefly and aphids
- 0.8 mm to exclude leaf miners and beetles
- 20 mm against birds

However, netting also has a negative side: it reduces light and raises humidity, and therefore increases the risk of fungal diseases. This is especially true for nets with a mesh size of < 2 mm.

8.2.6.2 Trapping

Traps may be used to monitor or detect a pest population, to catch and identify the pest, and to reduce local pest density. Commercial traps are available for controlling or detecting various moth species (pheromone traps), whiteflies and thrips (sticky traps), flies and yellowjackets, snails and slugs, bed bugs, spiders, cockroaches and many other pests. Coloured sticky traps attract different pests. They should be positioned slightly above the canopy of plants. Blue sticky cards trap adult stages of thrips. Yellow sticky cards are used for whiteflies and harmful butterflies. When applying beneficial organisms for pest control, it is best to consult an expert first.

8.2.7 Support the natural community of disease suppressing organisms

Controlled environments include both risks and opportunities for integrated pest management. Greenhouse conditions promote organisms with increased temperature and air moisture requirements, such as fungal diseases. But these climate factors also stimulate the development of many beneficial insects. The use of beneficials is well established in greenhouse farming. Pests and disease can appear even with the best prevention. One of principles of integrated and organic farming is for plants to thrive in the presence of pathogens or pests. This is only possible if beneficial macro- or microorganisms support the control of pests and diseases. A natural community of disease suppressing organisms can be supported by adding biological agents to the water as a stimulant for plant resistance.

8.2.7.1 Beneficial microorganisms

Important beneficial microorganisms are:

- *Bacillus amyloliquefaciens* or *Trichoderma harzianum* as prevention against root diseases (e.g. *Pythium*) in early stages of the crop (e.g. seedling stage)
- *Bacillus subtilis* against *Rhizoctonia*
- *Gliocladum catenulatum* against *Fusarium, Phytophthora, Pythium, Rhizoctonia* on cucumber, tomato, pepper, and culinary herbs

Products are commercially available in online shops or garden centres.

8.2.7.2 Beneficial insects and banker plants

Beneficial insects (or natural enemies) are normally used in organic and conventional vegetable greenhouse production. Widespread and commercially available types are:

- Ichneumonids against aphids, whitefly and similar
- Gall midges (*Aphidoletes aphidimyza*) against aphids
- Predator mites against spider mites
- Mirid bugs (*Macrolophus pygmaeus*) against whitefly

With this kind of pest control, pesticide residues as well as pesticide-induced resistance can be avoided. However, successful pest control using beneficials can be challenging. Each beneficial insect has its own individual needs. Specific attracting flowers (so-called banker plants) planted near or in the greenhouse can support beneficials (Conte *et al.* 2000). Examples of such plants are buckwheat (*Fagopyrum esculentum*), cornflower (*Centaurea cyanus*) and corncockle (*Agrostemma githago*).

8.2.7.3 Compost extracts

These are also known as 'compost tea' and contain many beneficial microorganisms. They are made by brewing and aerating compost in water (normally for 24 hours) in order to extract the beneficial organisms. Compost tea has to be applied immediately, either directly on the root zone or on the leaves. A first application can be made just after seeding, and a second before planting. Recipes and brewing methods can be found on the internet, for example here: www.soilfoodweb.com.

8.2.8 If all else fails …

Sometimes interventions with chemical products can be justified, but in that case stringent regulations have to be considered. Whenever possible botanical pesticides should be used first, because they are of biological origin. Some extracts from microorganisms are safe for fish and can be used in aquaponics. One is a toxin from *Bacillus thuringiensis*, which can be used against caterpillars, leaf rollers or other butterfly larvae. The other is *Beauveria bassiana*, a fungus that enters the insect's skin, and is effective against a number of pests such as termites, thrips, whiteflies, aphids and beetles. Most of the chemical synthetic fungicides and insecticides, but also some products permitted in organic farming, are toxic and harm aquatic organisms. An application is only worth considering in young plants before being transplanted into the aquaponic system. If chemical control is the last resort, the specific fish toxicity of the product has to be considered very carefully. Appendix 2 of 'Small-scale aquaponic food production' (Somerville *et al.* 2014) lists a selection of possible insecticides with indications of their relative toxicity to fish. Aquaponics is a complex ecosystem composed of different kind of bacteria, fungi and higher organisms with high potential in natural power resistance. It is important to maintain the ecological balance of this ecosystem by proper prevention measures, as described above. This should help to reduce the necessity of implementing direct methods of pest management to a minimum.

8.3 The most common pests and diseases

8.3.1 Identification of pests and diseases

Proper identification of pests and diseases is important. Whether the pest is an insect, rodent, phytopathogenic fungus, or other organism, correct identification makes controlling it easier and more effective. A mistake in identification can lead to improper control tactics that cost time and money. It may also lead to unnecessary risks to people, to the fish, or to the environment. To identify a potential disease, one should follow the steps described in Figure 5 and 6. Sometimes disease symptoms are similar to plant nutrient deficiency symptoms. In case of doubt, one should consult a specialist. If this is not possible, describe the symptoms and take photos (which will also serve for future reference). Then search on the internet to find photos and descriptions of disease symptoms that match those of your plants.

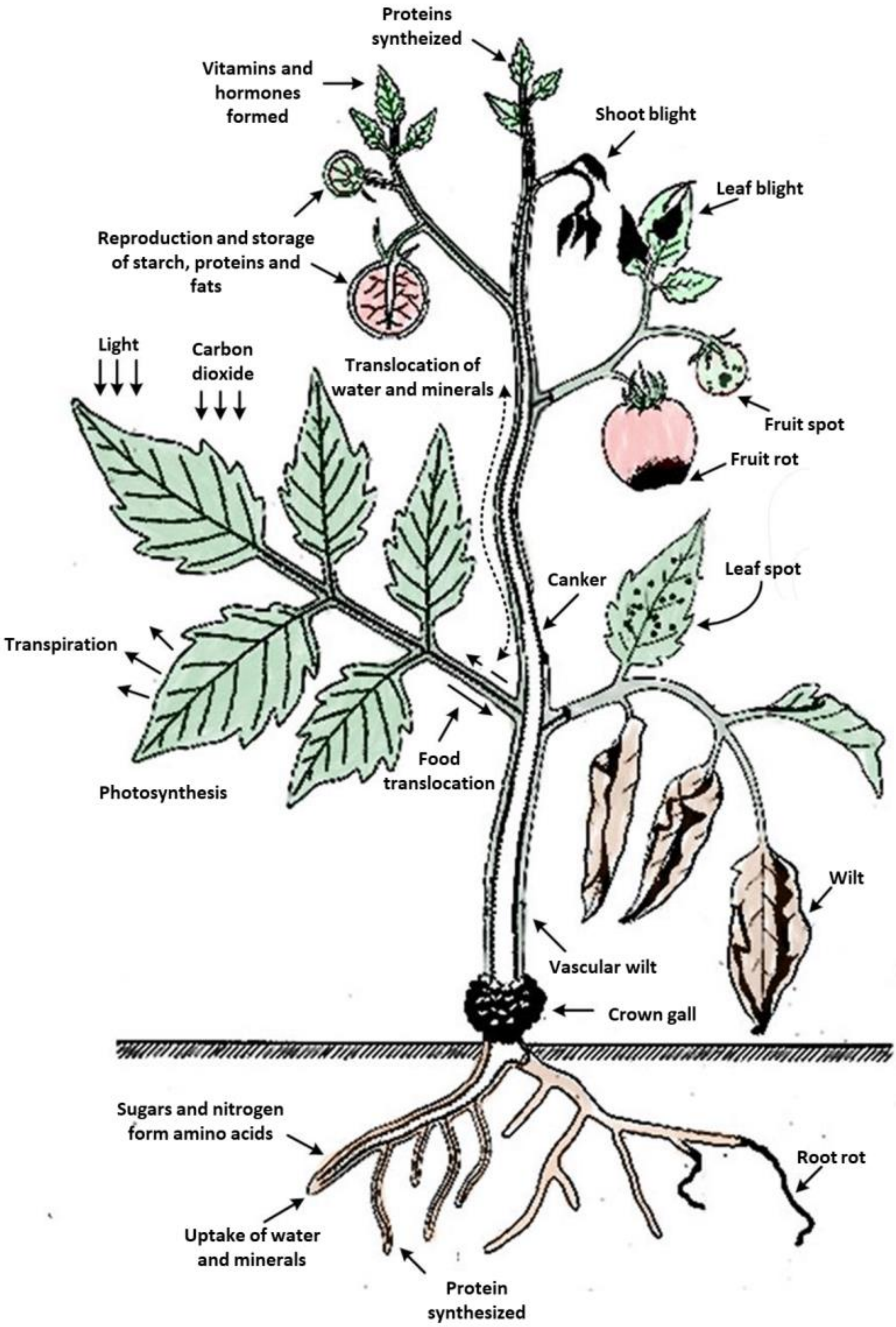


Figure 5: Disease symptoms on plants

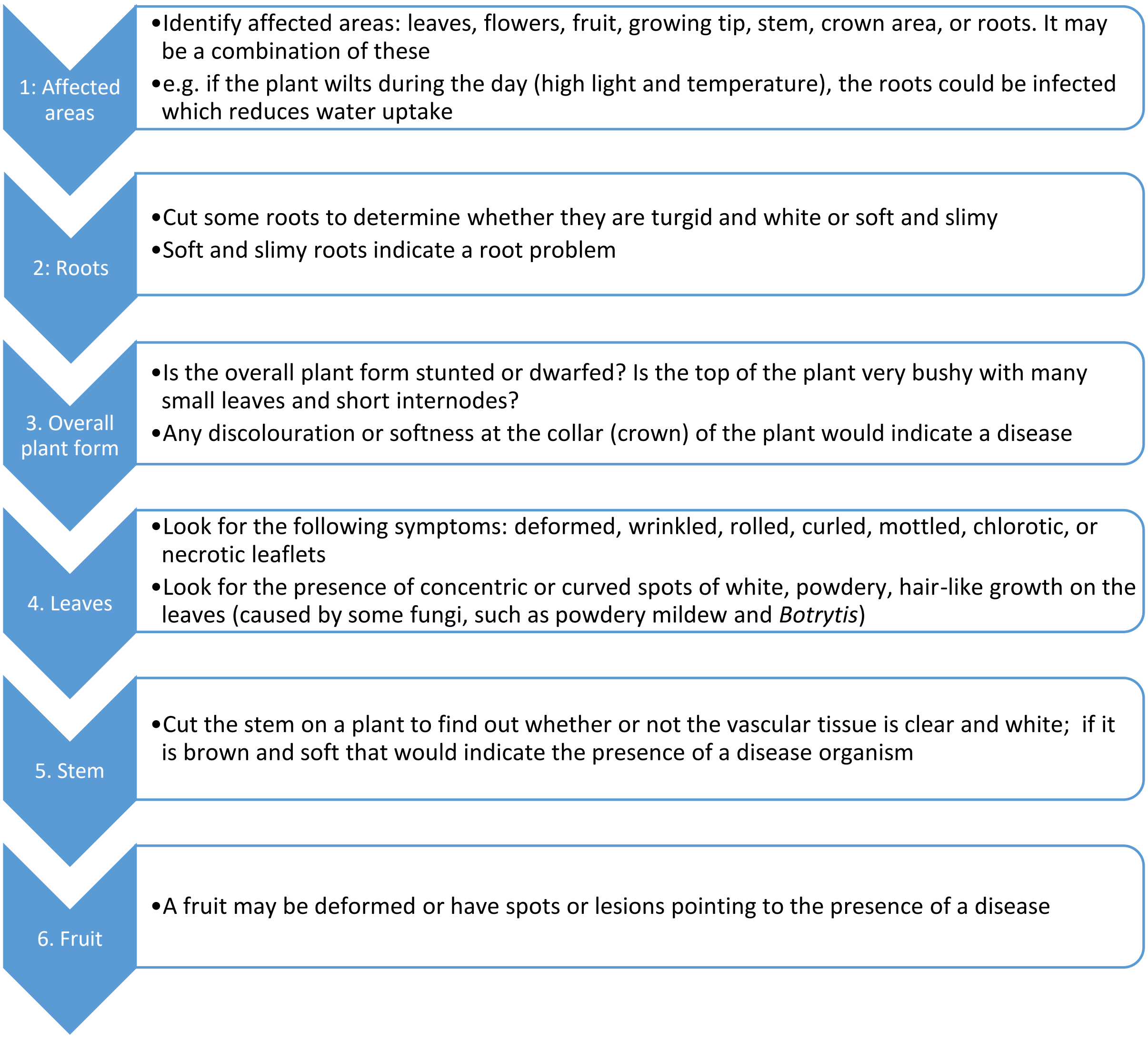


Figure 6: Procedure to follow when identifying plant diseases

8.3.2 Common plant diseases

8.3.2.1 Grey mould (*Botrytis*)

This is the most prevalent fungal disease of lettuce, aubergines, tomatoes and cucumbers (Figure 7) when the humidity levels are too high and there is bad air circulation. Maintain optimum humidity levels through ventilation and temperature regulation. In general, a relative humidity of 75% is good for most crops and is not too humid which promotes diseases. Removing lower, yellowing leaves will assist in keeping the humidity low near the plant base and will allow the air to circulate. Make a clean break or cut at the base of the leaf petiole (where the leaf joins the stem). *Botrytis* will also affect fruits, stems, and leaves. Cut the fruit during harvesting with pruning shears or a sharp knife to encourage rapid healing of the wound. After flowering remove dead flowers that have not set fruit, as often *Botrytis* quickly invades these dead tissues.

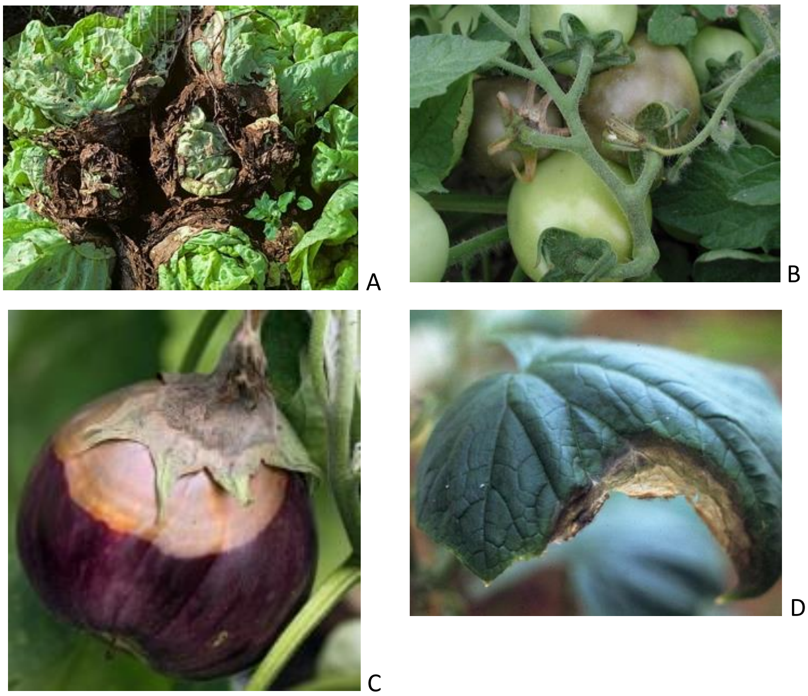


Figure 7: Symptoms of *Botrytis* infection on lettuce (A), tomato (B), aubergine (C) and cucumber leaves (D)

8.3.2.2 Stem rot (*Sclerotinia*)

This fungus infects the stem of aubergines, lettuce (Figure 8) and tomatoes. Treat it as for *Botrytis*. Proper sanitation and ventilation assist in preventing this disease.

Figure 8: Symptoms of stem rot on lettuce

8.3.2.3 Powdery mildew (order Erysiphales)

Powdery mildew diseases are caused by many different species of fungi in the order Erysiphales. It is the most common disease on cucumbers and lettuce (Figure 9). Powdery mildew is one of the easier plant diseases to identify, as its symptoms are quite distinctive. Infected plants display small white powdery spots on the upper leaf surface and stems. The lower leaves are the most affected, but the mildew spreads rapidly on any aboveground part of the plant. As the disease progresses, the spots enlarge and spread to cover the entire leaf surface as large numbers of asexual spores are formed, and the mildew may spread up and down the length of the plant. Proper sanitation and ventilation assist in preventing this disease. The best prevention is the selection of resistant or highly tolerant varieties.

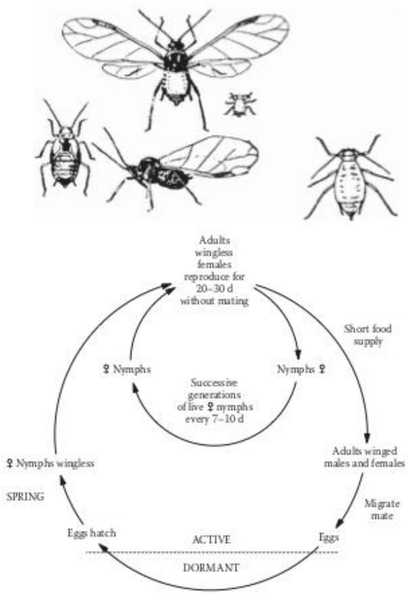
Figure 9: Symptoms of powdery mildew on lettuce (left) and cucumber (right)

8.3.3 Common plant pests

Most pests, such as aphids, larvae of caterpillars and moths, mealybugs, two-spotted spider mites, thrips, and whiteflies infest all crops. However, some are more aggressive on certain crops than on others. Place yellow sticky traps on overhead wires or support strings about 300 mm above the top of the plant to catch and monitor the presence of these pests.

8.3.3.1 Aphids

These pests are almost always present. They are green, brown, or black depending upon the species (Figure 10). There are winged and wingless forms. One prominent characteristic of their infestation on plants is the presence of 'honeydew' excreted from their abdomens as they suck on the plants, which causes stickiness of leaves and plant parts. Often sooty moulds (fungi) infect the leaves as a secondary organism, creating a black film on the leaves.

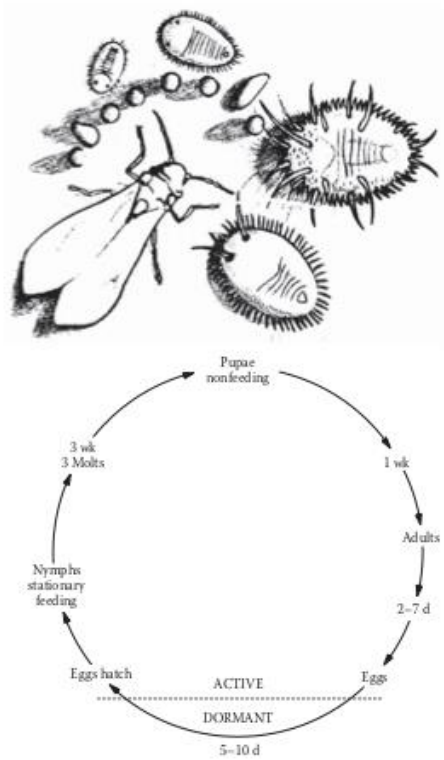


Above – Figure 10: Green aphids on a leaf

Right – Figure 11: Life cycle of aphids (Drawing courtesy of J.R. Baker, North Carolina Agricultural Extension Service)

8.3.3.2 Whiteflies (family *Aleyrodidae*)

Whiteflies are small hemipterans that typically feed on the undersides of plant leaves (Figure 12). More than 1550 species have been described. This is one of the most troublesome pests associated with tomatoes. These insects can be identified by their white wings and body. They are most prevalent on the undersides of leaves, and they fly quickly when disturbed. There are beneficial insects as well as pesticides available for their control.



Above – Figure 12: Whiteflies

Right – Figure 13: Life cycle of whiteflies (Drawing courtesy of J.R. Baker, North Carolina Agricultural Extension Service)

8.3.3.3 Two-spotted spider mite or red spider mite (*Tetranychus urticae*)

Mites are related to spiders and ticks (Figure 14). They have four pairs of legs in contrast to insects that have only three pairs of legs. Two-spotted spider mites have, as the name says, two dark-coloured spots on their bodies. As they suck on the leaves, small yellow spots form that eventually coalesce to give a bronze appearance to the leaves. They also produce webbing on the leaf surface as the infestation increases. If not controlled when numbers are manageable, they will cause complete bleaching and death of the leaves as they suck out all the contents of the cells.

Other spider mites that also damage greenhouse crops are carmine mites (*Tetranychus cinnabarinus*), and broad mites (*Polyphagotarsonemus latus*). These, however, are not as prevalent as the two-spotted mite and they differ in colour. The carmine mite is bright red, while the broad mite is translucent and can only be seen with a hand lens. Broad mites cause leaf and fruit deformation.

Figure 14: Two-spotted spider mite (adult and egg)

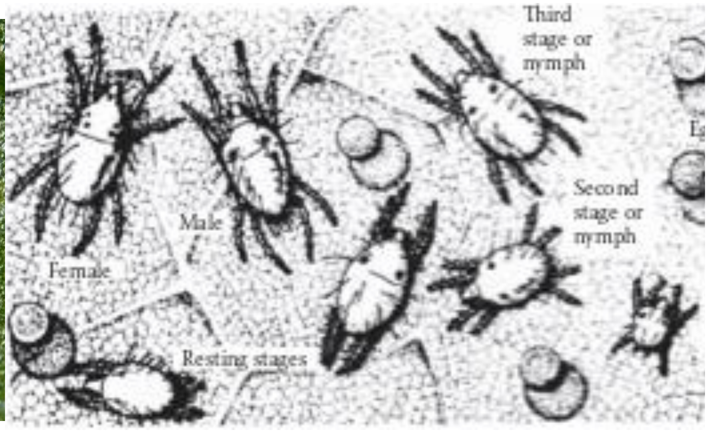
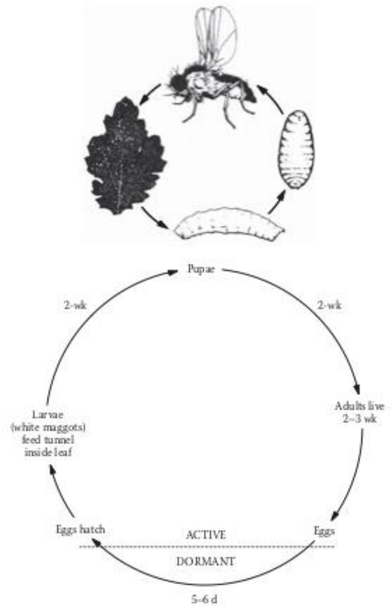


Figure 15: The life cycle of two-spotted spider mites (Drawing courtesy of J.R. Baker, North Carolina Agricultural Extension Service)

8.3.3.4 Leaf miners

A leaf miner is the larva of an insect that lives in and eats the leaf tissue of plants (Figure 16). The vast majority of leaf-mining insects are moths (Lepidoptera), sawflies (Symphyta, close relatives of wasps) and flies (Diptera), though some beetles also exhibit this behaviour. Adult leaf miners deposit eggs in the leaves that show as white swellings. As the larvae hatch, they eat 'tunnels' through the leaf between the upper and lower leaf epidermis, creating 'mines'. As infestation increases, the mines coalesce resulting in large areas of damage that eventually lead to the death of the leaf. The mature larvae drop to the ground (surface of the substrate) where they pupate (go through metamorphosis to adults) within 10 days. The cycle then begins all over again. The infestations can be reduced by the removal of badly infected leaves and any fallen leaves from the floor. If the substrate is covered with white polyethylene to prevent the larvae from entering as they fall from the leaves, it will minimize the reproduction of the insects. This is particularly helpful if plants are growing in pots or grow beds. The use of plastic wrapped slabs will restrict the infestation by breaking the life cycle.



Above – Figure 16: Leaf damage caused by a leaf miner

Right – Figure 17: The life cycle of a typical leaf miner (Drawing courtesy of J.R. Baker, North Carolina Agricultural Extension Service)

8.3.3.5 Thrips (order Thysanoptera)

Thrips are minute slender insects (Figure 18) with fringed wings and unique asymmetrical mouthparts. There are more than 6000 thrips species sucking the life from plants all over the world. These insects are especially attracted to the flowers. Their distinctive feature is the presence of feathery wings. They have rasping mouthparts that scrape the leaf surface and suck the plant sap, causing white, silvery streaks on the leaves. They, like whiteflies and aphids, also carry viruses. Thrips are attracted to blue sticky traps.

a)

b)

Figure 18: Thrips damage on basil (a) and thrips nymph (b)

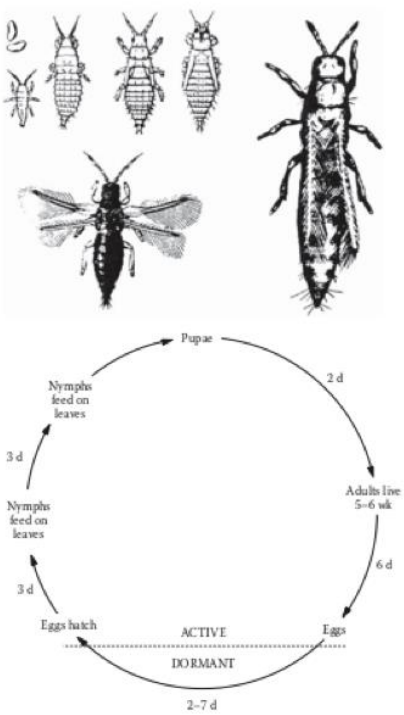


Figure 19: The life cycle of thrips (Drawing courtesy of J.R. Baker, North Carolina Agricultural Extension Service)

8.4 Biological pest control

The terms 'biological control' and its abbreviated synonym 'biocontrol' have been used in different fields of biology, most notably entomology and plant pathology. In entomology, it has been used to describe the use of live predatory insects, entomopathogenic nematodes, or microbial pathogens to suppress populations of different insect pests. In plant pathology, the term applies to the use of microbial antagonists to suppress diseases as well as the use of host-specific pathogens to control weed populations. In both fields, the organism that suppresses the pest or pathogen is referred to as the biological control agent (BCA).

8.4.1 Natural enemies of pests

Parasites, pathogens, and predators are the primary groups used in biological control of insects and mites. Most parasites and pathogens, and many predators, are highly specialized and attack a limited number of closely related pest species.

8.4.1.1 Parasites

A parasite is an organism that lives and feeds in or on a host. Insect parasites can develop on the inside or outside of the host's body. Often only the immature stage of the parasite feeds on the host. However, adult females of certain parasites (such as many wasps that attack scale insects and whiteflies) feed on and kill their hosts. Although the term 'parasite' is used here, true parasites (e.g., fleas and ticks) do not typically kill their hosts. Species useful in biological control, and discussed here, kill their hosts; they are more precisely called 'parasitoids'. Most parasitic insects are either flies (order Diptera) or wasps (order Hymenoptera). It is important to note that these small to medium-sized wasps are incapable of stinging people. The most common parasitic flies are the typically hairy *Tachinidae*. Adult tachinids often resemble houseflies. Their larvae are maggots that feed inside the host.

8.4.1.2 Pathogens

Natural pathogens are microorganisms including certain bacteria, fungi, nematodes, protozoa, and viruses that can infect and kill the host. Populations of some aphids, caterpillars, mites, and other invertebrates are sometimes drastically reduced by naturally occurring pathogens, usually under conditions such as prolonged high humidity or dense pest populations. Some beneficial pathogens are commercially available as biological or microbial pesticides. These include *Bacillus thuringiensis*, entomopathogenic nematodes, and granulosis viruses. Additionally, some microorganism by-products, such as avermectins and spinosyns, are used in certain insecticides; but applying these products is not considered to be biological control.

8.4.1.3 Predators

Predators kill and feed on several to many individual preys during their lifetimes. Many species of amphibians, birds, mammals, and reptiles prey extensively on insects. Predatory beetles, flies, lacewings, true bugs (order Hemiptera), and wasps feed on various insect pests or mites. Most spiders feed entirely on insects. Predatory mites feed primarily on spider mites.

8.4.1.4 Distinguishing pests from natural enemies

Proper identification of pests, and distinguishing pests from natural enemies, is essential for effective biological control. Carefully observe the mites and insects on your plants to help discern their activity. For example, some people may mistake syrphid fly larvae for caterpillars. However, syrphid fly larvae are found feeding on aphids and not chewing on the plant itself. If you find mites on your plants, observe them with a good hand lens. Predatory mites appear more active than plant-feeding species. In comparison with pest mites, predatory mites are often larger and do not occur in large groups.

Table 3: Some pests and their common natural enemies

	Natural enemies					
Pests	**Lace-wings**	**Lady beetles**	**Parasitic flies**	**Parasitic wasps**	**Predatory mites**	**Other groups and examples**
Aphids	X	X		X		Entomopathogenic fungi, soldier beetles, syrphid fly larvae
Caterpillars	X		X	X		*Bacillus thuringiensis,* birds, entomopathogenic fungi and viruses, predatory bugs and wasps, *Trichogramma* spp. (egg parasitic wasps), spiders
Giant whitefly	X	X		X		*Encarsia hispida, E. noyesi, Entedononecremnus krauteri*, *Idioporus affinis* (parasitic wasps), syrphid fly larvae
Lace bugs	X	X		X		Assassin bugs and pirate bugs, spiders
Mealybugs	X	X		X		Mealybug destroyer, lady beetle
Psyllids	X	X		X		Pirate bugs
Scales	X	X		X	X	*Aphytis, Coccophagus, Encarsia,* and *Metaphycus* spp., parasitic wasps
Slugs, snails			X			*Rumina decollata* (predatory snail), predatory ground beetles, birds, snakes, toads, and other vertebrates
Spider mites	X	X			X	Big-eyed bugs and minute pirate bugs, *Feltiella* spp. (predatory fly larvae), six-spotted thrips, *Stethorus picipes* (spider mite destroyer, lady beetle)
Thrips	X			X	X	Minute pirate bugs, predatory thrips
Weevils, root or soil-dwelling				X		*Steinernema carpocapsae, Heterorhabditis bacteriophora* (entomopathogenic nematodes)
Whiteflies	X	X		X		Big-eyed bugs and minute pirate bugs, *Cales, Encarsia,* and *Eretmocerus* spp., parasitic wasps, spiders

8.4.2 Examples of biological agents

Table 4 shows selected biological control agents (BCA) available on the market against plant pathogens. Different countries have different regulations about who is allowed to use these products. It may be necessary to take an exam in order to be able to purchase these products. Also, not all of these products might be available in every country.

Table 4: Selected biological control agents (BCA)

Plant diseases	**BCA**	**Crops**
Powdery mildew	*Ampelomyces quisqualis*	Strawberry, tomato, pepper, cucurbits
Powdery mildew, grey mould, white mould (*Sclerotinia*)	*Bacillus amyloliquefaciens* ssp. Plantarum strain D747, *Bacillus subtilis* strain QST 713	Strawberry, tomato, cucumber, pepper, cucurbits, watercress, lettuce, spinach, aromatic herbs
White mould (*Sclerotinia*)	*Coniothyrium minitans*	Any crop
Grey mould, downy mildew, Fusarium wilt, damping off	*Gliocladium catenulatum*	Strawberry, tomato, cucurbits, pepper, watercress, lettuce, spinach, aromatic herbs
Soil cryptogam	*Streptomyces* K61	Any crop
Damping off	*Trichoderma asperellum, Trichoderma harzianum*	Any crop

8.4.2.1 Common green lacewings (*Chrysoperla carnea*)

Named lacewings after the delicate wing venation of adults, or the aphid lion after the voracious appetite of its larvae, *Chrysoperla carnea* is an active predator of many soft-bodied arthropods and their eggs. Various species of the genus *Chrysoperla* are mass-produced in several countries for use on both outdoor and protected crops. The third instar larva is extremely voracious and can consume an aphid or a whitefly pupa in less than a minute. The larvae are cannibals and when young may eat unhatched eggs, other larvae, and even adults if food becomes scarce. In the presence of mixed prey, green lacewings attack aphids first, followed by thrips and spider mites. They are also known to feed on young caterpillars and moth eggs, mealybugs, scale insects, whitefly larvae, and pupae. Plants with dense foliage are best suited to these predators, particularly when there is an even spread of prey through the canopy. Lacewing larvae are useful on organic crops where pesticide restrictions necessitate a more generalist predator to control many pest species. *C. carnea* are more tolerant of low humidity than other lacewing species.


Figure 20: Lacewing predatory larva (left) and adult (right)

Figure 21: Life cycle of lacewing (K. Kos, with copyright permission)

8.4.2.2 The whitefly parasitoid *Encarsia formosa*

Encarsia formosa was discovered in England and successfully first used in 1926. Within two years, 250,000 parasitoids had been reared for use on nurseries around England, France, and subsequently Canada. This species is now commercially available in many countries. Adult females are 0.6 mm long with a black head and thorax, a yellow abdomen, and translucent wings. The most obvious sign of *Encarsia spp.* activity is the presence of black 'scales' on leaves. These are the pupal stages of the parasitoid and are formed inside the pupae of the whitefly. Adult wasps are attracted to the host whitefly 'scale' (so-called because the larval stage of whitefly is mostly immobile and resembles miniature scale insects) by volatile compounds given off from whitefly honeydew. Adults feed on the honeydew. Usually, a single egg is laid that passes through three larval stages, during which time the whitefly scale remains white and develops normally. When fully developed the whitefly scale turns black as the parasitoid pupates. The pupae remain attached to the leaf and the adult emerges some 10 days later from a hole cut through the puparium with a special 'tooth'. *E. formosa* is introduced to crops as black scales stuck to cards from which adults emerge a few days later.

Figure 22: *Encarsia formosa* laying an egg on whitefly (left) and presence of black 'scales' (right)

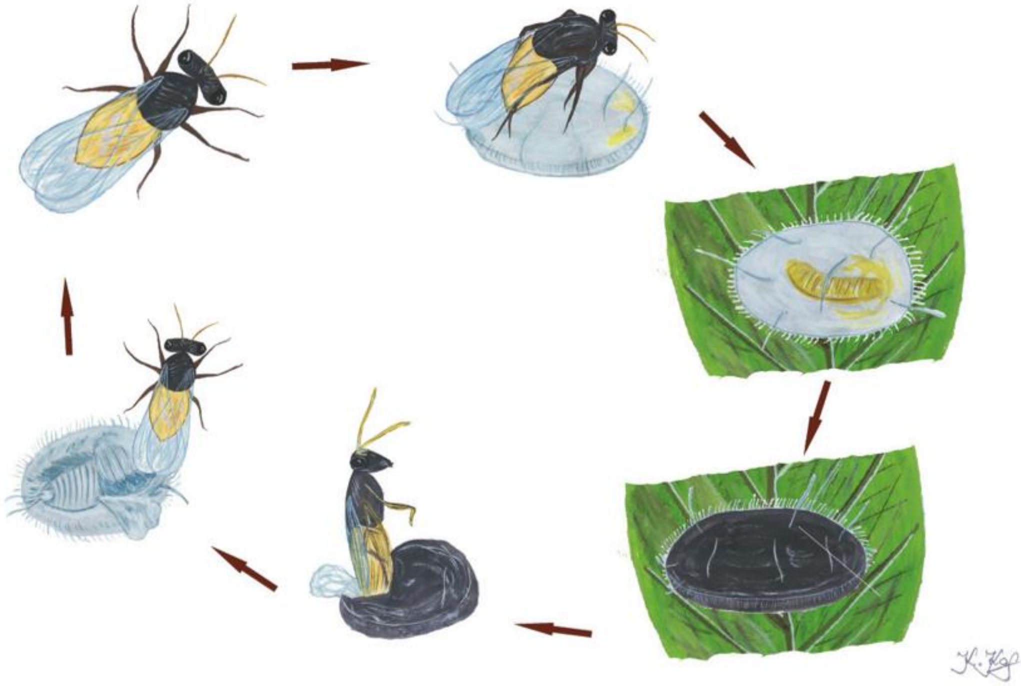


Figure 23: Synchronized life cycle of *Encarsia formosa* with the lifecycle of whitefly
(K. Kos, with copyright permission)

8.4.2.3 Entomopathogenic nematodes

Entomopathogenic nematodes are also called eelworms or roundworms. These minute organisms are relatively simple — bilaterally symmetrical, elongated, and tapered at both ends. The species described here are facultative parasitoids (i.e., they can live as saprophytes as well as parasitoids). Although found in nature, they can be mass produced on artificial diets using a liquid medium fermentation type process and are commercially used as biological control agents. Unlike plant pathogenic nematodes, these entomopathogenic species have symbiotic bacteria in their alimentary tract. These produce a toxin and it is this that is the lethal agent. Once the nematode has entered the host and is feeding on its hemolymph (the fluid, analogous to the blood in vertebrates, that circulates in the interior of the arthropod body), it defecates a small pellet containing the pathogenic bacteria which, under the right temperature conditions, will kill the host after only 2-3 days. The nematodes then reproduce in the soup of bacteria and hemolymph, leaving the cadaver as third-stage infective larvae. These are unusually resistant to adverse environmental conditions and can survive for several months.

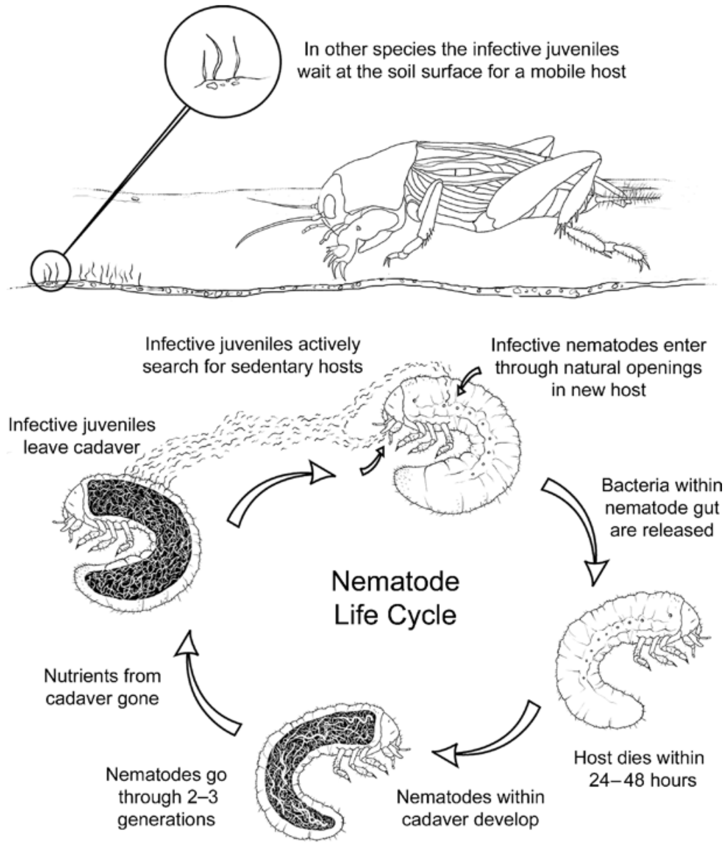


Figure 24: Life cycle of a steinernematid or heterorhabiditid nematode (Drawing by A.E. Burke)

8.4.2.4 Predatory mites

These are small, fast moving mites that can be specific predators, such as *Phytoseiulus persimilis*, or more generalist in their diet, such as many of the *Amblyseius* species. All deposit eggs close to the intended prey that hatch as six-legged nymphs, pass through two moults, and then develop as eight-legged adults. Location of prey is usually by kairomones (semiochemical) released by the prey faeces, plant damage or, in the case of spider mites, by their webbing that produces an attractant and arrestment stimulus in the predator that retains them in close vicinity of their host prey. Most predatory mites are capable of surviving on relatively low numbers of prey and can increase rapidly to provide adequate levels of control before any major outbreak occurs.

Predatory mites are found throughout the world and several are in commercial production for mass release, particularly for protected crops. However, their use on outdoor crops is increasing, especially on edible crops where post-harvest intervals of many pesticides restrict or even prevent chemical intervention. Many of the *Amblyseius* species can be mass produced on a bran-based diet that may be packaged along with a factitious host mite in paper sachets for ease of distribution and improved establishment on a crop.

Figure 25: Adult predatory mite eating phytophagous mite (left), controlled release system (CRS) sachet placed in a commercial crop to introduce amblyseid predatory mites (right)

Figure 26: Life cycle of predatory mites, family *Phytoseiidae* (K. Kos, with copyright permission)

8.4.2.5 Parasitoid wasp (*Aphidius colemani*)

Aphidius colemani is a small, black wasp, 4-5 mm long, that inserts a single egg into a host aphid. All other life stages occur within the aphid. The appearance of a golden-brown mummy indicates the presence of these parasitoids on a crop. In general, this parasitoid attacks the smaller aphid species. This species is commercially available in many countries. *Aphidius* spp. are good at host location and can provide reasonable levels of control if introduced early when pest numbers are low. However, if aphids are established in colonies, *A. colemani* will take some time to make an impact on the pest population, so predators or a selective pesticide should be considered. The mummy stage is tolerant to most short-persistence pesticides, but those such as synthetic pyrethroids have long residual activity and may kill the adult as it emerges from the aphid mummy. Banker plants of cereals infested with a specific aphid are useful in crops where a continuous supply of parasitoids is required.

Figure 27: Adult parasitoid wasp (*Aphidius colemani*) ovipositing in an aphid (left). Aphids parasitized by *Aphidius colemani*: mummy stage (right)

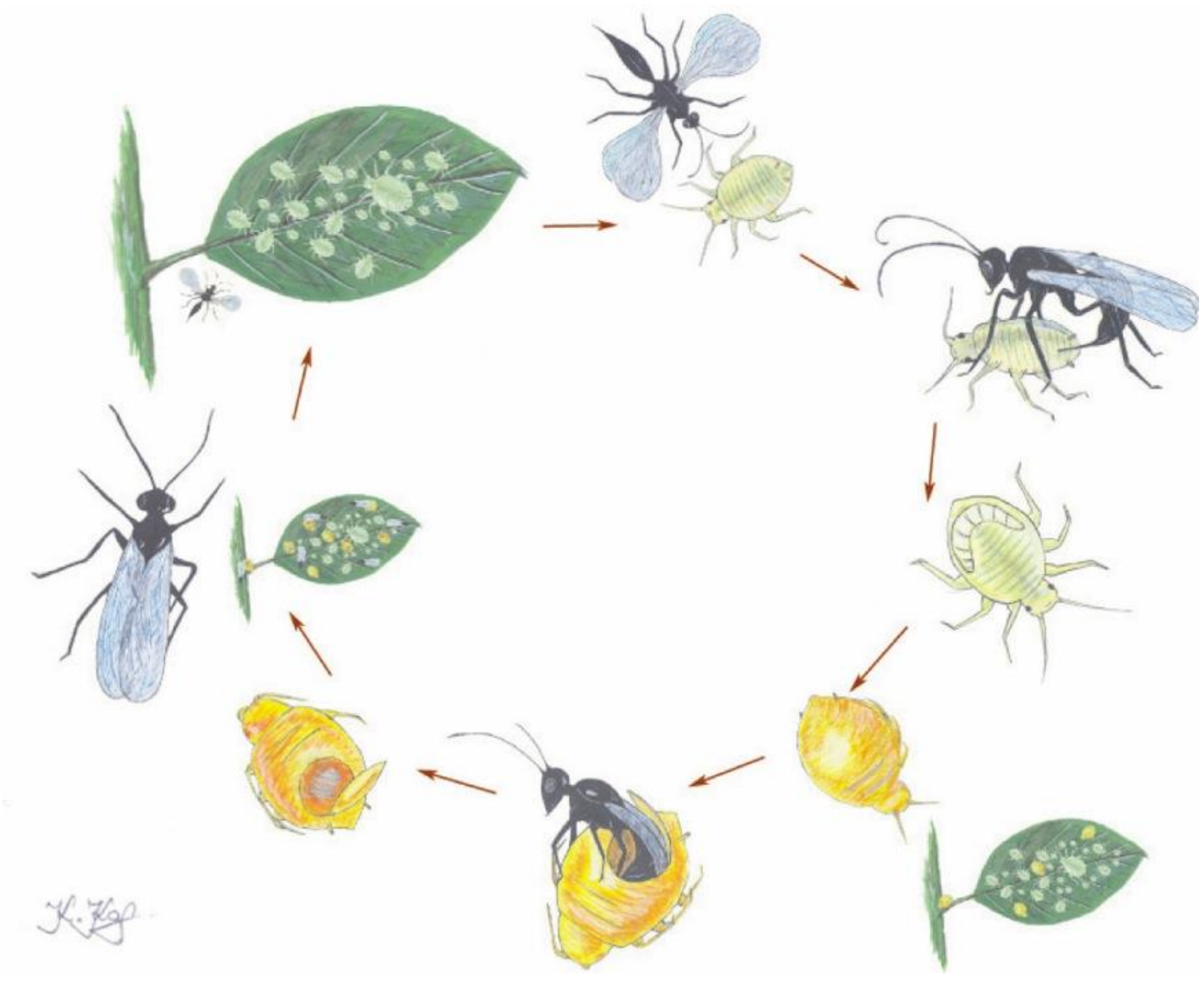


Figure 28: Parasitoid wasp (*Aphelinus mali*) for biological control of aphids (*Eriosoma lanigerum*) (K. Kos, with copyright permission)

8.5 References

Bittsánszky, A., Gyulai, G., Junge, R., Schmautz, Z. & Komives, T. 2015. Plant protection in ecocycle-based agricultural systems: Aquaponics as an example. In *Proceedings of the International Plant Protection Congress (IPPC)*, Berlin, Germany Vol. 2427.

Conte, L., Chiarini, F., Zancanaro, A., & Monta, L.D. 2000. Biological control of *Aphis gossypii* Glover (Rhynchota, Aphididae) in organic greenhouse cucumbers using 'banker plants' as open rearing units of beneficials: two years of trials. In *IFOAM 2000: The World Grows Organic. Proceedings 13th International IFOAM Scientific Conference*, Basel, Switzerland. vdf Hochschulverlag AG an der ETH Zurich.

FAO 2018. *Pest and Pesticide Management*. Food and Agriculture Organization of the United Nations, Rome.

FiBL 2019. *Betriebsmittelliste 2019 für den biologischen Landbau in der Schweiz*.

Gravel, V., Dorais, M., Dey, D. & Vandenberg, G. 2015. Fish effluents promote root growth and suppress fungal diseases in tomato transplants. *Canadian Journal of Plant Science* 95: 427-436.

Kleinhenz, M.D., Waiganjo, M., Erbaugh M.J. & Miller, S.A. 2011. *Tomato grafting guide. Preparing Grafted Tomato Plants using the Cleft Graft Method.*

Raviv, M. & Lieth, J.H. 2007. *Soilless Culture: Theory and Practice*. Elsevier.

Resh, H.M. 2013. *Hydroponic Food Production: A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower* (7th edition). CRC Press, Boca Raton.

Schmautz, Z., Graber, A., Jaenicke, S., Goesmann, A., Junge, R. & Smits, T.H. 2017. Microbial diversity in different compartments of an aquaponics system. *Archives of Microbiology* 199 (4): 613-620.

Somerville et al. 2014. Appendix 2 – Plant pests and disease control In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-scale Aquaponic Food Production: Integrated Fish and Plant Farming*, pp. 183-186. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome

Tang, S., Xiao, Y., Chen, L. & Cheke, R.A. 2005. Integrated pest management models and their dynamical behaviour. *Bulletin of Mathematical Biology* 67: 115-135.

The European Parliament and the Council of the European Union 2009. Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides. *Official Journal of the European Union* L 309/71.

Vermeulen, T. & Kamstra, A. 2012. The need for systems design for robust aquaponic systems in the urban environment. In *International Symposium on Soilless Cultivation* 1004: 71-77.

Vincent, C., Weintraub, P. & Hallman, G. 2009. Physical control of insect pests. In V.H. Resh & R.T. Cardé (eds.) *Encyclopedia of Insects* (2nd edition), pp. 794-798. Academic Press, San Diego.

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9. MONITORING OF PARAMETERS

9.1 Introduction to monitoring

9.1.1 Scientific parameters

A **scientific parameter** is a definable or measurable characteristic or a value, selected from a set of data. A **variable** is any factor, trait, or condition that can exist in differing amounts or types. In experimental science, there are usually three types of variables: 1) independent, 2) dependent, and 3) controlled. The **independent variable** is the one that the experimenter changes in order to measure or observe a response or an effect. The **dependent variable** is the measured response to the changes made to the independent variable. The **controlled variables** are the variables which are kept constant in an experiment.

Let us illustrate these variables with an imaginary experiment using an aquaponic system. We are interested in how the total mass of fish affects ammonia production in the fish tank connected to the hydroponic unit. The ammonia concentration will be measured in g/L in the fish tank as well as in the hydroponic unit. The feed amount and rate will remain constant, whereas the total mass of fish will vary with the addition of fish into the fish tank. In this imaginary experiment, the total mass of fish is the independent variable (this is what we are changing), and the ammonia concentration is the dependent variable (this is what we are interested in – it is what we are measuring as a response to varying the mass of fish). Variables, such as the amount of feed, feeding rate, the time intervals between feeding and varying the total mass of fish, water temperature in the fish tank and in the hydroponic unit, surface area of the biofilter, the number of plants in the hydroponic unit, etc., all have to be kept constant in order to measure just the effect of varying the total mass of fish on ammonia production, and they are therefore the controlled variables.

It is important to note that scientific experiments (or measurements of the same parameter in monitoring) are done in multiples, usually triplicates, in order to validate empirical data or the observed results. Three replications are usually enough to rule out any potential outliers (if the other two measurements agree). An average (in statistics called the arithmetic mean) of such measurements is then taken in order to improve the precision of the result. The standard deviation (SD) of the three replicates should also be calculated in order to report on variability among the data. A low standard deviation is preferable. Do not forget to include units in your measurements. The equations for calculating the arithmetic mean and the standard deviation are shown below:

$$\overline{x} = \frac{x_1 + x_2 + x_3 + \cdots + x_n}{n}$$

Where:
$\overline{x}$ = arithmetic mean
x_1, x_2, x_3, x_n = individual values in the data set
n = the number of data points in the set (the number of ‘x’ values)

$$SD = \sqrt{\frac{\sum(x - \overline{x})^2}{n - 1}}$$

Where:

SD = standard deviation

Σ = summation symbol

x = each individual value in the data set

$\overline{x}$ = the arithmetic mean

n = the number of data points in the set (the number of 'x' values)

9.1.2 Why monitor?

The need for monitoring in aquaponics arises from two points of view: **legislation** and **management**. The holistic nature of aquaponics means that it falls into several different legislative categories with regards to policy at the EU level. The Common Fisheries Policy (CFP) and the Common Agricultural Policy (CAP), as well as policies on food safety, animal health and welfare, plant health, and environmental legislation, among others, may all apply, depending on the operational characteristics of the system. The legislation and regulations which need to be observed during aquaponic production include, but are not limited to:

- Water Framework Directive (2000/60/EC) (WFD) – Among other things, the WFD lays down the rules for monitoring, sampling, and analysing effluent discharge into watercourses. It also requires member states to set up monitoring regimes within their country, which often includes inspections at discharge sites to analyse effluent
- Nitrates Directive (91/676/EEC) specifies the parameter limits of effluents that can be discharged
- Food safety regulations, which will be covered in greater detail in Chapter 10 of this textbook
- Animal Welfare and Fish Health regulations, such as Directive 91/496/EEC, which lays down the principles governing the organisation of veterinary checks on animals entering the EU from third countries

In most countries help will be available from government agencies to keep aquaponic farmers in line with the law, and they should therefore seek comprehensive information from the competent authorities in regards to their particular situation (Joly 2018).

Regular monitoring of parameters is an indispensable part of the management, operation, and maintenance of the aquaponic system. Monitoring the water quality, and the health of the fish and the plants, will indicate how well the system is performing and has significant cost benefits. Keeping good records of your measurements can help greatly in observing trends and diagnosing future problems. It is important to record all of your readings. Parameters such as ammonia, nitrite, dissolved oxygen, and pH can give an indication of whether the system is underperforming.

Identifying the parameter that is problematic (i.e. outside of the desired range) helps the operator to fix the problem quickly and restore the functioning of the aquaponic system back to optimum levels, which will result in the highest yield of fish and plants.

9.1.3 Different monitoring approaches

The monitoring approaches for testing the quality of aquaponic water range from very simple and cheap to complex and involving expensive analytical equipment. The simplest and cheapest approach is to use test strips, which you submerge in the water. These contain a reagent which changes colour when it comes into contact with the water. The intensity of this reaction can be compared to the colour chart provided with the kit, which will then give a relatively accurate measure of what is being tested for. These kits are often cheap and simple to use, although as they are a consumable material, stocks will need to be constantly replenished. These, however, can usually only be used for a limited range. For example, some test strips for pH only work within a pH range from 5 to 8. If the pH in the aquaponic system falls outside of this range (below 5 or above 8), then the test strips may give false results.

The next level in terms of complexity and cost are tests using chemical reagents and a colour chart. Here the sample is put into a small test tube and drops of reagents are added according to the instructions. A reaction occurs and the colour of the solution in the test tube is compared to the colour chart that comes with the kit. The price of these tests varies. A more precise and advanced version of these tests measures the colour with spectrophotometers.

Spectrometry is a method of quantitative analysis that utilises the absorbance of light. Usually a water sample is centrifuged to remove suspended solids and a reagent specific to the desired test is added. This is then placed inside a spectrophotometer for analysis. The reading given by the spectrophotometer can then be related to known standard curves for that particular chemical parameter to give a concentration. Some manufacturers also provide test kits for a quicker analysis, without the need to use calibration curves, and these are available for a wide range of water quality parameters.

The most advanced and expensive approach to monitoring involves using probes and electronic meters. These exist in single parameter configurations, or in multiprobe single meter configurations. The probes are connected to a digital electronic meter and submerged in the water. Continuous online monitors can also be installed inside the fish tank, with a probe constantly in contact with the water. They cost more in comparison with tests described previously, however, they are the most accurate instruments for monitoring, and have the largest measuring range (Klinger-Bowen *et al.* 2011).

The chosen monitoring approach is usually associated with the size of the aquaponic system and the level of productivity. Professional commercial systems usually employ continuous online monitors for dissolved oxygen (DO), water level and electric supply. On the other hand, hobby backyard systems often rely on the simplest and cheapest approaches, such as test strips, or even just visual inspections of water turbidity, oxygenation in biofilter, plant and fish health.

9.1.4 Classification of monitoring parameters

The parameters that need to be monitored in an aquaponic system are the water quality, the health of the fish, and the health of the plants, and can be classified into the following types: 1) chemical, 2) physical, and 3) biological. Chemical parameters have to do with the quality of the water and include pH, DO, ammonia, nitrite, nitrate, phosphorus content, and water hardness. Physical parameters include water and air temperature, relative humidity, and UV light intensity. Biological parameters provide direct insight to system performance, and include everything from the mass and health of the fish and the plants, nutrient deficiencies in the plants, algae contamination, and other microbiological parameters. Each organism in an aquaponics unit – the fish, the plants, and the bacteria in the biofilter – has a specific tolerance range for each physico-chemical parameter (Table 1). The tolerance ranges are relatively similar for all three organisms, but there is a need for compromise and therefore some organisms might not be functioning at their optimum level (Somerville *et al.* 2014a).

Table 1: Optimal ranges of physio-chemical parameters for fish (warm- and cold-water), plants and nitrifying bacteria

Organism type	Temperature (°C)	pH	Ammonia (mg/L)	Nitrite (mg/L)	Nitrate (mg/L)	DO (mg/L)
Warm water fish	22-32	6-8.5	<3	<1	<300	4-6
Cold water fish	10-18	6-8.5	<1	<0.2	<300	6-8
Plants	16-30	5.5-6.5	<30	<1	-	> 3
Bacteria	14-34	6-8.5	<3	<1	-	4-8

The goal is to maintain a healthy ecosystem with physico-chemical as well as other parameters that satisfy the requirements for growing fish, vegetables, and bacteria simultaneously. There are occasions when the water quality will need to be actively manipulated in order to meet these criteria and keep the system functioning properly.

9.1.5 Frequency of monitoring

Frequency of monitoring varies depending on the parameter being monitored. As a general rule, start-up systems (at initial stocking of plants and animals) should be tested daily so that adjustments can be made quickly when needed. For example, feeding levels can be reduced, aeration can be increased, or water can be diluted in response to high ammonia levels. Once nutrient cycles are balanced (after a minimum of 4 weeks without significant fluctuations in parameters), weekly monitoring is usually sufficient to maintain good water quality. However, if a problem is suspected (change in the appearance or behaviour of the fish, deficiency indicators in plants), then more frequent monitoring of the water quality should be resumed. Therefore, daily monitoring of the health of the fish and plants is essential in order to discover potential problems early. It is also very important to keep a good record of monitoring parameters, e.g. appearance and behaviour of the fish (normal/out of the ordinary), appearance of the plants (normal/unhealthy look), and water chemistry parameters (pH, DO, ammonia, nitrites, nitrates). This way, the cause of a potential problem can be identified more easily and, in case the problem arises again, the amendment that previously worked well can be quickly implemented (Sallenave 2016; Somerville *et al.* 2014a). An example of a data log book is shown in Figure 1.

Sampling/ monitoring details		PHYSICAL PARAMETERS						CHEMICAL PARAMETERS																		BIOLOGICAL PARAMETERS		
Date	Time of sampling (h:min)	Electrical conductivity [µS/cm]			Water temperature [°C]			pH			Dissolved oxygen [mg/L]			Ammonia [mg/L]			Nitrate [mg/L]			Nitrite [mg/L]			Phosphate [mg/L]			Mass of fish [g]	Appearance & behaviour of fish	Appearance of plants
		SS1	SS2	SS3	SS1	SS2	SS3	SS1	SS2	SS3	SS1	SS2	SS3	SS1	SS2	SS3	SS1	SS2	SS3	SS1	SS2	SS3	SS1	SS2	SS3			

Figure 1: An example of monitoring data log table. SS in the table stands for 'sample site'

9.2 Important parameters in aquaponics

In addition to monitoring the general physico-chemical parameters that are important for maintaining water quality in aquaponic systems, and the biological parameters that indicate the system's performance and reveal potential problems with water quality, it is also necessary to carry out regular check ups on the performance of the technology (filters, water, air pumps, etc.).

9.2.1 Technology

Solids removal

OPERATING PROCEDURE: A major consideration in aquaponics is the retention time and the removal of large particulate matter. These particles include uneaten food, fish waste, as well as other sources of biological material, such as plant particles. They can negatively impact chemical parameters such as pH and DO. Mechanical filtration (physical screens and barriers) will be the first important step in monitoring to enable the efficient removal of particulate matter. Visual inspection of the screens and filters is often the best method for checking for large particles. It is important that the particles are removed quickly, in order to prevent them from breaking down into smaller pieces, which would increase the time needed for them to be removed and would lead to increased oxygen demand due to an increased nutrient load (Thorarinsdottir *et al.* 2015). The screens should be cleaned frequently to ensure that the debris is removed.

MONITORING: For smaller particles, a useful measure is water clarity, otherwise known as turbidity, although this can be a subjective measurement, depending on the method used. The method is a representation of how well light is transferred through the water. The main cause of turbidity is often suspended solids, determined as total suspended solids (TSS). These can be measured accurately by dry weight. Firstly, around 1 L of water is taken from the system. The sample volume can be reduced for water laden with TSS, or increased if the water is clear. The water sample is then filtered through a pre-weighed filter paper of a specified pore size. Solids will remain on the filter paper, which can be weighed when completely dry (i.e. when the paper stops losing weight after continued drying). The increased weight of the filter paper provides a measure of the quantity of particulates present, which can be expressed in mg/L or kg/m^3 (Rice *et al.* 2012) (Table 2).

Table 2: The procedure for measurements of suspendend solids

No.	Procedure	Remarks
1	Weigh the filter paper to the nearest 0.1 mg	Record the mass as Mass 1
2	Set up the filtration apparatus, insert a filter, and apply a vacuum with a vacuum pump in order to draw the water through the filter	
3	Wet the filter paper with a small volume of deionised (DI) water	
4	Shake the sample vigorously and then measure out the predetermined sample volume using a graduated cylinder.	Record the volume filtered
5	Rinse the graduated cylinder and filter with three 20 mL volumes of DI water, allowing complete drainage between washes	
6	Continue suction with the vacuum pump for three minutes after filtration is complete	
7	Carefully transfer the filter to an aluminium weighing dish, and place the filter on a cookie sheet or similar device	
8	Place the filters in an oven set to 104 ± 1 ^{o}C, and dry for a minimum of one hour	
9	Remove the filters from the oven and transfer them to a desiccator in order to cool them to room temperature. Weigh one sample filter to the nearest 0.1 mg	Record the mass as Mass 2 and apply the following equation: TSS (mg/L) = (Mass 1 – Mass 2) / Sample volume

TROUBLESHOOTING PROCEDURE: If it is found that large debris is accumulating on filters at rates which exceed the filters' ability to remove them, an increased cleaning schedule should be implemented. If turbidity begins to increase, this can be a sign of a problem within the filtration system. Filters should therefore be checked regularly to ensure there are no blockages or, if possible, screen sizes should be reduced in order to capture smaller particles.

Biofiltration

OPERATING PROCEDURE: Daily checks should be made on the mechanical function of the biofilter unit to ensure that the aeration system is functioning properly and that air bubbles are visible; this will ensure that there is a proper air supply for bacterial colonies. Light should be excluded from the biofilter, as this can encourage the algal growth; it should therefore be ensured that free water surfaces, i.e. above the fish tanks as well as at the plant unit, are covered with lightproof covers. Sludge may also build up on the biofilter media, so weekly checks should be made to ensure build-up is at acceptable levels, otherwise the efficiency of the system could be compromised.

MONITORING: The best way to monitor the functioning of the biofilter is by analysing the water for ammonia, nitrite, and nitrate levels, using specialised electronic or with photometrics tests to ensure that the water qualityis kept within optimal ranges for the target species, and to comply with national and EU legislation. These concentrations of ammonium, nitrite, and nitrate are usually measured using specialised electronic sensors since specific amounts create signatures in the conductivity of the water. The numerical readout can then be compared with the desired amounts. Another way of measuring levels of these nutrients is with photometrics tests.

TROUBLESHOOTING PROCEDURE: There are several steps which have to be taken if high levels of either ammonia or nitrite are detected. First, it has to be ascertained whether the biofilter has a suitable oxygen supply and is free from sludge. pH should be monitored closely, since nitrogen is converted to toxic ammonia (NH_3) at higher pH levels and is especially harmful to fish. If pH is kept neutral or acidic, nitrogen is in the form of non-toxic ammonium (NH_4^+) (see Table 3 in Chapter 5). The fish should then be starved for a few days to prevent increase in ammonium in the form of fish waste being added to the system. This will decrease the availability of ammonium, limit the growth of *Nitrosomonas,* and allow *Nitrobacter* colonies to convert excess nitrites into nitrates. Ammonia and nitrite may also compromise oxygen uptake in fish, therefore DO concentrations in the fish tanks should be kept optimal (Thorarinsdottir *et al.* 2015).

Formation of biofilms

OPERATING PROCEDURE: Not to be underestimated is the formation of biofilms, which can clog system components such as pipes or outlets or cause automatic sensors to take faulty readings. Therefore, biofilms should be checked and removed regularly (cleaning on a weekly basis is recommended).

TROUBLESHOOTING PROCEDURE: If, for example, only one sensor of the system displays a too low / too high value in the case of an oxygen alarm, it is possible that a biofilm has formed on the corresponding sensor, which leads to incorrect measurements. It has been observed that as the biofilm increases, the values for EC and oxygen continuously decrease. In case of an alarm, action must be taken immediately. It must not be assumed that the measurement is due to biofilm formation on the sensor.

Water and air pumps

OPERATING PROCEDURE: The mechanical devices that provide DO and flow have to be checked frequently (Table 3) to ensure proper functioning. Water pumps create a flow in aquaponic systems which transports nutrients and oxygen around it. They also move waste products towards the filters so that they can be removed. The misfunction of devices will result in decreased production. Without sufficient aeration, the fish and later also the plants will die. The check of the air pumps can often be done visually, by ensuring there is a steady stream of bubbles coming from the aerators. A reduction in DO may also be indicative of a problem. If problems occur, a suitably trained engineer should be sought to remedy the issue.

Table 3: Tasks related to an aquaponic system

Daily:	• Observe water flows at different system points in the aquaculture and the hydroponic unit (the water needs to circulate constantly) • Verify the water pump interval; shorter interval = better water flow • Ensure that the water pump is synchronized with the valves through which water enters the fish tanks and the hydroponic unit • Check that no overflows are clogged (for example by fish slurry, uneaten food or plant material, or by system parts)
Seasonally:	• Check the functioning of the water pump and aeration system • Clean the pump(s), aeration system, pipes, and the hydroponic unit if necessary • Check the condition of the pipes and valves • Check and regularly clean the pre-filter of water pumps • Periodic replacement of membranes and wear parts in air pumps with membranes

Screens

Screens create a physical barrier between pumps, filters and, in some cases, the outside environment. Fish escaping from aquaponic systems can damage equipment, filters, and in extreme cases, can result in non-native species entering a natural ecosystem. It is important that appropriate locations for screens are identified. These will include pumps, input streams for filters, and pipes where water enters and exits the system.

OPERATING PROCEDURE: The screens should be checked daily for signs of wear and tear, and any damaged or worn screens should be replaced using suitable replacements.

Decoupling of the hydroponic of aquaponic compartment

In case of contamination in one system area, it is advantageous if the affected system part can be decoupled from the rest of the system easily (e.g. unplug a pump). This can be ensured by linking the hydroponic and aquaculture unit by, for example, a pump sump that connects the two system loops. It is important that all system components for water treatment are located on the aquaculture part, i.e. in front of the pump sump, so that appropriate water quality for the fish can be ensured.

TROUBLESHOOTING PROCEDURE: The main important application is that the fish can be saved if contamination occurs in the hydroponic section, for example due to improper use of pesticides. But it can also be advantageous the other way around, for example if fish need to be treated for disease with salt. . During the period of decoupling, the hydroponic system water can be fertilized with organic fertilizers, which certainly do not harm the fish (always remember that the two system loops should be linked together again as soon as possible).

9.2.2 Water quality

The term water quality includes anything that adversely affects the conditions required for maintaining healthy fish and plants. Maintaining good water quality in an aquaponic system is of extreme importance. Water is the medium through which all essential macro- and micronutrients are transported to the plants, and the medium through which the fish receive oxygen; therefore, it will directly affect the productivity and viability of the system. There are five key water quality parameters that are crucial for close monitoring in the system: DO, pH, water temperature, nitrogen compounds (ammonia, nitrites, and nitrates) and water hardness. Other parameters also need to be monitored in order to maintain a healthy balanced system, such as phosphorus and other nutrients, algae contamination, TSS, carbon dioxide concentration, etc. However, these parameters can be monitored less frequently in a well-balanced system (Somerville *et al.* 2014a; Thorarinsdottir *et al.* 2015).

Dissolved oxygen (DO)

DO describes the amount of molecular oxygen in water and is usually measured in milligrams per litre (mg/L). If DO levels are not sufficient, fish are under stress or suffer from slow growth, and could die. DO requirements differ for warmwater and coldwater fish. Bass and catfish, for example, which are warmwater species, require about 5 mg/L for maximum growth, whereas trout, a coldwater fish, requires about 6.5 mg/L of DO. High DO levels are needed by the nitrifying bacteria in the biofilter, which are essential for converting fish waste into plant nutrients. DO therefore indirectly affects plant growth as well. Also, plants need high levels of DO (> 3mg/L), which makes it easier for the plant to transport and assimilate nutrients across its root surfaces. Moreover, in low DO conditions, plant root pathogens may occur. It is recommended that DO levels be maintained at 5 mg/L or higher in an aquaponic system.

MONITORING: Oxygen levels should be measured frequently in a new system, but once procedures become standardised (e.g. proper fish stocking and feeding rates have been reached, and sufficient aeration is provided) it is not necessary to measure DO quite as often. Monitoring DO can be challenging because the measuring devices can be very expensive. There are some aquarium kits available that include reagents for testing DO content, but the most reliable approach is using DO probes with electronic meters, or online monitors that constantly measure the most significant parameters in the fish tank. In a small-scale unit it might be sufficient to frequently monitor fish behaviour, water, and air pumps instead. If the fish come to the surface for oxygen-rich surface water, this indicates that DO levels in the system are too low.

TROUBLESHOOTING PROCEDURE: Low DO levels are not usually a problem with hobby aquaponics growers using low fish stocking rates. The problem tends to arise more in operations with high stocking rates. If DO levels in your system are too low, increase aeration by adding more air stones, or by switching to a larger pump. There is no risk of adding too much oxygen; when the water becomes saturated, the extra oxygen will simply disperse into the atmosphere. Note that DO levels are closely related to the temperature of the water. Cold water can hold more oxygen than warm water, so in warmer weather, the monitoring of DO or preventively increasing aeration is essential.

Oxygen consumption is also related to the size of the fish: smaller fish consume considerably larger amounts of oxygen than large fish. This fact needs to be taken into consideration when setting up the system and stocking with small fish (Sallenave 2016; Somerville *et al.* 2014a). If low DO levels are detected in water in the hydroponic unit, this might be solved by installing an air pump.

pH

The pH of a solution is a measure of how acidic or alkaline it is on a scale from 1 to 14 pH 7 is neutral, pH <7 is acidic and pH >7 is alkaline. pH is defined as the amount or the activity of hydrogen ions (H^+) in a solution:

$$pH = -log(H^+)$$

The equation shows that pH is lowered as the hydrogen ion activity rises. This means that acidic water has high levels of H^+ and hence low pH. The pH of water is an especially important parameter for plants and bacteria. For plants, the pH controls the availability of nutrients. At a pH of 5.5-6.5, all nutrients are easily accessible for plants, but outside this range it becomes difficult (Figure 2). Even a slight pH deviation to 7.5 or above can lead to deficiencies of iron, phosphorus, and manganese in plants (see also Figure 10 in Chapter 5).

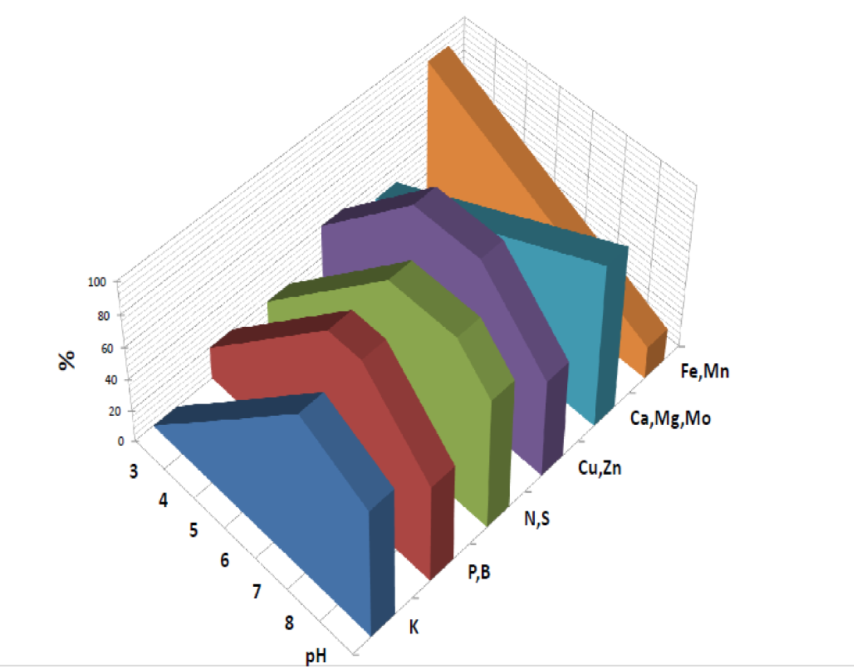

Figure 2: The impact of pH on nutrient availability for plants.
By F. Moeckel [Public domain], from Wikimedia Commons

Nitrifying bacteria are unable to convert ammonia into nitrate at pH of 6 or below. This makes biofiltration less successful and ammonia levels may begin to increase. Fish have a pH tolerance range from about 6.0 to 8.5. In order to satisfy the needs of all three organisms (plants, fish, and bacteria), the pH in the aquaponic system should be kept somewhere between 6 and 7.

Certain events or processes in the aquaponic system will affect the pH, so it will not stay constant and will need to be regularly monitored. These processes are nitrification, fish stocking density, and phytoplankton contamination. In the nitrification process, bacteria produce small concentrations of nitric acid and the pH of the aquaponic system is lowered. Fish stocking density also affects the pH of the system. When fish respire they produce CO_2 which is released into the water. Upon contact with water, CO_2 is converted into carbonic acid (H_2CO_3), which also lowers the pH of water. This effect is greater at higher fish stocking densities. Phytoplankton is generally always present in aquaponic system, although high amounts are undesirable, because it competes with plants for the nutrients. Because phytoplankton photosynthesises, which uses up the CO_2 in the water, this raises the pH, especially during the day when photosynthesis is at a maximum. All in all, aquaponic water generally acidifies and the pH will need to be regularly monitored and adjusted (Somerville *et al.* 2014a; Thorarinsdottir *et al.* 2015).

MONITORING: There are several methods for monitoring pH. The simplest is to use pH test strips, which is the cheapest method, but it is only moderately accurate. The next level of accuracy involves using water testing kits; however, the recommended and the most accurate method is to use digital meters with pH probes and on-line monitors for continuous monitoring. Ideally, the pH level should be monitored continuously or at least daily and properly adjusted.

TROUBLESHOOTING PROCEDURE: There are several ways to raise the pH in the system. The most common methods include:

- Adding $NaHCO_3$ whenever needed. Dissolve $NaHCO_3$ in some water, add it gradually to the tank, and measure the pH. You might need up to 20 g per 100 L. Do not add too much at one time as this can kill the fish.
- Adding strong bases, such as calcium hydroxide ($Ca(OH)_2$), or potassium hydroxide (KOH). Dissolve the pellets or powder in water and add it gradually to the fish tank.

In some cases, the water in the system can be hard with a high pH, typically in regions with limestone or chalk bedrock. pH can also rise if there is a high evapotranspiration rate, or if the fish stocking density if not sufficient to produce enough waste to drive nitrification. In these cases, pH will need to be lowered by adding acid in the water reservoir prior the fish tank. In this case, phosphoric acid (H_3PO_4), which is a relatively mild acid, can be added to the reservoir water (never directly to the fish tank!) (Thorarinsdottir *et al.* 2015).

Water temperature

Water temperature affects all aspects of aquaponic systems. Each organism within the system has its own optimum water temperature range, which has to be considered when choosing the species of fish and type of crops. Moreover, a combination of fish and plants should be chosen that matches the ambient temperature of the system's location, as changing the water temperature can be very energy-intensive. Temperature has an effect on DO as well as on the toxicity of ammonia; water contains less DO at high temperatures and more unionised (toxic) ammonia. High temperatures can also restrict the absorption of calcium in plants.

MONITORING: Water temperature can be monitored with analogue or digital thermometers, or with temperature probes. If using an on-line measuring device, temperature monitoring is usually included in the system.

TROUBLESHOOTING PROCEDURE: The water surfaces on the fish tanks, hydroponic units, and biofilters should be shielded from the sun by using shading structures. Similarly, the unit can be thermally protected using insulation against cool night temperatures wherever these occur. Alternatively, there are methods to passively heat aquaponic units using greenhouses or solar energy with coiled black hose pipes, which are most useful when the ambient temperatures are lower than 15 °C (Somerville *et al.* 2014a).

Total nitrogen (ammonia, nitrite, nitrate)

Nitrogen is a crucial water quality parameter. The sum of the un-ionised toxic form and the non-toxic ionic form of ammonia is called Total Ammonia Nitrogen (TAN). TAN is what most commercial ammonia test kits measure. In a fully functioning aquaponic unit with adequate biofiltration, ammonia and nitrite levels should be close to zero, or at most 0.25–1.0 mg/L (see Chapter 5).

OPERATING PROCEDURE: Water analysis for nitrogen compounds (TAN, NO_2^-, NO_3^-) should be performed daily or at least weekly in order to keep an eye on ammonium and nitrite peaks (Table 4).

Table 4: Parameters with target, maximal, and minimal values of nitrogen compounds in the system water

Parameter	Abbr.	Unit	Target value	Lower threshold	Upper threshold
Total Ammonia Nitrogen	TAN	mg/L	0.0	-	1.0
Nitrite	NO_2^-	mg/L	0.0	-	0.2
Nitrate	NO_3^-	mg/L	0.0	-	300

MONITORING: Aquarium kits for measuring ammonia, nitrite, and nitrate are quite accurate and cost efficient. Spectrophotometric analysis can be used for more accurate measurement. There are spectrometric test kits available for measuring ammonia, nitrite, and nitrate.

TROUBLESHOOTING PROCEDURE: If nitrite or ammonia peaks occur, don't feed the fish for several days, but do not stop feeding them completely as this will also starve the microorganisms in the biofilter (Klinger-Bowen *et al.* 2011) (see also the troubleshooting procedures for biofiltration in section 9.2.1).

Phosphorus and other nutrients

Nutrition plays a crucial role in plant health, and one method to check this parameter is by observing the condition of plant tissues by noting the overall condition of the plant. Changes in leaf shape and colour, as well as wilting of the plant, can be an indication of certain nutrient deficiencies, and prompt investigation will be needed to ensure the survival of the crop. The signs that plants may display if the presence of their most important nutrients becomes limited are described below. Optimal ranges of nutrients will differ from crop to crop, so it is therefore important that the operator is familiar with the optimal nutrient range for the chosen crop (Thorarinsdottir *et al.* 2015).

Phosphorus (P)

Deficiencies are characterised by poor root growth, reddening of the leaves, as well as dark green leaves and delayed maturity. The tips of plant leaves may also appear burnt (Thorarinsdottir *et al.* 2015).

Potassium (K)

Deficiency will cause lower water uptake and will impair disease resistance. Indications of potassium deficiency include burnt spots on older leafs, wilting, and the failure of flowers and fruits to develop properly (Thorarinsdottir *et al.* 2015).

Calcium (Ca)

Deficiencies are quite common in aquaponics, and signs include tip burn on leafy plants, blossom end rot on fruiting plants, and improper growth of tomatoes (Thorarinsdottir *et al.* 2015).

Magnesium (Mg)

Deficiencies usually involve changes in the colour of old leaves, with the area between the veins turning yellow, stiff, and brittle before falling off. It is rarely encountered in aquaponics (Thorarinsdottir *et al.* 2015).

Sulphur (S)

Deficiencies usually involve changes in the colour of new leaves, with the area between the veins turning yellow, stiff, and brittle before falling off. It is a problem rarely encountered in aquaponics (Thorarinsdottir *et al.* 2015).

Iron (Fe)

A lack of iron in a system presents itself visually, by turning the tips of the plants and the whole leaves of young plants yellow. This will eventually change to white with necrotic patches. A deficiency can easily be identified by noting changes to new leaves compared to old leaves. New leaves will grow and appear white, while old leaves will remain green. In order to facilitate uptake by plants, iron is often added in its chelated form, in concentrations of up to 2 mg/L. Iron can also be applied directly on leaves, with a spray. It is also important to monitor pH when iron deficiency is suspected, because at a pH below 8 iron may precipitate from water and prevent uptake by plants. A good rule to follow is to add 5 mL of iron per 1 m^2 of cultivated plants. A high concentration of iron will not harm an aquaponic system, although it may give a slight red colour to the water (Roosta & Hamidpour 2011; Thorarinsdottir *et al.* 2015).

Zinc (Zn)

As a result of deficiency of zinc, the growth of plants will be stunted, presenting as shortened internodes and smaller leaves. Generally speaking, a major problem in aquaponics is zinc toxicity, because while plants can tolerate an excess, fish cannot and it can cause mortality. Zinc is used as part of the galvanisation process of fish tanks, nuts and bolts etc., and it is found in fish waste. Deficiencies are therefore rarely a problem. Levels of zinc should be kept between 0.03 and 0.05 mg/L, as most fish will become stressed at 0.1 to 1 mg/L, and will start dying off at 4-8 mg/L. As zinc is introduced to the system mainly through the coating on equipment, the best way to keep zinc levels within range is to use alternatives to galvanised equipment, such as stainless steel or plastic (Storey 2018) (for detailed information, see also Table 9 in Chapter 5).

MONITORING: Although monitoring plant tissues gives an indication of the nutrient status of the water, it only reveals itself after a deficiency has got to the stage that an issue has presented itself within the crop. The best solution is therefore consistent monitoring of water (see Water quality in 9.2.2.).

Water hardness

There are two types of water hardness, which are especially relevant for aquaponics: general hardness (GH) and carbonate hardness (KH). GH can essentially be described as the amount of calcium (Ca^{+}), magnesium (Mg^{+}) and, to a lesser extent, iron (Fe^{+}) ions present in water. GH usually occurs naturally in areas where water courses flow through and into areas with high concentrations of limestone deposits. GH is important for both plants and fish within aquaponic systems, as Ca^{+} and Mg^{+} are essential plant nutrients and are therefore required for healthy plant production. It can also be a useful source of micronutrients for fish within the system; for example, Ca^{+} within the water can prevent fish from losing other salts, thereby increasing the overall productivity of the system.

KH is important primarily as a buffering agent. KH can be described as the total amount of carbonates (CO_3^{2-}) and bicarbonates (HCO_3^{-}) within a system, which gives water alkalinity. KH therefore has an impact on pH levels, and acts as a buffer to increased acidity which can arise from certain physiological processes. For example, the nitrification process, which as previously discussed converts ammonium from fish waste into the nitrates used by plants, generates nitric acid as a by-product. This can build up and ultimately sufficiently decrease pH until it causes stress to organisms. H^{+} ions from acid added to the water will bind to carbonates (CO_3^{2-}) and bicarbonates (HCO_3^{-}), buffering against increasing acidity (Sallenave 2016; Somerville *et al.* 2014a; Thorarinsdottir *et al.* 2015).

MONITORING: It is often not necessary to constantly monitor water hardness within a flow-through system if it is ensured that water input sources have adequate levels of GH to promote plant and fish health, as well as KH to neutralise the nitric acid built up during the nitrification process. The optimum hardness level (Table 5) for aquaponic systems is between 60-120 mg/L (moderately hard). In RAS systems, however, this should be monitored once a week. Water hardness expressed as milligrams of calcium carbonate equivalent per litre can be classified as:

Table 5: Water hardness classification based on corresponding concentrations of calcium carbonate

Water Hardness Classification	Concentration (mg/L)
Soft	0-60
Moderately Hard	60-120
Hard	120-180
Very Hard	>180

Hardness can be measured using simple test strips. Total hardness can be measured in mg/L or °dH (degree of German hardness). pH will also give a measure of hardness, with more alkaline water being harder.

TROUBLESHOOTING PROCEDURE: If it is found that the water is not at a suitable level of hardness, it is often possible to fix this with additives to increase the level. Limestone or crushed coral can also be added to water to increase hardness (Sallenave 2016; Somerville *et al.* 2014a; Thorarinsdottir *et al.* 2015).

Algae contamination, settleable solids

Algal growth in an aquaponic system can have negative effects on its performance. Algae are photosynthetic organisms and will quickly and easily grow in water if exposed to light. Since they occur naturally in all sources of water, it is almost inevitable that they will occur within an aquaponic system. Algal morphology ranges from single celled organisms, known as phytoplankton, and multicellular types, known as macroalgae Phytoplankton can reproduce rapidly, turning water green, while macroalgae form long filamentous strands, which can attach to the bottom of tanks. Algal growth can affect the chemical characteristics of the water and can interfere with the mechanics of the filters and pumps. Algae compete with other organisms for nutrients. They produce oxygen during the day, and consume it at night. In serious cases, algal consumption of oxygen during the night can result in water becoming anoxic, causing fish death. Filamentous algae can also grow to quite large sizes, and are often tough to break down. This means that a build up of algae can cause damage to the filters and pumps which may be expensive to repair and which can compromise the performance of the system.

MONITORING: Monitoring algal growth is mostly simple, usually relying on visual inspection of the areas such as the walls of fish tanks, around pumps and filters, and around the roots of the plants.

TROUBLESHOOTING PROCEDURE: Algal growth can be prevented by blocking the light using screens (Somerville *et al.* 2014a).

Suspended solids can be categorised into settleable and non-settleable solids. Settleable solids are those which settle on the bottom of the fish tank. The largest contributor is fish solid waste, made up of faeces, uneaten food, and other biological material. It is estimated that 0.45 kg of fish feed produces 0.11-0.13 kg of solid waste (Sallenave 2016). Buildup of excess settleable solids will have a negative impact on an aquaponic system for several reasons. Firstly, the increased organic load will decrease DO as it decomposes. This will affect other organisms in the system, such as nitrifying bacteria which require oxygen in order to convert ammonia to nitrates. Secondly, particles can adhere to the plant roots, decreasing their efficiency.

MONITORING: To measure settleable solids, take 1 L of a well-mixed water sample, place it in an Imhoff cone (Figure 3), and leave for 1 hour to settle. The cone is graduated into mm, so a direct reading of mm/L can be directly inferred from the depth of settled material (MadeCivilEasy 2016).

TROUBLESHOOTING PROCEDURE: Settleable solids are removed by filtration, and it is therefore necessary to ensure that all the filters are of the correct size, and in good working order.

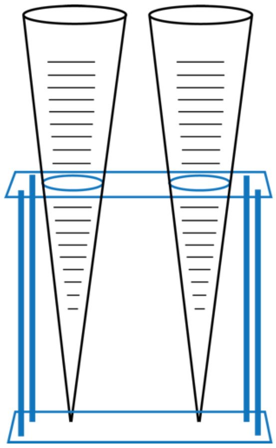

Figure 3: Imhoff cones for measuring settleable solids.

9.2.3 Plant health

Unfavourable conditions (e.g. suboptimal temperature, insufficient light intensity, nutrient deficiency, or pests and diseases) will decrease the overall performance of crops.

MONITORING: It is most important to ensure that parameters are set within the optimum range for the species and cultivars being grown.

TROUBLESHOOTING PROCEDURE: In such instances, close monitoring of the appearance of plants will help to identify the underlying cause (Somerville *et al.* 2014b).

Disease

One of the major benefits of aquaponic systems is the comparative resilience of plants to disease. Root rot is a disease which infects numerous species of plants growing in hydroponic systems. It has been shown, however, that crops grown in aquaponic systems have an increased resilliance to the causative agents, such as *Pythium aphanidermatum* (Stouvenakers *et al.* 2018).

OPERATING PROCEDURE: Operators should be diligent when it comes to monitoring for disease. A familiarity with the system is crucial in order to be able to observe any changes. Most important is the control of water quality and the physical parameters. Because of the controlled nature of aquaponics, it is possible to set parameters in such a way that the introduction and spread of disease are minimised.

MONITORING: For example, since root rot is only virulent at temperature ranges between 20-30 ^{0}C, control of temperature is therefore an effective measure against its spread (Grosch & Kofoet 2003; Sirakov *et al.* 2016). Another important consideration is the microbial flora: beneficial bacteria and other microbes play an important role in plant health, so it is important that inoculants of these organisms are utilised, and their presence occasionally checked for using cultures; however, this is not easy and requires expertise.

TROUBLESHOOTING PROCEDURE: Plant health and leaf colour should be observed daily. Leaf shape can also tell us if a plant is doing well. Wilting and signs of stress can be useful indicators of plant health issues (root, collar, or vascular problems) as well as nutrient imbalances.

Relative humidity

Relative humidity can be described as the amount of moisture in the air, relative to the total carrying capacity of the air for water; for example, 75% relative humidity is equal to 75% of the total water content which could be present in the air. The level of water which air can hold is dependent on temperature, so a room at 30 ^{0}C could have significantly more water than the same room at 25 ^{0}C. The point at which relative humidity reaches 100% is known as the dew point.

OPERATING PROCEDURE: This parameter is an important consideration in aquaponics, because controlling humidity in a desired range can prevent disease, as well as fend off parasites. Like most organisms, parasites have an optimum threshold that they can efficiently operate under; for example, spider mites can cause damage to plants by puncturing the plant cells while feeding. As they cannot tolerate wet and humid conditions, misters are often used to increase humidity and prevent such damage being caused. Microorganisms such as mould and fungi can also cause an issue in aquaponic systems and as they are difficult to remove through filtration, humidity can be used to control spores (Brown 2006; Storey 2016). Some plant species are adapted to survive in humid conditions, while the converse is true of plants from more temperate regions. It is therefore important to understand what conditions best suit the plants that are being grown.

MONITORING: Once the optimum relative humidity for a crop has been established, it should be monitored constantly to ensure it does not fall outside this range for prolonged periods. Measuring humidity is a straightforward procedure, using a meter known as a hygrometer. This gives the relative humidity of an area as a percentage.

TROUBLESHOOTING PROCEDURE: If relative humidity falls outside of the desired range the temperature can be altered, as relative humidity is a function of temperature, and therefore if relative humidity is too low, an increase in temperature will allow water which has condensed to evaporate. Conversely, if humidity is too high, lowering the temperature will decrease the moisture in the air. One can also manipulate the airflow. Ventilation, for example, will dilute the water vapour in the air, thereby reducing humidity. There are also devices known as dehumidifiers which can be set to activate at a certain point to draw water out of the air. These can be especially useful in automating the process, thereby reducing operational costs (labour) (Brown 2006; Somerville *et al.* 2014b; Storey 2016).

Air temperature

Ambient air temperature will have an effect on how well plants grow. Most vegetables grow in the range between 18-30 ^{o}C, though there are some species which are adapted to either higher or lower thresholds. Swiss chard and cucumbers, for example, will perform well between 8-20 ^{o}C, while tropical species such as okra prefer temperatures between 17-30 ^{o}C. Temperature can affect a plant's ability to fend off disease, by causing stress, and by allowing pests and parasites to thrive. Another consideration is the plant's physiological response to temperature. Leafy greens, for example, begin to flower and seed at higher temperatures, which affects their taste, making them bitter and unpalatable.

OPERATING PROCEDURE: It is important to consistently monitor the air temperature in an aquaponic unit, and the measurements should be taken at different locations.

MONITORING: It can either be done using a digital thermometer or with of an analogue thermometer. Any changes in temperature should be noted.

TROUBLESHOOTING PROCEDURE: If the temperature falls outside of the desired range, it can be increased or decreased using specialist equipment (e.g. air heaters, air conditioning units). The best way to ensure that the optimum temperature is kept throughout the year is to ensure that the cultured crop is adapted to the local climate (Leaffin 2017).

Light intensity

Under normal growing conditions, plants receive the light necessary for photosynthesis from the sun. Like other variables in nature, this depends on the geographical location, time of day, and local environmental conditions. Light is a fundamental requirement for plant growth, and therefore it is essential that the right levels are provided for the chosen crop, in order to ensure optimal yield (Chen Lopez 2018). Light may be measured by its intensity (lux), which is the number of photons reaching a surface of a defined size. The metric unit of light intensity is the lumen (lm), and lux is equal to one lumen per square meter. In aquaponics what is of interest is the number of photons reaching the surface of a leaf. Photons are a type of elementary particle, and are essentially packets of energy which make up a stream of light. The number of phototons trapped by a leaf is the determining factor in the rate of plant growth (Badgery-Parker 1999).

OPERATING PROCEDURE: Without the proper light intensity, plants cannot grow or perform as well as they should. The point at which photosynthesis is equal to respiration is known as the compensation point. This is the intensity that will allow plants to survive, but not to grow, and it differs from plant to plant. Conversely, the point at which light intensity does not increase photosynthesis, and therefore stops limiting growth, is known as the saturation point. Generally, the upper leaves will be saturated at around 32,000 lux. Due to shadowing, the lower leaves will not receive as much light as the upper leaves. In order for the whole plant to become saturated, the light levels need to be around 100,000 lux. Photosynthetically active radiation (PAR) is the part of the light spectrum which plants use for photosynthesis, and includes wavelengths from 400-700 nm, which represents almost all visible light (Badgery-Parker 1999; Chen Lopez 2018).

MONITORING: There are several ways of measuring light, and there are even apps which can be purchased for smartphones (although the reviews of these should be carefully checked, as they can sometimes be less than accurate). Because light intensity is based on its power, the energy used to power the lights can be extrapolated to give a measure of luminescence in watts, or watts per meter squared (Wm^{-2}). Similarly, we can measure the amount of energy emitted from a source, such as a lightbulb, from a distance. A radiometer is a device that measures the power of a light source, and a pyranometer can be used to measure the total amount of short-wave radiation. Short-wave radiation includes photosynthetic light, as well as energy from UV and near infra-red (IR) light. Plants and people experience IR light as heat. These meters are cheap to purchase and use, although they do have their limitations, the biggest of which is that their use under electric lights can give erroneous readings, especially when the light source has high levels in the blue or red spectrum. Quantum sensors are a more accurate way of measuring light; however, they are more expensive than foot-candle meters. These are usually hand-held, battery-operated devices, which measure PAR. They display their reading digitally, and some come with data logging capabilities to enable the easy transfer of data to a computer. Thirdly, instruments measuring radiant flux, which is the amount of energy per unit of time, can be used to measure the intensity of light.

TROUBLESHOOTING PROCEDURE: As plant growth is not uniform, readings should be taken from different locations – dark and light – to ensure that there are no areas with severe deficiencies. If, for example, the lower parts of the plants are falling below optimum levels, then productivity will be reduced (Runkle 2009; Runkle 2012). Correcting light intensity when it falls below the optimum range is usually quite a simple process. If there are obvious issues, such as blown bulbs, these should be replaced. More lights can be added to areas which are darker, and the positioning of lights can be changed to ensure that all areas of plants receive the optimum level.

9.2.4 Fish health

Monitoring fish health is a central aspect of keeping a healthy aquaponic system.

OPERATING PROCEDURE: This is typically achieved through observation of the behaviour and physical appearance of stocks, and an understanding of what constitutes ‘normal’. To this end it is important to understand typical behaviour patterns and physical appearances of the fish species in question. Water quality plays an important role in fish health, and maintaining consistent good quality enables that the fish remain in a stress-free condition. Maintaining a healthy immune system will allow them to fend off complications arising from the introduction of disease and parasites.

MONITORING: Generally speaking, fish should be observed on a daily basis, and their condition, as well as any changes, should be noted; the clinical signs of stress, disease, and parasitic infestation.

TROUBLESHOOTING PROCEDURE: Another important consideration is stocking density and feeding rates. The potential introduction of stress and disease into a system, can be avoided by ensuring that the fish are kept at an appropriate stocking density, and that feeding is maintained at appropriate levels (Somerville *et al.* 2014c).

Feeding rates

It is important to monitor feeding rates for several reasons. Too much food can lead to an oversupply of nutrients in the water, resulting in complications in the chemical and micro(biological) parameters.

OPERATING PROCEDURE: Feeding fish too little can cause stunted growth, leading to decreased productivity in the system, as well as increased stress and aggression, which can cause fish to attack each other, resulting in wounds and sores which may become infected.

MONITORING: Typically, the quantity of feed is weighed, although the feeding rates can also be measured visually, by monitoring the fish until feeding rates decrease and they cease feeding; in some systems this is done using underwater cameras. Many fish feed companies will also give recommended feed rates, allowing operators to accurately estimate how much feed to give. Feeding rates should be observed and noted at each feeding to allow for monitoring.

TROUBLESHOOTING PROCEDURE: If feeding rates begin to reduce, this could be a sign that something is wrong in the system and appropriate action, such as investigation by a veterinarian, should be undertaken. An increase in feeding rates could be a sign that the fish are not being fed enough, in which case the feed should be increased (Masser *et al.* 2000).

Growth

Growth is an important measure of how well fish are doing in a system, and feed companies often provide growth charts which give an estimation of the expected growth rate of fish as a function of feeding rates.

MONITORING: Growth is measured physically, by first weighing and taring a suitably sized net on a hook scale. Fish are then caught using the net and both are weighed. Another way of weighing fish is to place them in buckets of water on a scale. This is especially practical if the fish are small, and more than one fish can therefore be weighed at the same time. Note that with this method, care should be taken as larger distressed fish can forcefully hit the sides of the bucket, thereby causing themselves damage. In order to measure the length of fish, it is generally advisable to anaesthetise them using a suitable anaesthetic, such as tricaine methanesulphonate. An appropriate amount of tricaine methanesulphonate is dissolved in a separate container of water, which is of a suitable size for the fish. The fish should be placed in the water until they become limp and safe to handle, and they can then be placed on a flat surface, measured using a ruler, and released. These measurements should be taken once a week and noted. Any unexpected change to size and weight should be investigated.

Indicators for assessing fish stocks

The most important indicators of healthy fish stocks are behaviour and physical condition. Anything out of the ordinary can be classed as clinical signs of disease, or stress.

MONITORING: Typically, fish should be monitored during and directly after feeding, and changes in the amount of food eaten should be noted. Healthy fish will exhibit some of the following behaviour (OIE 2018):

- Swimming in an ordinary, purposeful way
- Clean, intact fins, which are properly extended and utilised
- Clear, clean skin, with intact scales
- Not breathing at the surface of the water

Abnormal behaviour and clinical signs of problems within a stock are quite general, and it can be impossible to determine the cause of an issue based on these alone. Things to watch out for include (Bruno *et al.* 2013):

Behavioural signs:

- Changes in feeding rates
- Lethargy and morbidity
- Changes in swimming patterns, such as flashing, spiralling, or failing to maintain buoyancy
- Hanging around near water outlets
- Hanging around at oxygen exchange points
- Breaching the surface and gasping near the surface

Clinical signs:

- Shortened or flared opercula
- Haemorrhaging
- Exophthalmia (raised, popped out eyes)
- Enophthalmia (sunken eyes)
- Pale, zoned, or necrotic gills
- Lesions
- White patches
- Inflamed vent

An ideal way to measure and record these signs is by way of a clinical score sheet, an example of which is shown in Table 5. A clinical score sheet is a sheet where clinical and behavioural signs can be recorded and noted, based on their severity – for example, weak, mild, and severe.

Table 5: An example of a clinical score sheet for recording clinical and behavioural signs in fish

		Severe	Mild	Weak	No sign
Behaviour	Moribund				
	Lethargic				
	Hanging vertical				
	Spiralling				
	Flashing				
	Loss of equilbrium				
Body	Dark				
	Distended abdomen				
	Anorexic				
Eyes	Exophthalmic				
	Enophthalmic				
Gills	Pale				
	Zoned				
	Necrotic				
Lesions	Flank				
	Elsewhere				

Stress

Stress can be one of the most damaging factors for fish in aquaponic systems. Alone, it may not be enough to kill stocks; however, chronic stress can lead to a number of complicating factors, usually caused by suppression of the immune system. Immunocompromised fish are more likely to fall victim to infectious agents, such as bacteria, viruses, and fungi, as well as parasitic infestations. It can also reduce a fish's ability to counter sudden changes in its environment, leading to mortality.

MONITORING: Stress can be monitored directly in the organism, through the release of certain hormones, such as cortisol. However, this requires trained personnel, in order to ensure that no additional stress occurs. Such measurements also fall into the category of animal experimentation, and the local animal protection laws should be adhered to. The best way is to ensure that stressful situations are avoided. This can be achieved by ensuring that the fish are kept at the proper stocking density, fed appropriately, and that physical characteristics of the water (temperature, pH, DO, etc.) are kept at physiological optimums for the chosen species (Rottmann *et al.* 1992; Somerville *et al.* 2014c).

Disease

Disease is an important consideration in any system where animals are kept in higher stocking densities than would otherwise be found in nature, and this is also true of aquaponic systems. Issues involving disease can be exacerbated by poor conditions, such as low DO, and can also cause opportunistic pathogens to introduce infection.

OPERATING PROCEDURE: Generally speaking, contained recirculating systems are somewhat insulated from the introduction of the causative agents of disease. This can be a double-edged sword, however, as it may be difficult to eradicate disease following its introduction, and the sooner that issues are identified, the more effective treatment and remedial action will be. In flow-through systems, filtration through sand, for example, or treatment using UV light can all reduce the likelihood of the introduction of disease. In either case, careful and consistent monitoring is necessary. Even with careful prevention, it is possible that disease may be introduced to the system, and it is important that this is recognised and addressed with the aid of veterinary advice, if necessary.

MONITORING: In order to appropriately monitor stocks, it is important that operators are familiar with clinical and behavioural signs which fish may exhibit and are identified above. In a system with a high number of animals, it is likely that there will be instances of fish which are poorly, and while it may not be indicative of a disease, it is recommended that daily checks are carried out in order to monitor the overall health of the stock and mortalities; dead fish should be removed from the system and disposed of in a bio-secure manner. If the frequency of clinical signs or mortalities begin to increase, it is important to ensure that procedures are in place to first identify the issue and then take remedial action.

TROUBLESHOOTING PROCEDURE: For this reason, it is important that operators are aware of how to contact a veterinary specialist in fish health (Martins *et al.* 2010; Somerville *et al.* 2014c).

9.2.5 Parameters of special interest

Sometimes non-standard parameters in water quality will become relevant in an aquaponic system, especially when choosing the source of your water. You can choose to use water from the environment (rain water, river or lake water, etc.), or municipally treated tap water. Depending on the water source, the water may differ in the levels of DO, presence or absence of heavy metals and other micropollutants, trace chemicals, and disinfectants, and it may or may not be contaminated with coliform bacteria. The water that is added to the system can be of a very different quality depending on:

- The location of source water
- The recent weather (if using water from the environment)
- Municipal water treatments (if using tap water)

OPERATING PROCEDURE: Drinking water treatment often includes the addition of disinfectants, such as clorine and chloramines. These must have a residual effect, which means they remain active in the water after application of the disinfectant. This can be problematic in an aquaponic system, since it relies heavily on the microbial communities in the biofilter. On the other hand, water taken directly from the environment can have other issues, including contamination with undesirable microbes, such as coliform bacteria, or the presence of pollutants, such as endocrine disrupting chemicals and heavy metals (Godfrey 2018).

MONITORING: Monitoring of these non-standard parameters is impossible without access to analytical techniques such as high-performance liquid chromatography (HPLC), inductively coupled plasma mass spectrometry (ICP-MS), atomic absorption spectroscopy (AAS), and microbiology lab equipment and materials, such as an incubator, laminar flow hood, autoclave, vacuum filtration apparatus, and microbiological growth media. Since this equipment is very expensive, it is best to consult a national laboratory for specific measurements if a problem with source water is suspected.

TROUBLESHOOTING PROCEDURE: A more economical and practical solution is to avoid problems with the source water altogether by installing a carbon filter, which will remove any disinfectant residues and potential pollutants, and a UV filter which will deactivate any unwanted microbes in the source water.

9.3 References

Badgery-Parker, J. 1999. Light in the greenhouse. *Agnote* DPI/254, 1-2.

Brown, J.W. 2006. *Relative Relative Humidity*. Cropking Incorporated.

Bruno, D., Noguera, P.A. & Poppe, T.T. 2013. *A Colour Atlas of Salmonid Diseases* (2nd edition) Springer Netherlands, Dordrecht.

Chen Lopez, J. 2018. *Influence of Light on Crop Growth*. Promix Training Centre.

Godfrey, M. 2018. *How to Evaluate the Quality of Your Aquaponic Source Water.* Upstart University.

Grosch, R. & Kofoet, A. 2003. Influence of temperature, pH and inoculum density on bottom rot on lettuce caused by *Rhizoctonia solani*. *Journal of Plant Diseases and Protection* 110 (4), 366-378.

Joly, A. 2018. *Aquaponics in EU – Basic regulation you need to know.* EU Aquaponics Hub.

Klinger-Bowen, R.C., Tamaru, C.S., Fox, B.K., McGovern-Hopkins, K. & Howerton, R. 2011. *Testing your Aquaponic System Water: A Comparison of Commercial Water Chemistry Methods*. Center for Tropical and Subtropical Aquaculture, Honolulu.

Leaffin 2017. *What is the Optimum Range of Temperature or Aquaponics*.

MadeCivilEasy 2016. *Measurement of Settleable Solids*.

Martins, C.I.M., Eding, E.H., Verdegem, M.C., Heinsbroek, L.T., Schneider, O., Blancheton, J.P., d'Orbcastel, E.R. & Verreth, J.A.J. 2010. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aquacultural Engineering* 43 (3), 83-93.

Masser, M.P., Rakocy, J. & Losordo, T.M. 2000. *Recirculating Aquaculture Tank Production Systems: Management of Recirculating Systems*. Southern Regional Aquaculture Center, SRAC Publication No. 452.

OIE 2018. *Manual of Diagnostic Tests for Aquatic Animals* (8th edition) Office International des Epizooties, World Organisation for Animal Health, Paris.

Rakocy, J.E., Masser, M.P. & Losordo, T.M. 2006. *Recirculating Aquaculture Tank Production Systems: Aquaponics — Integrating Fish and Plant Culture*. Southern Regional Aquaculture Center, SRAC Publication No. 454.

Rice E.W., Baird, R.B., Eaton, A.D. & Clesceri, L.S. 2012. *Standard Methods for the Examination of Water and Wastewater* (22nd edition). American Public Health Association, American Water Works Association, Water Environment Federation, Denver.

Roosta, H.R. and Hamidpour, M., 2011. Effects of foliar application of some macro-and micro-nutrients on tomato plants in aquaponic and hydroponic systems. *Scientia Horticulturae* 129 (3), 396-402.

Rottmann, R.W., Francis-Floyd, R. & Durborow, R. 1992. *The Role of Stress in Fish Disease*. Southern Regional Aquaculture Center, SRAC Publication No. 474.

Runkle, E. 2009. Tips for Using Light Sensors. *GPN Magazine* January 2009, 66.

Runkle, E. 2012. Which Light Sensor Should I Use? *GPN Magazine* September 2012, 62.

Sallenave, R. 2016. *Important Water Quality Parameters in Aquaponics Systems*. New Mexico State University Circular 680.

Sirakov, I., Lutz, M., Graber, A., Mathis, A., Staykov, Y., Smits, T.H. & Junge, R., 2016. Potential for combined biocontrol activity against fungal fish and plant pathogens by bacterial isolates from a model aquaponic system. *Water* 8 (11), 518.

Somerville, C., et al. 2014a. Water quality in aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 21-34.

Somerville, C. et al. 2014b. Plants in aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 83-102.

Somerville, C. et al. 2014c. Fish in aquaponics. In Somerville, C., Cohen, M., Pantanella, E., Stankus, A. & Lovatelli, A. *Small-Scale Aquaponic Food Production – Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper No. 589. Food and Agriculture Organization of the United Nations, Rome, pp. 103-121.

Storey, A. 2016. *The True Costs of Greenhouse Humidity Control.* Upstart University.

Storey, N. 2018. *Why You Need to Be Careful About Zinc in Aquaponics*. Upstart University.

Stouvenakers, G., Massart, S. & Jijakli, H. 2018. *Suppresive effect of aquaponic water in the development of root rot caused by Pythium aphanidermatum in lettuce*. Abstract at the XV Meeting of the Working Group 'Biological and integrated control of plant pathogens': Biocontrol products: from lab testing to product development, Lleida.

Thorarinsdottir, R.I. et al. 2015. System control and optimization. In Thorainsdottir, R.I., Kledal, P.R., Gangenes Skar, S.L., Sustaeta, F., Ragnarsdottir, K.V., Mankasingh, U., Pantanella, E., van de Ven, R. & Shultz, R.C. *Aquaponics Guidelines*. EU Lifelong Learning Programme, Reykjavik, pp. 33-41.

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10. FOOD SAFETY

Consumers are very concerned about food safety and quality due to a number of food-related news which has received a great deal of media attention. Consumers are more than ever concerned about obtaining safe food. Food safety is about handling, storing and preparing food to prevent illness and to help to ensure that food retains enough nutrients in order for us to have a healthy diet. Food safety is ***the assurance that food will not cause harm to the consumer when it is prepared and/or eaten according to its intended use*** (WHO & FAO 2009). Ignoring food safety principles means that good food will go bad. Taking shortcuts by avoiding preventive measures which make food safe can have negative effects on health and even shorten people's lives.

Whoever sells food, regardless of the amount, has both an ethical and legal obligation to ensure that the food is safe to consume. All steps in the food chain (*from farm to fork* or, in the case of aquaponics, *from raft to plate*), including plant harvesting and fish slaughter, should be managed in a way that ensures that the food is safe and suitable for its intended use (WHO & FAO 2009). Primary produce (products of primary production consisting of a natural raw material - an unmanufactured product) should also be protected from different kinds of hazards. A hazard is a (micro)biological, chemical or physical agent in, or condition of, food which has the potential to cause an adverse health effect. In general, we distinguish between four types of food-related hazards (Table 1), where the biggest focus in aquaponics is on the (micro)biological. Allergen control is an emerging area of concern, and detailed labelling requirements are now in place in the EU. Fish and products thereof are listed in Annex II to Regulation (EU) No. 1169/2011 on the provision of food information to consumers as one of fourteen allergens which have to be considered in hazard analysis.

Table 1: Main food-related hazards in aquaponics

(MICRO) BIOLOGICAL
Pathogenic bacteria, viruses, fish parasites, moulds, fungi
CHEMICAL
Residues of plant protection products, veterinary medicines, sanitizers, cleaning agents, test kit reagents, lubricant
PHYSICAL
Foreign bodies (metal, glass, wood, parts of packaging material, dust, stones, plastic or glass fragments, needles, etc.)
ALLERGENS
Cereals containing gluten, crustaceans and products thereof, eggs and products thereof, fish and products thereof, peanuts and products thereof, soybeans and products thereof, milk and products thereof (including lactose), nuts and products thereof (almonds, hazelnuts, walnuts, cashews, pecan nuts, Brazil nuts, pistachio nuts, macadamia or Queensland nuts), celery and products thereof, mustard and products thereof, sesame seeds and products thereof, sulphur dioxide and sulphites, lupin and products thereof, molluscs and products thereof. **Note:** for exceptions please see Annex II to Regulation (EU) No. 1169/2011.

The main objective of this chapter is to ensure consumer protection through the production of safe food at the first stage of the food supply chain. Therefore, aquaponic producers must be aware of the food safety risk factors, and should maintain the highest level of adherence to good agricultural practice (GAP) and good hygiene practice (GHP) which are described in detail below. Primary produce that is grown with little contamination is less likely to result in health hazards caused by poor handling during the food preparation stages.

10.1 Legal framework

The goal of the food safety policy of the EU is to ensure safe and nutritious food from healthy animals and plants while supporting the food industry (EC 2014). The integrated Food Safety policy also includes animal welfare and plant health. In the strategy for animal welfare there is an action on the welfare of farmed fish, though there are no specific rules in place (EC 2012). Because of the great variety of potential produce, food safety norms are not explicit for aquaponic produce and there are no specific EU regulations yet (Joly *et al.* 2015). Aquaponics falls under the common EU policies related to agriculture, fisheries, food safety and the environment. Because aquaponics includes both fish and plant production, different policies apply. Like aquaculture operators, aquaponic producers use a shared primary resource (water) and generate effluents, and their activities are subject to a significant amount of policies and legislation (Hoevenaars *et al.* 2018; Joly *et al.* 2015). Table 2 lists the key EU regulations on food safety.

Table 2: Key EU regulations on food safety

Regulation	Description
Regulation (EC) 178/2002	General principles and requirements of food law and food safety
Regulation (EC) 852/2004	Hygiene of foodstuffs
Regulation (EC) 853/2004	Specific hygiene rules for food of animal origin
Regulation (EC) 2073/2005	Microbiological criteria for foodstuffs
Regulation (EC) 1169/2011	Provision of food information to consumers

10.2 Food safety risks in aquaponics

A major food safety concern with aquaponics is the cultivation of vegetable crops in water containing fish excreta and other organic matter, including fish and plant particulate residuals. Pathogenic bacteria can enter the system via water, animal faeces, plant seedlings, tools or humans. The major risk from warm-blooded animals is the introduction of *Escherichia coli*, while birds can carry *Salmonella* spp. (FAO 2014). *E. coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes* are the main foodborne pathogens that can be found in recirculating water system and which have been shown to survive in these conditions. Faecal contamination of aquaponic systems has mostly been detected when a poor quality water source was used or when faecal inputs from domestic animals or wildlife were possible (Fox *et al.* 2012). Despite previously published reports indicating internalization[2] of human foodborne pathogens such as *E. coli* O157:H7 and *Salmonella* in vegetables, the study done by Moriarty *et al.* (2018) did not provide evidence for bacterial internalization. Internalization may be a phenomenon only seen in specific circumstances such as very high bacterial concentration and plant injury (especially when roots are damaged) that increase the probability for the occurrence of bacterial internalization.

In addition, fish from non-reliable sources can introduce foodborne viruses and disease (e.g. *Vibrio* spp.) that are not commonly associated with fruits and vegetables (Fox *et al.* 2012). Parasites such as *Cryptosporidium* and *Girdia lamblia* can also be introduced in the water itself, so the source of water used in aquaponics is very important for the safety of the food produce (Ljubojević *et al*. 2017). The main route of bacterial contamination of produce is from water depositing bacteria on the surface.

Conditions in aquaponic systems (warm, wet, low-oxygen environments with high organic material) favour foodborne pathogens that are also hazardous to fish and plants. The presence of sediment appears to be one of the primary factors influencing pathogen persistence (Aquaponics Association 2015). Therefore, aquaponic producers should not allow these conditions to develop in their systems for technological as well as for food safety reasons. Studies with foodborne pathogens in fish suggest that if exposed, fish can carry foodborne pathogens for a short period. When they are in a tank with good aeration and solids removal, pathogen survival in fish is very low. When fish are in a tank with sediment accumulation and poor aeration, however, pathogens persist in the fish much longer and at higher levels (Aquaponics Association 2015).

Most fish do not contain significant levels of human disease-causing hazards. If fish are thermally treated before consumption, any contamination is usually quickly eliminated (Lee *et al.* 2015). However, special care is needed if the fish will be eaten raw (e.g. sushi, carpaccio, or ceviche). Leafy greens and other raw vegetables are also high risk products: 13.9% of the foodborne outbreaks in the EU are caused by fruits and vegetables (EFSA & ECDC 2017). Leafy greens are a high-risk crop because they:

- are frequently eaten raw
- grow close to the surface
- have a very high surface area for their mass

Leafy greens tend to deliver a much higher dose of pathogens per serving than any other type of produce if they are contaminated (Aquaponics Association 2015). Herbs, like basil or mint, tend to have a lower risk because smaller quantities of these plants are eaten compared to lettuce (Lee *et al.* 2015). A study by Barnhart *et al.* (2015) demonstrated no significant difference between contamination of unpacked smooth-textured leafy greens at grocery stores grown using aquaponics, hydroponics, and soil cultivation.

[2] Bacteria enter through natural openings in the plant surface and/or through sites of biological or physical damage, or bacteria are pulled into the internal tissues along with water (Deering *et al.* 2012)

Chemical and toxin contamination is a concern as well. However, the controlled environment in aquaponic facilities may make these hazards less likely compared to other forms of agricultural production. The aquaponic producer has to be aware that any chemical product used with plants could affect the fish, and any product used with the fish could affect the plants and consumers. The potential public health consequences of physical hazard contamination in primary production appear to be relatively uncommon.

To eliminate or reduce the risks to acceptable levels, aquaponic producers should implement preventive measures such as GAP (**G**ood **A**gricultural **P**ractice) and GHP (**G**ood **H**ygiene **P**ractice). A hazard analysis and critical control point (HACCP) systemic preventive approach should also be implemented as an upgrade of GAP and GHP (Figure 1).

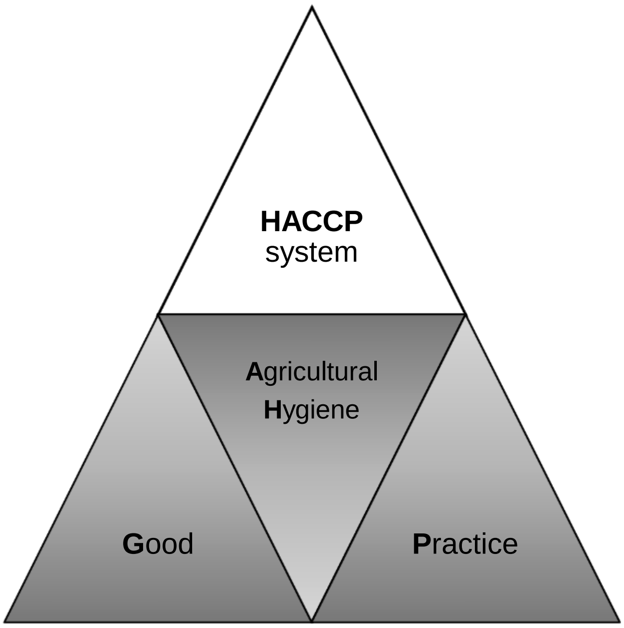


Figure 1: GAP and GHP as important prerequisites of the HACCP, constituting ¾ and ¼ respectively of preventive approach to food safety

10.3 Good agricultural and good hygiene practices

In general, good practice means quality assurance activities which ensure that food products and food related processes are consistent and controlled and assure quality procedures in food systems (Raspor & Jevšnik 2008), or simply defined as *Doing things well and guaranteeing it has been done so* (FAO 2006). GAP is the selection of methods which can best achieve the objectives of agronomic and environmental sustainability in primary food production. GHP consists of practical procedures and processes that return the production or processing environment to its original condition (cleaning programme); ensure that buildings and equipment operate efficiently (maintenance programme); and control for cross-contamination (usually related to people, surfaces, and the segregation of raw and processed products) (Raspor & Jevšnik 2008). GAP and GHP should be adopted to reduce as far as possible any source of contamination (Figure 2).

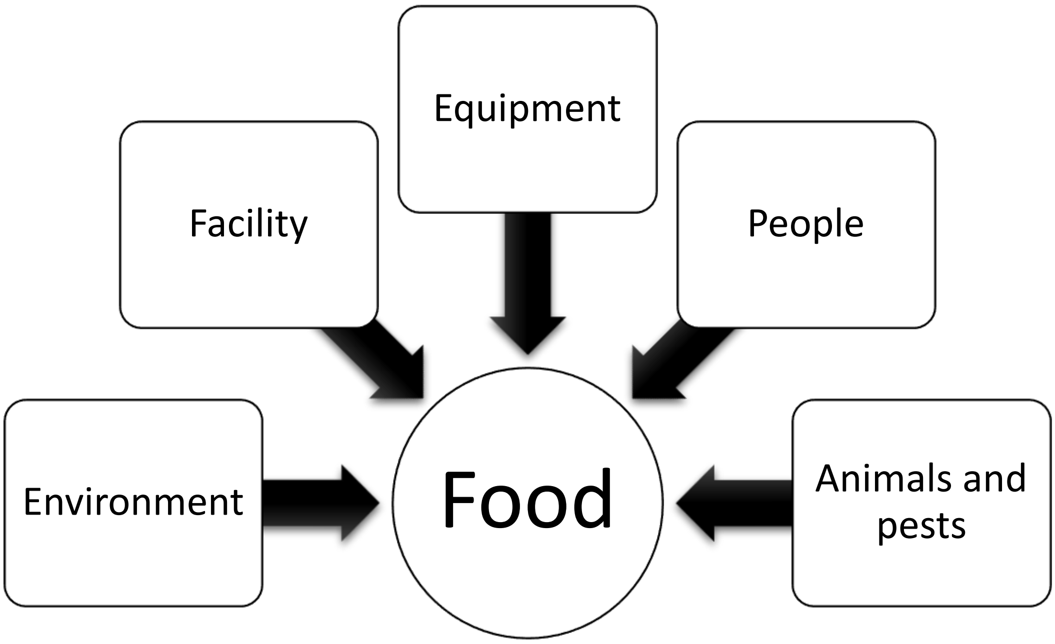


Figure 2: Contamination sources of food products addressed by GAP and GHP

10.3.1 Location, design and layout

Aquaponics requires a greenhouse in most climates. When deciding on the location of the aquaponic unit, the owner should consider certain factors such as the proximity to industrial plants, or to locations susceptible to airborne pollution or the proliferation of pests (e.g. incineration plants, plants releasing heavy metals, roads with heavy motor traffic, open air rubbish tips, etc.) (Copa – Cogeca 2018). The aquaponic producer should also consider the potential risk of natural disasters (flooding, heatwaves, etc.). Air and dust can act as a vehicle for hazards, which can be prevented with controlled ventilation. Additional wind protection for Deep Water Culture (DWC) systems is recommended since wind causes rafts to bounce, thereby splashing water through the holes and causing contact between the water and the leaves (Aquaponics Association 2015). If there is vegetation surrounding the aquaponic unit, it should be kept mown/strimmed, in order to reduce the risk of rodents and pest insects from getting into the greenhouse. There are some food safety concerns about liver flukes and other parasites carried by snails in aquaponic systems. However, snails are only one step in the liver fluke life cycle, which requires cattle to complete it. If there are no cattle or other ruminants in the immediate surroundings of the aquaponic unit, the risk is minimised or even eliminated since snails are unlikely to carry liver flukes (Aquaponics Association 2015).

Use of construction materials that may be a potential source of contamination (e.g. lead-based paint) should be avoided. Since pests can be very small (e.g. whiteflies and thrips), very fine mesh screens can prevent their entry into the unit. In Europe, screens are generally characterized by the number of spaces per centimetre in each direction (e.g. a 10x20 screen has 10 spaces per centimetre in one direction and 20 in the other direction). The reduction of natural ventilation caused by the use of fine mesh screens can be mitigated by increasing the screen area (e.g. by using concertina-shaped screens).

There should be washrooms available to workers at all times when they are on site. These should be connected to an effective drainage system. Handwashing stations (whether attached to the toilet facility or located near it), should be equipped with:

- a basin
- running potable water
- liquid soap
- disposable paper towels
- a covered waste container (see an example in Figure 3)

Facilities for washing produce after harvesting must be separate from the hand-washing facility. There should be a clean, safe place off the ground for employees to store personal items. This area can be small and simple, such as a shelf (Aquaponics Association 2015).

Figure 3: An example of handwashing station at ZHAW, Institute of Natural Resource Sciences (covered waste container is not visible on this photo)
(Photo: Andrej Ovca)

10.3.2 Equipment

Produce will have physical contact with many surfaces during harvest and processing. These may include harvest equipment and containers, transport bins, knives and other utensils, sorting and packaging tables, and storage areas. Equipment with which food comes into contact should be:

- made of materials such as stainless steel, food-grade plastic, aluminium, ceramics, or tinned copper, and be kept in good condition in order to minimise any risk of contamination
- where relevant, fitted with control devices (e.g. a thermometer in the refrigerator)
- effectively cleaned

Whenever possible, dedicated equipment (Figure 4) should be used. Fish equipment and contact materials must be clean and uncontaminated (scoops and nets, transport containers, fish killing machine). Harvesting equipment should not be placed on the ground (Figure 4a). All weighing and dispensing equipment should be regularly calibrated. Storage equipment should be fitted with devices that enable constant monitoring of the temperature and an even distribution of the temperature conditions in order to maintain the cold chain (Copa – Cogeca 2018).

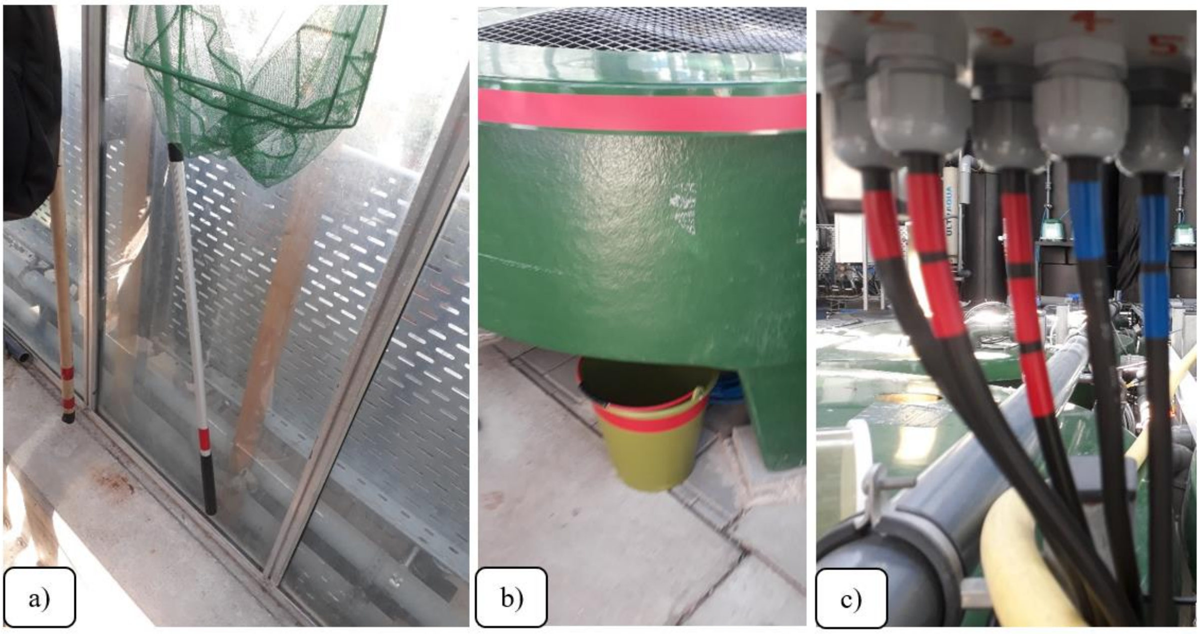


Figure 4: Colour coding system preventing cross-contamination through equipment at ZHAW, Institute of Natural Resource Sciences (Photo: Andrej Ovca)

10.3.3 Worker hygiene

Anybody working in the aquaponic unit should follow a simple rule: ***always be healthy and clean***. It is also recommended to wear dedicated working clothes. Most diseases that affect humans can be introduced into the system by the workers or by visitors. One of the biggest risks to fresh produce safety is **people and their hands**, which are in continual contact with the environment. Sick workers, and those with open wounds or cuts, should not handle produce, fish, or equipment (Lee *et al.* 2015), or if they have yellow skin or eyes, a sore throat with fever, are vomiting or have diarrhoea, until the symptoms have stopped for at least 48 hours.

Smoking, chewing gum, or eating around the production areas should be prohibited. Hands should be washed every time after using the bathroom, eating, shaking hands with someone, handling fish, putting hands into the system’s water, touching one’s mouth, nose, ears, hair and, of course, before harvesting the plants. When washing hands liquid soap should be used at all times. The recommended hand washing technique (Figure 5) should be used. Hands should be rinsed with potable water and dried with single-use paper towels.

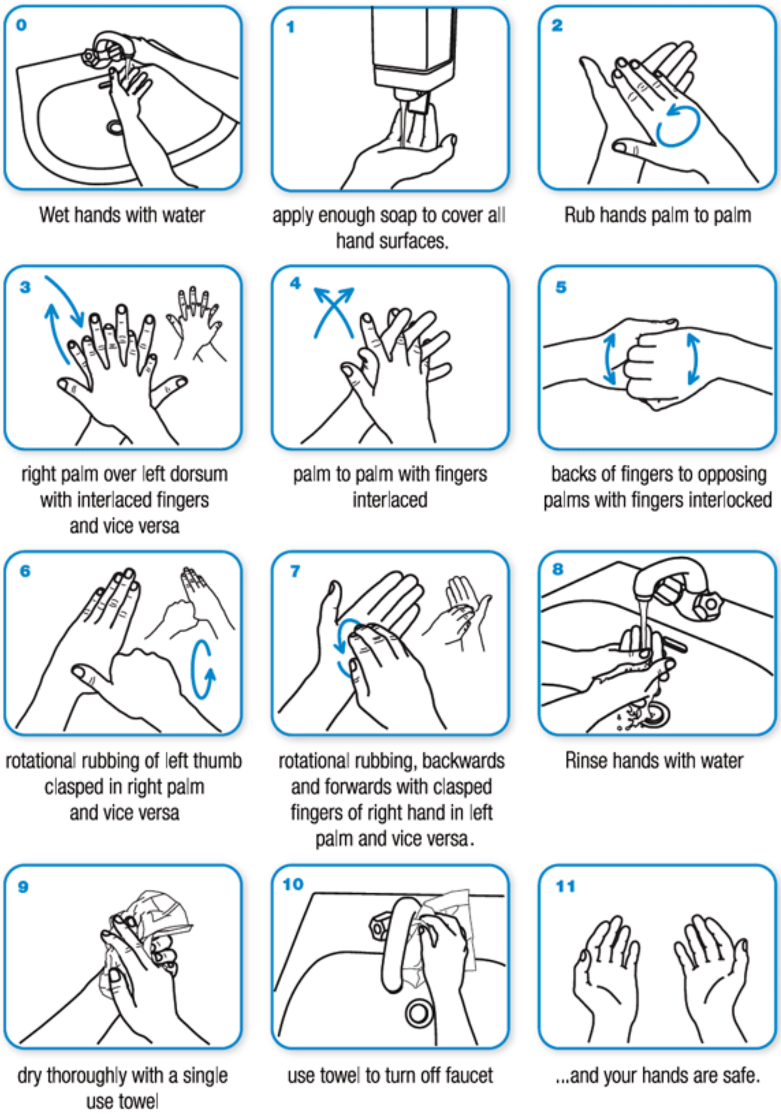


Figure 5: Handwashing technique
(Source: WHO / http://www.who.int/gpsc/clean_hands_protection/en/)

The number of personal items carried while working should be minimized. This includes cell phones, jewellery, nail polish, hair extensions, etc., which can fall into the produce. If an injury occurs while handling fish or working in the system water, the area should be immediately washed with clean water and disinfected. If someone needs to wear a band-aid, it has to be of a non-food colour (e.g. blue), properly secured, and covered with a glove.

Walking into the greenhouse from outside is an important route of entry for food safety hazards. The risk can be reduced by hygienic barriers such as footbaths and a handwashing station at the entrance to the greenhouse or, if this is not possible, hand disinfection (Figure 6). As an alternative to footbaths, workers can use 'in-greenhouse' shoes or boots, or disposable paper booties. The latter is also an alternative for visitors (Aquaponics Association 2015). Footbaths should always be wet and have an active disinfectant solution in the mat. If the footbath mat is dry, it is not effective. Care should be taken to rinse out the footbaths on a regular basis to ensure that they do not get clogged up. The chemical solution should be changed on a regular basis depending on the product used.

Figure 6: Disinfection point for sanitising workers' boots and hands at the greenhouse entrance at ZHAW, Institute of Natural Resource Sciences (Photo: Andrej Ovca)

Preventing cross-contamination

The concept of cross-contamination is usually used in terms of cross-contamination by microorganisms and lately also in terms of allergens.

CROSS-CONTAMINATION ROUTES:

- produce to produce
- through equipment, containers and accessories
- through workers
- through cleaning procedures
- through other possible means of transport (rodents, insects)

Cross-contamination from produce to produce is less likely to occur in aquaponics. Cross-contamination through equipment can be (besides efficient cleaning) effectively managed by colour coding (Figure 4). Different types of tasks should be done separately. For example, a worker who is cutting lettuce heads or arranging lettuce heads in boxes should only be handling plants, not moving rafts, pulling net pots, or any other jobs where their hands come into contact with the system water. Similarly, a worker doing tasks where their hands are in contact with the water should not be handling plants without first washing their hands and/or changing their gloves (Aquaponics

Association 2015). Preferably the fish, plants or media should not be handled with bare hands, but with disposable gloves. However, hands should also be washed before putting the gloves on. It is a good idea to get one-use, latex-free nitrile gloves, and dispose of them after each use. Dermatological zoonotic diseases including those caused by bacterial species such as, for example, *Mycobacterium, Streptococcus (iniae),* and *Vibrio spp*. have been discussed by Gauthier (2015). Although most humans have a strong natural immunity to wounds infected by bacteria such as *Mycobacterium*, more serious infections are often associated with immune-compromised individuals, deep puncture wounds, and highly virulent strains of bacteria. These topical infections usually occur as the result of injuries from the spines of fish or through contamination of open wounds.

It is important to prevent the system water from coming into contact with the produce during the harvest. Food and drinks should stay outside the aquaponic unit. In addition to unwanted bacteria, external food and beverages may bring allergens into your system that could pose risks to your consumers.

Training

Aquaponic workers must have the appropriate skills and information which match the complexity of the operations for which they are responsible (training in animal/plant management, health risks and safety practices in the workplace, operation of equipment, use of chemicals, etc.). The owner of the farm should ensure that all workers have been trained in the relevant health and safety and hygiene practices.

WORKER TRAINING SHOULD INCLUDE AT LEAST:

- the importance of being in good health when handling fish, equipment, and produce
- proper hand-washing technique
- correct use of gloves
- clean clothing and footwear policy
- first aid procedures for cuts and injuries

Visitors

Another method of introducing new pests and diseases into the aquaponic system is by visitors, and therefore it should be always assumed that visitors are ‘contaminated’. Visitors have to follow protocols such as washing or disinfecting hands before touching the system, using footbaths, and storing personal items in a designated location. Generally, visitors should be accompanied by someone so that these practices can be demonstrated (Aquaponics Association 2015).

10.3.4 Water supply

From the perspective of food safety, the source of water used in aquaponic systems has the potential to have a significant bearing on the quality of the final products, whether they are fish or plants (Chalmers 2004).

- **Municipal (potable) water** usually has the best quality because of previous testing and safety requirements. Potable water from a clean source is always preferred for a recirculating aquaponic system
- **Ground or well water** will have fewer pathogens than surface water (such as ponds, streams, or rivers) because there is less chance of contamination
- **Surface water** can be contaminated with animal manure and parasites
- It is important **not to use rainwater collected from roofs** as it may be contaminated by bird faeces. If using rainwater, it has to be ensured that birds are not roosting on the collection area. Otherwise treating the water before adding it to the system should be considered.

10.3.5 Fish feed

After water, fish food is the primary input into aquaponic systems. Feed should be purchased from a reputable source and should be always stored in a dry and secure area where birds, rodents and other pests will not be able to contaminate or eat it. Contaminated feed is an important route by which dangerous bacteria like *Salmonella* could be introduced in the system (Lee *et al*. 2015). Fish feed and other incoming materials should be checked for:

- pests
- expiry date
- intact/undamaged packaging

Additionally, fish feed should be routinely checked before feeding the fish to be sure that there is no condensed water or visible mould.

10.3.6 Harvesting and processing

Produce can become contaminated or cross-contaminated during harvesting and processing. If possible the *'all-in-all-out'* production system (in which all of the fish and plants are introduced at the same time and harvested at the same time) is recommended to minimise the possibility of contamination. Processing means changing plants or animals into what we recognize as food. For produce, processing can be as simple as washing and sorting, or it can involve trimming and/or slicing. For fish, the first step of processing is slaughter. If processing of produce and/or fish on the site is planned, a special area/room is needed which is separated from the rest of the greenhouse and dedicated only to these kinds of activities.

Plants

It is crucial to prevent the aquaponic water from coming into contact with the leaves of the plants. If possible, the system should be designed in the way that physically prevents water from contacting the edible parts of the crops, rather than simply counting on workers to be careful (Aquaponics Association 2015). This prevents many plant diseases as well as potential contamination of produce by the fish water, especially if the produce is to be eaten raw. Vegetables (produced in an aquaponic system or otherwise) must always be washed before consumption (FAO 2014). Diseased plants and compost piles should be kept far from the system in order to prevent contamination.

For Nutrient Film Technique (NFT) and DWC beds where harvesters can reach the whole bed from the aisles, bench harvesting (cutting plants directly out of the raft while the rafts are still in the bed) minimizes splashing. Removing rafts from DWC beds before harvest poses a food safety hazard because of splashing and dripping, and in the case of small beds often adds more work than it saves (Aquaponics Association 2015).

The producer should look very carefully for small snails and slugs that might be stuck deep down in the plant. Produce that has pest damage should not be harvested, because it main contain pathogens. Any product that has snails, slugs or their slime on it should be thrown away (collected as waste). Produce should be pulled apart as appropriate and rinsed in clean, cool, potable water (never in aquaponic system water) (Hollyer *et al.* 2009).

Fish

Sick or injured fish should be identified and separated from the healthy ones to avoid cross-contamination. After slaughter, the fish should be immediately chilled. The temperature of the fish should reach 4^{o}C or less as fast as possible, and this temperature should thereafter be maintained throughout storage and distribution. Ice used for chilling aquaculture products should be made from potable water. Processing fish involves certain risks beyond what usually occurs with plant production. If fish slaughter and processing is foreseen on-site, the legal and ethical requirements of the competent food safety authorities should be followed.

Storage of vegetables and fish

If harvesting is done a long time before selling, cold storage should be used. If the harvested fish is stored, the storage should be in a dedicated facility that meets minimum standards of hygienic design and construction for fish storage and processing facilities. Produce needs to be kept cool after harvest. The safe temperature is 4°C or below. 4°C is also the maximum storage temperature for fresh fish. Storage of fresh fish between -1°C and 2°C will maintain better quality and more than double the shelf life. -18°C is the minimum required storage temperature for frozen fish. Storage at -27°C or lower maintains quality for 1-2 years (CDC 2014). The temperature for preservation has to be maintained at all times. Different types of produce will require different storage regimes. After the fish or plants have been harvested, the produce should be kept at the appropriate temperature in order to slow or stop the growth of harmful bacteria. The 'cold chain' starts at harvest and ends with the consumer (Lee *et al.* 2015). One should store food packaging materials separately from chemicals and cleaning, disinfecting, and plant protecting products.

Traceability

Good record-keeping allows the possibility of tracing (both forwards and backwards) any possible source of contamination, or of finding the origin and cause of problems in the food chain. Therefore the aquaponic producer should ensure that record-keeping systems are in place so that traceability can be guaranteed (Copa – Cogeca 2018).

RECORDS ON PLANT PRODUCTION:	RECORDS ON ANIMAL PRODUCTION:
• use of any plant protection products and biocides (product, application date, quantity, application method) • any cases of pests or disease that may affect the safety of products of plant origin (type of pest or disease, date, measures taken) • the results of any relevant analyses carried out on samples taken from the plants or other samples that are significant to human health (results, type of sample, location if appropriate, analysing laboratory, date)	• the nature and origin of the feed given to the animals (feedstuff, quantity, date) • veterinary medicinal products or other treatments administered to the animals (product used, date of administration, withdrawal period[3]) • cases of diseases that may affect the safety of products of animal origin (type of pest or disease, date, measures taken) • the results of any analyses carried out on samples taken from the animals or other samples taken for diagnostic purposes, that are significant to human health (results, type of sample, location if appropriate, analysing lab, date) • any relevant reports on checks carried out on animals or products of animal origin

The produce containers have to be labelled if the produce is sold to mass caterers and/or to final consumers. Where foods are offered for sale to the final consumer or to mass caterers without pre-packaging, but prepared for direct sale at the aquaponic unit, the following information is mandatory:

- The name of the food (for fish both the commercial and scientific names must be displayed)
- Any allergens present (any ingredient or processing aid listed in Annex II of Regulation 1169/2011 causing allergies or intolerances used in the manufacture or preparation and still present in the finished product). **Note:** Not required when the food name clearly refers to allergen(s) e.g. fish
- ‘Best before’ or the ‘use by’ dates should be displayed on all non-prepacked products
- Date of catch/harvest (voluntary information). The date of catch / harvest can be considered as a lot or batch. ‘Lot’ or ‘batch’ are useful for traceability in case of a necessary product recall
- A statement advising consumers to *‘rinse before eating or serving’* is recommended for plant produce (voluntary information)

Mandatory information for farmed fish (aquaculture) is also:

- Production method
- Country of production

[3] Withdrawal period refers to the minimum period of time from administering the last dose of medication and the production of animal-derived products for food

How to label your produce?

- *On the product*. If possible, the information should be presented in a label either on the packaging, attached to the packaging, or visible through the packaging
- *On a notice*. The information can be presented on a notice in close proximity to the produce or on the shelf edge
- *Verbally*. In the case of allergen information only, you can give the customer the information verbally. You must place a notice in close proximity to the produce (or on the produce itself) inviting customers to ask a member of staff for allergen information – for example, *'Please ask us about allergens in our food'*

Commission Regulation (EC) No 710/2009 (Organic Aquaculture Regulation) lays down detailed rules governing practices in the production of aquaculture products which can be labelled as organic.

Food contact materials

Food contact materials (FCM) are either intended to be brought into contact with food, are already in contact with food, or can reasonably be brought into contact with food or transfer their constituents to the food under normal or foreseeable use. Examples include:

- containers for transporting food
- machinery to process food
- packaging materials
- kitchenware and tableware

The safety of FCM is tested by the business operators placing them on the market, and by the competent authorities during official controls. Any material or article intended to come into contact with food should be sufficiently inert to preclude substances being transferred to food in quantities large enough to endanger human health or to bring about an unacceptable change in the composition or a deterioration in the organoleptic properties of the food. There is a wide range of FCM types, the most common being:

- Ceramics
- Cork
- Glass
- Metal and alloys
- Paper and cardboard
- Regenerated cellulose
- Rubber
- Silicone
- Wood

The international symbol for material appropriate for contact with food (Figure 7) generally assures that the material surface is free of any toxic contaminants from the manufacturing process and that the material will not potentially become a source of toxic contamination through usage.

Figure 7: international symbol for material appropriate for contact with food
(Source: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:338:0004:0017:DE:PDF)

10.3.7 Cleaning and sanitation

Cleanliness is a key requirement applying to personnel, the facility, and equipment. For the latter two, good conditions must continually be maintained. Harvest tools, cutting utensils, and produce contact surfaces have to be kept clean.

HUMAN HEALTH

If you don't keep the environment clean (especially surfaces coming into contact with plants and fish after the harvest), you will more than likely be harvesting produce that isn't clean or healthy

PLANT HEALTH

If you don't keep your grow room clean, you are opening up pathways for disease and fungal pathogens

FISH HEALTH

If you don't keep your fish tanks clean, you are opening up pathways for fish disease and pathogens

Chemicals used for cleaning and sanitising must be used according to their instructions and always stored away from areas where food or feed is produced, stored or handled. Chemicals in their original packaging and those transferred to smaller units should always be labelled (readable, unmistakeable, waterproof) with at least the following information: name, date, concentration.

The aquaponic producer has to make sure that **tools** are cleaned before and after each use, and ensure that any cleaning supplies such as brooms and mops are specifically designated to the aquaponic unit. If there are multiple systems the cleaning equipment (brushes, sponges, cloths, water sampling pots, etc.) should be separated for each system, with colour-coded labelling (Figure 8a).

Figure 8: Cleaning tools separated for each line with colour coding system (a) and stored away from the aquaponic unit with cleaning agents in the closed closet (b) at ZHAW, Institute of Natural Resource Sciences (Photo: Andrej Ovca)

IMPORTANT!

- Make sure you use food-grade chemicals

- Wear eye protection and gloves when you are handling harsh chemicals

Cleaning process

The surfaces cleaned should include hydroponic channels, fish tanks, sides of greenhouses, pathways, etc. It is recommended to prepare the cleaning schedule where the following information is defined:

- What is to be cleaned?
- How?
- When/how?
- Who is cleaning?

What to clean?

Surfaces can be divided into different zones (Bihn *et al.* 2014), for example:

- Zone 1: Direct food contact surfaces (sorting tables, racks, utensils, harvest/storage bins)
- Zone 2: Non-food contact surfaces that are in close proximity to the produce (internal and external parts of washing or processing equipment, housing, framework)
- Zone 3: Areas inside the aquaponic unit such as trash cans, floors, drains, restrooms, forklifts)
- Zone 4: Areas outside of the aquaponic unit

How to clean?

One should always begin the cleaning process in zone 1 and finish in zone 4. Additionally, the cleaning should always start at the top and continue downwards, sweeping and mopping the floors at the end.

- Step 1: The surface should be rinsed so any obvious dirt and debris are removed. All biological matter (plants, algae, etc.) should be removed before further cleaning procedures
- Step 2: Detergent/cleaning agent should be applied and the surface scrubbed
- Step 3: The surface should be rinsed with potable water
- Step 4: An appropriate disinfection agent should be applied if needed. If the disinfection agent requires a final rinse, this will require an extra step
- Step 5: The surface should be left to air dry

After the fish have been removed from the system, it should be drained and the tanks cleaned properly using a high-pressure hose. Using a high-pressure hot water unit with detergent is a good way to clean and sanitise surfaces too. All the equipment (nets, buckets, etc.) coming into contact with the system water must be disinfected. **Note**: After harvest the rafts should be cleaned but not disinfected, and left to dry so as to avoid killing the nitrifying bacteria on the submerged surface of the raft. Cutting boards and knives should be washed with soap in hot water before cutting produce. All soap should be rinsed under running water and dried as necessary with a single-use paper towel. Cutters may also be routinely cleaned using a disinfecting solution such as bleach, alcohol, or other commercial product.

How to disinfect?

Aquaponics producers should always follow the labelling on a product and wear the proper protective gear. Different agents can be used for disinfection. Chlorine bleach, mixed to a 10 percent solution and allowed to stand for five minutes, is very effective at killing disease pathogens (Moran 2013). Other types of products are those containing quaternary ammonium, which are less volatile and more stable than bleach, and are mostly recommended for metal surfaces. Chlorine dioxide is a gas, so it can penetrate and infiltrate greenhouse nooks and crannies far better than liquid products. Vinegar is another disinfectant (Godfrey 2015). Concentrated peroxyacetic acid (max. 15 ml per 3 m^3 of fish tank water) can be used for disinfecting drum filters and also for removing any limestone which has formed on the mesh. Care must be taken that the acid does not get into the biofilter and the fish tank all at once. **Important**: Disinfection should only ever be done by properly trained personnel.

How often to clean?

- Debris and standing water should be removed daily for worker safety as well as to minimize the risk of attracting pests. The removal of all plant debris, including the roots, at the end of each harvest helps to reduce the incidence of pests and diseases
- The floor of the system should be cleaned once a week (spider webs, fish feed, etc.) with a broom and, if necessary, with the wet cloth
- Pumps and drum filters should be cleaned at least once every 2 months

- Once or twice a year the fish tanks should be scrubbed to remove algae and biofilm from the walls.

10.3.8 Animal and pest control

Pest control was already addressed in Chapter 8 (Integrated Pest Management), so only the key points will be addressed here. Pests and wild animals such as birds, vermin and insects, and domestic animals (dogs, cats, etc.) can be a source of food contamination and can also act as a vector for infectious diseases. The aquaponic producer should take steps to prevent pests from contaminating produce directly, and any equipment and other materials coming into contact with produce. Wildlife/pest exclusion is also needed to prevent fish and vegetables from being predated by wildlife (Aquaponics Association 2015). Vermin, wildlife, and pets should be excluded or minimised in the general area where the greenhouse is located. Birds can be prevented from contaminating the system by using netting and deterrents.

The greenhouse doors should be kept closed most of the time, and waste removed from the facility surroundings. Visual inspection of pest presence should be in place, and any corrective measures taken if signs of pests are detected. The improper or illegal use of chemicals to control pests can result in hazards to human health. The best practice is to net all production systems. Netted systems severely restrict any warm-blooded animal access. To prevent rodents in the greenhouse, mousetraps should be used and checked 3-4 times per week, especially in autumn and winter when the chances of them appearing are higher. If produce is sold to consumers and/or food business operators, the mousetraps should be installed by a registered and competent authority which should also take care of any animals captured. Insect lamps should be checked and cleaned.

10.3.9 Waste and hazardous substances

Veterinary products and chemicals (plant protection products, biocides, cleaning agents, etc.) should be stored according to the guidance provided by the manufacturer and away from any areas where food production, storage and handling is carried out.

Table 3: Measures to prevent risk from veterinary products, chemicals, waste and waste water (Copa – Cogeca 2018)

VETERINARY PRODUCTS	• Only authorised products should be used and over-dosage avoided. Veterinary treatments should always be administered in accordance with the guidance provided by the manufacturer • Veterinary products that have passed their expiry date should not be used • After the application of veterinary treatments of medicated feed, the waiting period should be respected to avoid the possible presence of chemical residues. Animal goods produced during this period should never be destined for human consumption. They should instead be disposed of according to national rules or put to alternative uses authorised in your country • Unused veterinary medicines and their containers should be disposed of according to the requirements laid down by your national authority. As far as possible aquaponic producers should prevent medicines from

	entering the environment, as resistance problems may emerge
CHEMICALS	• Only authorised chemicals should be used and the instructions of the manufacturer followed • Where necessary, the waiting periods established by the manufacturer should be respected in order to avoid any possible contamination of animals • Unused chemicals and their containers should be disposed of according to national rules
WASTE	• Waste like lubricants, litter, broken glass, batteries, etc. should be stored in closed containers, vessels or crates, free from humidity, inaccessible to rodents, and avoiding all possibilities of water, food or feed contamination • Dead animals, waste and other by-products not destined for human consumption should be rapidly removed from the facility in a way which avoids contaminating food • Containers are to be of an appropriate construction, kept in sound condition, be easy to clean and, where necessary, to disinfect (closable containers)
WASTE WATER	• It is best to apply 'used' fish effluent water to soil. It can be used to irrigate and fertilize grassy areas or plants. Fish tank water should not be put directly into a stream, sewer, irrigation ditch, or reservoir, because small fish or other aquatic life forms might be released into the environment

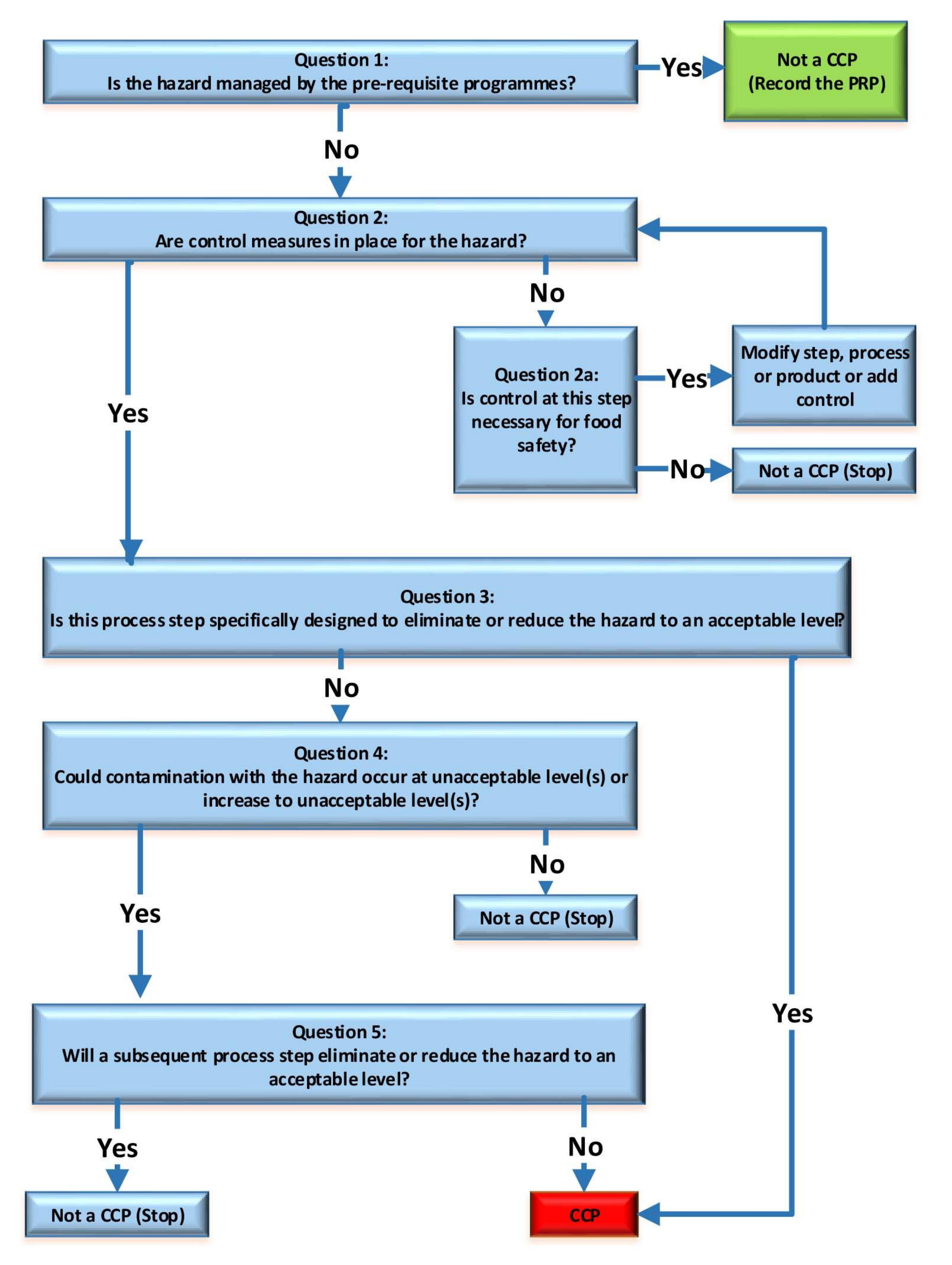
10.4 HACCP system

Food safety management consisting of prerequisite programmes (GAP and GHP) and upgraded with a HACCP (Hazard analysis and critical control points) system is a roadmap for aquaponic producers for reducing the risks that may jeopardize product safety. A comprehensive HACCP plan describes procedures for all aspects of production and processing. It also provides a structure for assessing an operation, and serves as a reference for workers during training. Because a HACCP system always has to be adapted to each individual set-up, a generic approach is presented in Table 4.

If they are selling produce to the final consumer or other food business operators, the aquaponic producer should check the efficiency of the food safety management system by sampling and analysing the final produce/product. For this purpose, aquaponic producers should collaborate with an accredited laboratory performing microbiological analysis of the final products at least once per year. Beside food products, food contact surfaces can also be sampled and analysed. Additionally, chemical analyses of residues are also recommended.

Table 4: Generic approach for establishing a HACCP plan

<table>
<tr><th>STEP</th><th>DESCRIPTION</th></tr>
<tr><td>PRODUCT DESCRIPTION</td><td>In brief, the product description should include the name of the product, its potential to support microbial growth, appropriate packaging, and intended use, including target population. It is important, for example, to take into consideration whether sensitive segments of the population may consume the product (i.e. elderly, immune-suppressed, pregnant women and infants)</td></tr>
<tr><td>FLOW CHART</td><td>It is easier to identify routes of potential contamination and suggest methods of control if there is a flow diagram. The review of the flow from the point at which materials enter the system, through harvesting and processing, is the feature that makes a food safety management system a specific and important tool for the identification and control of potential hazards. The process flow diagram helps to identify the important process steps. Each process step should be considered in detail and the information expanded to include all relevant process data</td></tr>
<tr><td>HAZARD ANALYSIS</td><td>After listing all the hazards that may be reasonably expected, the potential risk of each hazard at each step of the process should be assessed by considering its likelihood of occurrence and severity using the following model:
<table>
<tr><th>Frequency</th><th>A</th><th>B</th><th>C</th><th>D</th><th>E</th></tr>
<tr><td>Consequence</td><td>Common</td><td>Known to occur (Published)</td><td>Could occur</td><td>Not expected to occur</td><td>Practically impossible to occur</td></tr>
<tr><td>(1) Fatality</td><td>1</td><td>2</td><td>4</td><td>7</td><td>11</td></tr>
<tr><td>(2) Serious illness</td><td>3</td><td>5</td><td>8</td><td>12</td><td>16</td></tr>
<tr><td>(3) Product recall</td><td>6</td><td>9</td><td>13</td><td>17</td><td>20</td></tr>
<tr><td>(4) Customer complaint</td><td>10</td><td>14</td><td>18</td><td>21</td><td>23</td></tr>
<tr><td>(5) Insignificant</td><td>15</td><td>19</td><td>22</td><td>24</td><td>25</td></tr>
</table>
The estimate of the risk of a hazard occurring is based upon a combination of experience and information in the literature. Severity is the degree of seriousness of the consequences of a hazard if the hazard is not controlled. Hazards may have already been addressed through good agricultural practice (GAP) and good hygiene practice (GHP)</td></tr>
<tr><td>CRITICAL CONTROL POINT (CCP)</td><td>A critical control point (CCP) is defined as 'a step at which control can be applied and is essential to prevent or eliminate a food safety hazard or reduce it to an acceptable level'. The determination of a CCP can be facilitated by the application of a decision tree (see below) which indicates a logical reasoning approach. The application of the decision tree should be flexible according to the type of the unit under analysis. It is important to stress that if the hazard/s are already managed by the pre-requisite programmes (GAP/GHP) then the step in the process is not classified as CCP</td></tr>
</table>



CRITICAL LIMITS	For each CCP determined in the previous step (if any, otherwise we stop at the previous step) critical limits have to be defined. Critical limits are defined as criteria that separate acceptability from unacceptability regarding the safety of your end product. Critical limits may be set for factors such as temperature, time (minimum time exposure), physical product dimensions, moisture level, etc. The critical limits should meet the requirements of regulations (if any) and/or internal standards. It is essential that the person responsible for establishing critical limits has knowledge of the process and of the legal and

	commercial standards required for the product. Sources of information on critical limits include: • Scientific publications/research data • Regulatory requirements and guidelines • Experimental studies If the information needed to establish critical limits is not available, a conservative value should be selected or regulatory limits used. Once the critical limits are established, they have to be recorded
MONITORING	Monitoring is *'the act of conducting a planned sequence of observations or measurements of control parameters to assess whether a CCP is under control'.* Monitoring is the scheduled measurement or observation of a CCP relative to its critical limits. The monitoring procedures must be able to detect loss of control at the CCP. The monitoring specifications for each CCP should give information on: • What will be monitored • How critical limits and preventive measures will be monitored • Frequency of monitoring • Who will monitor
CORRECTIVE ACTIONS	Corrective action is *'any action to be taken when the results of monitoring at the CCP indicate a loss of control'.* The diversity of possible deviations at each CCP means that more than one corrective action may be necessary. When a deviation occurs, it will most likely be noticed during the routine monitoring of the CCP. The deviation procedures at each CCP should be recorded. Corrective action procedures are necessary to determine the cause of the problem, take action to prevent recurrence, and follow up with monitoring and reassessment to ensure that the action taken is effective. If the corrective action does not address the root cause of the deviation, the deviation could recur
DOCUMENTATION	Records are essential for reviewing the adherence of the HACCP system to the HACCP plan. A record shows the process history, the monitoring, the deviations and the corrective actions that occurred at the identified CCP. It may be in any form, e.g. processing chart, written record, computerized record. Three types of records should be kept as part of the HACCP programme: • Support documentation for developing the HACCP plan (e.g. product description, flow diagram, hazard analysis, identification of CCPs) • Records generated by the HACCP system (monitoring records for all CCPs, deviation and corrective action records) • Documentation of methods and procedures used

10.5 References

Aquaponics Association 2015. *Provisional GAPs for leafy greens and fruiting crops in commercial aquaponics*.

Barnhart, C., Hayes, L. & Ringle, D. 2015. *Food Safety Hazards Associated with Smooth-Textured Leafy Greens Produced in Aquaponic, Hydroponic, and Soil-based Systems with and without Roots in Retail*. Minneapolis: University of Minnesota Aquaponics.

Bihn, E.A., Schermann, M.A., Wszelaki, A.L., Wall, G.L., & Amundson, S.K. 2014. *On-Farm Decision Tree Project: Sanitation and Postharvest Handling*. National Good Agricultural Practices Programme, Cornell College of Agriculture and Life Sciences.

CDC 2014. *Fish Cooking and Storage Temperatures*. BC Centre for Disease Control, British Columbia.

Chalmers, G.A. 2004. *Aquaponics and Food Safety*.

Copa – Cogeca 2018. *EU Guide to Good Hygiene Practice (GGHP) for the primary production of foodstuffs*. Copa – Cogeca European Farmers European Agri-Cooperatives, Brussels.

Deering, A.J., Mauer, L.J. & Pruitt, R.E. 2012. Internalization of E. coli O157:H7 and Salmonella spp. in plants: A review. *Food Research International* 45 (2), 567-575.

EC 2012. *The Common Agricultural Policy - A story to be continued*. Publications Office of the European Union, Luxembourg.

EC 2014. *Food Safety*. European Commission, Brussels.

EFSA & ECDC 2017. The European Union summary report on trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2016. *EFSA Journal* 15 (12), 5077.

FAO 2006. Glossary. Food and Agriculture Organization of the United Nations, Rome.

FAO 2014. *Small-scale Aquaponics Food Production: Integrated Fish and Plant Farming*. FAO Fisheries and Aquaculture Technical Paper 589. Food and Agriculture Organization of the United Nations, Rome.

Fox, B.K., Tamaru, C.S., Hollyer, J., Castro, L.F., Fonseca, J.M., Jay-Russell, M. & Low, T. 2012. *A Preliminary Study of Microbial Water Quality Related to Food Safety in Recirculating Aquaponic Fish and Vegetable Production Systems.* Food Safety and Technology 51. University of Hawaiʻi at Mānoa, College of Tropical Agriculture and Human Resources.

Gauthier, D.T. 2015. Bacterial zoonoses of fishes: A review and appraisal of evidence for linkages between fish and human infections. *The Veterinary Journal* 203 (21), 27-35.

Godfrey, M. 2015. *How to Sanitize and Sterilize Hydroponic Systems*. Upstart University.

Hoevenaars, K., Junge, R., Bardocz, T. & Leskovec, M. 2018. EU policies: New opportunities for aquaponics. *Ecocycles* 4 (1), 10-15.

Hollyer, J., Tamaru, C., Riggs, A., Klinger-Bowen, R., Howerton, R., Okimoto, D., Castro, L., Ron, T., Fox, B.K., Troegner, V. & Martinez, G. 2009. *On-Farm Food Safety: Aquaponics*. Food Safety and Technology 38. University of Hawaiʻi at Mānoa, College of Tropical Agriculture and Human Resources.

Joly, A., Junge, R. & Bardocz, T. 2015. Aquaponics business in Europe: some legal obstacles and solutions. *Ecocycles* 1 (2), 3-5.

Lee, J., Phelps, N., Driessen, S., Schermann, M. & Waters, K. 2015. *Keeping Aquaponics Products Safe*. University of Minnesota.

Ljubojević, D., Pelić, M., Radosavljević, V. & Ćirković, M. 2017. Food safety hazards related to fish produced in aquaponics. Conference paper, Aquaculture Europe 2017, Dubrovnik, Croatia.

Moran, N. 2013. Keep it clean. *Greenhouse Management* November 2013.

Moriarty, M.J., Semmens, K., Bissonnette, G.K. & Jaczynski, J. 2018. Inactivation with UV-radiation and internalization assessment of coliforms and *Escherichia coli* in aquaponically grown lettuce. LWT - *Food Science and Technology* 89, 624–630.

Raspor, P. & Jevšnik, M. 2008. Good nutritional practice from producer to consumer. *Critical Reviews in Food Science and Nutrition* 48 (3), 276-292.

WHO & FAO 2009. *Food Hygiene: Basic Texts* (4th edition) World Health Organization / Food and Agriculture Organization of the United Nations, Rome.

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11. SCIENTIFIC RESEARCH METHODS

11.1 What is science, what is research? Basic terms

11.1.1 General definitions

Science

The word 'science' comes from the Latin word *scientia*, which means knowledge. Science refers to systematic and organized knowledge in any area of investigation that has been obtained using the 'the scientific method'. The scientific method is the best method we have, to obtain reliable data about the world, which helps both to explain and predict different phenomena. Science is based on observable and measurable things/phenomena. However, there is no absolute scientific truth; it is just that some knowledge is less likely to be wrong than others (Nayak & Singh 2015). Statements produced through scientific research must be testable, and research by itself must be reproducible (a good scientific paper is one which enables the method to be replicated).

Research

Research is defined as a scientific and systematic search for relevant information on a particular issue. In that case the term 'research' refers to the systematic method that includes articulating the problem, formulating a hypothesis, gathering the facts or data, analysing them, and drawing certain conclusions, either as a solution(s) to the investigated problem or as generalisations for some theoretical formulation. Research is termed 'scientific research' if it contributes to the pool of science and follows the scientific method.

Generally, research can be divided into two groups:

- *Basic research:* the main goal is to acquire an organized body of scientific knowledge and not necessarily to generate results with direct practical impact. Basic research is about fundamental properties of objects, their relationship and their behaviour, which includes theoretical and experimental research.
- *Applied research:* the main goal is to solve practical problems and the goal of contributing to the pool of scientific knowledge is secondary. Applied research is focused on the usefulness of objects and their behaviour, and improvements of technology.

11.1.2 Research vocabulary

Variables and levels of measurements

A variable is a measurable characteristic of an abstract construct. A variable is something that can have more than one value and can vary from negative to positive, from low to high, etc. It is the opposite of a constant. The values of a variable can be words (e.g. gender) or numbers (e.g. temperature). Constructs by themselves cannot be measured directly; therefore, scientists need to find substitute measures called variables. For example, water quality is often measured as nitrate and orthophosphate concentrations and chemical oxygen demand, which are different parameters gained from analytical laboratory procedures done on a water sample. In this case, water quality is a construct, and nitrate and orthophosphate concentrations and chemical oxygen demand are the variables that measure it.

Variables that describe other variables are termed **independent variables**, while variables that are described by other variables are **dependent variables**. In a research experiment there may be other variables that are not relevant for studying a selected dependent variable but which could have some impact on it. These variables must be controlled throughout the experiment and are termed **control variables** (e.g. pH and oxygen concentration in the case of water quality). In research we want to select specific variables and search for relations among them; moreover, we aim to understand if and how variation in one variable affects variation in another.

Different variables have different **levels of measurement** in ascending order: nominal, ordinal, interval, and ratio. For research it is important to always select variables with the highest level of measurement (Nayak & Singh 2015):

- **Nominal level of measurement:** the values at this level include a list of names/words. Naming values is a qualitative measurement (e.g. vegetable species or varieties, colour of leaves). It is also possible to substitute the names of values with numbers (e.g. 1 for Boston Bibb, 2 for Red Leaf, 3 for Iceberg etc.); however, in this case the numbers only mean a different type of name, and do not make the variable quantitative. Giving numbers to characteristics facilitates statistical analyses of qualitative data. The statistical analysis of central tendency of nominal measurements is mode; mean or median cannot be defined (it is not possible to calculate an average sex or colour). Appropriate statistical analyses are chi-square and frequency distribution, and a one-to-one (equality) transformation (e.g. 1=green, 2=yellow, 3=red).

- **Ordinal level of measurement:** the values at this level can be ordered in ranks. All variables measured as high, medium, or low (e.g. yellowing of plant leaves), or as scales of opinion (strongly agree / agree / neutral / disagree / strongly disagree) are ordinal. Ordinal scales provide data about less and more – e.g. strongly agree is more than agree; however what ordinal variables do not tell us is *how much* more. The central tendency measure of an ordinal scale can be defined as median or mode, while mean cannot be interpreted. Appropriate statistical analyses are percentiles and non-parametric analysis, and monotonically increasing transformation (which retains the ranking); nevertheless, more sophisticated analyses like correlation, regression, and analysis of variance, are not suitable.

- **Interval level of measurement:** the values at this level have all the properties of nominal and ordinal variables; additionally, the distances between the observations are meaningful. Interval level of measurement is **quantitative measurement**. The measured values are not only ordered in ranks, but the distance between adjacent attributes on a scale is always the same; for example, the temperature scale in Celsius, where the difference between 30 and 40 degrees is the same as that between 80 and 90 degrees. Interval scale enables us to describe how much more, or how much less, one measurement is compared to another, which is not the case with nominal or ordinal scales. The central tendency measures can be mean, median, or mode. Measures of dispersion, such as range and standard deviation, are also possible. Appropriate statistical analyses include all of the methods suitable for nominal and ordinal scales, as well as correlation, regression, and analysis of variance. Scale transformation should be positive linear.

- **Ratio level of measurement:** in addition to having equal intervals, the observations can have a value of zero as well, meaning the absence of the phenomenon being measured. Ratio scales have all the characteristics of nominal, ordinal, and interval scales, as well as a 'true zero' point. Most measurements in the natural sciences and engineering, such as mass, volume, concentrations of compounds, and electric charge, are ratio scales. All statistical methods and transformations are suitable.

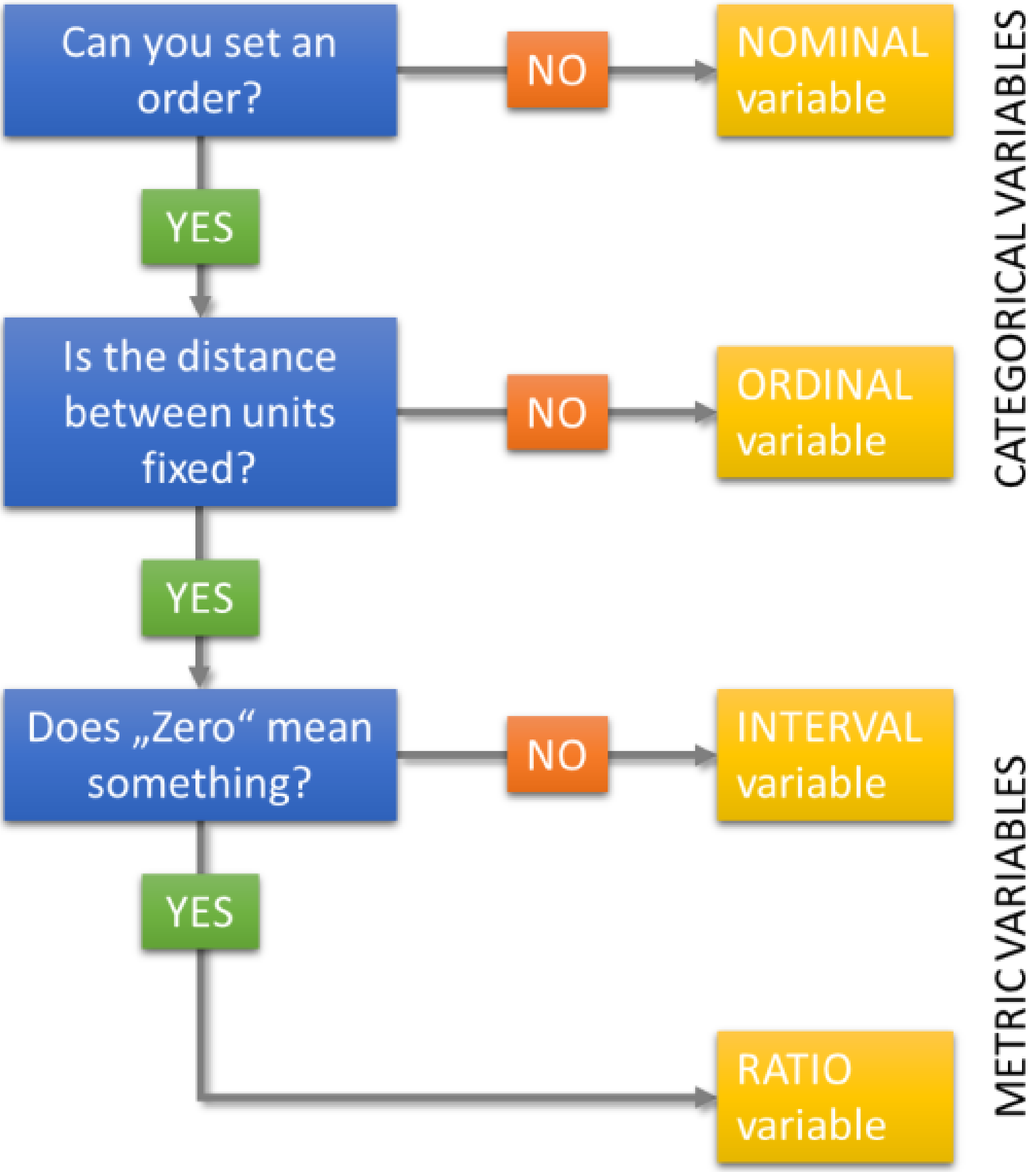

Figure 1: Levels of measurement

Validity, Reliability, Accuracy, and Precision

Validity is the quality of being legally or officially binding or acceptable. The validity of instruments, data, and findings is the most important requirement in research. It refers to their accuracy and trustworthiness. The validity of the data depends on the validity of the instruments; however, assuming that the instruments and data are valid, the validity of the findings and conclusions can still be questioned (Nayak & Singh 2015).

Reliability is the quality of performing consistently well. Reliability shows if it is possible to get the same result by using an instrument to measure a variable more than once. Instruments can be laboratory devices, scales, or they can be questions given to a group of people.

Precision refers to the number of decimals in a numerical result of a measurement.

Accuracy is the degree to which the result of a measurement, calculation, or specification conforms to the correct value or a standard. Accuracy refers to the level of precision of the scale.

11.2 Fundamentals of scientific research methodology

Research methodology is a discipline of scientific procedures. It includes theory, analysis and guidelines for how research should proceed: how research should be conducted and the principles, procedures, and practices that direct research. Research methodology is the specific set of procedures or techniques used to identify, select, process, and analyse information about a topic. Since methodology can differ between different disciplines, therefore there is an assortment of different research methodologies which may not be appropriate for all research problems (Nayak and Singh 2015). Methodology should not be confused with scientific methods, which mean ways or techniques for gathering information/results. Scientific methods describe the way in which scientific knowledge is gained. In a research paper, the materials and methods section allows the reader to critically evaluate a study's overall validity and reliability, because it states how the data were collected or generated, and how they were analysed. The following is an example of a research methodology:

1. Observe and question: selection and definition of the research problem
2. Review of the related literature
3. Formulation of hypothesis
4. Preparation of the research design, including sampling plan and selection of the tools for data collection
5. Execution of the research plan: gathering the data
6. Processing the data
7. Report, including supporting or rejecting the hypothesis

11.2.1 Research designs

A research design is a blueprint for empirical research that includes planning, organizing and directing the research, including definition of the research problem, research questions, and objectives. It outlines how the research study will be carried out; therefore, it includes a thorough plan for data acquisition, definition of instruments used, and procedures for sampling and monitoring, in order to resolve specific research questions or to test a specific hypothesis. Research designs can be grouped into two categories:

- Survey research design
- Experimental research design

Survey research design

Surveys are mainly used in the social sciences. In surveys the data are collected from a pre-defined test group to gain information and understandings on various topics of interest. There are three different types of surveys according to their purpose: exploratory, descriptive, and explanatory studies (Nayak & Singh 2015).

Exploratory study or research usually starts with reviewing available data, or qualitative methods such as informal discussions, in-depth interviews, focus groups, and case studies; therefore, the data collected are qualitative. The data are then quantified and assumptions are drawn. Exploratory research cannot be generalized to the whole population. The results of the exploratory research cannot lead to firm conclusions, but they can enable important understanding of a given situation. The purpose of exploratory study is to frame a problem for a more exact investigation or to form hypotheses. Exploratory research studies therefore do not have hypotheses. Exploratory research design is used when little is known about the phenomenon and when earlier theories have failed to clarify it.

Descriptive study describes as exactly as possible the connection between the characteristics of a population and the studied phenomenon. It cannot describe what caused the situation, just what the characteristics are. Descriptive study is usually done after a survey and prior to explanatory study, so it is used when there is already some knowledge about a phenomenon, but we want to know more about it. Descriptive research studies therefore have hypotheses.

Explanatory study: When there is a known phenomenon that is sufficiently described, research proceeds by finding out the causes and reasons for it. The aim of explanatory research studies is to explain 'why'. It goes beyond describing the problem and characteristics of the phenomenon, and aims to explain the causes and effects.

Experimental research design

Experimental research design is most common in environmental science. It is a real **experiment**, in which a researcher manipulates one variable and controls the other variables. Experimental research design provides evidence which contributes to a greater validity of the research. Experimental research always has a control group and a test group, in which a selected variable is manipulated (only one at a time), while extraneous variables are controlled. Experimental studies test a causal hypothesis, which refers to a causal relation between two variables where variable X (the cause) determines variable Y (the effect). Experimental studies thus aim to examine cause-effect relations (hypotheses) in strictly controlled conditions by separating the cause from the effect in time, exposing one group to the cause (the test or treatment group) while not exposing another group (the control group), and observing how the effects vary between these two groups. The main strong point of experimental design is the solid validity reached by isolation, control, and intensive examination of a small number of variables, while the main weakness is limited outward generalizability because situations in real life are frequently more complex and may include more extraneous variables than in artificial laboratory or field settings. Besides this, the researcher should identify all relevant extraneous variables and control them, otherwise the internal validity may be reduced, and false correlations may appear. The experiments can be carried out in a laboratory or in the field. Both ways have pros and cons. Laboratory experiments enable isolation of the target variables and control for the extraneous variables, which might not be the case in experiments in the field. Because of this, extrapolations made from laboratory experiments have a tendency to be stronger in internal validity, while those from field experiments tend to be stronger in external validity. Experimental data are processed by quantitative statistical methods (Nayak & Singh 2015).

11.2.2 Preliminary steps

Problem formulation

The first and most important step in research design is forming a problem. The problem should be identified and investigated. The problem cannot be explained successfully if a researcher does not have proper knowledge and understanding of specific issues causing or creating the problem. There are some main steps to follow when forming a problem (summarized by Nayak and Singh 2015):

1. Define a research field
2. The research field has to be well-known to the researcher carrying out the research (a specialist in the field)
3. Review previous research conducted in the area in order to be familiar with recent findings
4. Set the field of study, based on this review
5. Identify the problem in general
6. Identify the specific feature of the problem which is to be examined, and form a problem statement

A problem statement is an abstract of a problem formulation. It is important for further research design. Good problem statements focus on the relationship between two or more variables, are stated clearly and explicitly in a question form, can be tested empirically, and are not morally or ethically questionable.

Literature review

Following problem formulation, a systematic and detailed search of all types of scientific and expert literature referring to the research topic has to be executed with the aim of identifying a range of good quality references. The majority of the references should originate from peer-reviewed academic literature; however, other sources may also be relevant (legislation, publications of international organizations such as WHO and FAO, oral sources, etc.). The main academic literature consists of books, articles, journals, conference proceedings, research reports, databases, theses, and dissertations. After gathering all the information, a detailed review of the academic literature and a critical discussion of current knowledge have to be carried out. This is an important foundation for the success of the research project. The literature review gathers together the main theories and findings in the research area, identifies key authors, and highlights the gaps in knowledge that need to be focused on.

Nowadays literature review is mainly done with online searches in different databases. It is important to select appropriate keywords that can also be combined together using 'and' and 'or' to refine or specify the search results. Electronic journals and articles are the most up-to-date resources available. The papers can be published online as soon as they have been edited, with no need to wait for there to be enough papers to form the whole journal issue. This is of special importance in rapidly evolving fields (Nayak & Singh 2015). Some electronic resources are free ('open access'). However, most have to be paid for. It is possible to purchase papers online as an individual researcher; however usually universities, libraries and other education institutions have paid subscriptions for different databases and their employees or members can access them for free. The most common academic databases and search engines are:

- ScienceDirect is a leading full-text scientific database that includes journal articles from more than 2,500 journals and book chapters from almost 20,000 books
- SpringerLink is the most comprehensive online collection of scientific, technological and medical journals, books and reference works
- Google Scholar is a free search engine that catalogues academic information from various online web resources. It gathers information across a range of academic resources that are generally peer-reviewed. It is one of the most extensively used academic resources for researchers
- Web of Science is a scientific citation indexing service for subscribed customers that provides a comprehensive citation search. It gives access to numerous databases
- Mendeley research catalogue is a crowdsourced database of research documents. Researchers have uploaded nearly 100M documents into the catalogue with additional contributions coming directly from different repositories
- PubMed is a database primarily of references and abstracts on life sciences and biomedical topics
- Scopus is the world's largest abstract and citation database of peer-reviewed research literature. It contains over 20,500 titles from more than 5,000 international publishers. While it is a subscription product, authors can review and update their profiles via ORCID or by first searching for their profile at the free Scopus author lookup page

When preparing a literature review it is important to keep a database of the references, which can be used for making notes on the key points in each source (Nayak & Singh 2015). There are some software packages that enable the creation and organization of a personal database of scientific papers and the formation of citations when writing a scientific report. A database can be organized or browsed by authors, journals, date and other characteristics of the papers, or according to the topic, relevance, read/not read, favourites, etc. Particularly useful software packages for reference management are EndNote, Mendeley and RefWorks.

When a list of relevant articles is created, it is then necessary to peruse each article, or at least its abstract, to decide whether the article is suitable for a detailed review. Literature review should be comprehensive and not limited to a few papers, a few years, or a specific methodology. A literature review should examine if the primary research questions have previously been investigated, and what the outcomes were (in this case it should be explained why it is important to study them again), if there are novel or different research questions appearing, and if the primary research questions should be adapted or changed according to the findings from the literature. The literature review may also offer possible answers to the research questions, or help to identify theories that have formerly been used to discuss comparable questions (Nayak & Singh 2015).

A literature review is a well-structured and reasoned evaluative report of previous studies related to the research topic. The review provides description, evaluation and critique of this literature. It provides a theoretical foundation for the research and helps to determine its main characteristics. A literature review is more than gathering of information; it also comprises the identification of the relationship between the literature and the research topic.

Objectives of the study

In contrast to problem formulation, which describes the aim of the research, the objectives offer a definition of specific actions that will be taken to reach this aim. They describe what we expect to achieve by carrying out the research. There can be an overall objective followed by a list of specific objectives. The overall objective describes how we plan to address the problem: e.g. we need to find the answer to problem A by implementing action B. The specific objectives then describe action B in more detail. There are typically two to four specific objectives. Objectives thus explain how we are going to answer the research question. It is therefore a prerequisite that the research question is clear. Objectives usually begin with words such as: to identify, to establish, to describe, to determine, to estimate, to develop, to compare, to analyse, to collect, etc. (Nayak & Singh 2015). Good research objectives should be:

- brief and precise
- listed in a logical order as one objective may refer to another
- realistic, meaning that it is possible to achieve them within the given timeframe and available resources
- expressed in operative terms
- unchanged from the beginning of the study (they should not be moving targets)

Hypothesis

A hypothesis suggests a solution to the problem that is going to be empirically tested during the research and at the end it will be rejected or supported according to the observed results. The hypothesis is a guess or a proposal for generalisation (Nayak & Singh 2015). The hypothesis can be developed through analogy, induction, deduction, or intuition. The most important characteristic of a hypothesis is that it must be falsifiable, meaning that it can be disproven.

Hypotheses should be strong, not weak. An example of a weak hypothesis is 'high concentrations of phosphorus are related to algae growth', because it doesn't indicate either the direction (i.e. if the relationship is positive or negative), nor the causality (i.e. if high concentrations of phosphorus cause algae growth, or if algae growth causes high phosphorus concentrations). A stronger hypothesis would be 'high concentrations of phosphorus are positively related to algae growth', which indicates the directionality but not the causality; and the strongest hypothesis would be 'high phosphorus concentrations stimulate algae growth', which postulates both the direction and the causality.

11.2.3 Protocol design

Protocol design is a written plan of the activities that have to be taken to sufficiently answer the stated research question. It includes choosing a research method for collecting data, and planning an appropriate sampling strategy to select a sample from the target population. The protocol should specify precisely:

1. the characteristics of the test system (plant and fish species or varieties, source of supply, number, body weight span, illumination type and strength, etc.)
2. detailed information on the experimental design, including a description of the chronological procedure of the study, all methods, materials and conditions, how many samples, what kind of samples, how many parallels, the dose levels and/or concentration(s), the type and frequency of analysis, measurements, observations and examinations to be performed, and the statistical methods to be used.

A **sample** is a smaller group of a population. The sample should represent the whole population in order to enable generalization of the outcomes from the research sample to the population as a whole. An appropriate sampling plan also provides a cost-effective use of research funds and appropriate research tempo, flexibility, and accuracy. There are two types of sampling (summarized by Nayak & Singh 2015): probability and non-probability sampling (Table 1). In probability sampling there is an equal chance for every subject or unit to be selected from the population, while in non-probability sampling all individuals in the population do not have an equal chance of being selected. This type of sampling is done when random sampling is impossible to do, when research has limited time, budget or workforce, or when the research does not aim at generalization to the whole population. In general non-probability sampling is more appropriate for the social sciences than for natural sciences. However, it can be used in a preliminary study to get some basic information about the population and to inform the kind of probability sampling to choose in an experiment. For example, we want to study the growth of lettuce in aquaponics, but we don't know if there are differences between the plants that grow on the edges of a raft and those that grow in the middle, so in a preliminary study we could take a few plants from the edge and a few from the middle (non-probability sampling), and measure them. If there are no differences between them, then simple random sampling can be used for the experiment, but if there are differences, then it would be better to use systematic random sampling or maybe even cluster sampling.

Table 1: Types of sampling

	Type	How the sample is gathered	Additional explanation
PROBABILITY SAMPLING	**Simple random**	By picking basic units in a way that each unit in the population has an equal chance of being picked	*A simple random sample does not have a sampling bias*
	Systematic random	By picking one unit randomly and picking additional units at uniform intervals until the required number of units is gained	*E.g. vegetables growing in a line and we pick every 5th vegetable*
	Stratified random	By independently picking an individual simple random sample from every single population stratum	*A population is divided into different strata (e.g. rafts or fish ponds) regarding specific characteristics or variables. The number of units we randomly pick from each stratum has to be aligned with the size of the stratum, since strata can be of different sizes; e.g. we may decide to pick 10% of units from each stratum*
	Cluster	A population is divided into clusters, and a sample is gathered by picking a few clusters by simple random sampling. The sample comprises a unit of randomly selected clusters	*The clusters are often made according to geographical/space units (e.g. all regions in a country; all rafts in aquaponics) while the analysis is done on randomly selected clusters (we randomly select the required number of whole rafts, which represents a sample)*
NON-PROBABILITY SAMPLING	**Convenience**	A sample is gathered from cases that are available for the study, i.e. ready to participate	
	Purposive	A sample is gathered from cases that have similar characteristics. The characteristics are selected in order to find answers to a specific question and can be most similar/dissimilar, most typical or critical. The prerequisite is that the researchers already know some characteristics of the population	*In contrast to stratified probability sampling where there is an equal chance to be selected for every unit in the same strata, in the case of purposive sampling the sample is non-randomly selected*
	Snowball	Is where existing study subjects recruit future	*The sample group is said to grow*

		subjects from among their acquaintances	*like a rolling snowball. Also called chain sampling, chain-referral sampling, referral sampling*
	Quota	Divides the population into different groups similar to strata in stratified sampling (e.g. age, gender)	*A proportional or disproportional number of units is non-randomly chosen from every group*

Besides selecting the appropriate type of sampling, sample size also has to be defined. The sample size depends on the characteristics of a population, mainly how heterogeneous it is. Besides this, the sample size is also related to the number of variables we want to analyse, the statistical procedures that we want to use, the desired precision, and the number of comparisons we want to make. On the other hand, sample size can also be limited by available time and funding.

There are several methods available to define the sample size to be used, including the Neyman-Pearson decision methodology or power analysis (Neyman & Pearson 1933). To estimate the sample size required we need an idea of the variance of the variable from the literature. The variance (and standard deviation) will depend on the variable considered and the species to be evaluated.

The **data** in natural sciences are mainly collected from observations and measurements using different laboratory and field instruments. Original records from the instruments and documentation, or their verified copies, which are the result of the original observations and activities, represent raw data. Raw data can be, for example, recorded data from automated instruments (e.g. O_2, pH, EC probes), microscopic pictures, single measurements from laboratory instruments (e.g. readings from spectrophotometers), photographs, hand written observations (e.g. fish and plant health), and data from analogue measurements (e.g. analogue thermometer, settleable solids measured in Imhoff tank). Raw data must be converted into a computer-readable, numeric format, such as in a spreadsheet or a text file, so that they can be analysed by computer programs like R or SPSS Statistics.

A **test system** or **unit of analysis** is any biological, chemical, or physical system, or their combination, to be used in a study. It is a most basic element of research. The unit of analysis may be an organism or its part (e.g. fish), a colony or collective (e.g. vegetables), or an object (e.g. filtering system) that is the target of the investigation. The unit of analysis has to be defined at the beginning of a protocol design as it affects the instruments used and procedures taken during the research. Besides this, the lowest level of unit should always be chosen (e.g. collect data from separate plant tissues, not the whole plant together).

A **test item** is an item that is the subject of a study and a **reference item** ('control item') is an item used to provide a control for comparison with the test item.

A **batch** is a specific quantity, or a portion of test items or reference items formed by a defined experiment cycle in a way that it is expected that all items will have a uniform characteristic (e.g. one batch is lettuce under the same lighting conditions and different batches represent different lighting conditions).

Most project proposals include a section on the ethical aspects of the scientific protocols to be used. This usually involves previous approval of the methods by an ethics committee at the home institution, which mostly considers aspects related to animal welfare, in this case fish welfare. Those committees ask a set of questions including the justification for the research, its impact on the animals, and how distress can be prevented. For a set of guidelines about ethics, animal welfare and proper sampling procedures, see the NC3Rs Experimental Design Assistant, whose main aim is to replace, refine, and reduce the number of animals used in experimentation. It is thought that in the near future, scientists will be able to get their procedures and protocols approved by target journals before publishing the results, and thus have a certain guarantee that their studies will be published. This movement is called pre-registration (Nosek *et al.* 2018), and is aimed at strengthening methodologies and scientific results across the board. Finally, many journals are now asking that the raw data and results of published studies be made available in online databases, for example using the Data Research Item on Research Gate.

Good Laboratory Practice (GLP) means a quality system referring to the organisational process and the conditions under which studies are planned, performed, monitored, recorded, archived and reported (OECD 1998).

Standard Operating Procedures (SOPs) are documented procedures which describe how to perform tests or activities normally not specified in detail in study plans or test guidelines. SOPs include:

1. maintaining the records including test and reference items characterisation, date of receipt, expiry date, quantities received and used in studies
2. identification of handling, sampling, and storage procedures in order that homogeneity and stability are guaranteed as far as possible and contamination is avoided
3. storage containers should be marked with identification information, expiry date, and specific storage instructions.

After deciding which subject to study, what to measure, and how to gather and analyse data, it is time to execute the research. Research execution also includes preliminary tests of the equipment, laboratory instruments, sampling and analyses. **Preliminary testing** is an important part of the research process since it enables the detection of potential problems in the research design and for the laboratory instruments used in the study to be checked so that they are reliable and provide valid measures. After preliminary testing the research design may be optimized and then the real research can be executed.

All data generated during the research should be recorded directly, promptly, accurately, and legibly in the **laboratory diary**. These entries should be signed and dated. In order to ensure traceability, a research project needs to have a unique identification, and all samples, specimens, data files etc. concerning the study should carry this same identification. Any change in the raw data should be made in a way that does not to delete the previous entry, the reason for any changes should be indicated, and the change needs to be dated, and signed by the individual who made it.

11.2.4 Analysis of results

Tables and figures

Tables and figures are the quickest way to communicate large amounts of complex information. They have to be designed carefully. A good table or figure should present the data simply, clearly, and neatly, and allow the reader to understand the results without having to look at other sections of the paper; i.e. tables and figures should be self-explanatory and understandable even when they are taken out of the text; therefore, clear and informative titles are crucial. A good figure (graph or picture) should have:

- only the necessary information
- large enough lettering
- a frame
- a legend that explains everything necessary
- a graphical format in a high resolution (>300 dpi)

A good table should have:

- **a separate cell for each value**
- **only horizontal line borders**
- values with a reasonable number of digits after a decimal point

Larger tables are published in supplements to scientific papers.

In order to report the results, valid and internationally recognized units of measurements must be used. In science, industry and medicine the International System of Units (abbreviated SI) is used. In some geographic locations (e.g. United States) the imperial system is used, which includes units such as gallons, feet, miles, pounds and ppm. This system is not appropriate for international scientific publications. The SI system includes seven base units (Table 1).

Table 1: Seven base units of the International System of Units

Quantity	**Unit**	**Symbol**
Mass	kilogram	kg
Time	second	s
Temperature	kelvin	K
Electric current	ampere	A
The amount of a substance	mole	mol
Luminous intensity	candela	cd
Distance	meter	m

The most important methodological choice researchers make is based on the distinction between qualitative and quantitative data. Qualitative data take the form of descriptions based on language or images, while quantitative data take the form of numbers. The choice of which methodology to use will depend on your research questions, the formulation of which is consequently informed by your research perspective. Social science research can generate both qualitative and quantitative data, typically through the use of surveys. The data are collected from a pre-defined test group in order to gain information and understanding on various topics of interest. There are various different types of survey methods, including questionnaires, informal discussions, in-depth interviews, focus groups, and case studies.

Qualitative data are richer and are generally grounded in a subjective perspective. However, while this is generally the case, it is not always so. Qualitative research supports an in-depth understanding of the situation investigated and, due to time constraints, it generally involves a small sample of participants. For this reason, the findings are limited to the sample studied and cannot be generalised to other contexts or to the wider population. Popular methods for generating qualitative data include semi-structured or unstructured interviews, participant observations, and document analysis. Good qualitative analysis is generally more time-consuming than quantitative analysis.

Quantitative data, on the other hand, might be easier to collect and analyse, and they are based on a large sample. Quantitative measurements involve collecting data that can be 'objectively' measured with numbers. The data are analysed through numerical comparisons and statistical analysis. For this reason, it appears more 'scientific' and may appeal to people who seek clear answers to specific causal questions. Quantitative analysis is often quicker to carry out as it involves the use of measuring equipment and software. Owing to the large number of samples it allows generalisation to a wider group than the research sample.

Experimental research, on the other hand, is most common in environmental science. In *experiments*, a researcher manipulates one variable and controls the other variables in order to explore cause-and-effect relations. The data collected are quantitative and can be analysed using appropriate statistical methods.

11.2.5 Research report publication

An experiment is not completed until the results have been published and understood. The publication of results is important to allow for the reproducibility of experiments; therefore, the methods are shown separately from the results. As stated by the Council of Biology Editors (1968) 'an acceptable primary scientific publication must be the first disclosure of a research containing sufficient information to enable peers (1) to assess observations, (2) to repeat experiments, and (3) to evaluate the intellectual processes; moreover, it must be attractively formatted and transparent, essentially permanent, available to the scientific community without restriction, and available for regular screening by one or more of the major recognized secondary services' (e.g. Biological Abstracts, Chemical Abstracts) (CBE 1968).

Good scientific writing is simple writing. Science is complex, but the writing used to describe it does not need to be. The best writing is that which gives the sense in the fewest simple words. High-quality, simple writing:

- increases the chances of acceptance for publication
- increases the impact of a publication in the research community
- accelerates the understanding and acceptance of research
- increases the faith of the readers in the quality of the research

Poorly written and complicated manuscripts annoy readers, peer reviewers, and journal editors, and hinder their understanding of complicated scientific concepts. A submission is more likely to be accepted if it:

- describes research that advances the field
- is carefully prepared and formatted
- uses clear and concise language
- follows ethical standards

The publication process:

1. A need/wish to publish
2. Choose a journal according to: topics of the journal, the journal's audience, types of articles, reputation of the journal, impact factor, or personal requirements. We can find appropriate journals by checking where similar papers have been published and by online searches
3. Read back issues
4. Write the first draft
5. Use a critical friend for the first check
6. Refine further drafts
7. Check that the article adheres to the author guidelines
8. Proofread and submit

There can be more than one author of a scientific publication. The co-authors are the people **who made substantial intellectual contributions** to a study that is going to be published. It is important to keep the number of co-authors at a reasonable amount: the first author is usually the one that led the research and did the majority of the writing, and the last author is usually the one who is the head of the research group. In between it is customary to put the co-authors in alphabetical order by their surname, e.g. Wilson, T., Abercombie, J., Brown, E., Curwen, H., Davenport, K. & Albert, W.

Scientific manuscripts are peer-reviewed manuscripts in journals and books that typically have an impact factor (IF). The IF is used to compare different journals within a certain field. Reports, conference papers, posters and talks are not scientific manuscripts and do not have an IF. IF is a measure reflecting the **yearly average number of citations** of articles in that journal. For journals listed in Journal Citation Reports, IFs are calculated yearly for the year before, following the formula below:

$$IF_y = \frac{Citations_{y-1} + Citations_{y-2}}{Publications_{y-1} + Publications_{y-2}}$$

Where

IF_y = Impact Factor in year y

$Citations$ = number of citations

$Publications$ = number of articles published

$y - 1$ = current year minus one

$y - 2$ = current year minus two

All scientific articles follow the same prescribed structure. This structure provides a logical line through the contents, enables manuscripts to be predictable and easy to read, presents a 'map' so that the readers can quickly find the contents of interest in any manuscript and, last but not least, reminds authors what contents needs to be included. The structure is as follows:

- Title
- Abstract
- **Introduction**
- **Materials and Methods**
- **Results**
- **Discussion**
- Conclusion
- Acknowledgements
- References

Besides stated chapters, each manuscript usually also includes table(s) and figures, and supplemental data in a separate file(s). The main contents of the scientific paper are described in the core chapters: Introduction (which problem we are going to study), Materials and Methods (how we are going to study the problem), Results (what we found out), and Discussion (what it means). According to the capital letters of the chapters, this structure is called **IMRaD format**.

Title and abstract

Title and abstract are the most visible parts of the article. They can be seen on the journal website and in databases (e.g. Science Direct, PubMed, etc.); therefore, it is important to pay appropriate attention to their formulation. A well-prepared abstract enables readers to identify the basic contents of a document quickly and accurately, to determine its relevance to their interests, and thus decide whether they need to read the document in its entirety (Day 1998).

The title must be as accurate, informative, and as complete as possible. It gives the first information to the reader who then decides whether to continue reading or not. It is therefore crucial that the title is as descriptive as possible. To achieve this, specific rather than general terms should be used; however, the title should still be understandable and reasonably simple. The title usually does not include abbreviations, acronyms, or initials. Any scientific names should be written in full (e.g. *Lactuca sativa*, rather than *L. sativa*).

The abstract usually contains 200-300 words. It must outline the most important aspects of the study: it has to include the background, methodology, and results, but in limited details. It should only reproduce the facts covered in the manuscript. It is advisable to include synonyms for words and concepts that are in the title and, as for scientific writing per se, an understandable and reasonably simple writing style should be used. On the other hand, the abstract should not include abbreviations or cite references.

Introduction

The introduction should provide the information needed to understand the study, and the reasons why the experiments were conducted. It should explain **what** question/problem was studied, and give information from previous studies; therefore, it includes numerous citations. The latter should be well balanced, current, and relevant. The introduction is not a literature review, but literature reviews can be cited (Nayak & Singh 2015).

Materials and methods

Materials and methods provide all the details of **how** the study was conducted. Different methodologies that were used in the study can be divided by subheadings. Any new methods that were used should be described in enough detail such that another researcher can **reproduce** the experiment. Previously used and published methods should be cited, and any modification done to the established methods should be described accurately. All statistical tests and parameters should be listed. The materials and methods chapter should be written in the past tense.

Results

The results chapter gives an overview of the experiments, without repeating the details, which were described in the methods. Besides this, the researcher should critically review the data and select the results that are going to be published. A simple transfer of the data from the lab diary into the manuscript will not suffice for efficient presentation of the results. The presentation should be transparent and representative and can be done through either text or tables and figures. The data already described in the tables or figures should not be described again in detail in the text. The tables and figures should be quoted in the text only briefly. If there is only one or a few measurements of a characteristic, then it is usually described in the text, while if it is repeated measurements, then a table or graph is more representative. Depending on the journal, results can form an individual chapter or be joined with the discussion into a single chapter. The results should be written in a logical order, and divided into subsections with short, informative headings. Results of statistical analyses should also be included and presented in the text. The results chapter should be written in the past tense, while the present tense is used for referring to tables and figures.

Discussion

The majority of the discussion and conclusions chapter should be an interpretation of the results. Subchapters can be formed following the logical framework of the subchapters in the results chapter. In the discussion chapter, the results of the research are compared with previous studies. The limitations of the research also have to be described, any inconclusive results should be mentioned and, if the findings are preliminary, suggestions for future studies should be pointed out. The main conclusions should be repeated at the end of the discussion, or in a separate conclusions chapter.

References

When writing a scientific manuscript, it should always be clear what are the thoughts, evaluations, and text of the authors of this study, and what has been derived from the authors of other publications. The source should be provided for any statement that does not come from the writers of the manuscript, by writing the author and year of publication – for example, the microelement nickel plays an important role in the decomposition of urea in aquaponic systems (Komives & Junge 2018), while the complete citation is given in the references – for example, Komives, T. & Junge, R. 2018. Importance of nickel as a nutrient in aquaponic systems – some theoretical considerations. *Ecocycles* 4 (2), 1-3. The references should be written in a style as demanded by the journal where the manuscript is going to be published, and therefore the journal citation style in the Instructions for Authors has to be carefully checked. There are various software programmes that enable appropriate management of references (EndNote, Zotero, RefWorks, Mendeley etc) (see 6.2.2.2).

Plagiarism

Plagiarism is cheating and is morally wrong. It is the use of someone else's work without acknowledgment, as if it were your own. To avoid it, one has to know how to document the use of other people's work. A researcher is responsible for referencing the use of sources in every paper that he/she writes. There are two ways to reference the works of other authors:

a) **Paraphrasing** means summarizing another author's ideas in your own words, while still referring to the original source. Quotation marks are not required. A well-paraphrased statement is concise and demonstrates a researcher's understanding of what he/she has read. When paraphrasing or referring to an idea from another publication, it is beneficial to provide a page or paragraph number for the reference, especially when citing a long and complex text (e.g. a book).

b) **Direct quotes** mean a direct repetition of a statement and are rarely used in scientific writing. Quotations should be used economically, mainly for historical or political quotes from eminent persons. Quotations of the findings from previous researches have to be avoided as the reader also wants to see the writers' views and analysis of what has been read, which is not given in the direct quote. When using a direct quote, it is necessary to put quotation marks at the beginning and at the end of the quote.

11.3 Scientific research methodology applied to aquaponics

The following case studies illustrate some of the different kinds of methodologies that can be used for research relating to aquaponics. The first case study is an example of social science research conducted using a questionnaire. A questionnaire is a tool for collecting and recording information about a particular issue of interest in a standardized manner. The information from questionnaires tends to fall into two broad categories – facts and opinions; very often they include questions about both. The questions may be unstructured or structured or, as in the case study below, a combination of both. Unstructured questions ask respondents to provide a response in their own words, while structured questions ask respondents to select an answer from a given set of choices. Structured questionnaires are usually associated with quantitative research, i.e. research that is concerned with numbers (how many? how often? how satisfied?). The responses to individual questions in a structured questionnaire may be aggregated and used for statistical analysis (Nayak & Singh 2015).

Case Study 1	
Love, D.C. *et al.* 2014. An international survey of aquaponics practitioners. *PLoS ONE* 9(7), e102662.	
Aim	To track aquaponics in the United States and provide information that can better inform policy, research, and education efforts regarding aquaponics as it matures and possibly evolves into a mainstream form of agriculture
Objective	To document and analyse the production methods, experiences, motivations, and demographics of aquaponics practitioners, both in the United States and internationally
Methodology	1. Literature review to determine whether suitable survey tools exist to collect information on production practices and attitudes of individuals engaged in aquaponics 2. Development of a questionnaire informed by previously described methods for internet surveys and surveys about agricultural practice 3. Pre-test of the draft questionnaire for comprehension of contents with 10 people who were either experts in or practitioners of aquaponics, and were representative of the groups targeted in the survey (i.e. commercial farmers, educators, hobbyists, and non-profit organizations) 4. Online survey using the snowball sampling method in order to reach as many people as possible. Eighteen organizations distributed the questionnaire to their members or subscribers using their own preferred means of communication (e-mail, listservs, online newsletters, direct email, and social media). The incentive offered for participation in the survey was the chance to win one of four $75 gift cards 5. Of the 1084 respondents, 809 met the inclusion criteria (18 years of age or over, able to read English, and had operated and maintained an aquaponic system in the previous 12 months), and their responses constitute the sample 6. Data from the survey software (Qualtrics) were exported and analysed in Excel or SPSS, and figures were produced using Prism. T-tests were conducted to compare respondent demographics by sex, with significance set at an alpha of 0.05. Error was reported as standard deviation
Limitations of the	The use of the snowball sampling approach and social media to identify potential

research	participants means that it is not possible to calculate the survey response rate, and there is limited generalisability to aquaponics practitioners beyond those who responded to the study. The fact that the majority of respondents were from the US (80%) suggests that the results may be skewed because the survey originated in the US and was not offered in languages other than English

Questionnaires are one of the most affordable ways of gathering quantitative data. Online surveys in particular can have a very low cost and a generous reach, and the results can be analysed quickly and easily to highlight trends in the data. However, there are a number of drawbacks to using questionnaires. While every researcher hopes for conscientious responses, there is no way of knowing whether the respondent has really thought the question through before answering. At times, answers will be chosen before fully reading the question or the potential answers, and sometimes respondents will skip through questions, or split-second choices may be made. All of these will affect the validity of the data collected. While questionnaires may reveal patterns and trends in the data, they do not permit an understanding of their causes.

The second case study is an example of social science research using a comparative case study approach and semi-structured interviews to generate qualitative data.

Case study 2	
Laidlaw, J. & McGee, L. 2016. Towards urban food sovereignty: the trials and tribulations of community-based aquaponics enterprises in Milwaukee and Melbourne. *Local Environment* 21 (5), 573–590.	
Aim	To understand the socio-economic and cultural context that is essential for building food sovereign communities and cities, in particular the potentially catalytic role of urban aquaponics social enterprises in fostering a broader civic disposition and receptiveness towards food sovereignty
Objective	To explore stakeholder experiences of building community-based urban aquaponics enterprises in order to understand the internal and external factors that impact on their success or failure
Methodology	Comparative case study approach involving: 1. Unstructured qualitative interviews with key project stakeholders at two community-based urban aquaponics enterprises and an online survey of a broader cohort of stakeholders. The sample size is 23 (7 key project stakeholders and 15 other stakeholders) 2. Analysis of project documentation and observations compiled through a series of site visits 3. Discourse analysis of the interview transcripts
Limitations of the research	The small sample size (stakeholders associated with two aquaponics enterprises) means that there is limited generalisability of the findings. The methods used for the discourse analysis are not stated

Comparative case studies such as this involve the analysis and synthesis of the similarities, differences and patterns across two or more cases that share a common focus or goal. Given the focus on generating a good understanding of the cases and case context, methods such as fieldwork visits, observation, interviews and document analysis often dominate among the various data collection methods employed. Comparative case studies may incorporate both qualitative and quantitative data, and while they may be time consuming, they can generate rich detail about the context and features of two or more instances of specific phenomena.

The field of aquaponics is quite new, with the first scientific paper specifically using the term appearing in an impact journal in 2004[4]. Many advancements had been made before that, namely by James Rakocy and his group (University of the Virgin Islands) but their publications are more demonstrative and less experimental. According to the Web of Science, more than 60 peer-reviewed papers have been published on aquaponics since 2004, but many articles concentrate more on promoting the potential of aquaponics than on completing scientific trials per se. Part of the problem stems from having enough replicates and establishing proper control groups. It is usually quite difficult and time consuming to set up an aquaponic system, with its filter, bacteria, fish, and plants, let alone setting up several units or replicas per treatment. In feed trials in aquaculture, for example, it is common to have at least 3 replicas per treatment, each experimental unit usually being one tank, not the individual fish. That would mean, for example, were we to compare the effects of adding garlic extract to feed, we would need three tanks of fish to which we add garlic feed and three more tanks to which we add control feed. To do something similar using aquaponics is more complex. For example, if we want to compare the effect of water pH on fish welfare and lettuce growth, we would need six separate aquaponic units, three of which were at a specific pH and another three at another pH level, and all six units would need to have fish and lettuce in the same stocking densities. Thus, the cost of each experiment is higher than for feed trials, and the list of things that could possibly go wrong is also much higher. For this reason, when looking at the literature, we normally see very few or no replicates, or two replicates per treatment at the most.

The third case study is an example of an experimental research methodology. The purpose of experimental research design is to enable the researcher to credibly establish a cause-and-effect relationship. An experiment is a test under controlled conditions that is carried out in order to support, refute, or validate a hypothesis. Experiments provide insight into cause-and-effect by demonstrating what outcome occurs when a particular variable is manipulated. Experiments vary greatly in goal and scale, but they always rely on a repeatable procedure and logical analysis of the results. The research methodology is therefore explained in great detail in order to enable other researchers to repeat the experiment and thereby validate, or falsify, its results.

[4] Tokuyama, T., Mine, A., Kamiyama, K., Yabe, R., Satoh, K., Matsumoto, H., Takahashi, R.& Itonaga, K. 2004. Nitrosomonas communis strain YNSRA, an ammonia-oxidizing bacterium, isolated from the reed rhizoplane in an aquaponics plant. *Journal of Bioscience and Bioengineering* 98 (4), 309-312.

Case study 3	
Goddek, S. & Vermeulen, T. 2018. Comparison of *Lactuca sativa* growth performance in conventional and RAS-based hydroponic systems. *Aquaculture International* 2018, 1–10.	
Aim	To verify the findings of Delaide *et al.* (2016)[5] – that lettuce growth performance in complemented aquaponics solution outperforms hydroponics
Objective	To compare the growth performance of lettuce in a conventional hydroponic system with that in a RAS-based system
Methodology	Two NFT systems, each one consisting of sixteen 7.7 metre long gullies and a recirculation container holding 250 litres, were planted with 38 lettuces per gully, resulting in a planting density of 12 lettuce heads per square metre. The hydroponic treatment tank was continuously filled with rain water and the RAS treatment tank with 30% RAS water and 70% rain water. Analysis of the micro and macronutrient concentrations in the water was carried out once every two weeks using HPLC equipment according to the ISO 17025 norm. 20 lettuce shoots were randomly selected, harvested and weighed individually seven weeks after planting. Prior to sending the milled lettuce shoots for lead analysis, the lettuce heads of each system were cut into small pieces and dried (for 24 h at 103 °C) in order to determine their dry weight. The leaf nutrient content analysis was performed with an ICP-OES by Groen Agro Control according to their certified analysis protocol. Analysis of statistical significance and ANOVA were conducted in R. A nonparametric two-sample Kolmogorov–Smirnov test was used to test whether Na concentration probability distributions differ between the hydroponic and RAS systems. Genstat software was used to conduct a principal component analysis with respect to the nutrient composition of the lettuces

11.4 References

CBE 1968. *Scientific Writing for Graduate Students: A Manual on the Teaching of Scientific Writing* (ed. F.P. Woodford). Committee on Graduate Training in Scientific Writing of the Council of Biology Editors. Rockefeller University Press, New York.

Day, R.A. 1998. *How to Write and Publish a Scientific Paper*. Cambridge University Press. 5th Edition.

Nayak, J.K. & Singh, P. 2015. *Fundamentals of Research Methodology: Problems and Prospects*. SSDN Publishers & Distributors, New Delhi.

Neyman, J. & Pearson, E.S. 1933. *On the problem of the most efficient tests of statistical hypotheses*. *Philosophical Transactions of the Royal Society of London* A 231, 289-337.

Nosek, B.A., Ebersole, C.R., DeHaven, A.C. & Mellor, D.T. 2018. The preregistration revolution. *Proceedings of the National Academy of Sciences* 115 (11), 2600-2606.

OECD 1998. *OECD Principles of Good Laboratory Practice*. OECD Series on Principles of Good Laboratory Practice and Compliance Monitoring Number 1. Organisation for Economic Co-operation and Development, Paris.

[5] Delaide, B., Goddek, S., Gott, J., Soyeurt, H. & Jijakli, M.H. 2016. Lettuce (*Lactuca sativa* L. var. Sucrine) growth performance in complemented aquaponics solution outperforms hydroponics. *Water* 8 (10), 467.

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12. DESIGN AND BUILD

12.1 Starting to design an aquaponic system

Do not be confused by the great variety of designs for aquaponic systems which you may encounter in the literature or by browsing the web. When planning and building an aquaponic system, it is necessary to follow the basic principles in order for the system to function properly. There are big differences between systems in terms of investment costs, maintenance and operating costs, reliability, health and safety, potential for fish and crop growth, and total workload. It is therefore necessary to define all these aspects during the design phase.

The design of a new aquaponic system should be based on your goals and requirements:

- What is the purpose of the system? (food self-sufficiency, business, decoration, social impact, teaching)
- How much space is available? A commercial system needs more than 1000 m^2, while backyard aquaponics for self-sufficiency can be smaller
- Where is the system going to be placed? If it will be outside, construction costs may be lower but more energy will be spent on heating. If it will be inside, more energy will be spent on lighting
- How much time can be invested in the operation? Automatic regulation is expensive, while multiple daily checks are time consuming (although the fish have to be checked daily anyway)
- Should I buy a ready-made kit or build my own? Several kit designs are available but they might not suit your goals. On the other hand, building requires knowledge, even though recycled materials can be used to reduce costs
- When designing, consider all the activities in order to anticipate the routine procedures, maintenance, and how to deal with emergencies.

The design and construction of an aquaponic system follows a series of sequential steps: feasibility study and site selection, basic design, detailed design, construction site preparation, and construction. Basic design criteria have already been discussed in Chapter 2, so here we bypass this step and use the example from Chapter 2 as a template for detailed design. Table 1 summarizes the main steps involved in progressing from an idea for an aquaponic system to a fully operational system.

Table 1: Steps in the design and build of an aquaponic system

Feasibility study and site selection	In the feasibility study you check whether the site you plan to put the aquaponic system in has the basic needs to enable construction and operation. These needs cover space requirements, surface load, power availability and reliability, vehicular access, water quality and availability, cooling and heating possibilities, climate, sunlight etc. The feasibility study also includes the production planning of the site, so you need to know how many tanks will be required and with what water volume, the size of the plant cultivation area, and so on. These are the first things you need to know before the basic design process can start.
Basic design	In basic design you plan the basic dimensions of your system by following a step-by-step planning process (see Chapter 2). You either start with the production area of vegetables and then design the fish rearing system based on the nutrient needs of the plants, or vice versa. At the end of basic design, you will have defined a general process flow diagram with the main components: production rates for fish and plants; water flow rates; fish tank volume, shape, and water level; solids removal dimensions; biofilter type, size, and shape; piping length and diameters; water flow speeds in different pipes; water levels. Basic design will reveal whether your production goals can be reached on the site you have chosen.
Detailed design	Detailed design uses the same design considerations as basic design, but goes into more detail. While in the previous step you were focusing only on the hydraulics and dimensions, you now also need to focus on the materials you will use, and choose the individual technical components, their power demand, backup power requirements, measurements and control units, and do a detailed design of all the hydraulic components (pipes, outlet screens, biofilter etc. etc.). Depending on the size of the project and the country you work in, detailed design will end with construction plans which either you execute yourself, or can be given to a construction company to execute. Planning the plumbing, electrical wiring, ventilation channels and walkways in a 3D model will help you ensure that the installation process will go smoothly. During detailed design you also need to have a good understanding of the construction material and construction techniques needed, so that there is sufficient space to mount the system.
Construction	The main goal during construction is to build the farm as quickly as possible, since having a construction site for a long time is normally very costly.
Operation start up procedures	The system needs to be filled with water and the following basic operational requirements will need to be tested before the fish are transferred to the system: - recirculation rate - leaks - water levels - air flows - oxygenation capacity - degassing capacity - system monitoring and emergency protocols The next step will be the biological startup of the system, which has to be done 4-6 weeks before the first fish are added to the system. By this time, the SOPs (standard operating procedures) for running the system will need to be ready. Calculate at least 8 weeks from the end of construction until the first fish enter the system.

12.2 Feasibility study: location and infrastructure considerations

Table 2 outlines the most important location and infrastructure considerations when designing a new aquaponic system.

Aspect	Description
Site stability and foundations	Water is heavy. Choose stable and level ground for building your aquaponic system. If the ground is not stable, the foundations will be unstable and leaks could occur because of movement of the pipes.
Climatic conditions at the location	Consider how to protect the aquaponic system from extreme weather events. Europe is located in a moderate climatic zone characterized by changing seasons with different temperatures and day lengths. Therefore you should consider what to do during periods of low temperature and short daylight. One option is to stop production and start again in the spring; the other is to heat the water and air and provide artificial lighting. On the other hand, extremely high temperatures have to be avoided during summer. You can install shading nets, or paint the outside of the greenhouse with white paint. Good quality greenhouses have automated sprinklers and ventilation devices. Remember that systems with a large water volume are more resistant to overheating than those with a small water volume. Having access to additional water (spring water etc.) for cooling using a heat exchanger can also help. In addition to solar radiation, the fish and electrical components also produce a lot of thermal energy that has to be removed during warm weather.
Water and electricity sources	There must be a reliable source of electricity and of water of appropriate quality and quantity on the site. The possibility of power cuts also has to be considered. Do you have a backup electricity generator? How will you provide oxygen to the fish? How will you keep them warm/cool? Heat and mass balances have to be calculated during the detailed design stage in order to define the reaction time in such events.
Accessibility, entrance, fences	The location should be accessible for transporting equipment, harvested vegetables and fish. The system should always be accessible for urgent interventions. On the other hand, access by unauthorized persons has to be prevented, because of the risk of infections and disease.
Designated work and storage areas	When designing an aquaponic system one has to consider all the operations and processes that will take place, including storage space for fish food, cleaning material and tools, monitoring equipment and work clothes. A table will be needed for documentation work, and for displaying the operating, maintenance and troubleshooting instructions.

Figure 1: (left) Wind damage on a greenhouse; (b) Shading nets in a greenhouse provide protection from strong sunlight and prevent algae growth (photos: U. Strniša)

12.3 The fish tank

The basic components to consider are fish tanks, the sludge removal unit, the biofilter, the sump, plant beds, pumps, and piping. The function, required materials, and location of each of these, and their interaction with other components, all need to be considered. The interaction among the components, for example, will determine the number of pumps that will be required.

The fish tank will be the home of the fish for a relatively long period of time, so it should be chosen with care. The materials, design and size of the fish tank are all important, and should enable relatively easy observation and handling of fish, removal of solid particles, and good water circulation (simulation of natural water flow).

12.3.1 Volume

The volume of the fish tank depends on the following factors: (i) the number of fish it will have to house, (ii) the volume of the living space that each fish species requires, and (iii) the method of maintaining a stable water temperature. The design of aquaponic systems is based on the quantity of fish feed, which is related to fish density. The required volume of the fish tank is based on targeted fish density and biomass. For example, if the target density is 10 kg/m^3, and it is planned to cultivate 30 kg of fish, a 3000 litre fish tank will be needed. One must also be aware that the fish will grow, and therefore the fish density and biomass will also increase during the production cycle. Generally, larger systems are more stable in terms of water temperature oscillations.

Figure 2: The importance of fish tank volume for water temperature oscillations: (left) small fish tanks exhibit faster water temperature changes; (right) in larger water volumes the temperature will be more stable

12.3.2 Shape

Fish tanks are usually either circular or rectangular. In addition, there are double-D or endless tanks that are a hybrid between circular tanks and long basins (Figure 3). Table 2 summarizes some general advantages and disadvantages of round, square and double-D tanks. In addition to these, other factors need to be considered, such as the type of fish species that one wants to rear. Bottom-dwelling fish such as burbot, turbot, sole or similar flatfish mostly stay on the bottom of the tank and may prefer a slow waterflow. Moreover, the bottom-dwelling fish may be stocked in such a way that the self-cleaning of the tank is actually achieved through fish movements and not the hydraulic pattern of the water column. Therefore, a square tank design may not be the worst solution for farming bottom-dwelling fish. Another aspect of tank design is the inclination of the tank bottom. While it has very little effect on the self-cleaning ability of the system, a higher inclination may help with draining the whole tank.

Figure 3. Different forms of fish tanks: (left) circular tank, (centre) rectangular tank (raceway or plug flow), and (right) double-D tank or D-ended raceway (hybrid of circular and raceway) (source: www.aqua-tech.eu, Bregnballe 2015)

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Table 3: Advantages and disadvantages of round, square and double-D fish tanks

Type of fish tank	Advantages	Disadvantages
Circular	• Structural stability, no pressure points on corners • Less material needed (cheap tank equipment cost) • Conceptually simple • Allow for homogeneous distribution of water and good water quality • Flow conditions (centrifugal forces) wash the sediments towards the outflow in the centre of the basin centre towards the outflow (high self-cleaning effect) • Low residence time of particles • Oxygen control and regulation easy	• Low area efficiency, low space utilization • Hard to seal tank connectors (pipe through tank wall) • Hard to segment • Flow rates vary within the tank
Square	• Efficient usage of area and space • Easy to seal tank connectors • Simple segmenting • Easier to handle the fish	• Low self-cleaning (possible dead zones, concentration gradients of dissolved oxygen and ammonia emerge) • To prevent low self cleaning high flow rate needed • High residence time of particles • Medium oxygen control and regulation • Pressure points in structure • Feed waste is higher due to greater dispersion of the fish
• Double-D	• Efficient usage of area and space • Water mixing partly possible • Simple segmenting • Medium self-cleaning • Oxygen control and regulation easy • The fish can swim in circles	• Conceptually complex • High amount of materials needed • More expensive

12.3.3 Height and ratio

The fish tank should be at such a height that it allows staff to observe and work with the fish. If using deeper tanks, a window for observing the fish should be included and/or a stable walkway to access the tank. The height of the tank also determines the height of the water column and the rate of water flow to the next component of the aquaponic system (see Chapter 2).

Figure 4: Fish tanks positioned (left) above ground (photo: U.Strniša), and (right) at ground level (source: www.humblebynature.com/about-us/projects-at-humble- by-nature/aquaponics-solar-greenhouse)

If you are using a circular tank, you have to make sure that the water diameter/height follows a certain ratio. The maximum ratio should be 6:1. If the tanks are wider, then solids removal and even distribution of water from the inflow will be hindered. Reducing the ratio below 3:1 will create a vortex in the central drain, and oxygen will not be distributed evenly in the tank. Ratios below 3:1 should include a side drain (dual drain) to avoid the build-up of a vortex.

12.3.4 Materials

There are differences regarding investment costs, tank stability, and installation, but the most important thing is to make sure that the materials are safe for both the fish and the plants. This means that galvanized materials should be avoided, because of zinc toxicity. The wrong type of plastic can also be harmful to the fish. Thermally weldable plastics (so called thermoplasts such as PE, PP or PVC) are the best option, though they tend to be more expensive. The choice of plastic needs to take into account the following considerations:

- UV resistance (black PE is UV resistant)
- Porosity (PP is more porous than PE and therefore enables biofilms to grow)
- Thermal stability (PVC becomes brittle below 0°C)

Because of its resistance to hard weather conditions, PE is the material to choose for long-lasting installations in greenhouses or outdoors.

Figure 5: Different fish tank materials: (top left) polyethylene (photo: U.Strniša), (top right) concrete (photo: U.Strniša), (bottom left) steel tanks covered with plastic liner (photo: ZHAW), and (bottom right) PVC tanks

12.3.5 Tank cover

Healthy fish are lively creatures and can jump out of the tank. All tanks should therefore be covered in order to prevent accidental losses and injury to the fish. Covers also prevent foreign objects from falling into the tank (Figure 6a). Tank covers reduce water losses due to evaporation and provide shading, which reduces overheating, prevents algae growth, and thus improves the wellbeing of the fish. In addition, most fish prefer to be in the shade rather than in direct sunlight (Figure 6b).

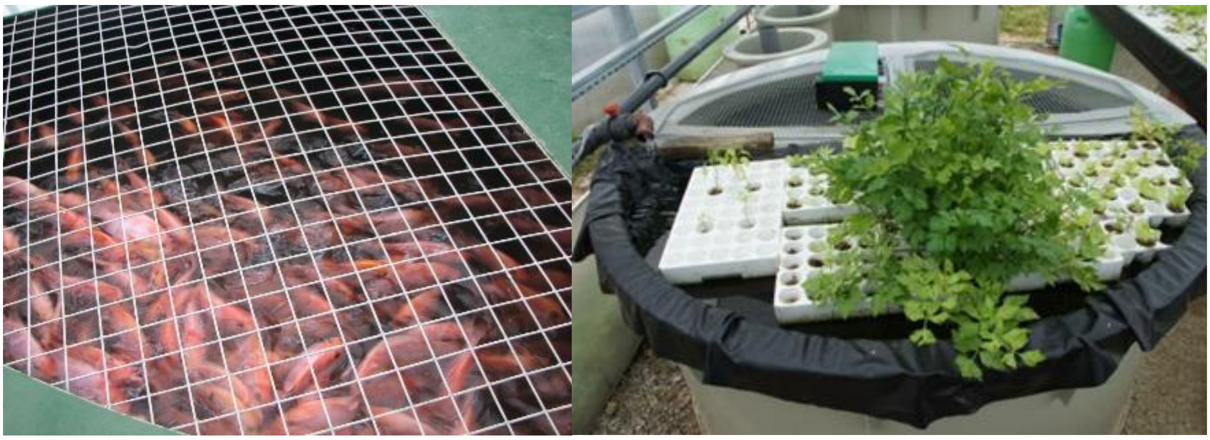


Figure 6: (left) A fish tank covered with netting to prevent accidental losses; (right) A tank liner and planted rafts prevent algae growth and provide shade (all photos: U.Strniša)

12.3.6 Water flow

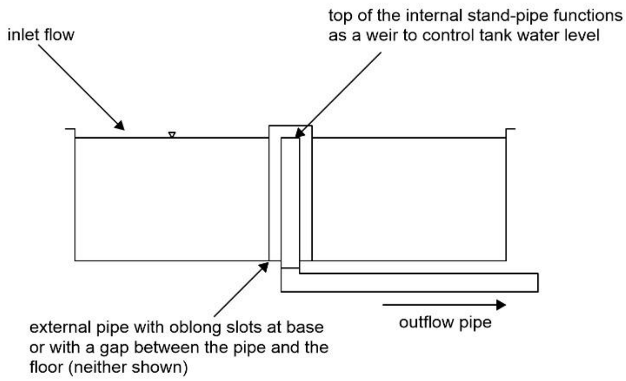
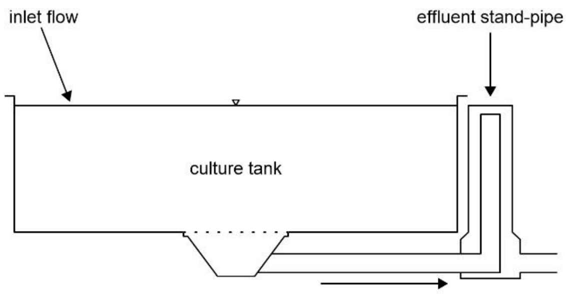
12.3.6.1 Inflow and outflow

Ideally water should flow into the tank at an angle from above in order to enrich the water with oxygen and generate a circular flow in the tank (Figure 7a). If the water is oversaturated (oxygen saturation >100%, caused by the oxygenation units such as a low head oxygenator or oxygen cone), then the water should enter the fish tank below the surface through a perforated pipe (flute) which creates a circular water flow. The first perforation should lie just above the surface of the water and the total cross section of all perforations in the inflow pipe should be equal to the pipe's cross section. The perforations also need to be smaller than the size of the fish that are kept in the system.

Figure 7: Examples of water inflow and outflow: (left) the water inflow is located above the tank at an angle; (right) the water outflow is in the centre of the bottom of the tank photos: U.Strniša)

The outflow of water from the tank should enable the removal of solid particles, while at the same time preventing the loss of fish; it is therefore usually placed in the centre of the bottom of the tank (Table 4). The correct dimensioning of the system and water flows prevents both clogging and overflowing. Each fish tank should be built as a separate hydraulic element, since hydraulic communication between fish tanks will end in total loss of all the fish if one pipe or one tank leaks. Therefore, every tank needs an option for overflow (Table 4). At ZHAW, we work with external standpipes or external overflows, so that structures within the fish tank do not interfere with fish handling procedures.

Table 4: Water outflow options (Source: Timmons & Ebeling 2007)

Type	(+) Advantages / (-) Disadvantages	Section
internal standpipe	(+) Water level control (+) No sediment deposition in pipeline (-) Disturbs netting of fish	
External standpipe	(+) Water level control (+) Tank free of installations (-) Solids can settle in the pipe segment	

12.4 Solids separation

The following decisions need to be made during the design stage:

(i) Is a separate solid removal step necessary? In systems with a low fish stocking rate, a media growing bed can remove solids and act as a biofilter. However, over time, clogging and anaerobic areas will occur as the amount of solids increases.

(ii) What is the appropriate device for solids removal? Waste particles in the water can be of different sizes, which affects the technologies used to remove them. Systems with a lower stocking density (<10 kg/m^3) may be able to use devices based on sedimentation for particle removal, while systems with a higher stocking density (>10 kg/m^3) may need rotational drum filters (Figure 7).

(iii) How should the fish tank be connected to the solids removal device? The water should always flow by gravity from the fish tank to the solids separator and not be pumped, since the latter will only decrease the particle size and make it more difficult to remove. To avoid sedimentation the flow velocity in the pipe should be between 0.7 to 1.0 m/s.

(iv) What to do with the sludge? Fish sludge is rich in nutrients that can be reused as fertilizer. There are several alternatives to dumping it into the sewage system, including the following:

- storing and re-using it in traditional gardening and agriculture; however, this may be prohibited by law
- co-composting with structurally rich green waste (tree cuttings, straw)

- vermicomposting (composting process using various species of earthworm).
- anaerobic digestion and reintroduction of digestate into the aquaponic system (Goddek *et al.* 2016).
- Denitrification to shift the N:P ratio in the aquaponic system in order to reduce P limitation.

Most low-tech systems use gravitational sedimentation for the removal of particles. Filters in this category are: vortex filter, lamella separator, and radial flow separator (Figure 8). The low-tech sedimentation filters can normally only cope with particles of a size larger than 100 µm. However, due to the high flow and active mixing of the water column, the majority of particles in most modern intensive RAS will be smaller than 100 µm. Therefore, using sedimentation filters only is not an optimal solution for intensive RAS.

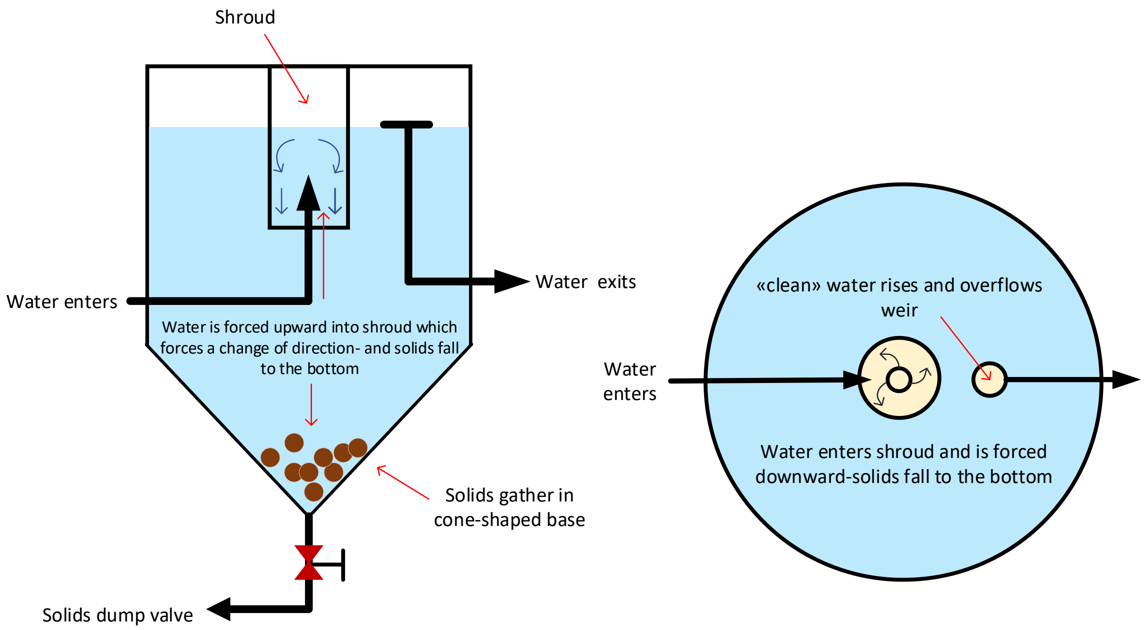


Figure 8: Diagram of a radial flow separator (adapted after www.garydonaldson.net)

Most modern and intensive RAS use microscreens, often applied as rotational drum filters for solids filtration (Figure 9). These drum filters work in the following way: water enters the drum filter and filters through the microscreens (usually with a filter cloth of 40-100 µm), solid particles are held back and then washed from the filter elements into the sludge tray, and the sludge water then leaves the fish system and enters the waste water treatment facility.

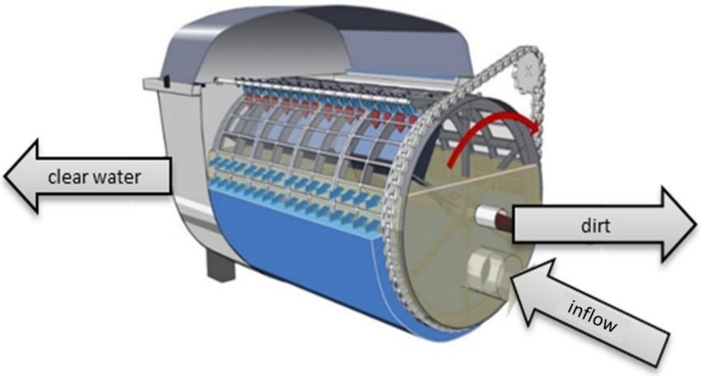


Figure 9: Diagram of a drum filter (www.nordicwater.com)

In addition to the drum filters, foam fractionators (also called protein skimmers) (Figure 10) are often used. These are mainly used to remove organic compounds such as proteins but they have also been reported to reduce a wide variety of other organic and inorganic molecules (e.g. fatty acids, detritus, bacteria, metals). Foam fractionators are mainly used in marine water, as their efficiency is very low in freshwater

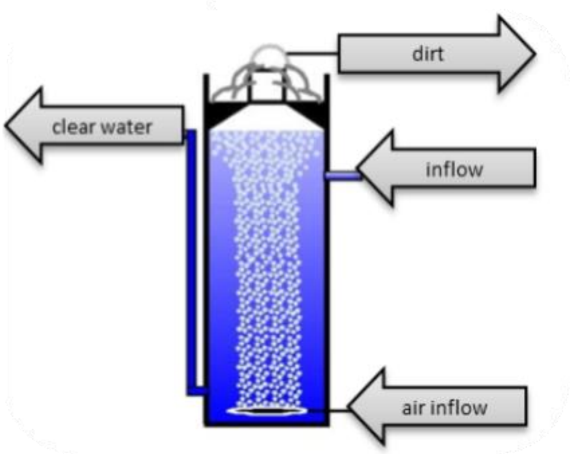


Figure 10: Diagram of a foam fractionator (www.epd.gov.hk)

Table 5: Characteristics of different solids filtration systems

	Sedimentation Filter	**Drum Filter**	**Foam fractionator**
Principle	Density (gravity)	Filtration (size)	Flotation (polarity/density)
Size	>100 µm	>30-100 µm	<30 µm
Pressure drop[1]	Insignificant	20 cm	Insignificant

[1] A pressure drop occurs when frictional forces, caused by the resistance to flow, act on a fluid as it flows through the tube. See the exercise in Module 2 – Aquaculture.

Figure 11. Different solids removal devices: (left) sludge trap; (centre) roughing filter; (right) rotational drum filter at ZHAW (all photos by U.Strniša)

Figure 12: Sludge storage tank (left) (photo: U.Strniša) and compost (right) (photo: pixabay)

12.5 The biofilter

The biofilter is the heart of every recirculating aquaculture system. Fish health, and therefore economic success, depend on correct operation of the biofilter. High ammonia and nitrite levels in fish tanks can be caused by several factors. One of these can be poorly designed or sub-optimal operation of the biofilter (too small, not mixed evenly, nitrate levels too high, pH too low, intoxication of the biofilter by salt or medical treatment, aeration too low or too high, etc.). The other main aspect of design failure is insufficient recirculation of the water. The biofilter can only degrade what it receives from the fish tank. If the recirculation rate is too low, even an over dimensioned biofilter will not lead to good water quality. To avoid this, follow the example in Chapter 2 to calculate the correct recirculation rate for your system.

12.5.1 Is a separate biofilter required?

In systems with low fish stocking density, a media growing bed can take over the role of both solids removal and biofiltration. If the solids load is too high, clogging and anaerobic areas can occur, which reduce the efficiency of biofiltration. Therefore, if the growing bed is to function as a biofilter, either a very low fish stocking or a separate solids removal device are recommended.

12.5.2 Choosing the biofilter

The most commonly used biofilter type in aquaponics and in RAS is the moving bed biofilter reactor (MBBR) (Figure 13, Table 6). The media of a moving bed filter consists of small (1-2 cm) plastic structures with high specific surface area (e.g. Kaldness k1). This filter media is kept in constant movement by aeration (e.g. through input of air through air-plates at the bottom of the biofilter tank). The constant movement of the media has a self-cleaning effect on the filter media and prevents extensive bacteria growth. For cleaning the moving bed filter should be disconnected from the RAS and then backwashed approximately once per week.

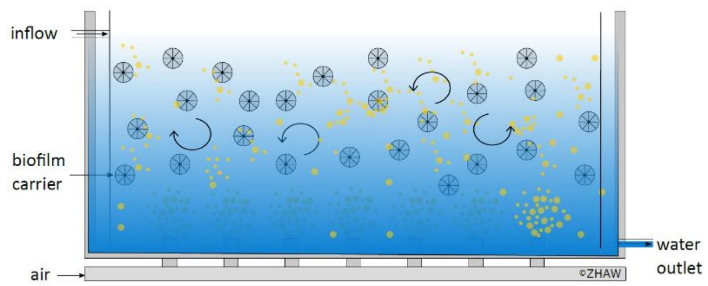
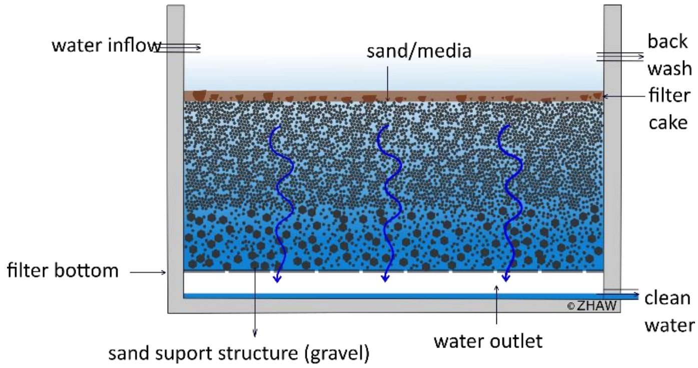
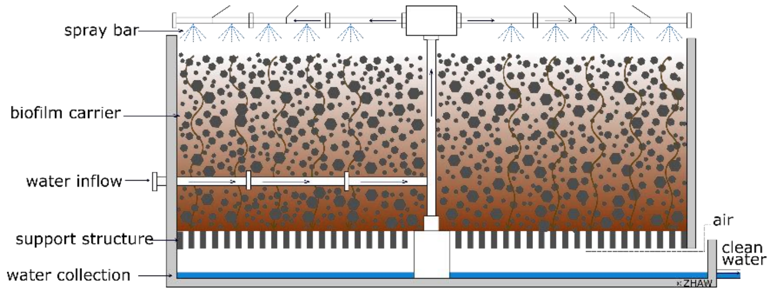
The carrier media supports microbial biofilm growth by providing a large surface area. Typically, MBBR are filled 40-60% with biocarriers, creating an absolute surface area of 300-600 m^2/m^3 bioreactor volume. Air movement creates shear forces on the biofilms and keeps growth and breakdown of the biofilm in equilibrium. If the biofilm on the carriers gets too thick, then aeration is too low, and if it is non-existent, then aeration is too high. A major advantage of MBBR is the degassing and aeration by air flow, which is not provided by fixed bed filters.

Fixed bed filters have fixed biofilter media. The fixed bed filter also works as a solids removal device as it has filtration capabilities to filter out leftover solids and organic compounds that have not been filtered out in the solids separation unit. If the organic loading is higher than the natural degradation on the surface, the filter cake can become clogged by particles and bacteria growth. The filter needs to be backwashed regularly and the backwash water treated separately (by sedimentation etc.). (Table 6).

Trickling filters are the last of the three common filter types and work by trickling water through a pile of biofilm carriers. The biggest benefit of the trickling filter is the high degassing effect through the high water to air surface caused through the trickling. The main disadvantage are the high pumping costs needed to bring the water to the required height. Since these carriers are not moved regularly like in a MBBR, the biofilm grows thicker on these carriers and reduces the nitrification rate. Trickling filters are very common in aquaponics, since they enable gas exchange (degassing of CO_2 and aeration) in the one step. In addition, they only need water circulation and no additional aeration device like MBBR (e.g. a blower), which makes them a very easy to build system.

Figure 13: Two versions of suboptimal moving media biofilters: (left) biofilter containing too many biochips (photo R. Bolt); (right) biofilter with no aeration (photo: U. Strniša)

Table 6: Types of biofilters and their pros and cons in terms of system performance: moving bed biofilm reactor (MBBR), fixed bed filter and trickling filter

Biofilter type	Basic construction	Pros and cons
Moving bed biofilm reactor (MBBR		Nitrification ++ Filtration - Degassing +
Fixed bed filter		Nitrification + Filtration + Degassing -
Trickling filter		Nitrification + Filtration - Degassing ++ (if aerated)-

12.5.3. Degassing and aeration

The fish tank(s), biofilter and grow bed(s) all need appropriate aeration. There are many ways to provide this, including using airlift pumps, water sprays, paddlewheels, rotors, blowers, and compressors. As with water pumping, water aeration needs to be reliable and energy-efficient. Aeration in smaller systems can be provided by using an energy-efficient and long-lasting air pump and food-grade vinyl tubing connected to airstones placed at or near the bottom of the tanks and grow beds. Air pumps are generally not large enough for aerating larger systems, which tend to use a regenerative blower or an oxygen generator.

In aquaponics, air pumps and air stones are used to force air into the water to provide plant roots and fish with oxygen. Air pumps are widely available in a range of sizes, from very small up to very large with a capacity to run from one to many airstones, each of which introduces hundreds of tiny bubbles of fresh, oxygen-rich air into the solution. While it is easier to push air out of an airstone that is in shallow water, you do not get as much oxygen into the water as you do if the airstone is deeper. When the airstone is deeper the large number of bubbles that come out are smaller because of the higher water pressure, which together have a greater surface area than fewer larger bubbles, and they have to travel further to the surface, with the surrounding water absorbing oxygen from the bubbles all the way to the top of the tank where they burst at the surface.

High efficiency oxygen input

The basic oxygenation technologies are the U-pipe, oxygenation cone, and low head oxygenator (Figures 14-16, Table 7).

Table 7: Characteristics of different possibilities of high efficiency oxygen enrichment in RAS

	U-Pipe	Cone	LHO
Principle	Pressure increase due to water column, long contact path between water and gas	Pump overpressure. Widening cross section keeps bubbles in suspension	Overpressure by means of water column, large contact surface between water and gas
Pressure loss	No	High (2-3 m, 0.2-0.3 bar)	Medium (ca. 1m, 0.1 bar)
Efficiency	High	High	Medium

One simple oxygenation technology to dissolve oxygen into the system water is the **U-pipe** (Figure 14). Oxygen is injected at the bottom of a 10-30 m deep pipe through which the system water flows. Due to the high hydraulic head, the high pressure leads to high dissolution of the oxygen into the water column. However, as this technique requires structures to be built deep into the ground, the method is often not implementable in practice.

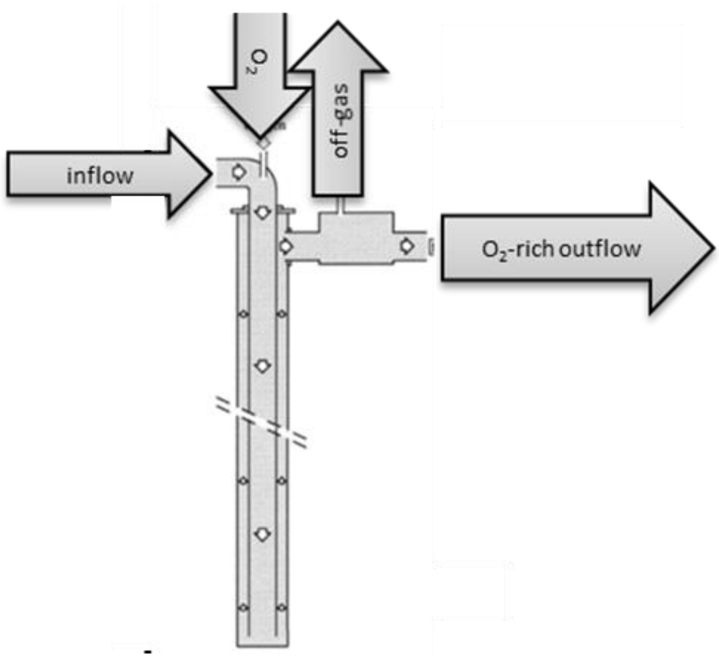


Figure 14: U-pipe

An **oxygenation cone** (Figure 15) uses the same principle as a U-pipe. The difference is that the high hydraulic pressure is induced by a pump (which uses a lot of energy). This technology is especially suited to cover peaks in oxygen demand, and it has a high efficiency in terms of oxygen dissolution.

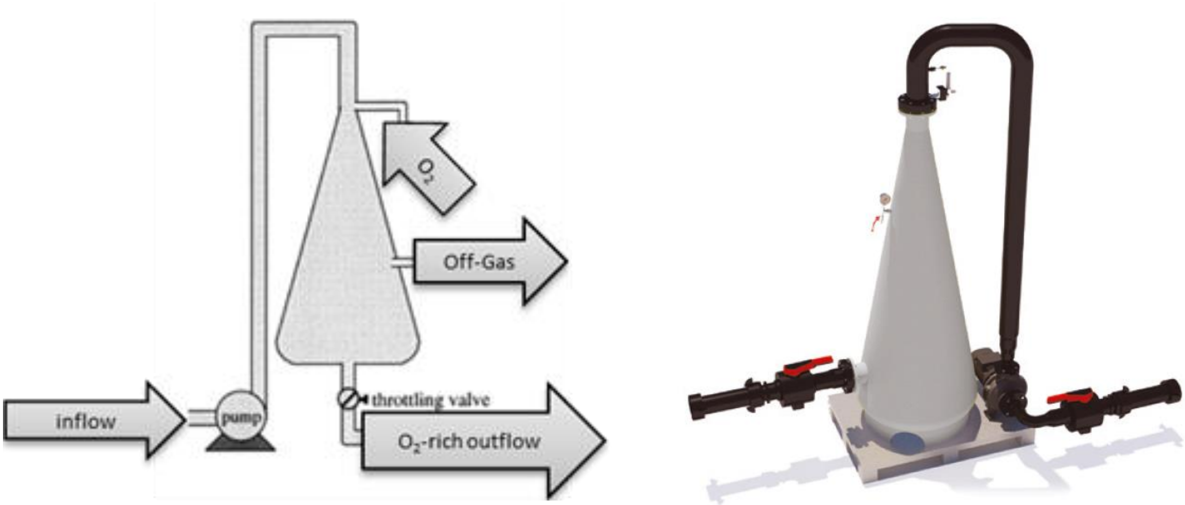


Figure 15: Oxygen cone for dissolving pure oxygen at high pressure
Source: Timmons and Ebeling 2007 (left), Bregnballe 2015 (right)

The **low head oxygenator** (LHO) (Figure 16) uses another method of oxygen enrichment. Water flows through a perforated plate and causes a high water to gas surface area in the mixing chamber below. LHOs operate very economically, although they cannot achieve oxygen concentrations as high as cones can.

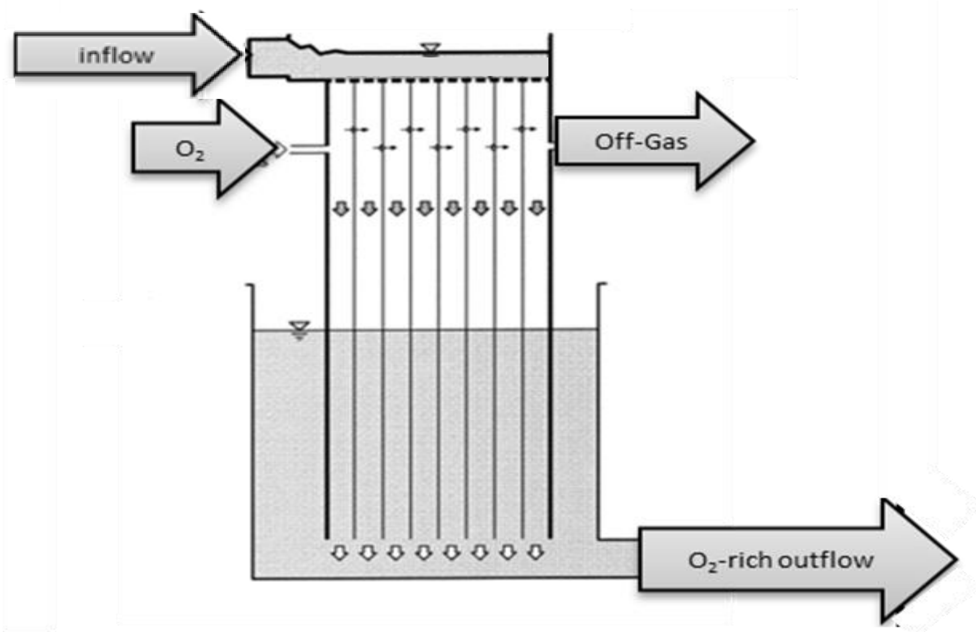


Figure 16: Low head oxygenator

Low efficiency oxygen enrichment

Figure 17 and Table 8 show different possibilities for low efficiency oxygen enrichment.

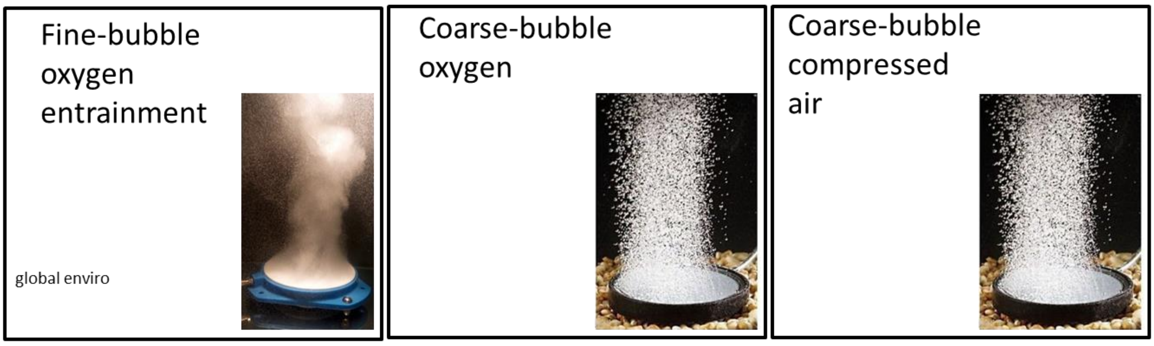


Figure 17: Different possibilities of low efficiency oxygen enrichment in aquaculture

Table 8: Characteristics of different possibilities for low efficiency oxygen enrichment in RAS

	Fine-bubble oxygen entrainment or loading	Coarse-bubble oxygen	Coarse-bubble compressed air
Application	Many fine bubbles that rise slowly and have a high surface to volume ratio	High concentration gradient (because it is pure oxygen). Most of the time used for emergency oxygenation	Does not need pure oxygen but has a low efficiency because air contains only 21% oxygen. The rest is N_2 etc. Can lead to oversaturation with N_2
Pressure loss	1.5 bar	Beginning from 300 mbar + water column	Beginning from 300 mbar + water column
Efficiency	Medium (up to 20%); with high water column up to 100% at approx. 5-10 m	Low (5%)	Very low (1% of total volume)

12.6 The grow beds

12.6.1 Water flow and positioning of the grow beds

Water flow is the most important part of proper system design, and the exact positioning of the grow beds has a major impact on this. Therefore it should be considered carefully and, if possible, an expert should be consulted. The grow beds should be positioned after the biofilter and before the water is recirculated to the fish tank. Consider how the water will flow from the grow bed into the fish tank. If it is by gravity, then the water level in the grow bed must be higher than the fish tank, which may mean that you have to dig the tank and connections into the ground, or that your grow beds will be so high that you would not be able to work comfortably. Usually, a sump tank with a pump is placed after the grow bed to enable water to be pumped into the fish tank. The connection between the biofilter and the grow beds should be as short as possible, and the inlet/outlet should be placed on the opposite sides of each grow bed. One of the advantages of soilless cultures is the possibility to design suitable conditions for working with plants. Ideally, the system should be designed at a height that enables you to monitor the plants easily (Figure 18).

Figure 18: Different levels of grow beds: (left) raised grow beds enable comfortable working; (right) ground level grow beds need no support construction, but are still perfect for production: easy access, lots of light, and deep enough for the roots. Also, if spraying is needed it is on perfect level to do so

(Photo A. Graber, ZHAW)

12.6.2 Construction material

As with fish tanks, the most important aspects are maximum safety for both the fish and the plants, and minimal risk of water leaks that will cause damage. Pond liners are often safe and low cost, but the risk of damage is rather high.

12.6.3 Constructing water inflow and outflow

The diameter of the water inlets and outlets should be large enough to enable water flow quantities designed for the entire system. The inlets and outlets should preferably all be of the same diameter. Every hole is a risk for water leaks if the sealing is not appropriate. This risk should be avoided by drilling as few holes in the system as possible.

12.7 Connections, water movement and aeration

12.7.1 Plumbing

PVC pipes are most commonly used for plumbing. They are available in many standard sizes, are cost-effective, easy to cut and adapt to a wide range of adapters and connectors, and also usually last a long time. Other materials could also be used, but they must be safe for both the fish and the plants, and for food production. Some general advice about pipes:

- pipes have to be 'just right' – if the pipes are too small there will be a problem with leaks, and if they are too big the solids will not get flushed out because the water pressure will be too low

- flexible pipes are to be avoided in order to reduce water flow risks and biofouling. Biofouling or biological fouling is the accumulation of microorganisms, plants, algae, or animals on wet surfaces (https://en.wikipedia.org/wiki/Biofouling).
- the connections between the different components of the system should be as short and as straight as possible. This allows for smoother water movement. Every curve or loop represents an obstacle for smooth water flow.

12.7.2 Water flow and pumps

Once the aquaponic components are connected and filled with water, the water should maintain a constant and equal level in all components. However, since it must circulate, the water has to be moved by either gravity or pumping. Hydraulic systems design follows the example in Chapter 2. After drawing a process flow diagram, in the detailed design stage each pipe has to be dimensioned, the diameter chosen depending on volume flow and flow speed (calculated earlier), and defined by length, fittings and elbows/bends. Friction losses then need to be calculated. These friction losses have to be compensated for by water pressure difference between the different heights of the water level. Pumping should only be done at one point in the whole recirculation flow (with two decoupled pumps in parallel) to ensure stable flow conditions.

The pump is an extremely important component of the aquaponic system as it ensures reliable water circulation throughout the system. Water needs to be recirculated to supply microorganisms and plants with the necessary nutrients, and to provide fish with an environment free of harmful components. An inadequate or unreliable pump can lead to insufficient or excessive nutrient supply, which can harm the bacteria, fish and plants. Lack of recirculation, or recirculation that is too fast or too slow, will quickly affect all life in the aquaponic system.

There is a wide range of pumps on the market but they can be divided into two main categories: submersible pumps or inline (centrifugal) pumps. Submersible pumps are immersed in the tank water which helps to keep them cool. They are usually less efficient than inline pumps and are more suitable for smaller systems. Inline or centrifugal pumps are air-cooled pumps and are located outside the tank. They can have higher powered engines capable of pumping large quantities of water.

When sizing the pump for the aquaponic system, the flow rate has to be determined first –i.e. how much water the pump can move over a given time period. It is usually measured in litres per minute or litres per hour. The pump should be able to recirculate the entire volume of water in the system. This can vary from 3 times per hour in very intensive systems to only a few times per day in extensive systems. There is no rule of thumb. The only way to calculate the required water recirculation rate is to do a proper mass flow calculation (see Exercise 7). Generally, it is better to purchase a more powerful pump since it will allow for flow adjustments. However, such pumps are expensive.

In order to size your pump it is also important to calculate the head height by calculating all the head losses described in Exercise 7. This head loss has to be compensated for by water level difference, which will be equal to the height of the two water levels the pump has to lift the water in between. Normally the fish tank and growing bed will be at different levels. The greater the distance or the larger the head, the more energy is required to pump the water. Anything that can be done to minimize the head will make the entire system more efficient.

The final step in determining the right pump size is combining the flow rate and head height. Generally, most pumps come with a chart that combines flow rate and head height. If not, then usually the maximum flow rate (Qmax) and maximum pumping height (Hmax) are stated. If you have no pump diagram you have assume the pump has it's optimal pumping efficiency around Hmax/2, which normally around Qmax/2. .

Design example: If you have to recirculate 10 m^3/h for 2 m, then first decide if you want to use one or two pumps. If you want to use two pumps in parallel, each pump has to pump 5 m^3/h for 2 m including friction losses in the pumping pipe. So you need two pumps, each with Hmax = 4 m and Qmax = 10 m^3.

The cost of energy used to run the pump is an important part of the cost structure for running an aquaponic system. It is therefore important to know the electrical consumption of the pump you plan to purchase, which means knowing the number of watts the pump uses. The ideal pump will get the job done while using the smallest amount of energy possible. When purchasing a pump do not forget to also purchase a backup pump in case the first one breaks down, or operate the system with two pumps in parallel (highly recommended) and have one backup pump.

12.7.3.1 Water flow and water level regulation

The target flow velocity in pipes is around 0.7-1 m/s. If it is below 0.7 m/s there is a risk of sludge deposition, while above 1 m/s there is an unnecessary loss of energy by friction. The water flow rate in the system can be adjusted by installing:

– a pump where the flow can be regulated
– a regulation valve
– an electric timer connected to the pump
– a water level float regulator with or without a water level sensor

In aquaponic systems, especially in media growing bed systems, a bell siphon is widely used for water flow and level regulation. Bell siphons allow water from the grow bed to be automatically drained into the fish tank and the pump then takes water from the fish tank into the grow bed. In addition to the automatic regulation of water which greatly saves time and effort, bell siphons have several other benefits when used with aquaponic systems:

- more aeration for the plants' roots
- constant and consistent movement of water
- the process is automatic

- ensures maximum efficiency
- simple and reliable

There are other simple ways to regulate water level using bulkheads, standpipes or loop siphons (Castelo 2018).

12.7.3.2 Problems with water movement

If the water is not circulating or the flow rate is reduced, there can be several reasons; for example:

- the pump is not working
- the propellers of the pump are abrased/damaged by sand/growing media
- there is not enough water in the system
- air bubbles disrupted the water flow
- the pipes are clogged
- there are dead fish in the pipes

12.7.3.3 Water losses and water reserves

Some water will inevitably be lost from the system due to evapotranspiration. The main problems are water losses due to leaks (which are caused by clogging) or pump breakdowns. One must be aware that each and every hole, every seal, every pipe connection and every mechanical damage is a potential danger that can cause a leak. However, if the piping is designed correctly, and properly sealed/glued, then this should not be a problem. It is imperative to test the water flow when starting the system to ensure that there are no leaks.

Also consider what will happen if the pump stops working or if there is a power outage. Where will the water flow? Proper systems design includes a buffer volume at the lowest level of the system (usually the pump sump) to store all water overflowing from the points higher in the system. If properly designed, fish tanks will lose between 5-10 cm of water depth that can be stored by the spare volume of the pump sump and biofilter. This is the reason why the biofilter and pump sump usually look quite empty in a properly designed system. One has to install appropriate alarms and, even better, methods to automatically switch on backup pumps, connected to an electric generator. Lost water has to be topped up every day (1.5% during normal operation, failures not included). A sump tank of adequate volume is therefore needed, or a very reliable connection to another water source.

12.8 Operating an aquaponic system

12.8.1 Basic system maintenance and operation procedures

To ensure that the aquaponic system is running well one should prepare clear operating, maintenance and troubleshooting instructions (manuals), and also checklists of daily, weekly and monthly activities for which records should be kept. This way, different staff members will always know what to do. All observations and tasks performed need to be entered (with specific dates) in a dedicated record book, that must be stored in a visible place. It is especially important to record the chemical and physical parameters of the water, and any changes in the appearance and behaviour of the fish (score sheet). Table 9 lists basic system maintenance and operating procedures.

Table 9: Basic system maintenance and operating procedures

Tasks related to … :	Daily	Weekly	Monthly	Extra
… fish feeding	Feed fish twice a day. After feeding, check how much feed has been eaten. If there is uneaten feed, reduce the amount at the next feeding		Weigh fish every 1-2 months and adjust the amount of feed according to the feeding rate suitable for the size of the fish	In case of a system malfunction stop feeding immediately
… fish behaviour	Check if all the fish are alive. Use a score sheet to evaluate their behaviour during experiments			Have the contact information of your veterinarian accessible at all times
… ensuring water quality for the fish	Check the colour and the smell of water. There should be no sludge in the fish tank	Analyse the water (T, pH, O2, NH_4^+, NO_2^-, NO_3^-). If the levels exceed threshold values, take appropriate action: • If NH_4^+ or NO_2 are too high, do not add fresh water. Stop/reduce feeding and add salt • If O_2 is too low, or NH_3 or T too high, increase aeration and reduce temperature using a plate heat exchanger (not direct water exchange)		If you notice anything unusual, immediately analyse the water. Take action, but bear in mind that fish do not like quick changes. Occasionally clean the fish tank and avoid using chemical cleaning agents
… growing plants	Observe the plants for signs of pests and diseases. Remove leaves with signs of disease or pest infestation. Remove dead leaves. If you detect pests or	Observe the plants for signs of nutrient deficiency. Check the level of the water. Analyse the water. If the values deviate from the optimum, take action (add		Design a yearly planting plan

	disease, take action (see Chapter 8)	fresh water, increase aeration, adjust nutrients)		
… other		Remove sludge from the sludge trap. There should be no sludge in the pipes		Provide shading in summer
… biofilter	Check the aeration (visible air bubbles). Cover the biofilter to shield it from light (prevention of algae growth)	Check the quantity of the sludge on biofilter media		After restarting the biofilter perform daily water analyses (NH4+, NO2-, NO3-) until the nitrate levels stabilize
… water flow/ recirculation system	Observe water flow (the water needs to circulate constantly). Verify the pump interval; shorter interval = better water flow. Check if the pump is synchronized with the valves through which water enters the fish tanks		Check (1) the functioning of the pump and aerator system (2) the state of pipes and valves (3) the functioning of the UV lamp	

12.8.2 System failures and emergency systems

The use of pure oxygen as a backup is the number one safety precaution. The installation is simple, and consists of a holding tank for pure oxygen and a distribution system with diffusers fitted in each tank. If the electricity supply fails, a magnetic valve pulls back and pressurized oxygen flows to each tank, thereby keeping the fish alive. The flow sent to the diffusers should be adjusted beforehand, so that in an emergency situation the oxygen in the storage tank lasts long enough for the failure to be corrected in time. To back up the electrical supply, a fuel driven electrical generator is necessary. It is very important to get the main pumps in operation as fast as possible, because ammonia excreted from the fish will build up to toxic levels when the water is not circulating over the biofilter. It is therefore important to get the water flow up and running within an hour or so.

If there is a power outage, always follow this protocol:

- Check the power lines
- Check the electric fuse
- Do not add fresh water. This will kill your fish by raising your pH and transforming NH_4 to NH_3
- Do not feed the fish under stressful conditions

If there are either pump and/or aerator system failures, follow this protocol:

- In case of pump failure, replace the pump with a spare
- In case of aerator failure, replace the aerator
- Do not feed the fish under stressful conditions
- Do not increase the water flow

Protocol in case of leaks:

- Stop the water flow
- Check the pipes and valves
- Replace the leaking part
- Replace the lost water
- Do not feed the fish under stressful conditions

12.9 References

Bregnballe, J. 2015. *A Guide to Recirculation Aquaculture: An introduction to the new environmentally friendly and highly productive closed fish farming systems*. Food and Agriculture Organization of the United Nations (FAO) and EUROFISH International Organisation.

Castelo, J. 2018. Why You Should Use a Bell Siphon for Aquaponics. *World Water Reserve*, October 3, 2018.

Goddek, S., Schmautz, Z., Scott, B., Delaide, B., Keesman, K.J., Wuertz, S. & Junge, R. 2016. The effect of anaerobic and aerobic fish sludge supernatant on hydroponic lettuce. *Agronomy* 6 (2), 37.

Mann, T. 2017. Aeration, air pumps, blowers, and airstones. *Friendly Aquaponics*, March 28, 2017.

Timmons, M.B. & Ebeling, J.M. 2007. *Recirculating Systems*. Northeastern Regional Aquaculture Center, Ithaca, NY.

Sarah Milliken

13. URBAN AGRICULTURE

13.1 Introduction to urban agriculture

Urban agriculture takes many forms. These can range from household, school and community gardens to rooftop and indoor farms. A fundamental distinction is often made between urban agriculture (involving food production in an urban area) and peri-urban agriculture, which occurs on the fringes of cities. In the case of the latter, farming is largely undertaken by professional farmers on land that has often already been used for farming for decades. An urban farm is a part of a local food system where food is cultivated and produced within an urban area, and marketed to consumers predominantly within that urban area. Besides growing fruit and vegetables, urban farming can also include animal husbandry, beekeeping, aquaculture, and non-food products such as producing seeds, cultivating seedlings, and growing flowers. It can be characterized in terms of the geographic proximity of a producer to the consumer, and sustainable production and distribution practices. Urban farms can take a variety of forms, including non-profit gardens and for-profit businesses. They can provide jobs, job training, and health education, and they can contribute to better nutrition and health for the community by providing locally grown, fresh produce (McEldowney 2017). This chapter focuses on commercial food production within urban areas and, specifically, on rooftop greenhouses and other types of indoor farms.

As towns and cities continue to grow both in population and surface area, their infrastructural needs for transporting and distributing food are constantly spreading, pushing food production further and further away from the urban consumer and generating globalized food systems that contribute to 19-29% of global greenhouse gas emissions (Vermeulen *et al.* 2012). Currently, the flow of food to cities follows a linear model, resulting in a high consumption of energy resources and the generation of waste and CO_2 emissions. Over two-thirds of the global population are projected to be living in cities by 2050, and with some experts being sceptical about the capacity of the biosphere to produce enough food for the entire human population, interest in local production to contribute to sustainable urban food systems has re-emerged among decision-makers. Urban horticulture has historically always contributed to the supply of fresh produce to urban dwellers, but recently it has been gaining popularity in the Global North, with growing awareness of environmental and health concerns. Over the past few years, commercial farms have been emerging in major northern cities, promoting a trend of environmentally friendly local food, grown in highly efficient installations on top of or inside buildings. Urban agriculture also provides opportunities for a closed cycle of resources in the urban metabolism, in stark contrast to the traditional unidirectional flow. Figure 1 shows the role of urban agriculture in an ideal resource circulation system: the red arrows indicate the unidirectional flow of classic urban metabolism, while the green arrows indicate the closed cycle in the urban metabolism with urban agricultural production, whereby waste can be transformed into biogas, digestates and technogenic (manmade) soils which can then be used for further agricultural production, all within the city itself. These ideas will be explored in more detail later in this chapter.

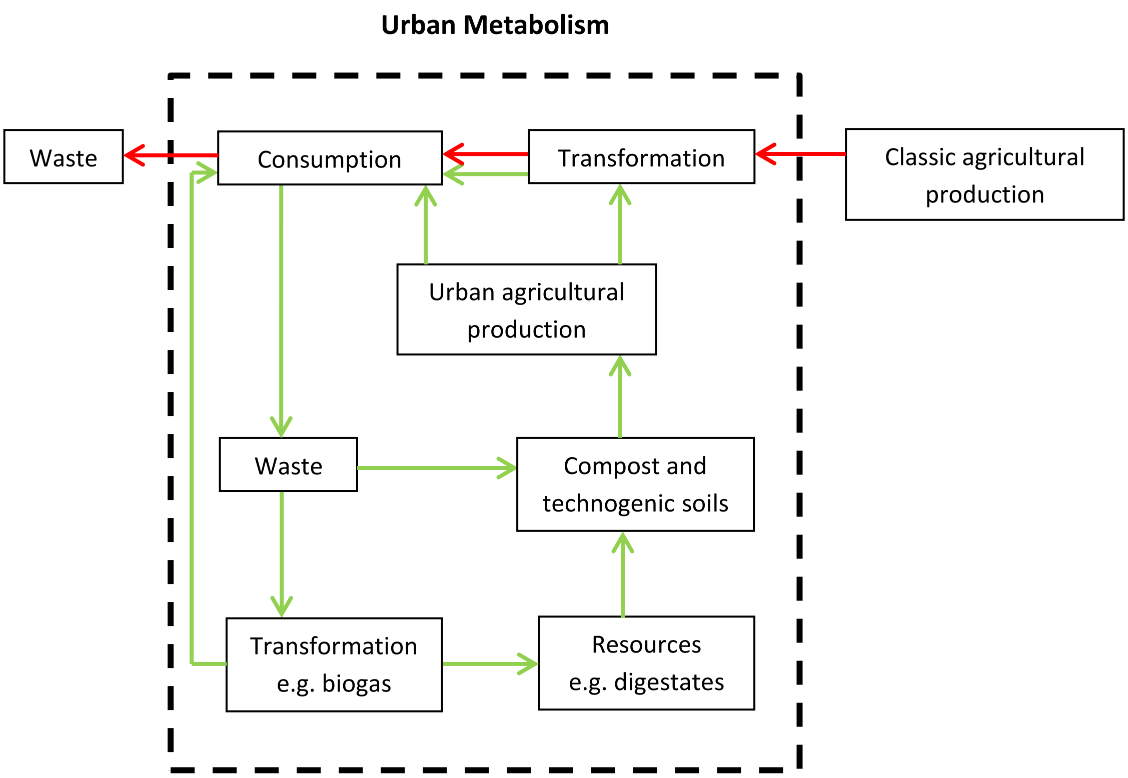


Figure 1: The role of urban agriculture in an ideal resource circulation system (after Nehls *et al.* 2016)

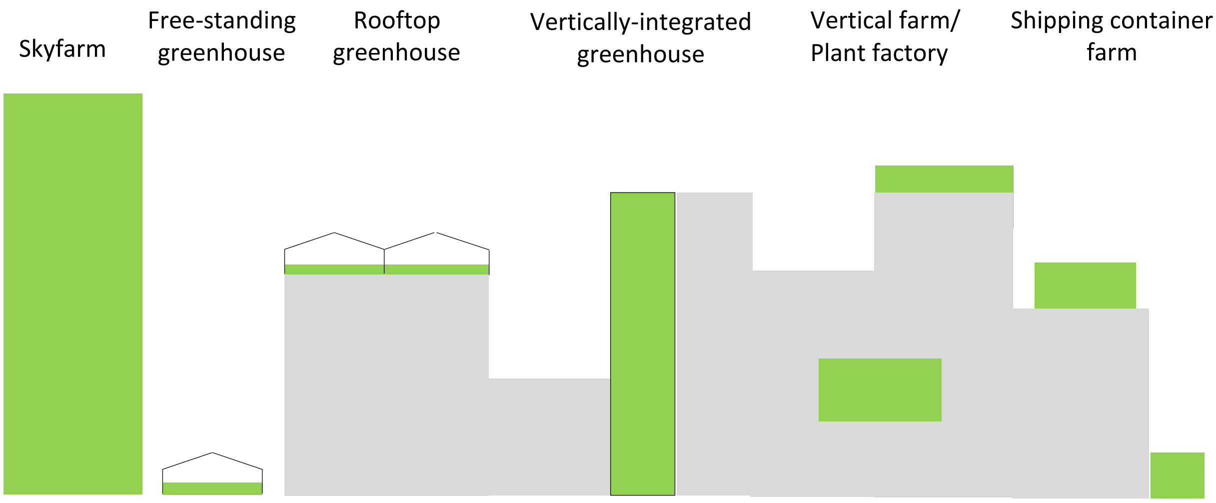


Figure 2: Typologies of commercial indoor farms

13.2 Typology of commercial indoor urban farms

Building-integrated agriculture (BIA) predominantly uses soilless cultivation techniques such as hydroponics, aquaponics or aeroponics. The benefits of BIA include year-round production, higher yields, greater control of food safety and biosecurity, and substantially reduced inputs with respect to water supply, pesticides, herbicides, and fertilizers, as well as improved building energy efficiency through the creation of symbiotic relations between the farm and its host building. BIA systems can be applied either on the building envelope – on the rooftop or facades, to take advantage of the availability of natural light – or indoors with artificial light, or in a free-standing building (Figure 2), and all the growing parameters are controlled. This is known as Controlled-Environment Agriculture, or CEA, which combines horticultural and engineering skills in order to optimize crop production, crop quality and production efficiency.

13.2.1 Rooftop greenhouses

Among the several existing forms of BIA, rooftop greenhouse farming is one of the most popular, since rooftops represent a considerable unutilized urban area, and lightweight hydroponic greenhouses do not necessitate any significant structural reinforcement of the host building (Benis & Ferrão 2018). The rooftop is an ideal landscape for growing plants in dense cities, as it typically has greater exposure to solar energy than the ground below. While yields from hydroponic greenhouses are higher than those from open-air soil-based rooftop farms, the range of vegetables that can be grown is smaller, and tends to be restricted to leafy greens, microgreens, herbs, tomatoes, cucumbers, aubergines, peppers and strawberries (Buehler & Junge 2016). Hydroponic greenhouses are often provided with climate control systems, such as fans, heaters, evaporative cooling, thermal screens, and operable windows, in order to condition the indoor air and achieve the optimal temperature, relative humidity, and carbon dioxide levels, regardless of outside conditions. They are heated with natural gas or electricity, with potential backup through photovoltaic (PV) panels. State-of-the-art installations capture waste heat from the building's HVAC system, and may be constructed with solar glass, which collects specific wavelengths of sunlight for generating electricity, while transmitting and diffusing other wavelengths into the greenhouse (Figure 3).

Several North American companies have already proven that significant amounts of food can be produced year-round for urban dwellers on unutilized rooftops in dense urban settings where available and affordable land is a rare commodity. Lufa Farms built the world's first commercial rooftop greenhouse on an industrial building in Montreal, Canada, in 2011. The 2880 m^2 greenhouse is used to grow a variety of different vegetables. They have since built two more, one designed to maximize tomato production (3995 m^2), and another designed for growing leafy greens (5853 m^2). Each of their greenhouses, which house NFT hydroponic systems, was designed to be not only bigger, but lighter, cheaper, and more efficient. In the US Gotham Greens operates 16,000 square metres of urban rooftop greenhouses across 4 facilities in New York City and Chicago, also using NFT hydroponics. Their flagship greenhouse, built in New York City in 2011, was the first ever commercial-scale greenhouse built in the United States. The 1394 m^2 facility produces more than 45,000 kg of leafy greens per year. Designed and built with sustainability at the forefront, the facility's electrical demands are offset by 60 kW of on-site solar PV panels, and high efficiency design features including LED lighting, advanced glazing, passive ventilation and thermal curtains all help to reduce electrical and heating demand. Rooftop integration further reduces energy use while also serving to insulate the building below. Gotham Greens' second greenhouse, built in 2013, is the first commercial scale greenhouse to be built on top of a supermarket. Measuring over 1858 m^2, it produces more than 90,000 kg of leafy greens, herbs and tomatoes each year. Their third and largest New York City greenhouse spans 5574 m^2 and grows more than 5 million heads of leafy greens each year. This is dwarfed by their Chicago greenhouse, which at more than 6968 m^2 represents the world's largest and most productive rooftop farm, growing up to 10 million heads of leafy greens and herbs.

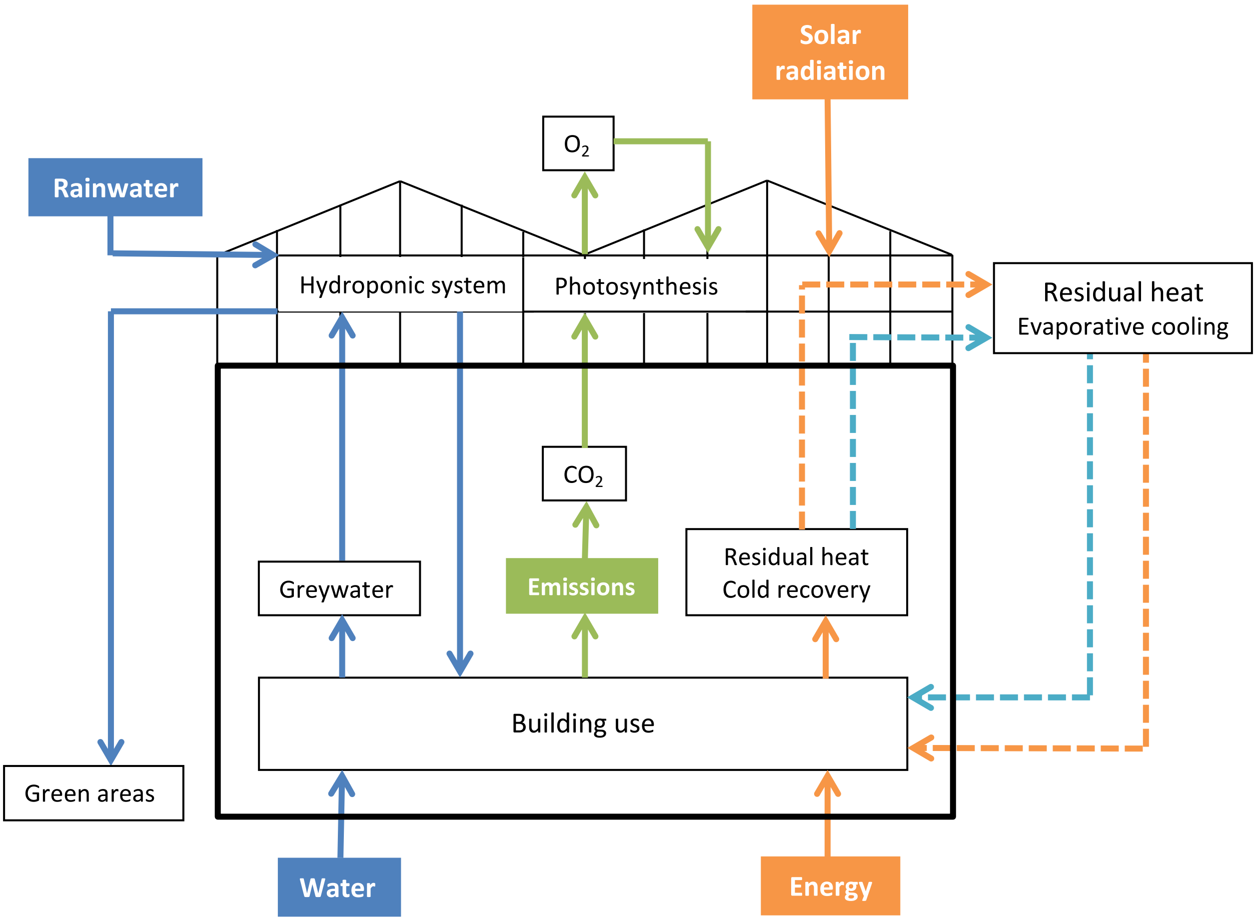


Figure 3: The potential interchange of water, energy and gas flows between the rooftop greenhouse and the host building (after Céron-Palma *et al.* 2012)

New York City hosts three other hydroponic rooftop greenhouses. Sky Vegetables grows herbs and greens, while The Vinegar Factory grows tomatoes, strawberries, herbs and greens. A rooftop greenhouse has recently been constructed on Arbor House, a block of affordable housing in New York City. Located in a neighbourhood with a disproportionately high number of low-income people with high rates of obesity, diabetes and heart disease, the 929 m^2 hydroponic farm will function as a Community Supported Agriculture (CSA) arrangement, in which the residents can purchase the produce through a weekly vegetable box subscription scheme. About 40% of the produce will be made available to the local community through outreach to nearby schools, hospitals, and markets. Edenworks is an aquaponic rooftop greenhouse farm, also in New York City, which grows microgreens.

In Europe Swiss start-up UrbanFarmers housed their pilot commercial aquaponic farm, UF001 LokDepot, in a rooftop greenhouse in Basel. The 260 m^2 growing space had an annual production capacity of 5000 kg of vegetables, while the aquaculture system had a capacity of 800 kg of fish.

Berlin-based start-up ECF Farmsystems has built two aquaponic rooftop greenhouses. Eco Jäger, which opened in Bad Ragaz, Switzerland, in 2016, grows lettuce, herbs and trout for restaurants, hotels and catering companies. BIGH opened in Brussels in 2018, and produces lettuce, herbs and hybrid striped bass for restaurants, the food retail market, and direct farm sales. The first urban rooftop greenhouse in France will open in 2019. Toit Tout Vert is situated in a residential part of Paris, and the produce from the 1400 m^2 growing space will be sold in local shops.

13.2.2 Free-standing greenhouses

Vacant urban lots also provide opportunities for free-standing greenhouses. Metropolitan Farms is located on a former carpark in Chicago. The aquaponic greenhouse produces lettuce, basil and tilapia which is sold through farmers markets, local food co-ops and speciality grocery stores. In Europe ECF Farmsystems operates an aquaponic greenhouse in the heart of Berlin. ECF Farm Berlin, which opened in 2015, has a footprint of 1800 m^2 and is used to grow basil and perch destined for the food retail market.

13.2.3 Vertical farms and plant factories

The concept of 'vertical farming' was introduced in 2010 by Dickson Despommier in his book *The Vertical Farm: Feeding the World in the 21st Century*. Vertical farms may be located in a greenhouse or inside a building, and use various different technologies to grow plants on a vertical plane in order to maximise yield in relation to the surface area of the production unit (see Chapter 14 for details of these vertical growing system technologies). In theory, vertical farms may also be placed on the façade of a building in the form of a Vertically-Integrated Greenhouse (VIG), which consists of double skin building facades combined with hydroponic systems. However, while VIGs have been developed as a concept and patented, none have yet been built. Vertical farms could also be in the form of purpose-built skyscrapers (sometimes called 'skyfarms'). Again, such utopian visions have yet to come to fruition. This is due, in large part, to the fact that such projects are not economically feasible.

Stockholm-based Plantagon has patented a number of designs for skyfarms. Construction of the World Food Building (Figure 4), a 60 metre tall office tower that doubles as a vertical farm, started in 2012 in the Swedish town of Linköping and was due to be completed in 2020. The $40 million building was intended to demonstrate the company's approach to urban architecture, which it calls 'agritechture' – a portmanteau word combining the terms agriculture, technology and architecture. The north-facing side of the building would contain 17 floors of office spaces, while a sloped glass facade would cover the south side to allow the maximum amount of sun to pass into the farming areas. A nearby waste incineration and bio-gas plant would provide the building with heating, as well as fuel for food-production, while the waste from the greenhouse would then be sent to the biogas plant for composting, thereby creating a circular movement of energy. However, the company went bankrupt in 2019, which raises questions about whether construction of the World Food Building will ever be completed.

Skyfarms are most likely to materialise first in Asian megacities such as Singapore and Shanghai. As a small island of only 750 km^2 and a population of over five million, Singapore faces potential issues of food security. With land at a premium, only 0.9% of the island is devoted to farming, which produces only 7% of the food it consumes. The remaining need is supplied by food imports from all over the world. However, the transportation costs of food are becoming increasingly prohibitive and, for these reasons, Singapore has been taking vertical farming seriously. The city's first farm, Sky Greens, started production in 2012, and the number of vertical farms grew from six in 2016 to 26 in 2018 (Wei 2018).

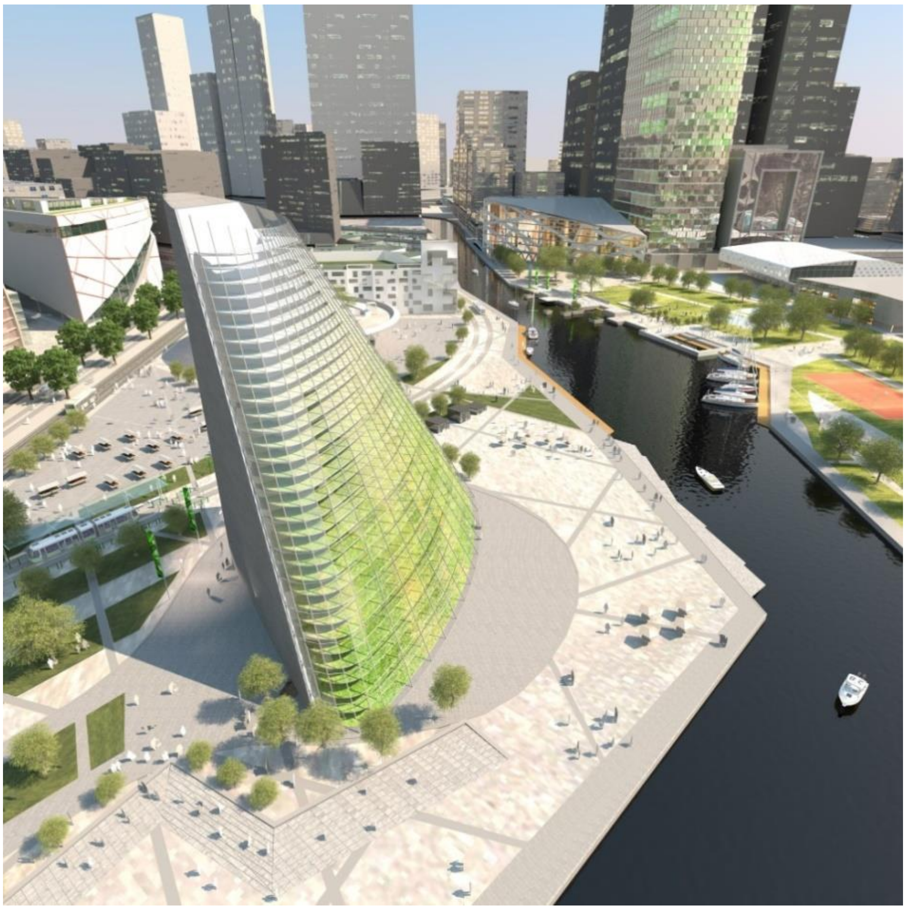


Figure 4: Rendering of the World Food Building in Linköping, Sweden
www.plantagon.com

Shanghai is another ideal city for vertical farming. With nearly 24 million inhabitants to feed and a decline in the availability and quality of agricultural land, high land prices make building upwards more economically viable than building outwards. Urban planners Sasaki Associates have developed a masterplan for the Sunqiao Urban Agricultural District. Located between the main international airport and the city centre, the 100 hectare district will include 66,611 m^2 of housing, 12,820 m^2 of commercial space, 69,956 m^2 of vertical farms, and 79,525 m^2 of public space. While primarily responding to the growing agricultural demand in the region, Sasaki's vision goes further, using urban farming as a dynamic living laboratory for innovation, interaction, and education, and deploys a range of urban-friendly farming techniques, such as algae farms, floating greenhouses, vertical seed libraries, and hydroponic and aquaponic vertical farms which will be used to meet the demand for leafy greens in the typical Shanghainese diet (Figures 5 and 6). The scale of Sasaki's approved scheme indicates the increased value placed on China's agriculture sector. China is the world's biggest consumer and exporter of agricultural products, with the industry providing 22% of the country's employment, and 13% of its Gross Domestic Product. The Chinese government is therefore keen to preserve, modernize, and showcase an industry which has helped to significantly reduce poverty rates. Construction of the district began in 2018 and is due to be completed in 2038.

Figure 5: Rendering of the Sunqiao Urban Agricultural District in Shanghai
http://www.sasaki.com/project/417/sunqiao-urban-agricultural-district/

Figure 6: Rendering of the Sunqiao Urban Agricultural District in Shanghai
http://www.sasaki.com/project/417/sunqiao-urban-agricultural-district/

While skyfarms remain a vision for the future, commercial plant factories are operational in both rural and urban locations in North America, Europe, East Asia and the Middle East. Plant factories are a type of closed plant production system in which ventilation is kept at a minimum, and artificial light is used as the sole light source for plant growth. The environment can be controlled as precisely as desired, regardless of the weather. In addition to the recirculating nutrient solution in a hydroponic system, the water transpired by plants can be condensed and collected at the cooling panel of air conditioners and then recycled for irrigation. Typically plant factories consist of 6 principal components: a thermally insulated and nearly airtight warehouse-like opaque structure; between 4 and 20 tiers of vertically stacked hydroponic culture beds equipped with either fluorescent or LED lamps; air conditioners (heat pumps) used for cooling and dehumidification to eliminate heat generated by the lamps and water vapour transpired by the plants, and fans for circulating air to enhance photosynthesis and transpiration, and to achieve a uniform spatial air distribution; a CO_2 supply unit to maintain CO_2 concentration at around 1000 mmol/L during the photoperiod for enhancing photosynthesis; a nutrient solution supply unit with water pumps; and an environmental control unit including electrical conductivity (EC) and pH controllers for the nutrient solution. While fluorescent lamps have mainly been used due to their compact size, LEDs are being increasingly used due to their low lamp surface temperature, high light use efficiency, and broad light spectra. The latest plant factories are using advanced robotic technologies including remote sensing, image processing, intelligent robot hands, cloud computing, big data analysis, and 3-D modelling (Kozai 2013).

The plants grown in plant factories need to be shorter than around 30 cm in height, because the distance between the vertical tiers is typically around 40 cm, which is the optimum height for maximising the use of space. Plants suitable for commercial production using plant factories are those that grow well at relatively low light intensity, thrive at a high planting density, are fast growing (harvestable 10-30 days after transplanting), and for which most parts (85% in fresh weight) are edible and saleable at a high price. In Japan and other Asian countries, plant factories are therefore being used for the commercial production of leafy greens, herbs, medicinal plants, and transplants. Small plant factories with a floor area of only 15-100 m^2 are also widely used for commercial production of seedlings in Japan, since the seedlings can be produced in a short time at a high planting density. Grafted and non-grafted seedlings of tomato, cucumber, aubergine, seedlings of spinach and lettuce for hydroponic culture, and seedlings and cuttings of high-value ornamental plants are all produced commercially in these small plant factories (Kozai 2013; Kozai *et al.* 2016).

In North America Plenty, Planted, Oasis Biotech, FreshBox Farms and We the Roots operate urban plant factories in former warehouses, while AeroFarms is in a former steel factory. Fresh Impact Farms is inside a suburban shopping mall, and Farm.One is in the basement of a restaurant. In Europe, PlantLab in 's-Hertogenbosch, Netherlands, is a 20,000 m^2 plant factory and R&D facility in a vacant factory and warehouse space. The farm uses advanced LED technology that calibrates light composition and intensity to precise needs, and employs an automated system that monitors and controls more than 80 different variables, including humidity, CO_2, light intensity, light colour, air velocity, irrigation, nutritional value, and air temperature, in order to improve plant yield and quality. GROWx in Amsterdam grows microgreens, herbs and lettuce in a warehouse that are harvested to order for elite restaurants. In London GrowUp Urban Farms operated a commercial aquaponic farm in a warehouse, and Growing Underground grows microgreens in a Second World War air raid shelter 33 metres below street level. La Caverne is an underground farm in a carpark under Paris which grows mushrooms, endive and microgreens.

Vertical farms can also be operated in greenhouses, in order to take advantage of natural light; the environment is therefore only semi-controlled. Examples include Vertical Harvest in the US, and Sky Greens in Singapore. Opening in 2019, Tour Maraichère in the Parisian suburb of Romainville is a purpose-built greenhouse consisting of two units, the tallest of which is 24 metres (Figure 7). The 2060 m^2 of growing space will produce 12 tonnes a year of fruit, vegetables, mushrooms and edible flowers, and the greenhouse will be used to showcase a short food production chain, to provide local residents with fresh food with a low ecological footprint, to reduce the use of road transport, and to generate jobs.

Figure 7: Rendering of Tour Maraichèchere, Paris
http://ilimelgo.com/fr/projets/tour-maraichere.html

13.2.4 Container farms

Another emerging trend in the field of urban farming is container farms, which also use vertical farming technologies. Equipped with state-of-the-art climate control technology and hydroponic growing towers or stacked NFT channels, container farms allow for year-round production and can be installed on vacant lots or on rooftops. The advantages of shipping containers include their compactness and modularity, large availability and, if using repurposed ones, their low cost. Since they are modular they can be easily stacked, so it is theoretically possible to create a very high density and high yield farm, although this opportunity has not yet been embraced. The CropBox system is a repurposed shipping container which has a footprint of 30 m^2 and uses an array of horizontal NFT channels; it can grow 5445 kg of lettuce, 3175 kg of strawberries, or 84 tons of microgreens a year. The Tiger Corner Farms system also uses a repurposed shipping container, but differentiates itself by using vertical aeroponic technology to grow between 3800 and 7600 crops per growing cycle. Freight Farms originally used repurposed containers (Leafy Green Machine) but now sells purpose-built containers (Greenery) with improved insulation and a more efficient climate control system. Both systems use vertical growing towers, and can house up to 4500 mature plants. The Leafy Green Machine has been adopted by a number of urban farms in North America to grow leafy greens and herbs, including Square Roots, Corner Stalk Farm, Acre in a Box, Very Local Greens, Bright Greens and Enlightened Crops. A third US company, GreenTech Agro, sells the Growtainer, a custom-built container which comes in four sizes – 6, 12, 13.7 and 16 metres – and uses a proprietary lightweight aluminium stack of grow beds. One such system has been installed at Central Market in Dallas where it is used to grow leafy greens and herbs which are then sold in the supermarket. The containers are manufactured in the US and in Rotterdam.

In Europe Agricool uses shipping containers to grow strawberries in Paris. IKEA, the world's largest furniture retailer, has started to grow lettuce in containers outside its stores in Sweden which are then served in the in-store restaurants (Thomasson 2019), and Swedish supermarket ICA Maxi has started selling leafy greens and herbs grown in containers outside its store in Halmstad (Jachec 2019). Belgian start-up Urban Crop Solutions has developed two container farm systems; FarmFlex and FarmPro. FarmFlex is a container farm that requires manual labour, while FarmPro is fully robotized and looks more like a plant factory inside a shipping container.

UrbanFarmers developed an urban aquaponic farm system consisting of a container with a greenhouse on top, called the UF Box. This system has been emulated by British start-up GrowUp Urban Farms: the GrowUp Box can produce 435 kg of greens and 150 kg of fish each year. Gembloux Agro-Bio Tech at the University of Liège in Belgium has been trialling a similar system, the PAFF Box (Plant and Fish Farming Box) (Delaide *et al.* 2017). In Canada Ripple Farms produces tilapia, greens and microgreens using a shipping container and rooftop greenhouse system in Toronto.

13.3 The sustainability of commercial indoor urban farms

Supplying urban populations with locally grown food is widely viewed as a more resource-efficient alternative to the conventional supply chain using food grown in peri-urban or remote rural locations. Indoor, soilless cultivation in urban areas is portrayed as a particularly sustainable solution, by reducing food miles, minimizing land use and water consumption, and improving yields. However, to ensure optimal growing conditions for the crops, controlled-environment farms all rely on the artificial control of light, temperature, humidity and water cycles, and can therefore be highly energy intensive, depending on local climatic conditions and the specific characteristics of the host building. The carbon emissions of urban farms should therefore be carefully weighed against potentially reduced emissions, such as those from transporting food from rural and peri-urban farms. The elevated economic costs of urban farms, both in terms of infrastructure and operational costs, also need to be carefully assessed before undertaking such a venture.

13.3.1 Environmental sustainability

Located within the city and therefore closer to the consumer, high yield urban agriculture is often claimed to have a lower carbon footprint than rural food production, by cutting transportation distances ('food miles'). However, depending on local climate conditions and urban farm typology, crop production in controlled environments can also be highly energy-intensive, which can considerably exacerbate its environmental impacts. The net carbon footprint depends on emissions caused by energy use for farm operation versus avoided emissions related to the existing supply chain, including the operational energy of the farms supplying the produce, and the energy used in transporting it. This can be illustrated by two examples from very different climatic zones in Europe. When the Global Warming Potential (GWP) related to the water, transportation and operational energy of three hi-tech urban farming scenarios in Portugal – a polycarbonate rooftop greenhouse, a vertical farm with windows and skylights on the top floor of a building, and a completely opaque vertical farm with no penetration of natural light on the ground floor of a building – were compared with the GWP of the current supply chain for tomatoes, and with a hypothetical low-tech unconditioned rooftop urban farm, the top floor vertical farm and the rooftop greenhouse had the best overall environmental performance, respectively cutting greenhouse gas emissions by half and by a third in comparison with the existing supply chain for tomatoes (Benis *et al.* 2017). These findings corroborate the results of a life cycle assessment of a rooftop greenhouse in Barcelona (Sanyé-Mengual *et al.* 2013; Sanyé-Mengual *et al.* 2015a). In contrast, Theurl *et al.* 2013 found that the production of tomatoes in heated greenhouses in Austria generated double the greenhouse gas emissions compared with the supply chain of tomatoes imported from Spain and Italy. Therefore, it is essential to keep in mind that while urban agriculture is claimed to be sustainable for cutting transportation distances, such energy intensive facilities may not be appropriate to every location, as the former does not consistently offset the latter.

However, the environmental performance of Building-Integrated Agriculture can potentially be enhanced by coupling flows of the agricultural practices – heat, water, CO_2 – with flows of the host building, and by optimizing the efficiency of the system through the implementation of passive conditioning methods, such as thermal insulation, natural ventilation, evaporative cooling, and the use of highly energy-efficient technologies, such as LED lighting.

13.3.2 Economic sustainability

The economic feasibility of commercial farms in urban contexts has to be evaluated taking into account the higher capital expenditures – in comparison with conventional rural farms – that are intrinsically related to their urban location. In a context of rapid urbanization, urban space is scarce and highly coveted, and the primary need that is generally sought to be fulfilled by municipalities is housing rather than food production, which is instead pushed further and further away from urban centres. While rooftop-integrated farming systems have to compete with other rooftop-integrated technologies such as solar photovoltaics or solar thermal, indoor systems compete with other urban uses which are usually more economically attractive than agriculture, like residential or commercial functions. Such a high competition for urban plots and buildings makes real estate ever more expensive (Benis & Ferrão 2018).

Around the world, the price of land is generally high in urban areas. Besides the elevated rents, high-tech commercial urban farming is a capital-intensive industry, as it involves the adaptation of the host building for cultivation, in accordance with local municipal regulations and building codes. This urban constraint was identified as one of the major barriers to the large-scale implementation of BIA (Cerón-Palma *et al.* 2012). The cost-effectiveness of the urban farm will depend on its typology. Plant factories need only 10% of the land area compared with greenhouses for obtaining the same productivity/m², and can easily be built in any disused building. While capital costs are high[1] – about 15% greater than that of a greenhouse – annual productivity is about 3000 lettuce heads/m²/year, which is 15 times that of a greenhouse (about 200 lettuce heads/m²/year). Thus the initial cost per unit production capacity of a plant factory is more or less the same as that of a greenhouse, although this estimation is rough and varies with many factors (Kozai *et al.* 2016).

In addition to involving high investment costs, high-tech commercial farming systems often lead to substantial operating costs due to their elevated energy needs (Thomaier *et al*. 2015). Moreover, whereas rural farms usually benefit from subsidized water and energy for agriculture, farms located in urban areas have to pay the urban costs of water supply and energy, applicable in accordance to the zoning. If the farm is located in a residential zone, then the costs will be higher than if it is located in a commercial zone (Benis & Ferrão 2018).

Productions costs (labour, electricity, depreciation, and others) vary around the world. In Japan, for example, the component costs of plants factories are, on average, 25-30% for labour, 25-30% for electricity, 25-35% for depreciation, and 20% for other production costs (land rent, seeds, water, lamp replacement, office goods, packing materials, delivery costs, etc.). Labour costs are so high because most plant factories are small-scale, and handling operations therefore have to be conducted manually. It is estimated that a 15-tier plant factory with a floor area of 1 ha needs more than 300 full-time employees. In comparison, most handling operations in a greenhouse complex with a floor area of 10 ha or more are automated, and so need only a few employees per hectare (Kozai *et al.* 2016).

Table 1 shows the energy conversion process in a culture room of an energy-efficient plant factory. The electrical energy fixed as chemical energy in the saleable part of the plants is 1-2%. The remaining electric energy is converted into heat energy in the culture room, so the heating cost of a thermally well-insulated plant factory is zero. In plant factory production cost management, the weight percentage of the edible or usable part of the plant to the total plant weight is an important index for improving cost performance. Since electric energy is consumed to produce the roots, if the

[1] about US$4000/m² in 2014 (Kozai *et al.* 2016)

roots are not saleable, the root mass must be minimised without compromising the growth of the aerial part of the plant.

Amount of energy consumed by lamps	100%
Light energy emitted by lamps	25-35%
Light energy absorbed by leaves	15-25%
Chemical energy fixed in plants	1.5-2%
Chemical energy contained in saleable part of plants	1-2%

Table 1: The energy conversion in a plant factory (from Kozai *et al.* 2016)

The electricity cost can be reduced by (1) using advanced LEDs to improve the conversion factor from electric to light energy; (2) improving the lighting system with well-designed reflectors to increase the ratio of light energy emitted by lamps to that absorbed by plant leaves; (3) improving the light quality to enhance growth and the quality of the plants; (4) optimally controlling temperature, CO_2 concentration, nutrient solution, humidity, and other factors; and (5) increasing the percentage of the saleable part of the plants by improving the culture method and selection of cultivars (Kozai *et al.* 2016).

Electricity costs can also be reduced by using solar panels. Urban plant factories in free-standing buildings, such as former warehouses and factories, have more possibilities for generating their own electricity than those located in buildings which are part of a dense urban matrix. The amount of energy required to power free-standing plant factories is contingent on the dimensions of the building. When a building occupies a larger area, the lighting and water requirements increase, but so does the amount of energy available via solar panels on the roof and, potentially, the facade. The amount of power that can be generated by solar panels obviously depends on the geographic location of the plant factory.

The net water consumption for irrigation in a plant factory is about 2% of that of a greenhouse, because about 95% of the transpired water vapour from the plant leaves is condensed at the cooling panel (evaporator) of the air conditioners as liquid water, which is collected and then returned to the nutrient solution tank after sterilization. Drained nutrient solution from the culture beds is also returned to the nutrient solution tank after sterilization. Thus the amount of water that needs to be added to the tank is equal to the amount of water kept by the harvested plants, and the amount that escapes outside as water vapour through air gaps. Similarly, the amount of nutrient that is added is equal to the amount of nutrients absorbed by the harvested plants. Thus the efficiency of water and nutrient use is more than 0.95 and 0.90 respectively (Kozai *et al.* 2016).

13.3.3 Urban farming and the circular economy

The circular economy is currently one of the most discussed terms among environmental economic scientists and is a focus of the European Union Horizon 2020 strategy. Its core defining element is the 'restorative use' of resources: instead of becoming discarded waste, raw materials are recycled and reused (Geisendorf & Pietrulla 2018). Urban agriculture offers various possibilities for embracing this approach, which is best exemplified by The Plant. In 2010, social enterprise Bubbly Dynamics LLC acquired a former meatpacking plant in Chicago and developed a plan to use the building as a space for incubating food and farming businesses, thereby bringing much-needed jobs back to a disinvested community in a 'food desert' lacking healthy food options. The 8686 m^2 facility currently houses over a dozen small businesses, including indoor and outdoor farms, kombucha and beer breweries, a bakery, a cheese distributor, a coffee roaster, and other food producers and distributors. As of early 2018, there were approximately 85 full-time equivalent employee positions based at the facility. The Plant is still under construction and is approximately 70% leased out; full occupancy is expected in 2019.

Founded on a model of closing waste, resource, and energy loops, The Plant is working to show what truly sustainable urban food production looks like. The planned anaerobic digester is a key feature, as it is designed to solve several critical issues by reusing what is conventionally considered 'waste' in order to create several valuable outputs. Waste from the building will be a fraction of the volume of waste processed by the digester, yet the digester will demonstrate that even food production businesses, which are typically waste and energy intensive, can operate sustainably by closing waste loops. Figure 8 is a conceptual diagram of the various processes anticipated at The Plant at full occupancy.

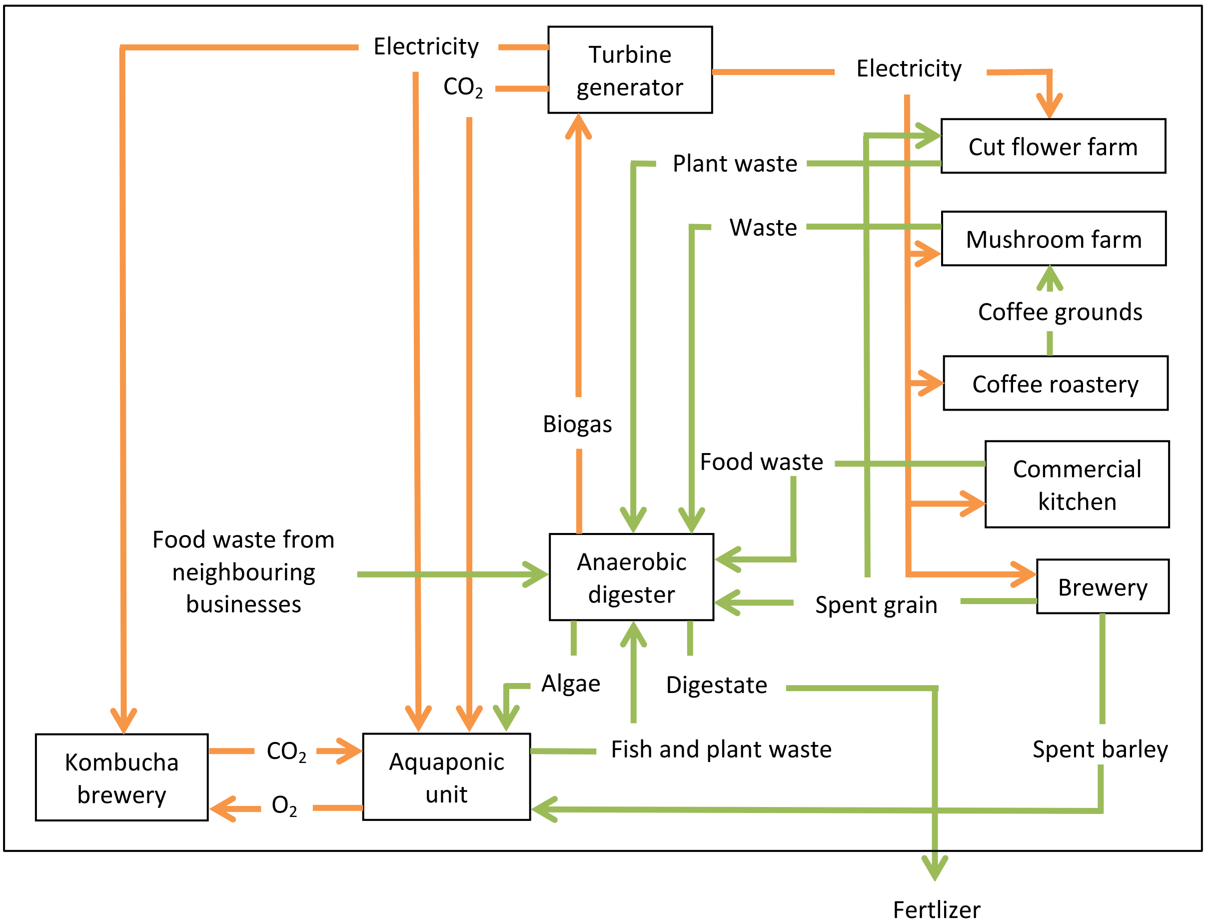


Figure 8: Waste (green) and energy/gas (orange) cycles at The Plant, Chicago

13.4 Legislation and governance

A range of factors – existing urban layout, perceptions and attitudes towards the use of urban space, and the prevalent political climate – all operate at the city-specific level to influence the development of urban agriculture. In most countries in the Global North there is no independent category for urban agriculture in municipal zoning plans, as agriculture has historically been regarded as a rural activity by urban planners. Urban agriculture in Europe appears to fall between different policy areas, despite assurances from the European Commission that Member State rural development programmes can be used for the benefit of urban agriculture. To some, it may not be sufficiently agricultural in nature to secure support under Pillar I of the Common Agricultural Policy (as typified by more conventional agriculture). To others, it is not considered sufficiently rural to secure support under the above-mentioned rural development programmes. Looking to the future, the challenge for urban agriculture is how to achieve the necessary integration across all EU policy areas over the next programming period, post-2020 (McEldowney 2017). The urban agriculture sector in Europe is therefore characterized by bottom-up initiatives, which are informal and non-institutionalized. Although urban agriculture is beginning to be recognised at the institutional level in some countries, there is still a lack of public policy focusing directly on it. Urban agriculture is generally considered to be the responsibility of local governments, but since a formal framework is often missing, support at local government level has the tendency to be informal and fragmented. For example, The London Plan, which is the spatial development strategy for the Greater London area, simply states that the boroughs should identify potential sites that could be used for commercial food production in their development plans. With an appropriate policy framework, initiatives could become better grounded and secured. The inclusion of building-integrated agriculture in urban development policies or urban planning framework plans would boost its importance for urban development. For example, modifying zoning codes – by allowing food growing activities in certain categories, or adopting a formal urban agriculture land use zone –, recognizing urban agriculture as an economic development strategy, facilitating land access, and eliminating restrictions that stem from other policy fields, could all impact positively on the development of urban agriculture (Prové *et al.* 2016).

A few cities have taken the first steps to adapt local codes to promote urban agriculture. Paris has taken a very structured and proactive approach, which started with making an audit of all the underexploited or empty public buildings that could potentially accommodate urban farms. In 2016 city planning rules were changed to allow construction above the maximum height limitations by 7 metres if it is to build an agricultural greenhouse, and the Mayor of Paris launched the Parisculteurs initiative that aims to cover 100 hectares of rooftops and walls in Paris with greenery by 2020, of which one third will be specifically set aside for urban farming. Public and private owners of real estate were asked to come forward with suitable spaces which could be used for this initiative, and architects and designers then submitted site-specific proposals. One of the winners of the first round of the competition was the Green'elle project, which proposed the city's first rooftop aquaponic farm. Planning permission was awarded in 2018, and when operational the 3000 m^2 greenhouse will have an annual production capacity of 30 tons of fruit and vegetables and 3 tons of trout. The products will be sold to local residents through a Community Supported Agriculture vegetable box scheme, and to markets, and restaurants and wholesalers. Another winner was La Caverne, a vertical farm which grows mushrooms, endive and microgreens in an underground car park. HRVST dans le Métro was one of the winners of the second round. Located in a disused underground metro turning loop beneath Parc Monceau, the 5000 m^2 vertical farm will grow produce destined for high-end restaurants. A third round of the competition is underway in 2019. Another initiative launched by the Mayor of Paris is Reinventir Paris, a call for innovative urban development projects to reveal the full potential of Paris's underground spaces. While broader in scope than the Parisculteurs initiative, with teams being invited to propose projects that are simultaneously architectural, economic, cultural and social, one of the winners of the first round was FlabFarm, a 450 m^2 insect microfarm and restaurant located in a two-storey basement which is due to open in 2021.

Over recent years, New York City has become an epicentre for urban agriculture. Prior to 2012 zoning laws in New York City viewed rooftop greenhouses as additional occupiable space that counted toward a building's calculable Floor Area Ratio (FAR), and were therefore not permitted on buildings already at or near the maximum FAR allowance. That changed in 2012 when the Department of City Planning passed a Zone Green Text Amendment that encouraged the construction of new buildings and retrofitting of existing ones to make them more energy efficient and sustainable, including renovations that encourage urban agriculture. Among the provisions in the amendment benefitting controlled-environment agriculture were allowing a rooftop greenhouse to be considered a 'permitted obstruction', exempting it from a zoning district's FAR so long as it was on a building without residences, used primarily for plant cultivation, less than 7.6 metres high, mostly transparent, and set back from the perimeter wall by 1.8 metres if it exceeded the district's building height (Goodman & Minner 2019).

A number of public officials have also proactively supported the development of urban agriculture For example, in 2015 the Mayor of New York City introduced a Local Law to amend the New York City Charter to create an urban agriculture advisory board, and in 2017 the Borough President of Brooklyn introduced legislation calling for the New York City Department of City Planning to create a comprehensive urban agriculture plan to capitalize on the urban farming movement and use it to address community and youth empowerment, economic development, and healthcare. Although the plan has not advanced, an interim Local Law has resulted in the creation of an official New York City urban agriculture website that serves as a landing page for interested farmers. Nevertheless, in terms of controlled-environment agriculture, the focus of the local authorities has been on providing funding for hydroponic farming in schools, rather than the development of commercial agriculture. A recent study found that, compared with 131 facilities in public schools, there only 8 commercial CEA farms in the city: six rooftop greenhouses (five hydroponic and one aquaponic), one plant factory and one container farm (Goodman & Minner 2019).

While commercial CEA has led to the creation of a small number of urban green jobs, it may not provide sufficient benefits to warrant public sector support. The produce grown by commercial CEA farms in New York City contributes minimally to the estimated 1,848,842,500 kilos of fruits and vegetables consumed annually by its residents. There is also little evidence that CEA produce grown in New York City is addressing food insecurity and access issues that affect nearly three million New

Yorkers, especially those in low-income communities. This may be because locally grown CEA produce is too expensive, or not available in enough neighbourhood grocery stores, or for reasons not yet identified. The produce grown in commercial CEA farms in New York City also tends to be of only moderate nutritional value: the high start-up costs mean that the urban farmers need to recover these costs by growing high value crops for wealthy consumers, such as lettuce and basil, rather than nutritional produce priced for low-income residents, such as spinach and kale. The produce therefore contributes only minimally to the goal of elected officials supportive of urban agriculture to increase New Yorkers' consumption of healthy fruits and vegetables, especially those at risk of obesity, diabetes, and related chronic health diseases (Goodman & Minner 2019).

While the findings of this study are specific to New York City, they have implications for the adoption of CEA in other urban centres. Municipal support for such ventures will only be gained if the purported benefits – the environmental, economic and social potential – of projects located on publicly-owned rooftops and land can be demonstrated.

13.5 Urban agriculture business models

There are many different types of model for the successful operation of a business. A business model is a strategy for how a company will make a profit. It identifies the products or services the business will sell, the target market, and the anticipated expenses. A new business in development needs to have a business model in order to attract investment, help it recruit talent, and motivate management and staff. Established businesses have to revisit and update their business plans regularly in order to anticipate trends and challenges ahead. Jan Wilhelm van der Schans, of Wageningen University, identifies five types of urban agriculture business model (van der Schans 2015; van der Schans *et al.* 2014):

1. Differentiation

A differentiation strategy is based on creating distinctions with conventional supply chains. An urban farming business can distinguish itself by keeping production, processing and distribution in its own hands (vertical integration). By including several steps of the supply chain, it may be able to capture more of the profit margin, or at least keep better control over the distinctive character of the product. An urban farming business can also distinguish itself in terms of its products by growing unusual crops such as heirloom vegetables and ethnic vegetables, as well as perishable varieties that are more difficult to transport over long distances, or products with high transportation costs, and by stressing the seasonal nature of the produce as opposed to the year round availability in supermarkets.

2. Diversification

A diversification strategy is aimed at providing other goods and services, aside from food production. An urban farming business can offer a number of business-to-consumer market-oriented activities, such as education and social care, as well as business-to-business activities, such as energy production from urban green waste and composting. Urban agriculture initiatives can make a difference by decentralizing waste management.

3. Low cost

The low cost strategy in conventional agriculture is usually about expanding the business in order to realize economies of scale. However, this is a business development strategy for which there is little or no space in the urban context. Urban agriculture can realize a low cost strategy by using urban resources that are currently underutilized, such as vacant plots of land, empty buildings, urban organic waste, excess rainwater, and urban heat waste. Using volunteer work or the deployment of disadvantaged people is also a form of cost reduction. Vertical integration, which cuts out the middleman, can also be considered a low cost strategy.

4. Reclaiming the commons

Urban agriculture provides citizens with the opportunity to regain control over their food supply and become aware of where their food is coming from. It reintroduces the feeling of ownership, sometimes literally when citizens become co-owners of a business through crowdfunding. Community Supported Agriculture (CSA) schemes, whereby a farmer offers members a share of production in return for a fixed subscription, and members have the opportunity to connect with the growers, the land where their food is grown, and with each other at regular social events, are becoming increasingly popular. The share may vary with the vagaries of production, so the risks and rewards are shared, while the subscription is generally payable in advance and for a relatively long term, thereby providing secure income to the producer.

5. Experience

This strategy is based on the insight that more value is added by providing memorable experiences than by providing basic goods and services (the experience economy). Urban farmers are capable of staging unique experiences precisely because of the short distance between the farm and the target audience. Urban agriculture is an experience of rural and urban dynamics in a unique symbiosis, and an enrichment of the metropolitan landscape.

From a business management perspective, urban farming is atypical: in business management it is a golden rule that a company's strategy should be based on one clear-cut revenue model. For urban farming, however, a mixture of business models may be a good foundation for survival: for example, using volunteers (low cost) and social care clients (diversification) to grow, process and distribute a distinctive product (differentiation) using a CSA vegetable box scheme (reclaiming the commons), and opening the farm to paying visitors (experience) (van der Schans 2015; van der Schans *et al.* 2014).

Some of the pioneers of urban farming (Lufa Farms, Gotham Greens) have refined their business model to boost profitability, by enlarging their rooftop greenhouses to achieve economies of scale, although Sky Vegetables which, like Lufa Farms and Gotham Greens started production in 2011, still operates from a comparatively small (743 m^2) rooftop greenhouse. Economies of scale are also important for indoor vertical farms, with the small size of the commercial production unit at GrowUp Urban Farm in London (762 m^2) being cited as the reason for its closure. However, at the other end of the scale, FarmedHere, which with 8361 m^2 of grow beds was hyped as the largest indoor farm in the United States when it opened in Chicago in 2013, closed down four years later because the very high energy and labour costs made it unprofitable (Beytes 2017).

The three urban farm pioneers have very different business models. Sky Vegetables grows only eight varieties of herbs and greens, which it sells online to retailers. Gotham Greens grows 13 different types of salad leaves, basil and tomatoes, which are sold to consumers via online grocery stores and in more than 500 supermarkets, grocery stores and farmers markets across 15 eastern states. It also sells its produce to 115 restaurants in New York City and Chicago, and to Delta Airlines. Lufa Farms grows 89 different varieties of leafy greens and fruiting crops. This is made possible by operating three large rooftop greenhouses with nutrient solutions optimised for different plants: one greenhouse is used to grow only tomatoes and aubergines; the second is used to grow lettuces, greens and herbs; and the third is used to grow cucumbers, chili peppers, microgreens, herbs and edible flowers. Lufa Farms' business model uses a combination of direct selling – which eliminates retail margins and other costs, subscription – which allows the company to tailor its production in relation to demand, and cross-selling – which involves offering complementary products and services beyond a company's own range in order to sell more goods. Lufa Farms has partnered with other mostly local and organic farmers to sell a wide range of foods alongside its own produce, including cheese, meat, seafood and bakery products, as well as a few growers in Florida who grow tropical produce (bananas, avocadoes and oranges). Customers subscribe to a weekly basket of produce with a minimum value of Can$15 using the farm's online marketplace, and this is either home-delivered for a fee, or can be collected from hundreds of neighbourhood pick-up points across Montreal, including pharmacies, barber shops, supermarkets, convenience stores, coffee shops and university campuses. This kind of hybrid business model is clearly attractive to customers: the farm is able to pass on the savings resulting from direct selling, while subscription and cross-selling both save the customers' time. Lufa Farms delivers 10,000 orders each week.

Fresh Impact Farms takes advantage of the controlled environment in its farm in a suburban shopping mall in Arlington, Virginia, to grow edible flowers and herbs catered to the taste preferences of top-tier chefs. Flavours are made more intense, or more subtle, by altering the nutrient mix, water temperature, or light spectrum. Since launching in 2016, the farm has experimented with 250 plant varieties and currently grows between 50 and 60 at a time. Many of the most successful varieties were originally suggested by chefs. The farm worked with a company to develop its own software that tracks the feedback received from chefs for each crop so that the flavour can be adjusted in the next batch.

Some urban farms have adopted a blend of for-profit and non-profit for their business model. Vertical Harvest in Jackson, Wyoming, is an impact-driven business that combines private investment, public resources and philanthropy in order to create a positive economic and social impact for the local community. The farm employs people with physical and intellectual disabilities, and the lettuce, greens, microgreens and tomatoes are sold to local grocery stores and restaurants. BetterLife Growers is an aeroponic lettuce and herb growing operation set up to provide new living-wage jobs in Houston, Texas, for people who might otherwise be difficult to hire, including those with criminal records. Employees receive workforce training in job skills and fiscal literacy, and the produce is sold to local anchor institutions such as universities, hospitals and government facilities, as well as wholesale distributors and retail grocery stores.

The rise of urban agriculture has led to a plethora of start-ups, not just of urban farms, but also of suppliers of equipment and consultancy. Some of these have grown into very successful companies. For example, Infarm was founded by three young entrepreneurs in Berlin in 2013 with an ambitious vision to feed the cities of tomorrow by bringing farms closer to the consumer. The company developed an easily scalable and rapidly deployable hydroponic modular farm system for growing lettuce, herbs and microgreens in any urban retail space or restaurant. Each farm is its own ecosystem, with growing recipes that tailor light spectra, temperature, and nutrients to ensure the maximum yield for each crop. A matrix of sensors collects and records growth data from each farm, and any necessary adjustments are remotely controlled. The company has since grown to 250 employees and is on track to book over $100m in contract value in 2019. Infarm has partnered with 25 major food retailers in Germany, Switzerland, and France and deployed more than 200 in-store farms and 150 farms in distribution centres of online grocery retailers. $100 million of new funding secured in 2019 from venture capital investors will be used to expand the company's growth in Europe and to spread to the US and beyond, and to grow the R&D, operational, and commercial teams (HortiDaily 2019).

Other start-ups which supply urban farming equipment include US companies Freight Farms and Vertical Crop Consultants, both of which sell turnkey container farms. In addition, to using different growing systems in their container farms – Freight Farm uses growing towers whereas Vertical Crop Consultants use a horizontal stacked bed system – the two companies differentiate themselves in their business models. Alongside their Greenery™ container farm, Freight Farms sells farm management software and an app which allows farmers to remotely monitor sensor data – from nutrient levels and pH to temperature and CO_2 – and to analyse the relationship between the farm's settings and yield. If necessary a client services team can access the metrics to help troubleshoot and find easy fixes. For a one-off fee, Freight Farm provides an online course on how to use the container farm, and a current subscription to the farm management software gives lifetime access to the online materials. Freight Farm has therefore adopted the solution provider business model, which offers total coverage of products and services in a particular domain. By paying an annual subscription for the cloud-based farm management software, rather than a one-off license fee, the farmer is guaranteed access to the latest version. Freight Farm's ability to access the farmer's metrics enables them to leverage customer data, which they can then use to optimise their container farm system. Vertical Crop Consultants, on the other hand, sell a much more diversified portfolio of products. Alongside their CropBox container farm and associated smartphone app, they sell bespoke vertical and horizontal hydroponic systems, and have an online store selling more than 5000 different hydroponic growing supplies – lighting, nutrient solutions, pumps, irrigation systems, aeration devices, etc. – manufactured by other companies.

In Europe, French start-up Refarmers, founded in 2015, is the official European distributors of the US manufactured ZipGrow vertical planting system. In the UK LettUs Grow, founded in 2015, sells aeroponic systems and modular farms, as well as farm management software for remote automated control, data collection and crop growth analysis. V-Farm, which started out in 2006 as a project for fodder and wheatgrass production, developed its first tiered rack system for growing herbs in 2011, and now produces a range of modular NFT and flood and drain systems suitable for commercial-scale cultivation. In Belgium Urban Crop Solutions, founded in 2014, offers a one-stop-shop in terms of turnkey indoor plant growing equipment and after sales service. Their R&D department has developed growing recipes for more than 200 crop varieties.

Established in 2018, Swedish start-up Bonbio defines itself as a 'turnkey provider operating in the field of circular farming and crop production'. They have developed a proprietary circular farming concept where they convert waste food into organic plant nutrients which have been optimized for hydroponic farming. In the long term, Bonbio Nutrients will be available from retailers or garden centres, but in the meantime the company is working with IKEA to convert waste from their in-store restaurants into a nutrient solution which is then used to grow lettuces in containers outside the stores, and the salad leaves are then used in the restaurants.

iFarm is a Russian start-up founded in 2017 which is seeking to revolutionise farming through the provision of automated vertical farm systems, greenhouses and growing modules which use soil rather than hydroponics. Aimed at small and medium-sized businesses, iFarm's modular automated greenhouses are able to accommodate all manner of crops, and are designed to fit in a variety of urban spaces such as vacant lots and rooftops, while the modular vertical farm system can be placed anywhere indoors. The growing modules are intended for cultivating greens and strawberries in restaurants and grocery stores. All three systems are operated by cloud-connected software which automatically controls all aspects of the environment – including the temperature, water supply, lighting, and the nutrients mixed into the soil – allowing the company to effectively programme the qualities of the plants. Using a centralised database, urban farmers are able to download growing recipes designed to maximise the quality of specific crops, based on the data collected which is analysed by a team of iFarm scientists. More than 50 different data parameters are collected from every square meter of soil: these verify the stages of growth, and signal when to harvest and what to do with every crop. Because the recipes can be easily downloaded, this type of system is designed to appeal to a new type of urban farmer – one who might be tech-savvy but doesn't know much about horticulture. It will also appeal to growers who want to be able to certify their produce as organic, which is currently not possible in Europe for produce grown using hydroponics. The company has also developed a planting robot.

In 2019 iFarm landed $1m in backing from Gagarin Capital, a Russia-based, venture-capital investor in high-tech start-ups, which it will use to grow its business in Russia and expand into Europe. As regards urban farms, there has been a series of high-profile investments in the industry in recent years. San Francisco-based Plenty raised a record-breaking $200 million from the Japanese conglomerate SoftBank Group Corp (Cosgrove 2017). One of France's urban farming start-ups that has succeeded in attracting millions in funds is Agricool, which grows strawberries in containers in Paris. Founded in 2015, the company has raised 12 million euros from private investors, a first in French urban farming history. The strawberries are sold to local wholesalers, supermarkets and gourmet food shops. The company has four operational containers producing an average of 200 boxes of strawberries a day, which is not yet enough to turn a profit. By scaling up its operations it hopes to become profitable by 2021 (Luquet 2018).

But while some urban agriculture start-ups are thriving, a large number have also failed. In Vancouver Alterrus declared bankruptcy after less than two years of operation. When the business launched in November 2012, it had promised to produce about 68,000 kg of leafy greens and herbs a year in the hydroponic rooftop greenhouse. The business model for the farm involved selling pesticide-free greens and herbs to high-end restaurants (Howell 2014). Stockholm-based Plantagon intended to move food production into high-density cities on a large scale by developing and operating farms that are integrated into existing city infrastructure – in office towers, underground parking garages, and on the facades of existing buildings. The farms could either be retrofits or extensions of existing real estate, or new builds, and would be implemented as symbiotic systems using existing infrastructure such as cooling/heating, biogas production, waste/water management and energy production to produce food. Plantagon's first farm, the Plantagon CityFarm, opened in the basement of an office building in Stockholm in 2018 and the company intended to roll out 10 more CityFarms in the city by 2020. The underground farm, which was expected to grow 100 kg of vegetables per day, stored the heat emitted by the LED growlights and then reused that energy to heat the offices above, which enabled it to pay nothing in rent. However, the farm had difficulty in selling the products it grew for the price it needed, and Plantagon was declared bankrupt in 2019, citing cash flow problems and the difficulty of attracting enough capital to remain financially sustainable. Plantagon may have been ahead of its time in terms of the size of its projects, and the speed at which it wanted to realise its ambitions. The gap between promising innovation and actually delivering on it is something that trips the agritech industry up again and again (Marston 2019).

Many of the start-ups that have failed were urban aquaponic farms. One of the main factors that determines the possible success of aquaponics is its competitiveness against alternative production methods. Investment costs in aquaponic farms are almost double those of hydroponic farms, and in order to be profitable, the farm needs to maximize both plant and fish production and revenues. The demise of FarmedHere and GrowUp Urban Farm has already been mentioned. Green & Gills, located in the basement of The Plant, Chicago, was operational for only three years, from 2012 to 2015. Urban Organics, an 8083 m^2 aquaponic farm in St. Paul, Minnesota, grew leafy greens and herbs in a former brewery, and sold the vegetables to wholesalers and the tilapia, Arctic char and rainbow trout to restaurants; it closed down in 2019 after six years of operation. UF002 De Schilde, an aquaponic farm run by UrbanFarmers in The Hague, Netherlands, was operational from 2015 to 2018. Tomatoes, cucumbers, bell peppers and leafy greens were grown in the rooftop greenhouse, while the aquaculture component housed on the top floor of the six storey former Philips building was used to rear tilapia. From here came the idea to fill the entire building with start-ups to act as an innovation and knowledge centre for urban agriculture. Ironically, New Urban Farm opened in the same month that UrbanFarmers went bankrupt. Current tenants on the fourth floor are HaagseZwam which grows mushrooms on coffee grounds, and sells mushroom growing kits. The other start-ups present when the hub opened in 2018 – Rebel Urban Farms and Uptown Greens – no longer appear to be active in the building.

UF002 De Schilde was losing money from the start, as costs were high and revenue was too low, and investors were no longer willing to finance the farm. Arguably the business model was flawed; a higher value, more specialist crop such as microgreens, which can be sold to high-end restaurants and other consumers, might have been a better choice than tomatoes and other fruiting crops which are produced on a vast scale in the Dutch countryside and are available in supermarkets at very competitive prices. The most fundamental question for all start-up farmers to ask, regardless of their growing technique, is what are they going to grow, and for whom? If they can't sell it, they shouldn't grow it. Being able to answer this question therefore involves market research to find out what the markets can't get or needs more of, who the customers will be, and the potential prices that could be charged. The social acceptance and preferences of potential consumers are decisive factors for the success or failure of an entrepreneurial business. A large-scale survey carried out in Berlin to identify consumer attitudes towards different forms of urban agriculture revealed a low level of acceptance of both vertical and aquaponic farms compared with rooftop greenhouses (Specht *et al.* 2016b). These results are consistent with those of previous studies investigating stakeholder perceptions of rooftop greenhouses in Barcelona (Sanyé-Mengual *et al.* 2015b) and Berlin (Specht *et al.* 2016a). A survey of consumer attitudes in Adelaide, Australia, towards urban aquaponic farms also revealed a low level of acceptance, which was positively correlated with the respondents' level of ignorance concerning aquaponics (Pollard *et al.* 2017). This corroborates the findings of a pan-European survey of consumer acceptance of aquaponics (Milicic *et al*. 2017).

These surveys all reveal a perception of soil-less farming as an 'unnatural' growing technique, with only a few stakeholders having a neutral opinion on it. Generally, they either accepted or radically rejected it. This may explain the lack of demand which means that many urban farming operations are not yet at full production year-round, despite touting the 12-month growing season as a main benefit of the industry. Indoor farms that have achieved the sales to produce continually, such as Gotham Greens with its New York City and Chicago rooftop greenhouses, have a customer base that is responding to strong 'local' branding rather than the technology behind the food.

Urban mushroom farms such as HaagseZwam owe the secret of their success to employing circular economy principles. In Paris La Boîte à Champignons use coffee grounds to cultivate oyster mushrooms in the basement of a supermarket, and sell their products to that and other nearby supermarkets and restaurants. They further diversify their operation by selling home growing kits that can be ordered online, as well as educational kits for school students. RotterZwam, which is located in a former swimming pool in Rotterdam, also grows oyster mushrooms. Besides coffee grounds, they also use coffee husk – another waste product – as a substrate. They have made supply agreements with the majority of the micro roasters in Rotterdam as well as with roasters in the surrounding region in order to secure the amount they need for their production, which they collect for free on a weekly basis. Since most coffee is consumed at home (about 70%), they have developed a growing kit so that people can use their own coffee waste to grow mushrooms. They also sell tickets for tours of the farm. GroCycle in Exeter, UK, cultivate their oyster mushrooms in coffee grounds in an unused office building (Figure 9). In addition to selling their produce to restaurants and food outlets, they also sell mushroom kits for home growing, turn the waste from their growing cycle into compost, and offer an online course in low-tech mushroom farming. Hut und

Stiel in Vienna, who again use coffee grounds to cultivate oyster mushrooms, sell the best looking produce to grocers, while the poorer quality mushrooms are used for pastes and sauces in collaboration with a Viennese delicatessen. They also sell starter cultures for home cultivation.

Figure 9: Oyster mushroom mycelium growing on coffee grounds in 12 kg hanging column bags
https://grocycle.com/

These examples of urban mushroom farms illustrate the range of different products and services that can be generated, in addition to the mushrooms themselves. Gourmet mushroom varieties such as oyster and shiitake are a premium product. For example, in the UK the retail price is around €13/kg, compared with €3/kg for cherry tomatoes. Mushrooms can grow in just 3 to 4 weeks from start to finish, and a 10 m^2 growing area can produce 10 kg of mushrooms a week. In addition to being able to reduce their costs by using free substrate to grow their produce, urban mushroom farms have much lower operating costs compared with urban farms growing leafy greens and fruiting crops: unlike plants, mushrooms can grow without light, so there is no need for expensive LED growlights, although coloured oyster varieties do require light in order to colour up. Basements are perfect for mushroom growing because it is relatively easy to stabilise both the temperature and the humidity, as long as you can maintain good airflow, and they are also a very common space in cities.

13.6 Conclusions

Commercial indoor urban farming requires engineers, horticulturists, data scientists, HVAC specialists, plant scientists and more, all with the knowledge and understanding of controlled-environment agriculture. The urban farmer is also confronted with specific logistics and downstream supply chain management, and therefore needs to know both the business and operational sides of urban farming. Topics such as market analysis, operational management, labour modelling, marketing, determining price points, logistics and distribution are key components that all urban farms utilize. Commercial indoor urban farming is a new and relatively untested field of business. In megacities in East Asia and the Middle East, it has the potential to make a significant contribution to the urban food supply chain. In North America and Europe, on the other hand, urban farms simply cannot compete with peri-urban and rural farms due to their limited size and the higher production costs per unit of output, and widespread changes to legislation and governance that would facilitate them are therefore unlikely to occur. However, they do offer opportunities to create high value, premium products which can be highly profitable. While the fruit and vegetable products cannot be marketed as 'organic' in Europe, since certification is restricted to soil-based farms, premium prices can still be obtained by emphasising the local nature of production, rather than the technology that was used to produce them. Other high value products that could be profitable to grow in indoor urban farms include medicinal plants, crocus (for saffron), samphire, watercress, and edible snails. Whatever the product, the typology of the farm – rooftop greenhouse, plant factory, container farm etc. – needs to be suited to it, and the product needs to be suited to the customer base. However, while quality products and processes are of great importance, they will not decide a company's success or failure: a company's fate increasingly depends on its ability to apply the appropriate innovative business model that differentiates it from its competitors.

13.7 References

Benis, K. & Ferrão, P. 2018. Commercial farming within the urban built environment – Taking stock of an evolving field in northern countries. *Global Food and Security* 17, 30-37.

Benis, K., Reinhart, C. & Ferrão, P. 2017. Development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA) in urban contexts. *Journal of Cleaner Production* 147, 589-602.

Beytes, C. 2017. FarmedHere shuts down. Grower Talks.

Buehler, D. & Junge, R. 2016. Global trends and current status of commercial urban rooftop farming. *Sustainability* 8 (11), 1108.

Cerón-Palma, I., Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I & Rieradevall, J. 2012. Barriers and opportunities regarding the implementation of Rooftop Eco.Greenhouses (RTEG) in Mediterranean cities of Europe. *Journal of Urban Technology* 19, 1-17.

Cosgrove, E. 2017. SoftBank invests in largest ever agtech deal, a $200m Series B for indoor ag startup Plenty. AgFunder News.

Delaide, B., Delhaye, G., Dermience, M., Gott, J., Soyeurt, H. & Jijakli, M.H. 2017. Plant and fish production performance, nutrient mass balance, energy and water use of the PAFF Box, a small-scale aquaponics system. *Aquacultural Engineering* 78, 130-139.

Despommier, D. 2010. *The Vertical Farm: Feeding the World in the 21st Century*. St Martin's Press, New York.

Geisendorf, S. & Pietrulla, F. 2018. The circular economy and circular economic concepts – a literature analysis and redefinition. *Thunderbird International Business Review* 60, 771-782.

Goodman, W. & Minner, J. 2019. Will the urban agricultural revolution be vertical and soilless? A case study of controlled environment agriculture in New York City. *Land Use Policy* 83, 160-173.

HortiDaily 2019. Infarm gets $100 million financial boost. HortiDaily.com.

Howell, M. 2014. Alterrus bankruptcy soils garden vision. Vancouver Daily.

Jachec, H. 2019. Swedish grocery store reveals line of produce grown on-site. iGrow.

Kozai, T. 2013. Plant factory in Japan – current situation and perspectives. *Chronica Horticulturae* 53 (2), 8-11.

Kozai, T., Niu, G. & Takagaki, M. 2016. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*. Academic Press, London.

Luquet, A. 2018. Paris leads the way in France's growing urban farming history. The Epoch Times.

Marston, J. 2019. What Plantagon's bankruptcy could tell us about the future of large-scale vertical farming. The Spoon.

McEldowney, J. 2017. *Urban agriculture in Europe: Patterns, challenges and policies*. European Parliamentary Research Service.

Miličič, V., Thorarinsdottir, R., Dos Santos, M. & Turnšek Hančič, M. 2017. Commercial aquaponics approaching the European market: To consumers' perceptions of aquaponics products in Europe. *Water* 9 (2), 80.

Nehls, T., Jiang, Y., Dennely, C., Zhan, X. & Beesley, L. 2016. From waste to value: Urban agriculture enables cycling of resources in cities. In F. Lohrberg, L. Lička, L. Scazzosi & A. Timpe (eds.) *Urban Agriculture in Europe*, pp. 170-173. Jovis, Berlin.

Pollard, G., Ward, J.D. & Koth, B. 2017. Aquaponics in urban agriculture: Social acceptance and urban food planning. *Horticulturae* 3 (2), 39.

Prové, C., Kemper, D., Loudiyi, S., Mumenthaler, C. & Nikolaidou, S. 2016. Governance of urban agriculture initiatives: insight drawn from European case studies. In F. Lohrberg, L. Lička, L. Scazzosi & A. Timpe (eds.) *Urban Agriculture in Europe*, pp. 64-69. Jovis, Berlin.

Sanyé-Mengual, E., Céron-Palma, I., Oliver-Solà, J., Montero, J.I & Rieradevall, J. 2013. Environmental analysis of the logistics of agricultural products from rooftop greenhouses in Mediterranean urban areas. *Journal of the Science of Food and Agriculture* 93, 100-109.

Sanyé-Mengual, E., Oliver-Solà, J., Montero, J.I. & Rieradevall, J. 2015a. An environmental and economic life cycle assessment of rooftop greenhouse (RTG) implementation in Barcelona, Spain. Assessing new forms of urban agriculture from the greenhouse structure to the final product level. *International Journal of Life Cycle Assessment* 20, 350–366.

Sanyé-Mengual, E., Anguelovski, I., Oliver-Solà, J., Montero, J.I. & Rieradevall, J. 2015b. Resolving differing stakeholder perceptions of urban rooftop farming in Mediterranean cities: promoting food production as a driver for innovative urban forms. *Agriculture and Human Values* 33, 101-120.

Specht, K., Siebert, R. & Thomaier, S. 2016a. Perception and acceptance of agricultural production in and on buildings (ZFarming): a qualitative study from Berlin, Germany. *Agriculture and Human Values* 33, 753-769.

Specht, K., Weith, T., Swoboda & Siebert, R. 2016b. Socially acceptable urban agriculture businesses. *Agronomy for Sustainable Development* 36, 17.

Theurl, M.C., Haberl, H., Erb, K.-H. & Lindenthal, T. 2013. Contrasted greenhouse emissions from local versus long-range tomato production. *Agronomy for Sustainable Development* 34 (3), 593-602.

Thomaier, S., Specht, K., Henckel, D., Dierich, A., Siebert, R., Freisinger, U.B. & Sawicka, M. 2015. Farming in and on urban buildings: Present practice and specific novelties of Zero-Acreage Farming (ZFarming). *Renewable Agriculture and Food Systems* 30, 43–54.

Thomasson, E. 2019. IKEA to start serving salad grown at its stores. Reuters.

van der Schans, J.W. 2015. *Business Models Urban Agriculture*. Wageningen University.

van der Schans, J.W., Renting, H. & van Veenhuizen, R. 2014. Innovations in urban agriculture. *Urban Agriculture Magazine* 28, 3-12.

Wei, L.D. 2018. Berry fresh prospects for vertical farming. The Straits Times.

Vermeulen, S., Campbell, B.M. & Ingram, J.S.I. 2012. Climate change and food systems. *Annual Review of Environment and Resources* 37, 195-222.

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14. VERTICAL AQUAPONICS

14.1 Introduction

Most aquaponic systems use horizontal grow beds, thereby emulating traditional soil-based practices for growing vegetables. However, over recent years, new vertical farming technologies have evolved which, when linked to the aquaculture part of an aquaponic system, may allow more plants to be grown in comparison to horizontal beds, by using the vertical space that is usually not utilized in production units and greenhouses, and could thus potentially make the systems more productive, especially in urban areas where growing space can be expensive (Palm *et al.* 2018). This premise would appear to be supported by comparative studies of vertical and horizontal hydroponic systems, which showed significantly greater productivity in vertical systems in terms of ratio of yield to occupied floor area (Liu *et al.* 2004; Neocleous *et al.* 2010; Ramírez-Arias *et al.* 2018; Ramírez-Gómez *et al.* 2012; Touliatos *et al.* 2016).

However, while optimal use of space is the most commonly cited advantage of vertical aquaponics, this is potentially outweighed by the various disadvantages. Biofouling in an aquaponic system is typical, and vertical systems are particularly susceptible to clogging and reduced flow rates that may starve the plants of water, so routine pressure washing of system components will be needed to avoid this (Patillo 2017). Furthermore, whereas a horizontal flow system only uses electricity to pump water back to the fish tanks, additional pumping is required to lift water to the top of vertical aquaponic systems. Growing plants on horizontal beds has the advantage that natural light is theoretically transmitted from all sides in a free-standing greenhouse without any blockages from other equipment and system components and, where lighting is required, these lighting systems can be readily located immediately above the plants without any interference. However, with vertical aquaponics natural light from above will be greater towards the upper part of the system compared to the bottom, and the vertical elements themselves will block light that is entering the greenhouse. Artificial lighting will therefore be required to compensate for these losses (Khandaker & Kotzen 2018). Careful cost-benefit analyses need to be undertaken, weighing up the benefits of potentially higher yields against the added costs of electricity, before embarking on vertical aquaponics.

There are a lot of different vertical hydroponic system designs which could potentially be combined with a fish production unit. Vertical growing may involve multiple layers of deep water culture, NFT, flood and drain systems, or growing towers that involve aeroponic growing methods, in which the plant roots are suspended in the air and sprayed with nutrient rich water. The design of the system will dictate how many plants can be grown per square metre, and will also influence yields. Numerous studies have shown that root and shoot growth, plant–water relations, nutrient uptake, transpiration and yield are all affected by root restriction in soilless culture. Plants may be more susceptible to growth abnormalities, such as blossom end rot in tomatoes and peppers, and leaf tip burn in lettuce. The smaller the root zone the more intensively the production system needs to be managed to provide a stress-free rhizosphere environment for optimum plant growth (Heller *et al.* 2015).

14.2 Growing towers

Growing towers are vertical tubes through which nutrient-rich water is diffused from the top, usually through a drip emitter, thereby creating 'rain' inside the tower as it drips over the plant roots that are suspended in the air. The towers, or columns, may either be hollow or filled with a substrate that provides support for the roots and aids in water dispersal. In its simplest form, a growing tower may be a section of PVC pipe with holes cut into the sides. In their comparative study of lettuce grown in a hydroponic tower system and a conventional horizontal NFT system, Touliatos *et al.* 2016 found that the tower system produced 13.8 times more crop than the horizontal system, calculated as a ratio of yield to occupied floor area. However, the mean fresh weight of the lettuces grown in the horizontal system was significantly higher than that of the lettuces grown in the vertical system. While crop productivity was uniform in the horizontal system, shoot fresh weight decreased from the top to the base of the tower, most likely as a result of gradients in nutrient availability and light intensity. Similar light gradients have been reported in other greenhouse trials using hydroponic tower systems (Liu *et al.* 2004; Ramírez-Gómez *et al.* 2012). Strawberries grown in vertical PVC towers filled with perlite at a plant density of 32 plants/m^2 produced a marketable yield of 11.8 kg/m^2; however, yield per plant was reduced by 40 g with every 30-cm decrease down the height of the tower, as a result of suboptimal light conditions in the lower sections of the tower (Durner 1999). The diameter of the towers will also have an effect on plant growth. Water content values in tall and narrow towers will be lower than in shorter and wide towers having an equal volume of growing medium per unit length, and the roots of the plants will be subjected to larger daily temperature variations which may affect nutrient uptake and disturb the carbohydrate metabolism in the root, resulting in inhibited growth (Heller *et al.* 2015).

The Tower Farms aeroponic system (Figure 1) is modular: a three metre high tower could grow 52 leafy greens, herbs, or fruiting crops, or 208 microgreens. Each food-grade PVC tower is equipped with a 50 W small pump and a timer which turns the pump on for 3 minutes and off for 12 minutes on a continuous cycle. Although technically each tower has a footprint of less than 1 m^2, 2 m^2 per tower would include enough space for the towers, the dosing station, the aisle spacing, and the propagation bench area. In Europe the Tower Farms system is distributed by Ibiza Farm.

Figure 1: The Tower Farm system
https://ibiza.farm/

In their survey of commercial aquaponics producers, Love *et al.* (2015) noted that almost one third of these used growing towers. However, comparative data on yields from aquaponic tower systems and conventional horizontal aquaponic systems are lacking. ZipGrow is a vertical hydroponic technology designed for high-density vertical crop production by Bright Agrotech, which operates a 400-tower vertical aquaponic system in Laramie, Wyoming (Figure 2). Their spacing density is one tower per every 0.7 m^2. The crop is planted in a channel which runs the length of one side of each rigid UV-resistant PVC square tube. The plants grow in the company's own patented growing medium called Matrix Media, which is made from recycled water bottles and a silicone oxide binder. The growing medium, which is irrigated from the top using drippers, provides many benefits to the aquaponic system. Firstly, it has an extremely high biological surface area of about 82-88 m^2/m^3, which allows the system to have very high nitrification rates and fosters healthy plant growth. Secondly, it has a void ratio of 91% due to its fibrous nature. This high porosity creates a highly aerobic environment for the plant roots and oxygen enrichment of the nutrient water trickling through the tower, and also allows for high percolation rates. Additionally, because of the aerobic environment, solids can collect and decompose on the media without creating an anaerobic microenvironment (Michael 2016). In Europe the ZipGrow system is distributed by Refarmers. A standard 5 ft (152 cm) tower provides mechanical and biological filtration for 0.7 to 1.1 kg of mature fish. A stocking density of between 12 kg and 15 kg per m^3 is recommended.

Figure 2: The ZipGrow system
https://www.greenlifeplanet.net/product-page/zipgrow-tower

As noted above, most tower systems experience a lot of light loss. This is especially true of 4-sided systems, which experience almost 90% light loss from the top front of the tower mass to the bottom rear of the tower mass, even when spaced generously. When ZipGrow towers are massed and managed properly, however, light loss is very low, even at 0.5-0.8 square metres per tower. There are three configurations that a grower can use, depending on their facility and crop types: massed configuration, line configuration, and facing aisles. Growers can also conserve light by using conveyor cropping (Figure 3).

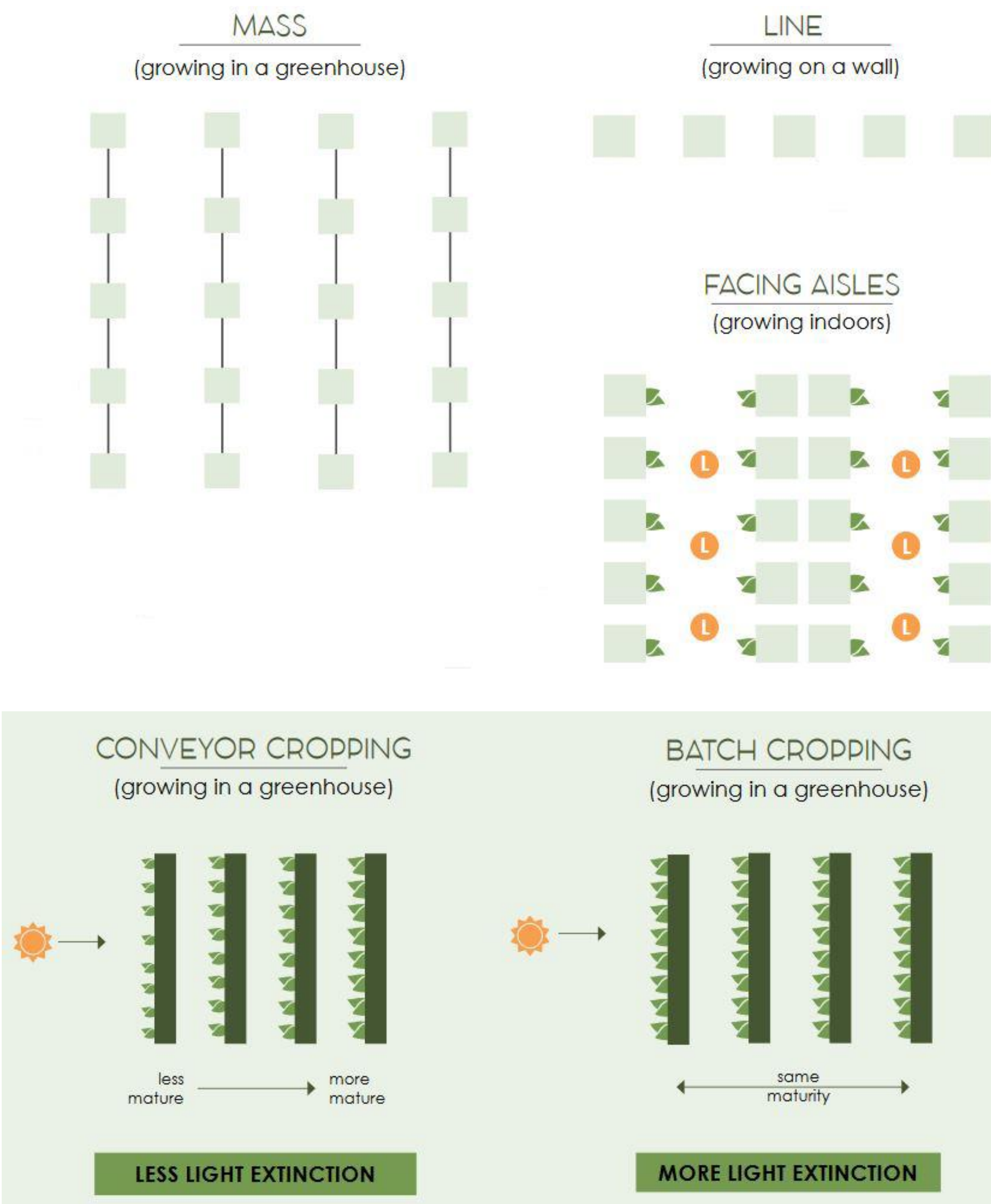

Figure 3: Configurations and cropping regimes for ZipGrow towers https://info.brightagrotech.com/hubfs/blog-files/Infographics/ZipGrow_Tower_Spacing_Guide_-Bright_Agrotech.pdf

A 1.5 metre ZipGrow tower can grow 8-10 lettuce sized plants or 5-8 basil-sized plants, depending on the variety. Mass configurations of towers hanging in rows on a rack are usually the best option for commercial producers looking for high yields. When the towers are massed and managed properly, 0.7 m^2 per tower is more than enough to get good crops with natural light. 50 cm of space between rows allows access the towers. The towers can also be mounted on walls (Figure 4).

Figure 4: Wall-mounted ZipGrow system
https://commons.wikimedia.org/wiki/File:Urban_Vertical_Farm_With_Woman_%26_Child.jpg

The ZipGrow system was used in the GrowUp Box, a shipping container community aquaponic farm with a rooftop greenhouse in central London (Figure 5). The GrowUp Box has a footprint of only 14 square metres and can produce over 435 kg of salads and herbs and 150 kg of fish annually.

Figure 5: The GrowUp Box
https://www.timeout.com/london/things-to-do/growup-box-tours

In the US, NaturePonics has developed BooGardens (Figure 6), a vertical system using bamboo grown in Indonesia and the Philippines which can be used for residential and commercial aquaponic, hydroponic or aeroponic applications. The bamboo harvested to make the towers regrows and can be reharvested three years later, making it the most sustainable growing tower system currently on the market.

Figure 6: BooGardens commercial aquaponics unit
http://www.natureponics.net/boo-gardens/

A variation of growing towers is the stacked pot system, such as that produced by Verti-Gro for hydroponic cultivation. The five litre EPS pots, which provide insulation for improved root growth, can be stacked up to ten pots high, with each pot providing enough space for four plants. The pots are mounted on rotation plates on a PVC riser, which means that they can be turned easily for even reception of light (Figure 7). The system, which was patented in 1994, has been subjected to a number of scientific evaluations. Stacks of 6 pots were found to perform significantly better than stacks of 7 or 8 pots, both in terms of biomass, yield and fruit quality, because the composition of the nutrient solution changed as it passed through the column and negatively affected plant growth in the lower section (Al-Raisy *et al*. 2010). Light can also be an issue: the intensity of sunlight reaching the plant canopy at the bottom of a tower of seven pots was only 10% of that reaching the top, and the suboptimal light conditions in the middle and bottom sections adversely affected strawberry plant growth and fruit yield. Plants in these sections did not develop an optimal number of branch crowns, and subsequently produced less fruit compared with plants in the top section (Takeda 2000). Fruit quality is also influenced by the position of the plants on the tower, with those in the top tier having higher total soluble solids (TSS) and lower titratable acidity compared to those produced on lower tiers (Murthy *et al.* 2016). A comparative study of hydroponic strawberry production using stacks of four Verti-Gro pots and two types of horizontal system found that the lower light intensity at the base of the tower, and consequent lower photosynthetic rate, resulted in lower numbers of fruit, lower fruit weights, and fewer marketable fruits compared with the horizontal systems. Low light levels cause stamen sterility and poor pollen quality, and hence a reduction in fertilization rate, which can contribute to malformed fruit production (Karimi *et al*. 2013).

The benefits of being able to grow high densities of plants in growing towers need to be balanced with the amount of space that is required to provide an even spread of light as well as the row space required for management and maintenance. Row width must ensure that produce is not compromised by moving items such as trolleys and scissor lifts. The grow lights will impede people's movements and thus they either need to be part of the growing structure, or retractable or movable so that workers can readily undertake tasks, or the planting structures will need to be movable and the lights remain static.

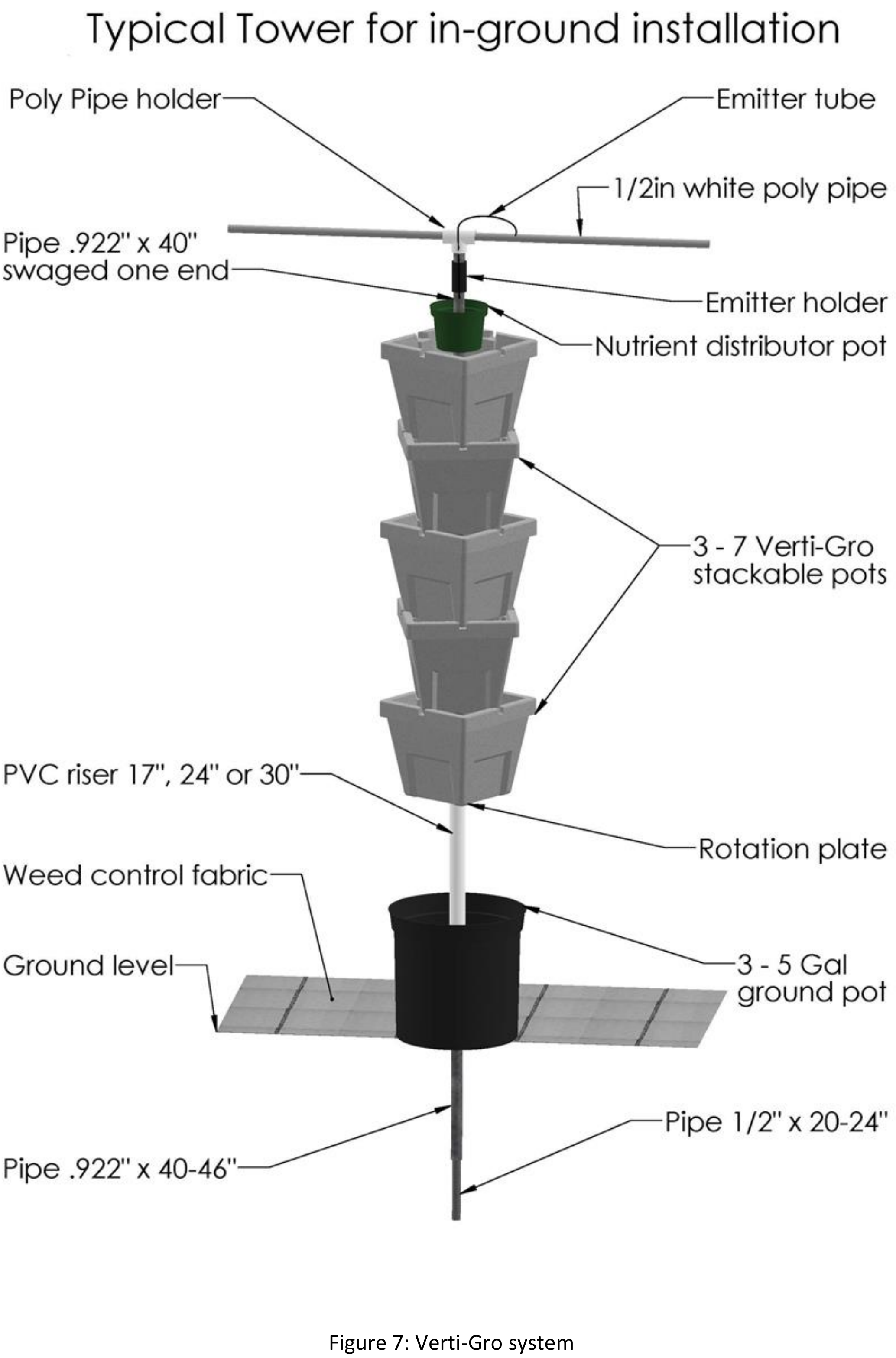

Figure 7: Verti-Gro system
https://www.vertigro.com/Verti-Gro-4-Tower-System-Automatic-p/vgk-16agp.htm

Stacked pot systems are most suitable for growing large and heavy plants, such as fruiting crops. Grow with the Flow aquaponics farm in Denton, Nebraska, uses towers made from stacked pots to grow tomatoes and cucumbers, as well as herbs (Figure 8).

Figure 8: Growing towers in the Grow with the Flow aquaponic greenhouse
https://commons.wikimedia.org/wiki/File:Vertical_Tower_Aquaponic_System.jpg

14.3 Stacked horizontal beds

In this type of system, horizontal grow beds are stacked vertically in tiers. This arrangement means that in a greenhouse, only the upper bed will be facing direct natural light, and supplementary lighting needs to be provided for the lower beds, usually from lights attached to the base of the bed above. While in principle this means that the grow beds could be stacked as high as the greenhouse or production unit allows, in practice growing at height means that the system is more difficult to manage, requiring the use of scissor lifts for planting, maintenance and harvesting, and additional energy to pump the water to all levels. The shorter the stature of the crop, the more tiers can be inserted into the system, which means that most stacked horizontal beds are used for growing microgreens. The grow beds may be DWC, NFT or media beds. For example, in the UK Hydrogarden produces various models of the V-Farm: the four and five tier NFT system suitable for herbs, leafy greens and strawberries can grow up to 35 plants/m^2, while the five tier flood and drain system can grow 4.6 m^2 of microgreens on a footprint of 1m^2.

Canadian company VertiCrop has developed a high density, fully automated, closed-loop conveyer NFT hydroponic vertical farming system (Figure 9). The system has been installed at the Local Garden rooftop greenhouse in Vancouver to grow microgreens, leafy greens and herbs. 3000 plant trays stacked 12 high move on an overhead conveyor system, thereby ensuring maximum sunlight for each plant.

Figure 9: The VertiCrop system
https://grow.verticrop.com/vertical-farming/

The Verticalis system (Figure 10), developed by Friendly Aquaponics in the USA, is designed to be deployed in rows inside a greenhouse, with the units of NFT channels stacked right up against each other, long side to long side, in order to maximise the use of space; in such a configuration, which requires the use of artificial light, it can produce 300 plants/m^2. Castors on the base of the units mean that they can be moved easily, and each rack of channels can be slid out from the unit to facilitate planting, maintenance and harvesting operations.

Figure 10: The Verticalis system
https://www.friendlyaquaponics.com/product/vertical-aquaponics-growing/

There have been few attempts to integrate aquaponics with commercial vertical farms. At 8361 m^2, FarmedHere in Chicago (Figure 11) was hyped as the first of its kind and the largest indoor vertical farm in America. It was opened in 2013 and was expected to become a new model for growing produce efficiently in a high tech manner. However, it closed down in 2017 due to high energy and labour costs. The farm resided in a two-storey, windowless warehouse. By stacking the fish tanks and DWC grow beds vertically, the facility contained 13,935 m^2 of growing space (1.4 hectares), and produced 136,000 kg of leafy greens and herbs per year (Al-Kodmany 2018).

Figure 11: Farmed Here, Chicago
https://www.wsj.com/articles/vertical-farming-takes-root-1449237679

Greens and Gills opened in the basement of The Plant, Chicago (see also Chapter 13) in 2012. The 300 m^2 farm used a 6-tier DWC aquaponic system to grow leafy greens, herbs and microgreens. The tilapia and greens were sold to restaurants, grocery stores and local distributors. The company closed in 2015 and the facility was put on the market with an asking price of $255,000 (Sijmonsma 2015). However, it remained unsold, and the aquaponic system is currently used by Plant Chicago to run monthly training courses.

In the UK, GrowUp Urban Farms combine aquaponics with vertical growing technologies and Controlled Environment Production (CEP) to produce year-round harvests of salads and herbs. From 2015 GrowUp operated 'Unit 84', a commercial-scale aquaponic urban farm in an industrial warehouse in east London (Figure 12). The 762 m^2 growing space could produce more than 20,000 kg of salads and herbs (enough for 200,000 salad bags) and 4000 kg of fish each year. The unit closed down in 2017, since the comparatively small volume of produce did not make the business profitable.

Figure 12: Unit 84, London
https://www.growup.org.uk/gallery/62tsypmu00xml48fks0sjme3rhdg2s

Edenworks in New York grows microgreens using four tiers of stacked DWC beds in a windowless warehouse. Their ready-to-eat microgreen mixes – broccoli, red cabbage and Russian kale, and radish, red cabbage and mustard greens – are sold in local grocery stores while the tilapia are either donated to local organizations or served at company events. Edenworks has also developed the 'Farmstack' system for rooftop greenhouses. The 75 m^2 prototype system is located on top of an industrial building in Brooklyn (Figure 13). The water from the tilapia fish tanks located at the bottom of each 3 metre tall stack is pumped up to the top, and then filters through the different levels and back into the tank.

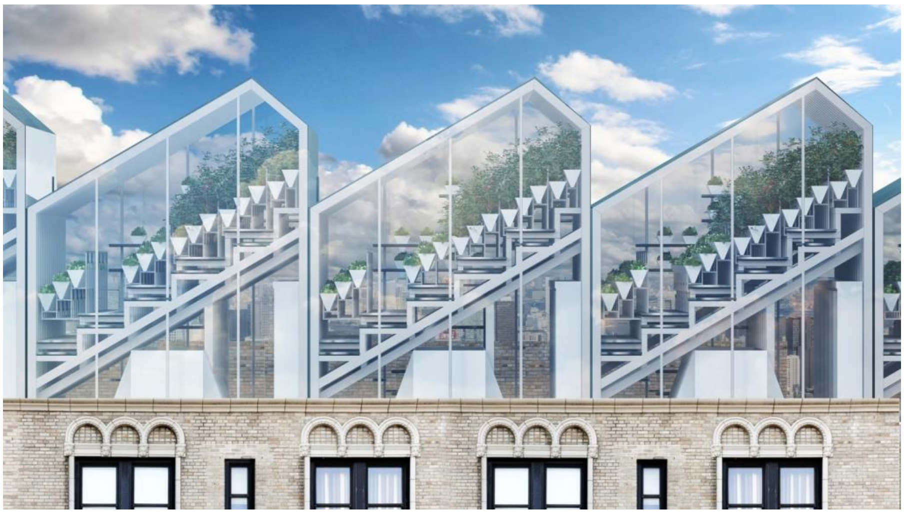

Figure 13: The Edenworks aquaponic rooftop greenhouse
https://viewing.nyc/edenworks-rooftop-aquaponic-farmlab-uses-tilapia-fish-to-grow-fresh-produce/

14.4 A-frame systems

A-frame systems consist of a stepped arrangement of hydroponic channels (Sánchez-Del-Castillo *et al.* 2014), or angled panels of geotextile for aeroponic cultivation (Hayden 2006). Fruit bearing crops growing in the lower sections of an A-frame system may experience partial shading, and consequently produce a high number of small and malformed fruit, experience increased fruit rot, and exhibit problems with fruit colouration. This can be avoided by using systems with grow beds that slowly rotate around the A-frame to ensure that the plants obtain uniform sunlight, irrigation and nutrients as they pass through different points in the structure. For example, the A-Go-Gro (AGG) system developed by Sky Greens in Singapore (Figure 14) consists of tall aluminium and steel A-frames that can be as high as 9 metres tall, with 38 tiers of growing troughs that can contain either soil or hydroponic solution. Each frame has a footprint of only 5.6 m^2, and the system is capable of producing 1000 tons of vegetables per hectare/year. The frames are housed in translucent greenhouses and the rotation of the troughs at a rate of 1 mm/s means that each trough rotates around the frame three times a day, which ensures uniform distribution of sunlight and good air flow, and reduces or even eliminates the need for artificial lighting in some areas of the greenhouse. Rotation is powered by a patented low carbon hydraulic system that makes efficient use of gravity and therefore consumes little energy; only 60 W is required to power one frame. Rainwater collected in an overhead reservoir passes down through the water pulley system, and is then redirected back up to the reservoir by a pump powered by a generator (Al-Kodmany 2018).

Figure 14: A-frame system at Sky Greens, Singapore
http://www.skygreens.com/wp-content/uploads/2014/05/Skygreens-Vertical-Farm1.jpg

THORILEX Ltd has developed a patent pending aquaponic system where the plants are grown on stainless steel A-frames ranging from 3 up to 8 metres high (Figure 15). Planting baskets designed to optimise root growth and maximise nutrient uptake are placed in double rows in stainless steel channels. The trays of plants then rotate around the frame so that they receive an equal amount of light from the LEDs positioned above each frame. The self-cleaning, stainless steel fish tanks come in two sizes, for juvenile and market-sized fish. The system is therefore adjustable and scalable for commercial-scale growing (Figure 16). Currently the system can only be found in the THORILEX 2 hectare showcase farm in the Czech Republic, but the intention is to bring this innovative system to markets across the world. That is why THORILEX designs products using the 'IKEA-model': being highly modular, they can be easily packed, shipped and delivered with minimal costs.

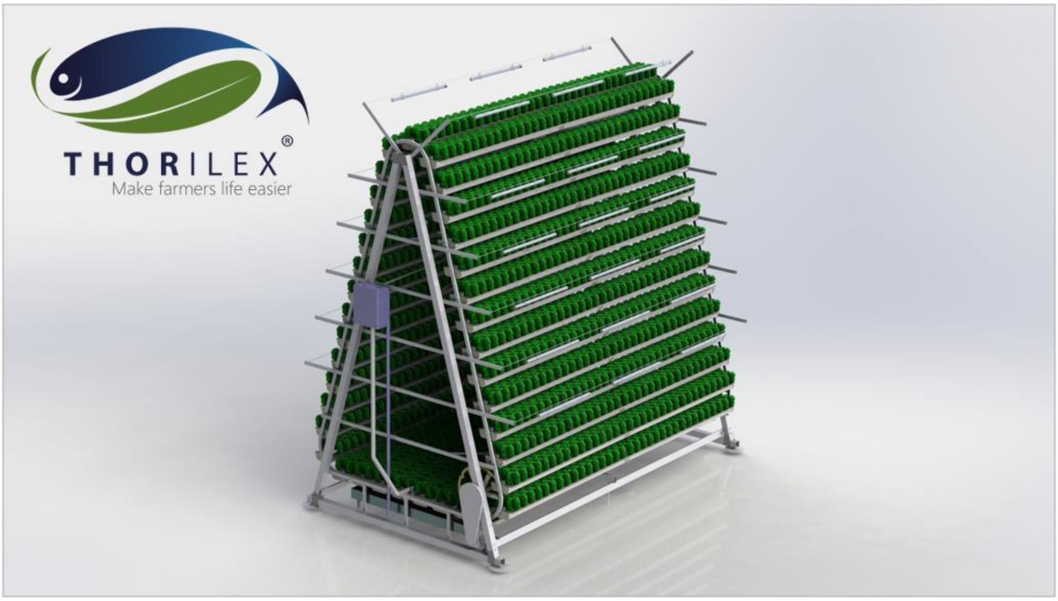

Figure 15: The THORILEX system
http://thorilex.com/

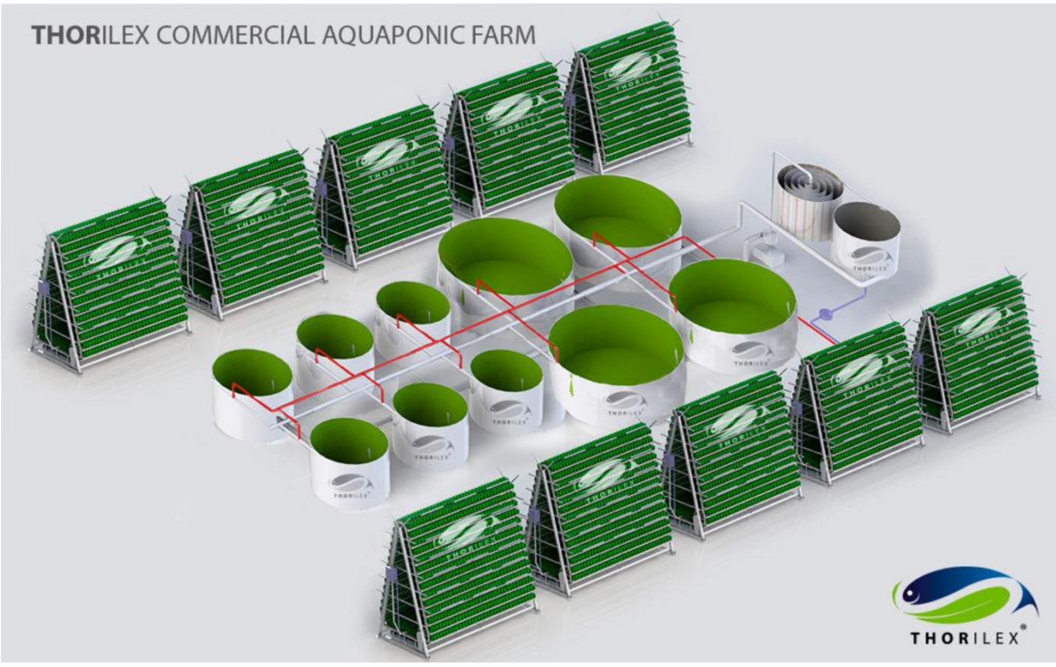

Figure 16: The THORILEX commercial aquaponics farm
http://thorilex.com/

The A-frame hydroponic system developed by the Chinese Jiangsu Skyplant Greenhouse Technology Company (Figure 17) could also be used for aquaponics. The structure has a footprint of 5 m^2, and each of the food-grade PVC-U channels contain 25 holes, resulting in 250 plants per structure, or 50 plants/m^2.

Figure 17: The Jiangsu Skyplant Greenhouse Technology Company system
http://thorilex.com/

14.5 Living walls

Living walls are often used in architecture to provide aesthetic, ecological and environmental benefits in urban areas. The modular panels, comprised of polypropylene plastic containers or geotextile mats, support plants which provide benefits not only in visual terms, but also with regards to amenity, biodiversity, thermal efficiency and amelioration of air pollutants, all for a very small ground level footprint (Manso & Castro-Gomes 2015; Perini *et al.* 2013).

Two universities have been investigating the potential for living walls for growing edible crops using aquaponics. A series of experiments were conducted at the University of Greenwich, UK, to identify the most suitable type of system, and the best growing medium (Khandaker & Kotzen 2018). The first experiment used a Terapia Urbana Fytotextile living wall panel. This semi-hydroponic modular panel system is made from a patented geotextile fabric composed of three layers of synthetic and organic material including PVC, Fytotextile and Polyamide. Each square metre holds up to 49 plants in individual pockets. Depending on the vegetable species grown, approximately 98 plants/m^2 can therefore be grown using back-to-back elements of this living wall system, compared with 20-25 leafy greens per square metre in a horizontal system. The felt panel was attached to an east-facing external wall, and planted with seven different plants (spinach, basil, chicory, asparagus pea, lettuce, mint and tomato) in seven different growing media (horticultural-grade mineral wool, vermiculite, charcoal, coconut fibre, sphagnum moss, pond grown algae, and straw). Each plant species was arranged vertically in columns, and the growing medium was arranged horizontally in rows (Figure 18). Water was pumped up to an internal drip irrigation pipe from a surrogate aquaponics tank with added hydroponic nutrients. The water then flowed down the back of the panel where it was made available to the substrate and the plant roots. Excess water dripped from the bottom of the living wall panel into a gutter and then back to the water tank (Khandaker & Kotzen 2018).

Figure 18: The Terapia Urbana living wall
(Photos: M. Khandaker)

The results of the first experiment showed that mineral wool and vermiculite were the best substrates, resulting in greater yield and better root growth. The plants located at the top and along the sides performed best, which suggests that overshadowing was an issue for the plants in the middle of the wall. However, the main problem with this type of living wall was that the plant roots grew into the geotextile, which made harvesting difficult. If one were to grow cut-and-come-again varieties, this would not be an issue (Khandaker & Kotzen 2018).

The second experiment was set up adjacent to Experiment 1 using the Green Vertical Garden Company (GVGC) pot system. The individual plant pots were attached to a stainless steel reinforcing mesh panel, with five horizontal rows and eight vertical columns of pots. Only one plant (basil) was used across the whole living wall, with different growing media used in the vertical columns (two columns each of hydroleca, vermiculite, horticultural-grade mineral wool and coconut fibre) (Figure 19). The system was irrigated using an irrigation pipe to supply nutrient-rich water to the top row of pots and the water then flowed through each pot to the one below via a small irrigation tube from a hole located at the bottom of each pot. The third experiment used the GVGC system and one plant (chicory) planted in two columns each of hydroleca, vermiculite, horticultural-grade mineral wool and coconut fibre (Khandaker & Kotzen 2018).

In the second and third experiments, the basil and chicory performed best in the coconut fibre and mineral wool. There are advantages and disadvantages to using both of these substrates. While coconut fibre and the roots within can be readily composted, blockages can occur if it is used in a system with small irrigation pipes. Horticultural-grade mineral wool performs well, but it cannot be readily recycled and thus is likely to be considered to be less sustainable. Hydroleca and vermiculite were more difficult to work with, as the material was easily displaced at planting and at harvest. Again, overshadowing caused plants in the middle of the wall to grow less well (Khandaker & Kotzen 2018).

Figure 19: The Green Vertical Garden Company living wall
Photos: M. Khandaker

Researchers at the University of Seville, Spain, have compared the performance of a felt pocket living wall system with small-scale NFT and DWC systems for growing lettuces and goldfish in a greenhouse (Peréz-Urrestarazu *et al.* 2019). The living wall system is composed of two layers, the outer one made of a porous material to favour the aeration of the roots, and the inner one of geotextile which helps to distribute the water. The panel was angled at 20° with respect to the vertical plane. The planting pockets were filled with expanded clay in order to favour a better aeration of the root zone, given that the felt was intended to be receiving water at all times. Although the living wall has a maximum capacity of 20 plants/m^2, not all the pockets were used in order to have an equivalent planting density to the other two systems. In terms of plant productivity, the living wall had the worst performance of the three systems. Part of this may have been due to a lower radiation influx due to the vertical nature of the growing space, even though it had a slight slope. While water was distributed through the felt, the evaporation rate was high, and the expanded clay inside the pockets did not receive enough water and nutrients, due to the slope; a substrate with a greater capillary action, such as perlite, might have helped to alleviate this issue. Another problem was the growth of algae on the felt, caused by the humid environment and the high levels of nutrients and light. This caused competition with the crop resulting in higher water consumption, caused obstructions in the irrigation emitters, and resulted in more hours being required for maintaining the system. In terms of fish production, on the other hand, the living wall system outperformed the NFT and DWC systems. This is most likely because the water had to be replenished more frequently due to the high rate of evaporation, resulting in better water quality (Peréz-Urrestarazu *et al.* 2019).

The results of the experimental studies by Khandaker & Kotzen 2018 and Peréz-Urrestarazu *et al.* 2019 suggest that geotextile living walls may not be the most suitable sort of system to use for vertical aquaponics, despite the potentially high number of plants that can be grown in them in ratio to occupied floor area, due to the problems encountered with algae growth, uneven biomass and yield, and difficulties with harvesting the plants. In addition, it is important to bear in mind that most geotextiles consist of a polymer from the polyolefin, polyester or polyamide family, and additives to improve their stability. Over time and under various conditions the polymer may degrade into microplastic particles, which could be ingested by the fish. Generally, a higher ambient temperature accelerates the degradation rate, and different degradation mechanisms may act in synergy. Leaching of additives is also likely when micro-sized plastic particles have been formed, and may even occur from non-degraded material, as the additives are often not covalently bound to the polymer backbone (Vé Wiewel & Lamoree 2016). The ecotoxicology of a geotextile living wall therefore should be tested before it is used with an aquaponic system. A geotextile made from biopolymers constructed from natural fibres, such as jute and coir, would be more suitable than a synthetic geotextile. Other types of living wall might also be suitable, such as the hydroponic system produced by Biotecture, which consists of rigid plastic panels filled with horticultural-grade rockwool.

14.6 Conclusions

While vertical aquaponic systems may increase the number of plants that can be grown per unit of surface area compared with horizontal systems, it is important that they also result in increased yields. From a commercial point of view, the effects of gradients within some types of vertical system on crop value will depend on how the crop is going to be processed and marketed. For example, if lettuce is grown to be sold as individual heads, then the non-uniform productivity of growing towers, living walls and static A-frame systems would be a potential weakness compared with conventional horizontal aquaponic systems or vertical stacked bed systems. However, if the crop is destined for pre-cut salad bags, then crop uniformity may be irrelevant, and the increased yield per unit area could be a significant advantage. Besides affecting crop yield and quality, harvest efficiency in vertical and multi-tier horizontal systems may also be adversely affected since it will require working at different heights. The costs of the different types of vertical growing system also vary widely, depending on their complexity and the degree of automation. Therefore, crop utilization and marketability, and an investigation of the cost-to-benefits ratio of these growing systems, will be the ultimate criteria to decide whether vertical aquaponics can provide a viable alternative to conventional horizontal systems.

14.7 References

Al-Kodmany, K. 2018. The vertical farm: A review of developments and implications for the vertical city. *Buildings* 8, 24.

Al-Raisy, F.S., Al-Said, F.A., Al-Rawahi, M.S., Khan, I.A., Al-Makhmari, S.M. & Khan, M. 2010. Effects of column sizes and media on yield and fruit quality of strawberry under hydroponic vertical system. *European Journal of Scientific Research* 43, 48-60.

Durner, E.F. 1999. Winter greenhouse strawberry production using conditioned plug plants. *HortScience* 34 (4), 615-616,

Hayden, A. 2006. Aeroponic and hydroponic systems for medicinal herb, rhizome, and root crop. *HortScience* 41, 536-538.

Heller, H., Bar-Tal, A., Assouline, S., Narkis, K., Suryano, A., de la Forge, A., Barak, M., Alon, H., Bruner, M., Cohen, S. & Tsohar, D. 2015. The effects of container geometry on water and heat regimes in soilless culture: lettuce as a case study. *Irrigation Science* 33, 53-65.

Sijmonsma, A. 2015. For sale: urban aquaponics farm of Greens & Gills in Chicago. HortiDaily.com.

Karimi, F., Arunkumar, B., Asif, M., Murthy, B.N.S. & Venkatesha, K.T. 2013. Effect of different soilless culture systems on growth, yield and quality of strawberry cv. Strawberry Festival. *International Journal of Agricultural Sciences* 9, 366-372.

Khandaker, M. & Kotzen, B. 2018. The potential for combining living wall and vertical farming systems with aquaponics with special emphasis on substrates. *Aquaculture Research* 2018, 1-15.

Liu, W., Chen, D.K. & Liu, Z.X. 2004. High efficiency column culture system in China. *Acta Horticulturae* 691, 495-500.

Love, D.C., Fry, J.P., Li, X., Hill, E.S., Genello, L., Semmens, K. & Thompson, R.E. 2015. Commercial aquaponics production and profitability: findings from an international survey. *Aquaculture* 435, 67-74.

Manso, M. & Castro-Gomes, J. 2015. Green wall systems: A review of their characteristics. *Renewable and Sustainable Energy Reviews* 41, 863–871.

Michael, C. 2016. *Understanding biological surface area in aquaponics*. ZipGrow.

Murthy, B.N.S., Karimi, F., Laxman, R.H. & Sunoj, V.S.J. 2016. Response of strawberry cv. Festival grown under vertical soilless culture system. *Indian Journal of Horticulture* 73 (2), 300-303.

Neocleous, D., Kaittanis, C., Seraphides, N. & Polycarpou, P. 2010. Horizontal and vertical soilless growing systems under Cyprus conditions. *Journal of Applied Horticulture* 12 (2), 140-144.

Palm, H.W., Knaus, U., Appelbaum, S., Goddek, S., Strauch, S.M., Vermeulen, T., Jijakli, M.H. & Kotzen, B. 2018. Towards commercial aquaponics: a review of systems, designs, scales and nomenclature. *Aquaculture International* 26, 813-842.

Pattillo, D.A. 2017. *An overview of aquaponic systems: hydroponic components*. NCRAC Technical Bulletin 19.

Peréz-Urrestarazu, L., Lobillo-Eguíbar, J., Fernández-Cañero, R. & Fernández-Cabanás, V.M. 2019. Suitability and optimization of FAO's small-scale aquaponics systems for joint production of lettuce (*Lactuca sativa*) and fish (*Carassius auratus*). *Aquacultural Engineering* 85, 129-137.

Perini, K., Ottelé, M., Haas, E.M. & Raiteri, R. 2013. Vertical greening systems, a process tree for green façades and living walls. *Urban Ecosystems* 16 (2), 265-277.

Ramírez-Arias, J.A., Hernández-Ibarra, U., Pineda, J. & Fitz-Rodríguez, E. 2018. Horizontal and vertical hydroponic systems for strawberry production at high densities. *Acta Horticulturae* 1227, 331-338.

Ramírez-Gómez, H., Sandoval-Villa, M., Carrillo-Salazar, A. & Muratalla-Lúa, A. 2012. Comparison of hydroponic systems in the strawberry production. *Acta Horticulturae* 947, 165-172.

Sánchez-Del-Castillo, F., Bastida-Cañada, O.A., Moreno-Pérez, E.C., Contreras-Magaña, E. & Sahagún-Castellanos, J. 2014. Tomato yield with different hydroponic production methods based on ladder-shaped canopies. *Revista Chapingo Serie Horticultura* 20 (3), 239-251.

Takeda, F. 2000. Out-of-season greenhouse strawberry production in soilless substrate. *Advances in Strawberry Research* 18, 4-15.

Touliatos, T., Dodd, I.C. & McAinsh, M. 2016. Vertical farming increases lettuce yield per unit area compared to conventional horizontal hydroponics. *Food and Energy Security* 5 (3), 184–191.

Vé Wiewel, B. & Lamoree, M. 2016. Geotextile composition, application and ecotoxicology – A review. *Journal of Hazardous Materials* 317, 640-655.

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15. SOCIAL ASPECTS OF AQUAPONICS

15.1 Introduction

Aquaponics can be used as a vehicle to address a number of social issues. Many people with mental and physical health problems face social exclusion because they do not have equal access to opportunities in society, including paid employment, housing, education and leisure. The operation of an aquaponics system provides opportunities for the elements of doing (engaging in a meaningful activity), being (having self-regard and esteem), becoming (building skills and self-efficacy) and belonging (having acceptance and interpersonal connection) that are necessary in order to foster a sense of social inclusion. Aquaponics also offers an innovative form of therapeutic horticulture, a nature-based approach that can promote wellbeing for people with mental health issues. There are particular qualities of the plant-person relationship that promote people's interaction with their environment and hence their health, functional level, and subjective wellbeing (Fieldhouse 2003; Heliker *et al.* 2001). Plants are seen to bestow non-discriminatory rewards on their carer without imposing the burden of an interpersonal relationship and, by responding to care or neglect, can immediately reinforce a sense of personal agency. Social networks such as those provided by community aquaponics initiatives can act as buffers to stressors, provide a structure for acquiring skills, and validate and enhance an individual's sense of self-worth (Cohen & Wills 1985). Aquaponics can also be used to improve the wellbeing of elderly citizens, by facilitating various cognitive functions through sensory stimulation, and by enhancing their balance and mobility, thereby helping to prevent falls. Aquaponics can be used to promote scientific literacy by providing a useful tool for teaching the natural sciences at all levels, from primary through to tertiary education. It provides multiple ways of enriching classes in Science, Technology, Engineering and Mathematics (STEM) (Brown *et al.* 2011), and can also be used for teaching subjects such as business and economics, and for addressing issues like sustainable development, environmental science, agriculture, food systems, and health. And aquaponics can be used to integrate livelihood strategies to secure food and small incomes for landless and poor households (Pantanella *et al.* 2010). Domestic production of food, access to markets, and the acquisition of skills are invaluable tools for securing the empowerment and emancipation of women in developing countries, and aquaponics can provide the foundation for fair and sustainable socio-economic growth.

15.1.1 Food security

Food security exists when all people at all times have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences and enables them to live an active and healthy life (FAO Policy Brief). The four pillars of food security are: food availability, access to food, utilization, and stability. Food availability is achieved when nutritious food is available at all times for people to access, while food accessibility is achieved when people at all times have the economic ability to obtain nutritious food according to their dietary preferences. Food utilization is achieved when all food consumed is absorbed and utilized by the body to make a healthy active life possible, and food stability is achieved when all of the other pillars have been achieved.

Urban and peri-urban agriculture are increasingly recognised as a means by which cities can move away from current inequitable and resource-dependent food systems, reduce their ecological footprint, and increase their liveability (Malano *et al.* 2014). On account of being almost completely dependent on produce imported from other regions, urban consumers are particularly vulnerable to food insecurity. For those of low socio-economic status, this dependence means that any fluctuation in food prices translates into limited purchasing power, increased food insecurity, and compromised dietary options.

Assuring food security in the twenty-first century within sustainable planetary boundaries (Rockström *et al.* 2009) will require a multi-faceted intensification of food production (Godfray *et al.* 2010) decoupled from unsustainable resource use. Aquaponics may be part of the solution. Nutrition, which is integral to the concept of food security, is improved by incorporating fish and fresh vegetables in the diet. Fish provides a significant source of protein and vitamins and, even when consumed in small quantities, can improve dietary quality by contributing essential amino acids which are often missing or underrepresented in vegetable-based diets. In addition, fish oils are a source of omega three fatty acids that are crucial for normal brain development in unborn babies and infants.

Various initiatives around the world illustrate how aquaponics is starting to be used in efforts to enhance food security. Byspokes Community Interest Company, a UK-based social enterprise, has set up a pilot aquaponics system and training programme at the Al-Basma Centre in Beit Sahour, Occupied Palestinian Territories (OPT), a region where availability of space for food production is a serious problem, particularly in the urban areas and refugee camps. Even in agricultural areas, land access is being lost through Israeli controls and through effective annexation by the Israeli 'Security Fence'. 40% of the population in the OPT (25% in the West Bank) are classed as 'chronically food insecure', and unemployment stands at around 25%, with highs of 80% in some refugee camps. From an economic viewpoint the project demonstrated that an aquaponics system could contribute significantly to household incomes and so help lift families out of poverty, while also providing a range of fresh vegetables and fish to families least able to afford such high quality food.

Since 2010 the Food and Agriculture Organization of the United Nations (FAO) has been implementing an emergency food production support project for poor families in the Gaza Strip, where 11 years of Israeli sea, land and air blockade, combined with low rainfall resulting in drought, have severely compromised the possibilities for domestic food production in one of the most densely populated areas of the world. With so many restrictions, fresh vegetables are expensive and hard to find. 97% of the Gaza Strip population are urban or camp dwellers, and therefore do not have access to land. Poverty affects 53% of the population, and 39% of families headed by women are food insecure. Enabling families to produce their own affordable fresh food is therefore a highly appropriate and effective response to the current situation. Food insecure female-headed households living in urban areas were given rooftop aquaponics units, and other units were installed in educational and community establishments. Having an aquaponics unit on their roof means that the women can simultaneously improve their household food security and income while still taking care of their children and homes. All of the beneficiaries have increased their household food consumption as a result.

Through its Adaptive Agriculture Program, INMED Partnerships for Children is dedicated to establishing sustainable food programs that improve food security, conserve natural resources, promote strategies for adapting to climate change, and provide opportunities for income generation in developing countries. INMED has developed a simple and affordable aquaponics system for small-scale farmers, schools, government institutions and home gardeners using easily accessible off-the-shelf local materials. Over the past decade, INMED has established a highly successful Adaptive Aquaculture and Aquaponics Program in South Africa, Jamaica and Peru. In South Africa INMED focuses on achieving food security and sustainable income generation by strengthening local capacity to understand and address climate change, while resolving interrelated issues of environmental degradation, increasing water scarcity, and poverty. It offers business-planning links to markets and assistance with applications for development grants and loans to expand and growing enterprises. At the core of this far-reaching vision, in addition to intensive traditional cultivation, is aquaponics. Several projects have been successfully implemented in different provinces in the country. An aquaponics system was installed at the Thabelo Christian Association for the Disabled in a remote area of the Venda region in Limpopo province. Because INMED's system requires no heavy labour or complex mechanical systems, it is ideal for individuals with disabilities and those unable to perform traditional farming activities. Since the installation, the co-op has increased its revenue by more than 400%. Co-op members receive stable monthly salaries and have invested in breeding animals for additional revenue. Communities that have embraced this new way of farming have strengthened their ability to ensure food security and to provide new and adaptive opportunities for income generation.

Another good example of community upliftment in South Africa is Eden Aquaponics. Eden Aquaponics (Pty) Ltd is the brainchild of Jack Probart who, with the realisation that food security is fast becoming just as vital as a healthy economy, had the vision of developing a commercial business with a community focus. Using aquaponics to produce fish and vegetables in the Eden area of the Garden Route in the Western Cape, Eden Aquaponics supplies fish for consumption, as well as fingerlings for fish farming, and grows a variety of organic vegetables for distribution to the local farmers' markets, restaurants and retailers. The Community Upliftment division manufactures and installs customised commercial systems of various sizes including DIY backyard aquaponics equipment, and supplies seedlings and fingerlings. They also teach less fortunate communities to become self-sufficient in growing, marketing, and selling their produce, thereby enabling previously unemployed people to develop skills, self-confidence, self-esteem, and the ability to provide for themselves.

Food insecurity is not only pertinent to the developing world. In Seville, Spain, social enterprise Asociacíon Verdes del Sur has set up an aquaponics greenhouse in the grounds of a school in Polígono Sur, the most socially deprived part of the city, which is characterised by long-term unemployment and a high incidence of drug-related crime. The aquaponics unit is used as part of an environmental education programme for local residents, including teaching the benefits of eating locally grown fresh food, and developing skills for the unemployed. A prototype domestic unit has also been set up in the house of one of the local residents.

Figure 1: Aquaponics facilities in Polígono Sur – anticlockwise from top left: the aquaponics greenhouse at the school; Soledad with a frozen tilapia raised in her domestic unit; tomatoes and an aubergine saved for their seeds; the domestic aquaponics unit (Photographs: Sarah Milliken).

15.1.2 Food deserts

Healthy food environments are imperative for public health. Access to supermarkets that offer wholesome food products at low prices varies across space, and is correlated with socioeconomic status and ethnicity. Areas characterized by poor access to fresh fruit, vegetables, and other healthy foods at affordable prices are known as 'food deserts' (Rex & Blair 2003). The United States Department of Agriculture (USDA) designates food deserts based on characteristics of low income, race/ethnicity, long distance to a grocery store, lack of access to fresh affordable food, and dependence on public transportation. The residents of food deserts rely on fast food, convenience stores, petrol stations and food banks for the majority of their food staples. Due to these factors, many people face significant challenges in terms of food security and access, resulting in dramatic increases in related health issues, in particular obesity. Food deserts are especially problematic for those on low incomes, and for vulnerable individuals such as those with a disability which limits their ability to travel. Not having access to a car in a food desert can limit an individual's ability to reach food stores offering fresh produce at affordable prices.

Empirical evidence for food deserts in the US and also in UK is extensive (Walker *et al.* 2010). Food deserts tend to have smaller populations, higher rates of abandoned or vacant homes, and residents who have lower levels of education, lower incomes, and higher unemployment (Dutko *et al.* 2012). In 2017 15 million US households (11.8%) were classified as being food insecure, which means that they had difficulty at some time during the year in providing enough food for all household members due to a lack of resources. More than one third of these households (5.8 million) were classified as having very low food security, which means that the food intake of some household members was reduced and normal eating patterns were disrupted at times during the year due to limited resources. Rates of food insecurity were higher than the national average in households with incomes near or below the poverty line, in single parent households, among people living alone, in black and Hispanic households, and in the major cities (Coleman-Jensen *et al.* 2018).

Discussion of food deserts in the UK was particularly prominent in the 1990s, amid a wider debate about poverty and deprivation. This discussion was concentrated on relatively economically deprived areas such as social housing estates, with many hypothesising that supermarkets might underserve such areas, given the lower profits that could be realised from basing a store in an area where residents' incomes are relatively low. Residents without cars, unable to reach out-of-town supermarkets, depend on the corner shop where prices are high, products are processed, and fresh fruit and vegetables are of poor quality or non-existent (Wrigley 1998). Arguably the rise of online grocery deliveries may limit the extent to which food deserts are a significant problem, although it is unclear whether online deliveries are used equally across society. 10.2 million people in the UK (16% of the population) live in food deserts, of which 1.2 million live in economically deprived areas. The food deserts are spread out across the country, and cover both rural and urban areas. However, about three quarters (76%) of food deserts in England and Wales are in urban areas. Food deserts are very much a local problem rather than a nationwide or even town/citywide problem, which suggests that local, rather than nationwide, policy interventions are needed to tackle the problem (Corfe 2018).

Implemented either as professional urban agriculture or as community farming, aquaponics could potentially help to alleviate the food deserts, especially in urban areas where vacant buildings and rooftops provide opportunities for creating inner city growing spaces. However, this will require municipal governments to make changes to existing land use legislation in order to facilitate urban agriculture and make access to healthy foods and fresh produce easier for vulnerable populations (Tomlinson 2017).

15.1.3 Food sovereignty

The food sovereignty movement is a global alliance of farmers, growers, consumers and activists. It asserts that people must reclaim their power in the food system by rebuilding the relationships between people and the land, and between food providers and those who eat. Food sovereignty is the right of peoples to healthy and culturally appropriate food produced through ecologically sound and sustainable methods, and their right to define their own food and agriculture systems. It puts the aspirations and needs of those who produce, distribute and consume food at the heart of food systems and policies, rather than the demands of markets and corporations. Food sovereignty therefore goes well beyond ensuring that people have enough food to meet their physical needs.

If implemented as a programme to be managed by local people, community-based aquaponics enterprises offer a new model for blending local agency with scientific innovation to address food sovereignty, by re-engaging and giving communities more control over their food production and distribution. Bringing food production closer to where people live and helping them to engage with different agricultural approaches could encourage them to make positive changes to their diets, thereby contributing to food security. Access to food production can also be seen as a way of encouraging people to waste less food. A survey carried out in the UK (Vanson & Georgieva 2016) found a high level of social acceptance of aquaponics as an efficient, self-sufficient and clean method of urban food production. However, these findings contradict those from a survey carried out in Berlin, Germany (Specht *et al.* 2016), which found a comparatively low social acceptance of aquaponics compared with more low-tech forms of urban agriculture, such as rooftop gardening, though this might be explained by a general lack of knowledge about that type of production system.

15.1.4 Alternative food networks

Alternative food networks (AFNs) have emerged as part of the food sovereignty movement (Maye & Kirwan 2010). AFNs represent concrete efforts to respatialize and resocialize food production, distribution and consumption. AFNs can be defined as the systems or channels of food production, distribution and consumption which are built upon the re-connection or close communication between producer, produce and consumer, and which are committed to the social, economic and environmental dimensions of sustainable food production, distribution and consumption. AFNs are typically characterised by:

(1) Shorter distances between producers and consumers. By growing food in proximity to where people buy and eat their food, AFNs minimize transport distances and fuel consumption, and bypass middlemen in the distribution chain. This form of direct marketing allows farmers to capture and keep more profit, and it conserves fossil fuel both in production and transport. Direct marketing brings farmers and eaters face-to-face, thereby developing the bonds of trust and cooperation.

(2) Small farm size and scale and organic farming methods, which are contrasted with large scale, conventional agribusiness. The majority of farms in AFNs are small both in terms of acreage (under 50 acres) and in terms of revenue. They rely upon household labour, apprentices and interns and, in some cases, upon seasonal farm workers. Larger farms may employ year round workers, and may enable their owners to earn their livelihoods solely through farming. Alternative agriculture also stresses environmentally conscious food cultivation, and farmers in AFNs practice organic cultivation techniques, although their food may not be formally certified as such.

(3) The distribution of food through food cooperatives, farmers markets, Community Supported Agriculture (CSA) food box delivery services, and local food-to-school linkages. Rather than

contracting their food sales with brokers, wholesalers, corporations, processors, or supermarkets, farmers in AFNs adopt on-farm vertically integrated structures that involve the farm and the farm household directly in distribution and retail activities that occur near the farm.

AFNs seek to localize food systems and to encourage contact between food producers and consumers, seeking to respatialize food systems perceived to have become 'placeless'. AFNs are therefore sometimes called 'local food networks' (LFNs). The 'localisation' of food systems is seen as standing in a stark contrast to the mainstream agro-industrial and global food system characterised by 'food from nowhere'. The geography of local food systems, however, is only one key aspect. Apart from being rooted in a place, LFNs aim to be economically viable for farmers and consumers, use ecologically sound production and distribution practices, and enhance social equity and democracy for all members of the community.

Aquaponics fits well with the concept of Alternative Food Networks/Local Food Networks. It is an environmentally conscious method of food production that consumes less water than conventional crop production methods, and produces virtually no waste: the sludge can be easily composted and converted into valuable products. As a closed-loop system, the only input required for an aquaponics farm are the water and the food that feeds the fish, and therefore, unlike most traditional agricultural practices, it requires no or significantly reduced fertilizer or chemical-based pesticides in order to facilitate plant growth. This implies that plants harvested from an aquaponic system are grown in a system that is equivalent to organic production, although in the EU the produce cannot be certified as such, since the certification scheme currently only relates to soil grown crops.

Conventional aquaculture and agriculture can involve long value chains. The system boundaries are the fishery and greenhouse or field at one end, and the consumer at the other. Between the two are processing, retail, wholesale, and transportation, each of which has associated environmental, social, and economic impacts. The development of short value chains by urban aquaponics producers – e.g. selling directly to consumers, restaurants or supermarkets – can reduce these impacts.

The GrowHaus in Colorado is a social enterprise which focuses on healthy, equitable and resident-driven community food production. 97% of the food consumed in Colorado is produced out of state, and the neighbourhood where the GrowHaus is located has been designated a food desert. Initially in partnership with Colorado Aquaponics, and since 2016 independently, the GrowHaus operates a 297 square metre aquaponics farm and the produce is sold through a weekly farm fresh food basket programme at a price comparable to Walmart, as well as to restaurants, with a portion donated to the local community. To help the transition to healthier eating, the GrowHaus also organises free training and community events focused around food.

The Well Community Allotment Group (Crookes Community Farm) is social enterprise run by volunteers in Sheffield, UK, that is on a mission to connect the local community with their food by actively involving them in its production, and by educating them about the benefits of local food. In

2018 the association was awarded an Aviva Community Fund Award in order to build an aquaponics unit which will be used to educate individuals, schools, youth groups and other organisations.

15.2 Aquaponics and social enterprise

Social enterprises, as distinct from traditional private or corporate enterprise, aim to deliver products and services that cater to basic human needs. For a social enterprise, the primary motivation is not maximising profit but building social capital; economic growth is therefore only part of a much broader mandate that includes social services such as rehabilitation, education and training, as well as environmental protection. There is growing interest in aquaponics among social enterprises, because it represents an effective tool to help them deliver their mandate. For example, aquaponics can integrate livelihood strategies to secure food and small incomes for landless and poor households. Domestic production of food, access to markets, and the acquisition of skills are invaluable tools for securing the empowerment and emancipation of women in developing countries, and aquaponics can provide the foundation for fair and sustainable socio-economic growth.

Increasing public familiarity with aquaponics has seen a variety of social ventures being set up around the world. In the United States a number of social enterprises have started using aquaponics as part of a growing social movement focusing on using urban agriculture to increase food security and community cohesion. One of the first was Growing Power, which was founded by Will Allen in 1995 with the objective of using urban agriculture as a vehicle for improving food security in central Milwaukee and for the long-term strengthening of its neighbourhoods, and to give inner city youngsters an opportunity to gain life skills by cultivating and marketing organic produce. Growing Power provided facilities or land, guidance in food growing, and overall project maintenance, and the produce was either donated to meal programs and emergency food providers, or sold by the youngsters at local farm shops and farmers' markets, with the stipulation that one-quarter of the proceeds be returned to the local community.

In 2010 Will Allen was recognized by *Time Magazine* as one of the 100 most influential people in the world, and while Growing Power collapsed in 2017 under mounting debt, the legacy of the enterprise lives on in the form of other social ventures that were inspired to start similar initiatives. One such venture which acknowledges Will Allen's influence is the Rid-All Green Partnership in Cleveland, Ohio, whose mission is to educate the next generation to not only learn to grow and eat fresh food, but also to operate and grow their own businesses in the food industry, ranging from selling fresh produce and fish to food distributors, to full-fledged processing and packaging of fresh food products.

The urban agriculture movement in the United States has been fuelled by the US Department of Agriculture (USDA) Community Food Project (CFP) competitive grant program, which was established in 1996 with the aim of fighting food insecurity through the development of community food projects that promote the self-sufficiency of low-income communities. Since 1996 this program has awarded approximately $90 million in grants. One social enterprise which has benefited from this scheme is Planting Justice which built an aquaponics system on a vacant lot in East Oakland, California, which is run by former prison inmates. Twelve living wage jobs have been created, 2268 kilos of free produce has been given to the community, and the project has put $500,000 in wages and $200,000 in benefits back into the neighbourhood (New Entry Sustainable Farming Project 2018).

Trifecta Ecosystems (formerly Fresh Farm Aquaponics) in Meriden, Connecticut, aims to address urban food security by creating incentives for communities to grow their own food while also raising awareness about sustainable farming through education, workshops, and city projects. The enterprise employs six staff who provide aquaponics systems to organizations for educational purposes, workforce development, therapeutic gardening, and high-quality food production. The aquaponics systems range from commercial scale production facilities to small educational units for use in classrooms. In 2018 the South Central Regional Water Authority awarded a $500,000 grant to facilitate the creation of a series of controlled environment agriculture aquaponics systems, an urban farming technology platform, and workforce training programs aimed at improving food security.

The SchoolGrown social enterprise was set up in 2014 by aquaponics enthusiasts who felt that children weren't getting enough hands-on experiences growing food and learning about their connection to the world about them. Situated next to the commercial aquaponics operation at Ouroboros Farms, California, the aquaponics 'classroom' is run by volunteers and used to provide training. Their main focus, however, is on spreading aquaponics systems to schools and communities around the United States in order to teach sustainable agricultural practices, environmental stewardship and resource conservation, and at the same time produce fresh and local food, thereby building a deeper connection between communities and the food they eat. The LEAF (Living Ecosystem Aquaponic Facility) is a (167 square metre greenhouse with a solar powered aquaponics system that was specifically designed for this purpose. Costing $75,000, which includes salaries for two part-time staff responsible for maintaining the system and harvesting, the greenhouses are funded by a combination of Community Supported Agriculture (CSA) vegetable box scheme, local community or business sponsorship, and crowdfunding. Each LEAF is intended to be financially self-sustaining through the generation of revenue from the produce.

The examples above illustrate some of the different business models adopted by aquaponics social enterprises. Whether they will continue to thrive and grow or, like Growing Power, ultimately fail, remains to be seen. An in depth analysis of two aquaponics social enterprises conducted in 2012-13 revealed four distinct factors what were significant to their survival (Laidlaw & Magee 2016). Sweet Water Organics (SWO) began as an urban aquaponics farm in a large, disused, inner city industrial building in Milwaukee in 2008. It was funded primarily by its founders in order to develop creative capacity, employment opportunities and chemical-free, fresh and affordable food for the local community. In 2010 a new organisation, Sweet Water Farms (SWF), was split from SWO, with the idea that they would grow as a mutually supportive, cohesive hybrid organisation, including both a for-profit commercial urban farm (SWO), and a not-for-profit aquaponics 'academy' (SWF). SWF managed volunteer operations and hosted training and education programs at the Sweet Water urban farm, while developing programs on a local (Milwaukee and Chicago), regional, national, and international scale. Sweet Water had a loyal following among local restaurateurs and fresh food stores for its lettuce and sprouts produce, and sold its fish to a single wholesaler. However, the hybrid not-for-profit/for-profit enterprise model proved to be challenging, as both sides of the organisation struggled to identify their role in relation to the other. While each side had a different structure relating to their operational character, and although their operations frequently overlapped, their strategic planning and visions sometimes did not. After three years of operation, SWO had still not managed to make a profit, and in 2011 the Milwaukee municipal government awarded a $250,000 loan on condition that 45 jobs would be created by 2014. In October 2012, SWO had 11–13 permanent employees, but was still being sustained through loans financing and equity investment. By June 2013, as loan repayments fell due and the job creation targets were not met, the for-profit arm of Sweet Water went into liquidation, and SWF took over as the primary operator of the Sweet Water urban farm. Currently, SWF operates entirely as an educational and advisory enterprise run by volunteers and a small team of part-time employees, and no longer supplies restaurants with produce (Laidlaw & Magee 2016).

The Centre for Education and Research (CERES) in Melbourne, Australia, opened its aquaponics facility in 2010. The system was designed as a sub-optimised commercial system with the production capacity to support a single wage for the farmer who maintains it. Their wage varies based on how much he/she produces, with the vegetables being sold through the CERES Fair Food organic box delivery service. The scale of the operation does not generate a return that would permit the setting up of a fish-processing facility (Laidlaw & Magee 2016).

Stakeholders at Sweet Water Farms and CERES identified that the **p**rincipal factor behind their survival was ongoing commitment, in the form of continued support of personnel with technical and business management skills combined with an enduring leadership, and the willingness of the stakeholders to remain involved and prepared to cooperate without strong financial incentives. The second factor was the local political context. While the city of Milwaukee supported Sweet Water both through policy initiatives and direct financial aid, which allowed it to expand its fixed assets and human resources, build market awareness and acquire a sizeable regular commercial customer base, the CERES project had little such support, beyond an initial grant, and it had struggled to generate revenue which would have allowed it to expand. Costs of compliance and licensing also made it difficult to engage with local markets in more than a token way, which dampened its motivation to market and sell the produce, and made it untenable for the operation to develop beyond a small part-time income generating enterprise. The third factor was the availability of markets for urban aquaponics produce. While the urban aquaponics is attractive to a customer base that is increasingly responsive to issues of food security and ethical consumption, such as in Milwaukee, this was not the case in Melbourne. The final factor was diversification. Both CERES and SWO/SWF benefitted from translating social and technical experimentation into a range of training and educational services. SWO/SWF, being a larger concern, obviously had greater capacity for developing these services, and these proved vital in sustaining the social enterprise when commercial plans failed to materialise. The viability of aquaponics social enterprises therefore depends not only on stakeholder commitment, thorough market analysis, clear governance structures and a robust business plan, but also on external factors, such as the local political context and regulations (Laidlaw & Magee 2016).

15.3 Aquaponics as an educational tool

Aquaponics promotes scientific literacy and provides a useful tool for teaching the natural sciences at all levels, from primary through to tertiary education. An aquaponics classroom model system provides multiple ways of enriching classes in Science, Technology, Engineering and Mathematics (STEM). The day-to-day maintenance of an aquaponics system also enables experiential learning, which is the process of learning through physical experience, and more precisely the 'meaning-making' process of an individual's direct experience. Aquaponics can thus become an enjoyable and effective way for learners to study STEM content. It can also be used for teaching subjects such as business and economics, and for addressing issues like sustainable development, environmental science, agriculture, food systems and health.

There are many types of aquaponic systems available on the internet which can either be purchased as a kit, or a complete system can be delivered and installed. However, building an aquaponic system is in itself a valuable educational experience. A basic aquaponic system can also be built easily and inexpensively from reclaimed materials. Even a micro system (1.5 m^2) can mimic a full-scale unit in terms of water quality and water consumption, thus making it an effective teaching tool (Maucieri *et al.* 2018). However, implementing aquaponics in classrooms is not without its challenges. Technical difficulties, lack of experience and knowledge, and maintenance over holiday periods can all pose significant barriers to teachers using aquaponics, and disinterest on the teacher's part may also be a crucial factor (Hart *et al.* 2013; Hart *et al.* 2014). However, other studies revealed that many educators are willing to incorporate aquaponics in the classroom, particularly when it provides an opportunity for experiential learning (Clayborn *et al.* 2017). Teachers strongly agreed that bringing an aquaponics unit into the classroom is inspiring for the students and led to greater interaction between students and teachers, thereby contributing to a dialogue about science (Wardlow *et al.* 2002). A survey of the use of aquaponics in education in the USA found that in primary and secondary schools it tends to be project oriented and used for teaching single discipline subjects such as chemistry or biology, while college and university aquaponic systems were generally used for teaching interdisciplinary subjects such as food systems and environmental sciences. In vocational and technical schools aquaponic systems are rarely used to teach subjects other than aquaponics (Genello *et al.* 2015).

15.4 Aquaponics and wellbeing

Aquaponics offers an innovative form of therapeutic horticulture, a nature-based approach that can promote wellbeing for people with mental health problems through using a range of green activities such as gardening and contact with animals. Over the past decade, a number of social enterprises have emerged that provide therapeutic horticulture programmes for improving the wellbeing of local communities. The social enterprise approach builds on 'Social Firms' by facilitating people with mental health problems to develop new skills and re-engage with the workplace. A Social Firm is a specific type of social enterprise where the social mission is to create employment, work experience, training and volunteering opportunities, within a supportive and inclusive environment, for people who face significant barriers to employment, and in particular for people with a disability (including mental ill health and learning disability), abuse issues, a prison record, or homeless issues (Howarth *et al.* 2016).

There are particular qualities of the plant-person relationship that promote people's interaction with their environment and hence their health, functional level and subjective wellbeing. Plants are seen to bestow non-discriminatory rewards on their carer without imposing the burden of an interpersonal relationship and, by responding to care or neglect, can immediately reinforce a sense of personal agency. The efficacy of practising horticulture in a group context has also been demonstrated. Many people with mental and physical health problems face social exclusion because they do not have equal access to opportunities in society, including paid employment, housing, education and leisure. Social networks such as those provided by community horticulture initiatives can act as buffers to stressors, provide a structure for acquiring skills, and validate and enhance an individual's sense of self-worth (Diamant and Waterhouse 2010; Fieldhouse 2003).

To date there are few examples of aquaponics being used for therapeutic horticulture. In the United States, a small farming business called Green Bridge Growers in Indiana is growing produce all year-round, primarily using aquaponics. The company now employs a number of individuals with Autism Spectrum Disorder (ASD) and finds that the scheduling, precision and monitoring required in aquaponics perfectly match with their skills. Similarly, the ACRES Project (Adults Creating Residential and Employment Solutions) in Pennsylvania uses aquaponics to provide horticultural therapy, employment, and community integration for adults with autism and intellectual disabilities. They are involved in all facets of the aquaponics system, from care and maintenance to harvest and sales, and the scheduled procedures and daily routines that aquaponics requires provides them with the stability and structure that they find reassuring. By fostering social, vocational, and self-advocacy skills, ACRES therefore uses aquaponics to help autistic individuals optimize their potential, develop practical life skills, increase social capacity, and transition to work and independence.

The FabLab Nerve Centre in Northern Ireland has set up a social enterprise aquaponic digital farm to teach people with learning difficulties entrepreneurial and digital skills. Using state of the art digital equipment from the Nerve Centre's FabLab, such as 3D printers, CNC routers and laser cutters, students will receive hands-on training and experience in a range of digital design and making techniques that will allow them to design, build and operate an aquaponic farm. As part of the project a newly created social enterprise will be developed by the young people, allowing them to sell the produce from the farm to local businesses, thereby developing their skills in social entrepreneurship, business and marketing.

Solutions for Change, a social enterprise which is dedicated to solving family homelessness, runs Solutions Farms in California. The aquaponics farm provides training for homeless families in growing tilapia and seasonal leafy greens and herbs which are then sold to local restaurants, markets and schools. It functions as a laboratory for teaching important work values and preparing people for re-entry into the workplace, thereby raising hope, as well as produce.

Asociacíon Huerto Lazo is a social enterprise in the province of Malaga, Spain, which offers internships to young people from troubled backgrounds. The interns are given practical training in aquaponics in a safe environment. The catfish, tilapia and tench are sold to El Sollo restaurant in Fuengirola.

Figure 2: Aquaponics facilities at Asociacíon Huerto Lazo – anticlockwise from top left: catfish tanks in the aquaponics greenhouse; tilapia tanks with *Gynostemma pentaphyllum* which is sold for medicinal purposes; the water filtration tanks at Huerto Lazo; Ulrich Eich demonstrating his aquaponics system (Photographs: Sarah Milliken).

15.5 The potential of aquaponics for the wellbeing of elderly citizens

Aquaponics may provide an optimal environment to reach several therapeutic goals in a variety of clients with cognitive and/or physical disabilities, and special population groups like the elderly, children, or developmentally challenged people. The therapeutic goals of health care professionals such as occupational therapists and physiotherapists are the promotion of and/or treatment for wellbeing.

The primary goal of occupational therapy is to enable people to participate in the activities of everyday life. Occupational therapists achieve this by working with people and communities to enhance their ability to engage in the occupations they want, need, or are expected to do, or by modifying the occupation or the environment to better support their occupational engagement (WFOT 2012). In occupational therapy, occupations refer to the everyday activities that people do as individuals, in families, and with communities to occupy time and bring meaning and purpose to life. Occupations include things people need to, want to and are expected to do (WFOT 2012).

Physical therapists provide services that develop, maintain, and restore people's maximum movement and functional ability. They can help people at any stage of life, when movement and function are threatened by ageing, injury, diseases, disorders, conditions, or environmental factors. Physical therapists help people to maximise their quality of life, looking at physical, psychological, emotional and social wellbeing (WCPT 2016).

From a therapeutic point of view, an aquaponic unit is a tool that can promote the development of cognitive-behaviour, sensory-motor integration, and motor skills. Activities that can be used as a therapeutic means involve participation in selection of the plants and fish, and their daily care and observation. The expected therapeutic effect of aquaponics in respect of wellbeing can be found in different areas of a person‘s functioning.

15.5.1 Cognitive-behaviour skills

During the process of management and care for fish and plants in an aquaponic unit, cognitive functions such as decision making, short term memory, long term memory, attentional span, reaction time, switching between the tasks, planning, and problem solving can all be facilitated. Decision-making is the process of identifying and choosing alternatives based on the values, preferences and beliefs of the decision-maker. Like cognitive function, decision-making across the life span shows profound age-related changes (Tymula *et al.* 2013) Short-term memory, is a system for temporarily storing and managing the information required to carry out complex cognitive tasks such as learning, reasoning, and comprehension. Short-term memory is the capacity for holding a small amount of information in the mind in an active, readily available state for a short period of time. For example, short-term memory can be used to remember a phone number that has just been recited. The duration of short-term memory (when rehearsal or active maintenance is prevented) is believed to be in the order of seconds (typically about 18 to 30 seconds) (APA 2006).

With aging the memory storage capacity is not the issue; the brain is not an overloaded hard drive. Rather, the changes appear to come in how people encode and retrieve information. Interference, such as distraction, and slower processing may impede retrieval, such as being able to remember names and dates. However, even with these subtle changes, the majority of older adults still seem to be able to efficiently acquire new information and park it in long-term memory. And implicit learning – learning without conscious effort – seems to more or less be unaffected into old age.

It is believed that a healthy lifestyle supports brain health. Regular aerobic exercise has been shown to aid cognition, probably because it boosts blood flow and brings more oxygen to the brain. Attention span is the amount of concentrated time a person can spend on a task without becoming distracted. Most educators and psychologists agree that the ability to focus and sustain attention on a task is crucial for the achievement of one's goals. Attention span can have a major impact on performance at work and the ability to deal with the tasks of everyday life – one lapse in attention can result in missing out on important information, errors being made, or worse (APA 2006).

Reaction time is the elapsed time between the presentation of a sensory stimulus and the subsequent behavioural response. In psychometric psychology it is considered to be an index of processing speed: it indicates how fast the individual can execute the mental operations needed for the task at hand. In turn, speed of processing is considered to be an index of processing efficiency. Simple reaction time shortens from infancy into the late 20s, then increases slowly until the 50s and 60s, and then lengthens faster as the person gets into their 70s and beyond. In other words, contrary to their fervent belief, adolescents will probably have slower reaction times than adults. Reaction time also becomes more variable with age and with Alzheimer's disease. The reason for slowing reaction time with age are not just simple mechanical factors like the speed of nervous conduction, but may be related to the tendency of older people to be more careful and to monitor their responses more thoroughly. It was found that old people who tend to fall in nursing homes had a significantly longer reaction time than those that did not tend to fall.

15.5.2 Sensory-motor integration

Sensory stimuli are increased during the process of management and care for fish and plants in an aquaponic unit, especially in the olfactory and somato-sensory modalities. Everyday objects are used for sensory stimulation, which in an aquaponics unit would be the plants and fish. The goal of sensory stimulation is to promote sensory-motor integration, evoke positive feelings, influence mood, and enhance self-esteem and well-being. Repetitive contact with intensive stimuli promotes sensory integration and enables people to develop cognitive-behaviour skills. Fragrant herbs provide intensive olfactory stimuli which are known to be involved in the limbic system or so-called emotional brain (Figure 3).

Occupational performance difficulties due to sensory modulation challenges or poor integration of sensation can result from difficulties in how the nervous system receives, organizes, and uses sensory information from the body and the physical environment for self-regulation, motor planning, and skill development. These problems impact self-concept, emotional regulation, attention, problem solving, behaviour control, skill performance, and the capacity to develop and maintain interpersonal relationships. In adults, they may negatively impact the ability to parent, work, or engage in home management, social, and leisure activities. Occupational performance concerns due to poor integration and processing of sensation may occur in isolation, contribute to, or coexist with other conditions such as anxiety and panic disorders, depression, post-traumatic stress disorder, or schizophrenia. Those with learning disabilities, attention deficit disorder, developmental disabilities, or autism spectrum disorders may also experience these difficulties. Poor sensory integration can be seen in various aspects of human life throughout the life span (Table

15.1). Used in Europe since the 1960s, sensory integration was originally designed to help people with learning disabilities. It was a way for them to explore a safe, stimulating environment that provided age-appropriate and enjoyable activities. It has been also found that this technique can be used to reduce as much as 30 years of cognitive ageing (WFOT 2012).

Figure 3: Sensory stimulation of touch and smell during management of herbs and other plants

Table 15.1: The consequences of poor sensory organization in adulthood (WFOT 2012)

Body sensation (touch and movements)	**Motor Performance**
• Sensitive to texture and fit resulting in avoidance of some types of clothing (e.g., ties, turtlenecks, pantyhose) • Dislike of crowds or jostling in public places (e.g. standing in lines or shopping) • Becomes irritated with light or unexpected touch. May have difficulty with intimate touch • Limited engagement in food and meal preparation and/or variety in diet • May not discriminate when clothes are askew or food is on their face	• Difficulty driving, parking, shifting gears, or entering a freeway with a car • Difficulty managing common home and office equipment • Clumsy or awkward with motor activities (e.g. exercise, leisure, self-care tasks) • Difficulty organizing and planning materials and environment, possibly impacting work performance and health and safety at home • Difficulty following directions when navigating outdoors
Vestibular (inner ear balance)	**Social Performance**
• Difficulties with balance, dislike of walking on uneven surfaces • Dislike of or disorientation in elevators or on	• Difficulty discriminating visual and auditory cues, impacting social interactions and role performance • Difficulty with body awareness, affecting body

escalators • Nausea when riding in a car. Need to ride in the front seat or be the driver • Fearful of leaving the house or of flying	boundaries and body image • Difficulty discriminating sounds and following verbal directions • Difficulty managing self-care and hygiene
Auditory	**Emotion Regulation**
• Irritated by sounds not usually bothersome to others (e.g. pencils or pens scratching, lights buzzing, others eating, sweet wrappers rustling) • Sensitive to loud sounds	• Difficulty discriminating visual and auditory cues, decreasing the ability to understand the emotional expressions of others, resulting in frustration, anxiety, and anger management issues • Difficulty developing adaptive sensory-based physical supports (i.e. exercise, environmental adaptations) for emotional regulation

15.5.3 Motor skills

Mobility is the basic skill that allows someone to adapt to their environment and to fulfil their physiological and psychological needs. Mobility skills can decrease due to injury, disease, or ageing. Decreased mobility leads to loss of independent life and a decrease in the quality of life. A consequence of poor mobility skills is often a sudden and unintentional fall with various outcomes. Fall-related injuries are more common among older people and are a major cause of pain, disability, loss of independence, and premature death (WHO 2007). The financial costs are substantial and are increasing worldwide. The personal, family, and societal impact of fall-related injuries for older people, their families, and society, and the possibility of effective interventions, make this an important global health issue. Effectively targeting resources for the prevention of falls and related injuries requires knowledge of the scale and nature of the problem as well as evidence of effective interventions. This requires raising awareness about the magnitude of older adult falls, intensifying research efforts, and encouraging action towards prevention worldwide.

Increasing number of elderly adults, their need to sustain an active and healthy lifestyle, and increasing costs for rehabilitation after falls are the principal driving force for policy makers, health authorities, and clinicians in the allocation of financial and human resources to find effective programmes for fall prevention and balance enhancement or maintenance. Balance deficits can arise from impairments of the body sensations, inner ear balance, muscles and bones, and vision, and have a significant negative impact on mobility and functional independence. Regular physical exercise has demonstrated its beneficial effect in increasing functional capacity, general mobility, balance, and gait (Gheysen *et al.* 2018). These are all key components in fall prevention programmes (WHO 2007).

Stepping from level ground onto an elevated surface, such as stair climbing or aerobic step training during exercise, is a complex balance activity. It requires shifting the weight from one leg to the other and stabilisation of the loaded leg, dynamic stability during weight shifts, height and depth perception, eye-leg coordination for height and depth of stairs negotiation, sufficient concentric muscle power to lift the weight of the body during ascending, and sufficient eccentric muscle power to lower the body during descending. Stepping thus includes eight of the identified nine balance components. Dual tasking has become an increasing demand of everyday life. Dual tasking is defined as the concurrent performance of two tasks that can be performed independently and have distinct and separate goals. When humans attempt to do more than one thing at the same time, performance usually suffers. This is called dual task cost. These costs are assumed to arise in the level of information processing within the central nervous system. The decline in quality and speed in the simultaneous execution of two tasks is explained by tasks competing for a limited set of resources. In particular, the attention function is important, since greater attention is implicitly associated with the increased level of cognitive processing required to perform the desired task. The person must increase the level of attention devoted to one task in order to adapt to its increased complexity. The decline in the quality of performance in dual tasking is explained by two theories (Agmon *et al.* 2014). The capacity theory assumes that the consequence of the simultaneous use of limited attention resources is reduced and the person switches attention from one to the other task. The bottleneck theory, on the other hand, assumes that parallel processing is more difficult when the same cognitive operations are required, and a person prioritizes one task over another and treats them sequentially.

In everyday life people are engaged in the simultaneous performance of several different activities while maintaining postural control and walking. Common functional tasks coupled with standing and walking include cooking, talking on the phone while walking, and talking while crossing the road. Although balance and walking are basic skills for independent and active life, there is still no consensus on how far postural control and walking are automated, or how much attention is needed for their maintenance. Therefore, several therapeutic approaches have been developed where dual tasking situations are safely practiced. The pairs of tasks can be two motor tasks (carrying of objects while walking) and a motor and a cognitive task (standing or walking while talking or decision making). Current research indicates that there is a decrease of dual task cost after training, although it is limited to trained pairs of tasks (Agmon *et al.* 2014).

Figure 4: An example of obstacle negotiation path as a part of balance specific training of community dwelling elderly (Photographs by Darja Rugelj)

The aqaponic unit can be designed in a way that provides a reach environment for training mobility skills such as balance training, obstacle negotiation, and avoidance during gait, as well as for dual task training. The most prominent skills that are known to decrease the incidence of falls in elderly people are stepping, stair climbing, obstacle negotiation, and turning around vertical axes (Guirguis-Blake *et al.* 2018). However, environmental risk factors should be recognised, and the environment of an aquaponic unit should comply with known standards of environmental safety. Micro aquaponic system seem to provide an ideal tool for therapeutic and educational purposes given their low cost and low space requirements (Maucieri *et al.* 2018). Furthermore, the operation of an aquaponic system requires a variety of different professionals, and therefore it is an ideal environment for building interpersonal communication skills and team work in schools or with physically or mentally challenged groups (Morano *et al.* 2017).

15.6 References

Agmon, M., Belza, B., Nguyen, H.Q., Logsdon, R.G. & Kelly, V.E. 2014. A systematic review of interventions conducted in clinical or community settings to improve dual-task postural control in older adults. *Clinical Interventions in Aging* 9, 477-492.

APA 2006. *Memory Changes in Older Adults*. American Psychological Society.

Brown, J., Brown, R. & Merrill, C. 2011. Science and technology educators' enacted curriculum: Areas of possible collaboration for an integrative STEM approach in public schools. *Technology and Engineering Teacher* 71 (4), 30.

Clayborn, J., Medina, M. & O'Brien, G. 2017. School gardening with a twist using fish: Encouraging educators to adopt aquaponics in the classroom. *Applied Environmental Education & Communication* 16 (2), 93-104.

Cohen, S. & Wills, T.A. 1985. Stress, social support, and the buffering hypothesis. *Psychological Bulletin* 98 (2), p.310.

Coleman-Jensen, A., Rabbitt, M.P., Gregory, G.A. & Singh, A. 2018. *Household Food Security in the United States in 2017*. United States Department of Agriculture Economic Research Service.

Corfe, S. 2018. *What are the Barriers to Eating Healthily in the UK?* The Social Market Foundation.

Diamant, E. & Waterhouse, A. 2010. Gardening and belonging: reflections on how social and therapeutic horticulture may facilitate health, wellbeing and inclusion. *British Journal of Occupational Therapy* 73 (2), 84-88.

Dutko, P., Ver Ploeg, P. & Farrigan, T. 2012. *Characteristics and Influential Factors of Food Deserts*. U.S. Department of Agriculture, Economic Research Service ERR-140.

Fieldhouse, J. 2003. The impact of an allotment group on mental health clients' health, wellbeing and social networking. *British Journal of Occupational Therapy* 6 (7), 286-296.

Genello, L., Fry, J.P., Frederick, J.A., Li, X. & Love, D.C. 2015. Fish in the classroom: A survey of the use of aquaponics in education. *European Journal of Health & Biology Education* 4 (2), 9-20.

Gheysen, F., Poppe, L., DeSmet, A., Swinnen, S., Cardon, G., De Bourdeaudhuij, I., Chastin, S. & Fias, W. 2018. Physical activity to improve cognition in older adults: can physical activity programs enriched with cognitive challenges enhance the effects? A systematic review and meta-analysis. *International Journal of Behavioral Nutrition and Physical Activity* 15, 63.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. & Toulmin, C. 2010. Food security: the challenge of feeding 9 billion people. *Science* 327 (5967), 812-818.

Guirguis-Blake, J.M., Michael, Y.L., Perdue, LA., Coppola, E.L. & Beil, T.L. 2018. Interventions to prevent falls in older adults updated evidence. Report and systematic review for the US Preventive Services Task Force. *Jama-Journal of the American Medical Association* 319 (16), 1705-1716.

Hart, E.R., Webb, J.B. & Danylchuk, A.J. 2013. Implementation of aquaponics in education: An assessment of challenges and solutions. *Science Education International* 24 (4), 460-480.

Hart, E.R., Webb, J.B., Hollingsworth, C. & Danylchuk, A.J. 2014. Managing expectations for aquaponics in the classroom: Enhancing academic learning and teaching an appreciation for aquatic resources. *Fisheries* 39 (11), 525-530.

Heliker, D., Chadwick, A. & O'Connell, T. 2001. The meaning of gardening and the effects on perceived well being of a gardening project on diverse populations of elders. *Activities, Adaptation & Aging* 24 (3), 35-56.

Howarth, M.L., McQuarrie, C., Withnell, N. & Smith, E. 2016. The influence of therapeutic horticulture on social integration. *Journal of Public Mental Health* 15 (3), 136-140.

Laidlaw, J.& Magee, L., 2016. Towards urban food sovereignty: the trials and tribulations of community-based aquaponics enterprises in Milwaukee and Melbourne. *Local Environment* 21 (5), 573-590.

Malano, H., Maheshwari, B., Singh, V.P., Purohit, R. & Amerasinghe, P. 2014. Challenges and opportunities for peri-urban futures. In Maheshwari, B., Purohit, R., Malano, H., Singh, V.P. & Amerasinghe, P. (eds.) *The Security of Water, Food, Energy and Liveability of Cities*, pp. 3-10. Springer, Dordrecht.

Maucieri, C., Forchino, A.A., Nicoletto, C., Junge, R., Pastres, R., Sambo P. & Borin, M. 2018. Life cycle assessment of an aquaponic system built using recovered material for learning purposes. *Journal of Cleaner Production* 172, 3119-3127.

Maye, D. & Kirwan, J. 2010. Alternative food networks. Scociopedia.isa.

Morano, L. & Tzouanas, V. 2017. Urban agricultural and sustainability program at Houston's downtown university: Combining new curriculum, hands-on projects, and a hurricane. *Journal of Agriculture Food Systems and Community Development* 7 (4), 23-33.

New Entry Sustainable Farming Project 2018. *Community Food Projects: Indicators of Success FY 2017*.

Pantanella, E., Cardarelli, M., Danieli, P.P., MacNiven, A. & Colla, G. 2010. Integrated aquaculture-floating agriculture: is it a valid strategy to raise livelihood? *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on Horticulture for Development. ISHS Acta Horticulturae* 921, 79-86.

Rex, D. & Blair, A. 2003. Unjust des(s)erts: food retailing and neighbourhood health in Sandwell. *International Journal of Retail & Distribution Management* 31 (9), 459-465.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J. & Nykvist, B. 2009. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and Society* 14 (2), 32.

Specht, K., Weith, T., Swoboda, K. & Siebert, R. 2016. Socially acceptable urban agriculture businesses. *Agronomy for Sustainable Development* 36, 17.

Tomlinson, L. 2017. Indoor aquaponics in abandoned buildings: A potential solution to food deserts. *Sustainable Development Law & Policy* 16 (1), 16-40.

Tymula, A., Rosenberg Belmaker, L.A., Ruderman, L., Glimcher, P.W. & Levy, I. 2013. Like cognitive function, decision making across the life span shows profound age-related changes. *Proceedings of the National Academy of Sciences of the United States of America* 110 (42), 17143-17148.

Vanson, T. & Georgieva, I. 2016. *Urban Agriculture Project*. Global Food Security Food Futures Panel report.

Walker, R.E., Keane, C.R. & Burke, J.G. 2010. Disparities and access to healthy food in the United States: A review of food deserts literature. *Health & Place* 16 (5), 876-884.

Wardlow, G.W., Johnson, D.M., Mueller, C.L. & Hilgenberg, C.E. 2002. Enhancing student interest in the agricultural sciences through aquaponics. *Journal of Natural Resources and Life Sciences Education* 31, 55-58.

WCPT 2016. *What is Physical Therapy*. World Confederation for Physical Therapy.

WFOT 2012. *About Occupational Therapy*. World Federation of Occupational Therapists.

WHO 2007. *WHO Global Report on Falls Prevention in Older Age*. World Health Organization, Geneva.

Wrigley, N. 1998. How British retailers have shaped food choice. In Murcott, A. (ed.) *The Nation's Diet: The Social Science of Food Choice*, pp.112-128. Routledge, Abingdon.