Chapter 12
Aquaponics: Alternative Types and Approaches

Benz Kotzen, Maurício Gustavo Coelho Emerenciano, Navid Moheimani, and Gavin M. Burnell

Abstract Whilst aquaponics may be considered in the mid-stage of development, there are a number of allied, novel methods of food production that are aligning alongside aquaponics and also which can be merged with aquaponics to deliver food efficiently and productively. These technologies include algaeponics, aeroponics, aeroaquaponics, maraponics, haloponics, biofloc technology and vertical aquaponics. Although some of these systems have undergone many years of trials and research, in most cases, much more scientific research is required to understand intrinsic processes within the systems, efficiency, design aspects, etc., apart from the capacity, capabilities and benefits of conjoining these systems with aquaponics.

Keywords Aquaponics alternatives · Algaeponics · Aeroponics · Aquaeroponics · Biofloc Technologies · Digeponics · Haloponics · Maraponics · Vermiponics · Vertical aquaponics

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B. Kotzen (✉)
School of Design, University of Greenwich, London, UK
e-mail: b.kotzen@greenwich.ac.uk

M. G. C. Emerenciano
Santa Catarina State University (UDESC), Aquaculture Laboratory (LAQ), Laguna, SC, Brazil

CSIRO Agriculture and Food, Aquaculture Program, Bribie Island Research Centre, Bribie Island, QLD, Woorim, Australia
e-mail: mauricio.emerenciano@csiro.au

N. Moheimani
Algae R&D Centre Director, School of Veterinary and Life Sciences, Murdoch University, Murdoch, WA, Australia
e-mail: n.moheimani@murdoch.edu.au

G. M. Burnell
School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland
e-mail: g.burnell@ucc.ie

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12.1 Introduction

This chapter discusses a number of key allied and alternative technologies that either expand or have the potential to expand the functionality/productivity of aquaponic systems or are associated/stand-alone technologies that can be linked to aquaponics. The creation and development of these systems have at their core the ability, amongst other things, to increase production, reduce waste and energy and in most cases reduce water usage. Unlike aquaponics, which may be seen to be in a mid/teenage stage of development, the novel approaches discussed below are in their infancy. This, however, does not mean that they are not technologies valuable in their own right and have the potential to deliver future food, efficiently and sustainably. The methods discussed below include aeroponics, aeroaquaponics, algaeponics, biofloc technology for aquaponics, maraponics and haloponics and vertical aquaponics.

12.2 Aeroponics

12.2.1 Background

The US National Aeronautics and Space Administration (NASA) describes aeroponics as *the process of growing plants suspended in air without soil or media* providing *clean, efficient, and rapid food production*. NASA furthermore notes that *crops can be planted and harvested year-round without interruption, and without contamination from soil, pesticides, and residue* and that *aeroponic systems also reduce water usage by 98%, fertilizer usage by 60% percent, and eliminate pesticide usage altogether. Plants grown in aeroponic systems have been shown to absorb more minerals and vitamins, making the plants healthier and potentially more nutritious* (NASA Spinoff). Other advantages of aeroponics are seen to be that:

- The growing environment can be kept clean and sterile.
- This reduces the chances for plant diseases and the spread of infection.
- Seedlings do not stretch or wilt during root formation.
- Seedlings are easily removed for transplanting without transplant shock.
- Seedling growth is accelerated, which leads to increased crop cycles and thus more produce per annum.

For Weathers and Zobel (1992), aeroponics is defined as *the culture of whole plants and/or tissues with their roots or the whole tissue fed by an air/water fog (as opposed to immersion in/on water, soil, nutrient agar or other substrates).* For them, plants that are grown only partially with their roots in air and part in nutrient solutions or are grown for part of the time in air and part of the time in nutrient solution are grown through a process of aero-hydroponics and not areoponics.

Aeroponic systems thus function by spraying or misting the root zone area with nutrient solution. The roots of the plants are thus suspended in air and are subjected to a continuous or intermittent/periodic spray/misting of nutrient-rich water droplets, in the form of droplets or very fine mists, with droplet sizes from 5 to 50 μm (microns). It is usual to find 'hobby/domestic' kit with spray droplet sizes of 30–80 μm. Ultrasonic or dry-fog atomizers produce a droplet size <5 μm, but these require compressed air and very fine nozzles, or it may be possible to use ultrasonic transducers to produce these mists.

In aeroponics, as with hydroponics, nutrient supply can be optimized and in a comparison between hydroponics and aeroponics, Hikosaka et al. (2014) note that no difference was found between growth and harvest quality in lettuce using dry-fog aeroponics. However, there was a significant increase in root respiration rates and photosynthesis rates of leaves. They also note that this system also uses less water and that it can be more efficient and easier to manage than conventional hydroponics (Hikosaka et al. 2014). In a review paper on modern plant cultivation technologies in agriculture under controlled environments, Lakhiar et al. (2018) note that aeroponics 'is considered the best plant growing method for food security and sustainable development'.

12.2.2 Origin of Aeroponics

Richard J. Stoner II is considered the father of aeroponics. The NASA review of aquaponics (Clawson et al. 2000) notes that the origin of aquaponics is largely in the study of root morphology, but originates in nature, e.g. with plants, for example, orchids growing in tropical areas where mists occur naturally. Clawson et al. (2000) note the development of aeroponics from B. T. Barker, who 'succeeded in growing apple trees with a spray', and F. W. Went, who in 1957 grew tomatoes and coffee plants in mists and termed the process 'aeroponics'. With regard to the study of root morphology, Carter in 1942 used aeroponics as a way of investigating pineapple roots, and Klotz in 1944 investigated the roots of avocado and citrus, and then numerous others including Hubick and Robertson; Barak, Soffer, and Burger; Yurgalevitch and Janes; and Dutoit, Weathers, and Briggs all undertook various experiments in aeroponics (refer to Clawson et al. 2000 for details).

12.2.3 Aeroponics Growing Issues

Clawson et al. (2000) report the tests by Tibbits et al. (1994) that continuous misting can 'contribute to fungal and bacterial growth in the vicinity of or on the plants', and furthermore some researchers have found that due to fine droplets and with continuous fogging systems, there can be difficulties 'in delivering nutrients to all the plants where there is a high density of plants'. In this respect it has been shown that misting at intervals delivers a healthier system and healthier roots compared to continuous fogging and hydroponic techniques. Using intervals also makes the plants more resistant to any interruptions in misting, conditioning the plants to thrive longer on lower moisture levels, with a likely reduction in pathogen levels. For effective misting, 'droplet size and velocity are also important aeroponic parameters. The root's mist collection efficiency depends on its filament size, drop size, and velocity' (Clawson et al. 2000).

12.2.4 Combining Aquaponics and Aeroponics

Whilst a number of entrepreneurs and keen hobbyists are promoting combining aquaponics with aeroponics, there are a number of issues that need to be solved if considering this combo-technology for future farming. One issue that needs to be resolved is a name for this system, and it is suggested here that we call this combo-system 'aquaeroponics'.

Whilst there are numerous videos and discussion threads on the web, on combining aeroponics and aquaponics, the field is void of scientific literature. The web-based discussions raise the issues of clogging of mist sprayers and the need for fine filtration of aquaponic solutions. Another issue with aquaeroponics is the potential for pathogens to grow in the airy wet environment and research will be required to ascertain this. One solution to solving the problem of misters is to use ultrasonic vibration to create the mists but this does not solve any problems there may be with the growth of pathogens.

12.3 Algaeponics

12.3.1 Background

Microalgae are unicellular photoautotrophs (ranging from 0.2 μm up to 100 μm) and are classified in various taxonomic groups. Microalgae can be found in most environments but are mostly found in aquatic environments. Phytoplankton are responsible for over 45% of world's primary production as well as generating over 50% of atmospheric O_2. In general, there is no major difference in photosynthesis of microalgae and higher plants (Deppeler et al. 2018). However, due to their smaller size and the reduction in a number of internally competitive physiological organelles, microalgae can grow much faster than higher plants (Moheimani et al. 2015). Microalgae can also grow under limited nutrient conditions and have the ability to adapt to a wider range of environmental conditions (Gordon and Polle 2007). Most importantly, microalgal culture does not compete with food crop production regarding arable land and freshwater (Moheimani et al. 2015). Furthermore, microalgae can efficiently utilize inorganic nutrients from waste effluents (Ayre et al. 2017). In general, microalgal biomass contains up to 50% carbon making them a perfect candidate for bioremediating atmospheric CO_2 (Moheimani et al. 2012).

The increase in extensive worldwide agriculture and animal farming has resulted in significant increases in biologically available nitrogen and phosphorus entering the terrestrial biosphere (Galloway et al. 2004). Crop and animal farming and sewage systems contribute significant amounts to these nutrient loads (Schoumans et al. 2014). The infiltration of these nutrients into water streams can cause massive environmental issues such as harmful algal blooms and mass fish mortality. For instance, in the USA, nutrient pollution from agriculture is acknowledged as one of the major sources of eutrophication (Sharpley et al. 2008). Controlling the flow of nutrients from farming operations into the surrounding environment results in both technical and economic challenges that must be overcome to reduce such effects. There have been various successful processes developed to treat waste effluent with high organic loads. However, almost all of these methods are not very effective in removing inorganic elements from water. Furthermore, some of these methods are rather expensive to operate. One simple method for treating organic waste is anaerobic digestion (AD). The AD process is well understood and when operated efficiently, it can convert over 90% of the wastewater organic matters to bio-methane and CO_2 (Parkin and Owen 1986). The methane can be used to generate electricity and the generated heat can be used for various additional purposes. However, the AD process results in creating an anaerobic digestion effluent (ADE) which is very rich in inorganic phosphate and nitrogen as well as high COD (carbon oxygen demand). In certain locations, this effluent can be treated using microalgae and macroalgae (Ayre et al. 2017).

12.3.2 Algal Growth Systems

Since the United Nations committee recommended that conventional agricultural crops be supplemented with high-protein foods of unconventional origin, microalgae have become natural candidates (Richmond and Becker 1986). The first microalgal cultivation was achieved though in 1890 by culturing *Chlorella vulgaris* (Borowitzka 1999). Due to the fact that microalgae normally divide at a certain time of the day, the term cyclostat was developed in order to introduce a light/dark (circadian) cycle to the culture (Chisholm and Brand 1981). The large-scale culturing of microalgae and the partial use of its biomass especially as a base for certain products such as lipids was probably started seriously as early as 1953 with the aim of producing food from a large-scale culture of *Chlorella* (Borowitzka 1999). Typically, algae can be cultured in liquid using open ponds (Borowitzka and Moheimani 2013), closed photobioreactors (Moheimani et al. 2011), or a combination of these systems. Alga can also be cultured as biofilms (Wijihastuti et al. 2017).

Closed Photobioreactors (after Moheimani et al. 2011): Closed algal cultures (photobioreactors) are not exposed to the atmosphere but are covered with a transparent material or contained within transparent tubing. Photobioreactors have the distinct advantage of preventing evaporation. Closed and semi-closed photobioreactors are mainly used for producing high-value algal products. Due to the overall cost of operating expenditure (OPEX) and capital expenditure (CAPEX), closed photobioreactors are less economical than open systems. On the other hand, there is less contamination and less CO_2 losses, and by creating reproducible cultivation conditions and flexibility in technical design, this makes them a good substitute for open ponds. Some of the closed systems' weaknesses can be overcome by (a) reducing the light path, (b) solving shear (turbulence) complexity, reducing oxygen concentration, and (c) a temperature control system. Closed photobioreactors are mainly divided into (a) carboys, (b) tubular, (c) airlift and (d) plate photobioreactors.

Open Ponds (after Borowitzka and Moheimani 2013): Open ponds are most commonly used for large-scale outdoor microalgal cultivation. Major algal commercial production is based in open channels (raceways) which are less expensive, easier to build and operate when compared to closed photobioreactors. In addition, the growth of microalgae meets less difficulties in open than closed cultivation systems. However just a few species of microalgae (e.g. *Dunaliella salina*, *Spirulina* sp., *Chlorella* sp.) have been grown successfully in open ponds. Commercial microalgal production costs are high, approximated to be between 4 and 20 \$US/g^{-1}. Large-scale outdoor open pond commercial microalgal culture has developed over the last 70 years, and both still (unstirred) and agitated ponds have been developed and have been used on a commercial basis. The very large unstirred open ponds are simply constructed from natural water ponds with open beds that are usually less than 0.5 m in depth. In some smaller ponds the surface may be lined with plastic lining sheets. Unstirred open ponds represent the most economical and least technical of all commercial culture methods and have been commercially used for *Dunaliella salina* β-carotene production in Australia. Such ponds are mainly limited to growing microalgae which are capable of surviving in poor conditions or have a competitive advantage that allows them to outgrow contaminants such as protozoa, unwanted microalgae, viruses, and bacteria. Agitated ponds on the other hand have the advantage of a mixing regime. Most agitated ponds are either (a) circular ponds with rotating agitators or (b) single or joined raceway ponds.

Circular cultivation ponds have primarily been used for the large-scale cultivation of microalgae especially in South East Asia. The circular ponds up to 45 m in diameter and usually 0.3–0.7 m in depth are uncovered, but there are some examples which are covered by glass domes. The low shear stresses that are required for microalgae production are produced in these systems particularly in the centre of the pond, and this is a distinct advantage of these kinds of systems. Some disadvantages include expensive concrete structures, inefficient land use with large footprints, difficulties in controlling the movement of the agitating device and the added cost in supplying CO_2.

Paddlewheel-driven raceways are the most common commercial microalgal cultivation system. Raceways are usually constructed in either a single channel or as linked channels. Raceways are usually shallow (0.15 to 0.25 m deep), are constructed in a loop and normally cover an area of approximately 0.5 to 1.5 ha. Raceways are mostly used and recommended for the major commercial culturing of three species of microalgae including *Chlorella*, *Spirulina* and *Dunaliella*. A high risk of contamination and low productivity, resulting mainly from poor mixing regimes and light penetration, are the main disadvantages of these open systems. In raceways, biomass concentrations of up to 1000 mg dry weight.L^{-1} and productivities of 20 g dry weight.m^{-2}.d^{-1} have been shown to be possible.

The price of microalgal production makes economic achievement highly dependent on the marketing of expensive and exclusive products, for which demand is naturally restricted. Raceways are also the most used cultivation system used for treating wastewater (Parks and Craggs 2010).

Solid Cultivation (after Wijihastuti et al. 2017): An alternative microalgal cultivation method is immobilizing the cells in a polymer matrix or attaching them to the surface of a solid support (biofilm). In general, the biomass yield of such biomass cultures are at least 99% more concentrated than liquid-based cultures. Dewatering is one of the most expensive and energy-intensive parts of any mass algal production. The main advantage of biofilm growth is the potential of reducing the dewatering process and the related energy consumption and thus costs. Biofilm cultivation can also increase cellular light capture, reduce environmental stress (e.g. pH, salinity, metal toxicity, very high irradiance), reduce the cost of production and reduce nutrient consumption. Solid-based cultivation methods can be used for treating wastewater (nutrient and metal removal). There are three main methods for biofilm cultivation: (a) 100% directly submerged in medium, (b) partially submerged in medium and (c) using a porous substrate to deliver the nutrients and moisture from the medium to the cells.

12.3.3 Algal Growth Nutrient Requirements

A number of inhibitory physical, chemical and biological factors can inhibit high microalgal production. These are described in Table 12.1.

A basic knowledge of the critical growth limitations is probably the most essential factor before applying any microalgae to any process. Light is by far the most important limiting factor affecting the growth of any alga. Temperature is also a critical factor for mass algal production (Moheimani and Parlevliet 2013). However, these variables are difficult to control (Moheimani and Parlevliet 2013). Next to light and temperature, nutrients are the most important limiting factor affecting the growth of any alga (Moheimani and Borowitzka 2007) and each microalgal species tends to have its own optimum nutrient requirements. The most important nutrients are nitrogen, phosphorus and carbon (Oswald 1988). Most

Table 12.1 Limits to growth and productivity of microalgae (Moheimani and Borowitzka 2007)

Abiotic factors	Light (quality, quantity)
	Temperature
	Nutrient concentration
	O_2
	CO_2 and pH
	Salinity
	Toxic chemicals
Biotic factors	Pathogens (bacteria, fungi, viruses)
	Competition by other algae
Operational factors	Shear produced by mixing
	Dilution rate
	Depth
	Harvest frequency
	Addition of bicarbonate

algae respond to N-limitation by increasing their lipid content (Moheimani 2016). For example, Shifrin and Chisholm (1981) reported that in 20 to 30 species of microalgae that they examined, the algae increased their lipid content under N-deprivation. Phosphorus is also an important nutrient required for microalgal growth as it plays an essential role in cell metabolism and regulation, being involved in the production of enzymes, phospholipids and energy-supplying compounds (Smith 1983). Brown and Button's (1979) studies on green alga *Selenastrum capricornutum* showed an apparent growth limitation when the phosphate concentration of the medium was lower than 10 nM. CO_2 is also a critical nutrient for achieving high algal productivity (Moheimani 2016). For example, if additional CO_2 is not added to the algal culture, the average productivity can be reduced by up to 80% (Moheimani 2016). However, the addition of CO_2 to algal ponds is rather costly (Moheimani 2016). The most economical way for introducing CO_2 to a culture media is the direct transfer of the gas into the media by bubbling through sintered porous stones or using pipes under submerged plastic sheets as CO_2 injectors (Moheimani 2016). Unfortunately, in all of these methods there is still high loss of CO_2 to the atmosphere because of the short retention time of the gas bubbles in the algal suspension.

Although adding N, P and C is critical, other nutrients also affect microalgal growth and metabolism. A lack of other nutrients, such as manganese (Mn) and various other cations (Mg^{2+}, K^+ and Ca^{2+}), is also known to reduce algal growth (Droop 1973). Trace elements are also critical for microalgal growth and some microalga also require vitamins for their growth (Croft et al. 2005). One effective and inexpensive way of supplying nutrients is by combining algal culture and wastewater treatment which is discussed immediately below.

12.3.4 Algae and Wastewater Treatment

With an increase in environmental deterioration and a greater necessity to generate alternative food and energy sources, there is the impetus to explore the feasibility of biological wastewater treatments coupled with resource recovery. Microalgal wastewater treatments have been particularly attractive, due to algal photosynthetic activities, where light is transferred into profitable biomass. Under certain conditions, wastewater-grown microalgal biomass can be equivalent or superior in biomass production to higher plant species. Thus, the process can transform a waste product into useful products (e.g. animal feed, aquaculture feed, bio-fertilizer and bioenergy). Thus, the waste effluent is no longer a negative waste product, but it becomes a valuable substrate for producing important substances and successful microalgal wastewater bioremediation has been reported for over half a century (Oswald and Gotass 1957; Delrue et al. 2016). Algal phytoremediation indeed provides an environmentally favourable solution for the treatment of wastewater as it can utilize organic and inorganic nutrients efficiently (Nwoba et al. 2017). Microalgal cultures hold an enormous potential for the later steps of wastewater treatment, especially for reducing 'N', 'P' and 'COD' (Nwoba et al. 2016). Moreover, the added ability of microalgae to grow via different nutritional conditions such as photoautotrophic, mixotrophic and heterotrophic conditions also enhances its capabilities in removing various different types of pollutants and chemicals from aqueous matrices. The ability of microalgae in sequestrating carbon (CO_2) allows CO_2 bioremediation. The synchronized algal-bacteria relationship established is also ideally synergetic for the bioremediation of wastewater (Munoz and Guieysse 2006). Through photosynthesis, microalgae provide oxygen required by aerobic bacteria for the mineralization of organic matter as well as the oxidation of NH_4^+ (Munoz and Guieysse 2006). In return, the bacteria supply carbon dioxide for the growth of microalgae, significantly reducing the amount of oxygen required for the overall wastewater treatment process (Delrue et al. 2016). In general, waste effluents with low carbon to nitrogen ratios are fundamentally suited to the growth of photosynthetic organisms. Most importantly, the microalgal domestic and agricultural wastewater treatments is an attractive option since the technology is relatively easy and they require very low energy compared to the standard of effluent treatment. Optimization of microalgal wastewater treatment in large-scale raceway ponds is appealing since it combines the effective treatment of a harmful waste product and the production of potentially valuable protein-rich algal biomass. Figure 12.1 summarizes a closed loop system for treating any organic waste by combination of anaerobic digestion and algal cultivation.

12.3.5 Algae and Aquaponics

Microalgae in aquaculture and in aquaponic systems is most often seen to be a nuisance as they can restrict water flows by clogging up pipes, consume oxygen,

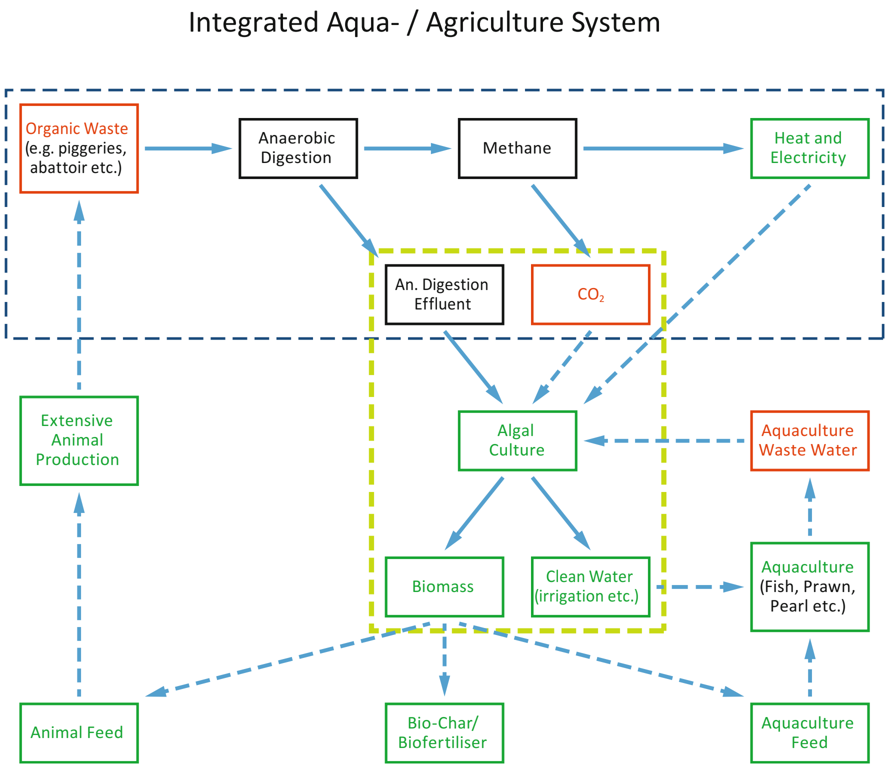

Fig. 12.1 Integrated process system to use algal culture for treating organic waste and potential end users. (The process is designed based on information from Ayre et al. 2017 and Moheimani et al. 2018)

may attract insects, reduce water quality and when decomposing can deplete oxygen. However, an experiment by Addy et al. (2017) shows that algae can improve water quality in an aquaponic system, help control pH drops related to the nitrification process, generate dissolved oxygen in the system, 'produce polyunsaturated fatty acids as a value-added fish feed and add diversity and improve resilience to the system'. One of the 'holy grails' of aquaponics is to produce at least part of the food that is fed to the fish as part of the system and it is here that research is required in producing algae that could be grown with part of the aquaponics water, most probably in a separate loop, which can then be fed as part of the diet to the fish.

12.4 Maraponics and Haloponics

Although freshwater aquaponics is the most widely described and practiced aquaponic technique, resources of freshwater for food production (agriculture and aquaculture) are becoming increasingly limited and soil salinity is progressively increasing in many parts of the world (Turcios and Papenbrock 2014). This has led to an increased interest and/or move towards alternative water sources (e.g. brackish to highly saline water as well as seawater) and the use of euryhaline or saltwater fish, halophytic plants, seaweed and low salt-tolerant glycophytes (Joesting et al. 2016). It is interesting to note that whilst the amount of saline in underground water is only estimated as 0.93% of world's total water resources at 12,870,000 km^3, this is more than the underground freshwater reserves (10,530,000 km^3) which makes up 30.1% of all freshwater reserves (Appelbaum and Kotzen 2016).

The use of saline water in aquaponics is a relatively new development and as with most new developments the terms used to describe the range/hierarchy of types needs to be established on a firm footing. In its short history, the term maraponics (i.e. marine aquaponics) has been coined for seawater aquaponics (SA), in other words, systems that use seawater as well as brackish water (Gunning et al. 2016). These systems are mainly located on-land, in coastal locations and in the case of SA, close to a seawater source. But there are fish as well as plants that grow and can be used in aquaponic units where water salinity levels vary. Thus whilst it makes etymological sense to use the term 'maraponics' for seawater aquaponics, it makes less sense to term brackish water aquaponics using this term. We thus suggest that a new term needs to be added to the aquaponic lexicon and this is 'haloponics', deriving from the Latin word *halo* meaning salt and combining this with suffix ponics. Thus maraponics is an on-land integrated multitrophic aquaculture (IMTA) system combining the aquacultural production of marine fish, marine crustaceans, marine molluscs, etc. with the hydroponic production of marine aquatic plants (e.g. marine seaweeds, marine algae and seawater halophytes) using oceanic strength seawater (approximately 35,000 ppm [35 g/L]). However aquaponic systems utilizing saline water below oceanic levels in a range of salinities should be termed haloponics (slightly saline water –1000 to 3000 ppm [1–3 g/L], moderately saline 3000–10,000 ppm [3–10 g/L] and high salinity 10,000–35,000 ppm [10–35 g/L]). These systems are also on-land IMTA systems combining aquacultural production with the hydroponic production of aquatic plants, but both the fish and plants are adapted to or grow well in what may be termed brackish water.

Although the concept of maraponics is very new, an interest in on-land seaweed-based integrated mariculture began to appear in the 1970s, starting from a laboratory-scale and then expanding to outdoor pilot-scale trials. In some of the earliest experimental studies, Langton et al. (1977) successfully demonstrated the growth of the red seaweed, *Hypnea musciformis*, cultured in tanks with shellfish culture effluent. Alternatively, crops that would usually be classed as glycophytes, such as the common tomato (*Lycopersicon esculentum*), the cherry tomato (*Lycopersicon esculentum* var. Cerasiforme) and basil (*Ocimum basilicum*), can achieve remarkably successful production levels at up to 4 g/L (4000 ppm) salinity and are often referred to as having low-moderate levels of salt tolerance (not to be confused with true halophytes, which are resistant to high salinities). Other crops that are tolerant of low-moderate salinities include turnip, radish, lettuce, sweet potato, broad bean, corn, cabbage, spinach, asparagus, beets, squash, broccoli and cucumber (Kotzen and Appelbaum 2010; Appelbaum and Kotzen 2016). For example, Dufault et al. (2001) and Dufault and Korkmaz (2000) experimented with shrimp waste (shrimp faecal matter and decomposed feed) as a fertilizer for broccoli (*Brassica oleracea italica*) and bell pepper (*Capsicum annuum*) production, respectively. Although their studies did not use maraponic techniques, they involved plants that are commonly grown using aquaponic (freshwater) techniques. Therefore, due to their salinity tolerance levels, these crops have enormous potential as candidate species for production in haloponic systems using low to medium salinities.

Recently, a number of studies have shown that halophytes can be successfully irrigated with aquacultural wastewater from marine systems using hydroponic techniques or as part of a recirculating aquaculture system (RAS). Waller et al. (2015) demonstrated the feasibility of nutrient recycling from a saltwater (16 psu salinity [16,000 ppm]) RAS for European sea bass (*D. labrax*) through the hydroponic production of three halophytic plants: *Tripolium pannonicum* (sea aster), *Plantago coronopus* (buck's horn plantain) and *Salicornia dolichostachya* (long spiked glasswort).

The majority of the maraponic work conducted so far involves the integration of two trophic levels – plants/algae and fish. However, an example of a system incorporating more than two trophic levels can be seen in an experiment conducted by Neori et al. (2000), who designed a small system for the intensive land-based culture of Japanese abalone (*Haliotis discus hannai*), seaweeds (*Ulva lactuca* and *Gracilaria conferta*) and pellet-fed gilthead bream (*Sparus aurata*). This system consisted of unfiltered seawater (2400 L/day) pumped to two abalone tanks and drained through a fish tank and finally through a seaweed filtration/production unit before being discharged back to the sea. Filter feeding molluscs could also be used in such a system. Kotzen and Appelbaum (2010) and Appelbaum and Kotzen (2016) compared the growth of common vegetables using potable water and moderately saline water (4187–6813 ppm) and found that basil (*Ocimum basilicum*), celery (*Apium graveolens*), leeks (*Allium ampeloprasum porrum*), lettuce (*Lactuca sativa* – various types), Swiss chard (*Beta vulgaris. 'cicla'*), spring onions (*Allium cepa*) and watercress (*Nasturtium officinale*) performed extremely well.

Maraponics (SAs) and haloponics offer a number of advantages over traditional crop and fish production methods. Because they use saline water (marine to brackish), there is a reduced dependence on freshwater, which in some parts of the world has become a very limited resource. It is typically practiced in a controlled environment (e.g. a greenhouse; controlled flow-rate tanks) giving better opportunities for intensive production. Many maraponic and haloponic systems are closed RAS with organic and/or mechanical biofilters and subsequently, water reuse is high, wastewater pollution is vastly reduced or eliminated, and contaminants are removed or treated. Even systems that are not RAS can significantly reduce the excess nutrients in the wastewater prior to discharge. Additionally, the occurrence of contaminants in non-RAS maraponic and haloponic systems can be reduced or eliminated through the use of water containing low levels of naturally occurring contaminants and the use of alternatives aquafeeds that do not contain dioxins or PCDs (e.g. novel feeds made from macroalgae). This improvement in water quality reduces the potential for disease occurrence and the need for antibiotic use is therefore vastly reduced. Due to their versatile configuration and low water requirements, maraponics and haloponics can be successfully implemented in a wide variety of settings, from fertile coastal areas to arid deserts (Kotzen and Appelbaum 2010), as well as in urban or peri-urban settlements. Another potential benefit is that many of the species that are suitable for these systems have a high commercial value. For example, the euryhaline European sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*) can fetch a market price of €9/kg and €6/kg, respectively. Additionally, edible halophytes tend to have a high market price, with sea-agretti (*Salsola soda*), for example, having a market price of €4–€4.5/kg and marsh samphire (*Salicornia europaea*) selling at €18/kg in supermarkets.

The evidence is therefore compelling. Maraponics and haloponics provide a dynamic and rapidly growing field that has the potential to provide a number of services to communities, many of which are explored elsewhere in this publication.

12.5 Vertical Aquaponics

12.5.1 Introduction

Whilst aquaponics can be seen as part of a global solution to increase food production in more sustainable and productive ways and where growing more food in urban areas is now recognized as part of the solution to food security and a global food crisis (Konig et al. 2016), aquaponic systems can themselves become more productive and sustainable by adopting alternative growing technologies and learning from emerging technologies such as vertical farming and living walls [LWs] (Khandaker and Kotzen 2018). Additionally by being space-efficient, they can be better integrated into urban areas.

In the developed world most aquaponic systems are placed in greenhouses in order to control temperature; in northern Europe and North America for example, winter temperatures are too cold in winter and in Mediterranean areas such as Spain, Italy, Portugal, Greece and Israel, summer temperatures are too warm. There are of course many additional advantages in growing food in controlled greenhouses, such as the ability to regulate relative humidity and control air movement, to quarantine fish as well as plants from diseases as well as pests and potentially being able to add CO_2, to aid plant growth. However, growing produce in a greenhouse can readily raise costs through (a) the capital costs of the greenhouse (a broad estimate of US $\$350/m^2$ Arnold 2017) and (b) allied infrastructure such as microclimate controls which include heating and cooling systems and lighting. On top of the initial infrastructure costs, there are also the specific greenhouse production costs which include the energy/power supply for heating and cooling as well as lighting.

Most aquaponic systems such as the University of the Virgin Island (UVI) system (Fig. 12.1), designed by Dr. James Rakocy and his colleagues, use horizontal grow tanks or beds, emulating traditional land-based arable growing patterns to produce vegetables (Khandaker and Kotzen 2018). In other words, the system relies on horizontal rows/arrays of plants usually elevated to around waist level so that plant-related management tasks can be readily undertaken. Parallel developments in living wall and vertical farming technologies have arisen at almost the same time that aquaponics has evolved and are similarly in the adolescent stage of development. Similarly as in aquaponics, as more people become involved there is a concomitant increase in systems and technological development to increase productivity and reduce costs. The coupling of vertical growing systems (vertical farming systems and living walls) rather than horizontal beds to the fish and filtration tanks is potentially one key way of increasing productivity as it should be possible to increase the number of vegetables grown compared to the numbers produced in typical horizontal bed aquaponics. The UVI aquaponic systems (Fig. 12.2) produce approximately 32 plants per square metre (Al-Hafedh et al. 2008), depending on the species and cultivar that is grown, but as Khandaker and Kotzen (2018) note, approximately 96 plants can be grown per square metre 'using back-to-back elements of the *Terapia Urbana*[1] LW system which is more than three times the density

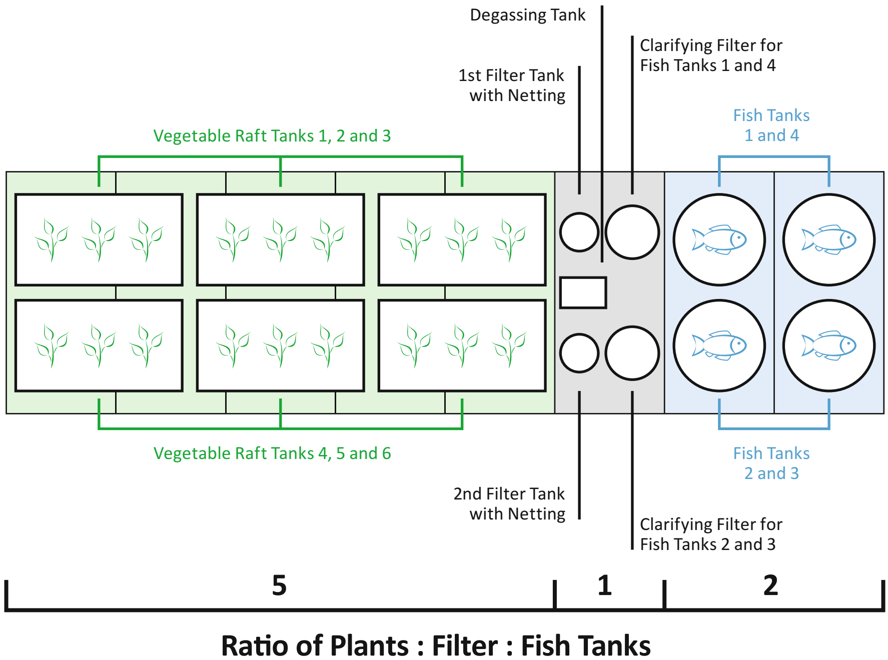

Fig. 12.2 Schematic diagram of a typical UVI system illustrating the ratio of fish tanks/filters/plant growing tanks which is 2:1:5. This shows that the greatest area is subsumed by the plants and it is in this area that space savings may be considered. (Khandaker and Kotzen 2018)

[1]Terapia Urbana S.L. produces a felt pocket type of living wall in Seville, Spain.

compared to the UVI horizontal growing system'. A conservative estimate should at least double the maximum amount grown in horizontal beds to 64 plants/m^2. In an experiment with lettuce (*Lactuca sativa* L. cv. 'Little Gem') using horizontal beds and planted columns, planted at similar densities, Touliatos et al. (2016) suggest that the 'Vertical Farming System (VFS) presents an attractive alternative to horizontal hydroponic growth systems (and) that further increases in yield could be achieved by incorporating artificial lighting in the VFS'.

Vertical Farming Systems (VFS)

Before we discuss the specific requirements for vertical systems we need to discuss the types of systems that are available. In VFS there are three main generic types (Fig. 12.3):

1. Stacked Horizontal Beds: Instead of only having one horizontal grow bed, the beds are stacked like shelves in tiers. This arrangement means that in a greenhouse, only the upper bed will be facing direct natural light and supplementary light needs to be provided at all levels. This is usually provided from directly under the grow bed above. In principle this could mean that the growing beds could be stacked as high as the greenhouse allows, but of course growing things at

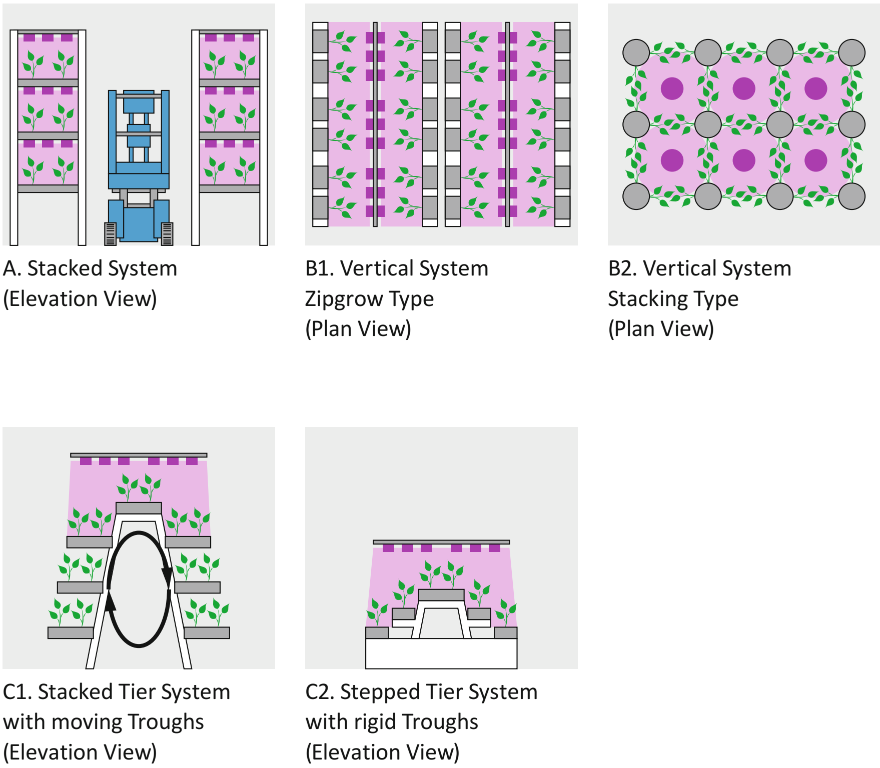

Fig. 12.3 Vertical farming systems and their lighting arrangements

height means greater difficulty in the system's management including planting, maintenance and harvesting, requiring scissor lifts and additional energy to pump nutrient-rich water to all levels. According to Bright Agrotech (Storey 2015), up to four tiers is profitable and anything above that is unprofitable. Storey (2015) further notes that labour increases by 25% at the second, third and fourth levels when a scissor lift is required (Fig. 12.3, Illustration A).

2. Vertical Tower Systems (VTS): Vertical Tower Systems comprise systems which grow plants in vertical arrays within a container or series of stacked modules. Depending on the system, plants are grown facing one direction or if, for example, they are planted in a tube-like form, then they can be arranged facing any direction. An example of a vertical array system, where plants are grown facing in a single direction is the ZipGrow™ which are either hung or supported in rows (Fig. 12.3, Illustration B1). The rows between are approximately 0.5 metres (20 inches). Growing in a more three-dimensional way occurs with stacked systems or in tubular systems which allow more plants to be grown, but lighting is more complex (Fig. 12.3, Illustration B2).
3. Stepped Tiers: These systems contain rigid or moving plant troughs. The Sky Greens VFS in Singapore uses a rotating trough system which moves the troughs upwards and into the light. Additional natural light is more significant towards the top and less so at the bottom (Fig. 12.3, Illustration C1). Other tier systems are stepped so that each tier has an unobstructed interface with the light from above, whether this is natural light from the greenhouse roof or artificial light. But these systems have to be quite low in order for people to reach the plants (Fig. 12.3, Illustration C2).

Living Walls

Living walls have yet to be used in aquaponics except in a number of trial systems such as at the University of Greenwich, London (Khandaker and Kotzen 2018). Whereas most VFS use nutrient film technique (NFT) grow channels or encapsulated mineral wool blocks, LWs sometimes also use soil type substrates in pots or troughs, which provide the rooting medium. Whilst this is fine for growing ornamental plants as well as vegetables and herbs, when coupled with fish tanks, any addition of soil to the system may complicate the microbial character of the system and be detrimental to the fish. This is however unknown and requires research. Experiments undertaken at the University of Greenwich (Khandaker and Kotzen 2018) indicate that from a number of single, inert substrates tested (including hydroleica, perlite, straw, sphagnum moss, mineral wool and coconut fibre), coconut fibre and then mineral wool were superior in terms of root penetration and root growth in lettuce (*Lactuca sativa*).

Vertical v. Horizontal: Factors to Be Considered

There are four key aspects which need to be taken into account when comparing the benefits (productivity and sustainability) of vertical growing, compared to horizontal growing. These are (1) space, (2) lighting, (3) energy and (4) life cycle costs.

1. *Space*

The benefits of being able to grow produce vertically, back to back, need to be balanced with the amount of space that is required to provide an even spread of lighting as well as the row space required for management and maintenance. The width of a row in hydroponic systems varies. As noted the standard ZipGrow™ system is approximately 0.5 metres, whereas the usual row width for growing tomatoes and cucumbers hydroponically varies from 0.9 to 1.2 metres (Badgery-Parker and James 2010). Growing smaller plants such as lettuce and herbs such as basil, may allow for narrower rows, but of course row width must ensure that produce is not compromised by moving items such as trolleys and scissor lifts. A key issue with growing vertically is the conflict that occurs between having fixed rows and fixed lighting, which needs to be located in the rows between the planting facades. These lights will impede people movements and thus either the lights need to be (i) part of the growing structure or (ii) retractable or movable, so that workers can readily undertake tasks, or (iii) the planting structures are movable and the lights remain static.

2. *Lighting*

Greenhouse production of vegetables and other plants rely on specific spatial arrangements which allow for planting, management through growth and then harvesting. The spatial arrangement will depend on the types of plants and the types of mechanization that is installed. Additionally, growing efficiently relies on the supplement of additional light of different types, which have their own pros and cons. In general what these lights do is provide specific wavelengths for plant growth and for fruit or flower production. Whereas it is relatively simple and more common to evenly light plants grown horizontally, it is more of a challenge to evenly light a vertical surface.

With regard to types of lighting, many producers have moved to or are tempted to install LEDs (light-emitting diodes), due to their long lifespan, up to 50,000 hours or more (Gupta 2017), their low power requirements and their recent reduction in cost. Virsile et al. in Gupta (2017) note that *most applications of LED lighting in greenhouses choose the combinations of red and blue wavelengths with high photon efficiency* but that green and white light *containing substantial amounts of green wavelengths has a positive physiological impact on plants*. However, *the combination of blue and red lights creates a purplish-grey image*, and this hampers the visual evaluation of plant health. The type of wavelengths chosen is complex and can have benefits at different stages in the plant's life and even according to the cultivars of, for example, lettuce. Red-leafed lettuces, for example, respond to blue LED lighting, increasing their pigmentation (Virsile et al. in Gupta 2017). Additionally, blue LED lighting can improve the nutritional quality of green vegetables, reducing nitrate content, increasing antioxidants and phenolic and other beneficial compounds. The light spectra also affect taste, shape and texture (Virsile et al. in Gupta 2017). The costs of LEDs have dropped significantly and as the efficacy of LEDs has increased so the break-even return time on investment has decreased (Bugbee in Gupta 2017).

Other lighting of course exists and this includes fluorescent lighting, metal halide (MH) lighting and high pressure sodium (HPS) lighting. The type of lighting that is used in vertical farming and with living walls varies considerably depending on the scale and location. Compact fluorescent lamps (CFLs) are relatively thin and can easily fit into small spaces, but they require an inductive ballast to regulate current through the tubes. CFLs use only 20–30% of an incandescent bulb and they last six to eight times longer but they are almost 50% less efficient than LEDs. They are by far the cheapest of the three major types of grow lights. HPS grow light technology is over 75 years old and is well established for growing under glass, but they produce a lot of heat and are thus not suitable for vertical farming and living walls, where light needs to be delivered quite close to the plants. The heat produced by LED grow lights, on the other hand, is minimal. The cost however is higher than other two types, and eye protection is needed for longer-term exposure to LEDs as the long-term exposure to the light spectra can be damaging to the eyes. The arrangement of VFS units will dictate the lighting arrangement but on the whole these are lit by LEDs. The method of lighting living walls will depend on the height of the wall. The taller the wall the more difficult it is to apply an even spread across the surface, although it should be noted that the number of lights used should be no different to those used in horizontal grow beds and if the wall is tall then the lights may need to be staggered. As most living walls are located for aesthetic purposes, lighting needs to be kept as far as possible, out of the way and the lighting has to not only provide adequate light for plant growth and health, but also so that the plants look good (Fig. 12.4).

Fig. 12.4 A 4-metre-tall, 5-metre-long living wall can be adequately lit with six high-efficiency discharge lamps. Note these were chosen not only to provide adequate light for growth but also so that the plants in the living wall would look good. (University of Greenwich Living Wall. Source: Benz Kotzen)

The advances in LED technology, where lighting frequencies and intensity can be engineered to suit individual species and cultivars as well as their various life cycles means that LEDs will become the technology of choice in the near future. This will additionally be enhanced by reductions in costs.

3. *Energy*

More energy for lighting is likely to be required for VFS as well as LWs as even natural lighting cannot be achieved over vertical surfaces. Additionally more pumping power for irrigation will be required and this will be relative to the height of the VFS or LWs.

4. *Comparative Life Cycle Analysis (LCA)*

Whilst there are numerous studies undertaken on life cycle analysis of aquaponics and various aspects of aquaponic systems, there are no comparative studies that compare vertical versus horizontal aquaponics. This has yet to be done. We are getting to a point where vertical aquaponics is likely to warrant further testing and research and in time vertical aquaponics, which couples vertical farming systems or living wall systems with the fish tanks and filtration units, is likely to become more mainstream, as long as these can be profitable and sustainable.

12.6 Biofloc Technology (BFT) Applied for Aquaponics

12.6.1 Introduction

Biofloc technology (BFT) is considered the new ‘blue revolution’ in aquaculture (Stokstad 2010) since nutrients can be continuously recycled and reused in the culture medium, benefited by the in situ microorganism production and by the minimum or zero water exchange (Avnimelech 2015). These approaches might face some serious challenges in the sector such as competition for land and water and the effluents discharged to the environment which contain excess of organic matter, nitrogenous compounds and other toxic metabolites.

BFT was first developed in the early 1970s by the Aquacop team at Ifremer-COP (French Research Institute for Exploitation of the Sea, Oceanic Center of the Pacific) with different shrimp penaeid species including *Litopenaeus vannamei*, *L. stylirostris* and *Penaeus monodon* (Emerenciano et al. 2011). In the same period, Ralston Purina (a private US company) in connection with Aquacop applied the technology both in Crystal River (USA) and Tahiti, which lead to the greater understanding of the benefits of biofloc for shrimp culture. Several other studies enabled a comprehensive approach to BFT and researched the inter-relationships between water, animals and bacteria, comparing BFT with an ‘external rumen’ but now applied for shrimp. In the 1980s and at the beginning of the 1990s, both Israel and the USA (Waddell Mariculture Center) started R&D in BFT with tilapia and Pacific white shrimp *L. vannamei*, respectively, in which environmental concerns, water limitation and land costs were the main causative agents that promoted the research (Emerenciano et al. 2013).

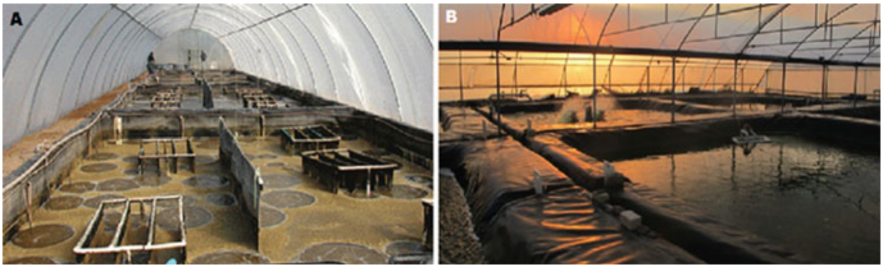

Fig. 12.5 Biofloc technology (BFT) applied for marine shrimp culture in Brazil (**a**) and for tilapia culture in Mexico (**b**) (Source: EMA-FURG, Brazil and Maurício G. C. Emerenciano)

The first commercial BFT operations and probably the most famous commenced in the 1980s at the 'Sopomer' farm in Tahiti, French Polynesia, and in the early 2000s at the Belize Aquaculture farm or 'BAL', located in Belize, Central America. The yields obtained using 1000 m^2 concrete tanks and 1.6 ha lined grow-out ponds were approximately 20–25 ton/ha/year with two crops at Sopomer and 11–26 ton/ha/cycle at BAL, respectively. More recently, BFT has been successfully expanded in large-scale shrimp farming in Asia, in South and Central America as well as in small-scale greenhouses in the USA, Europe and other areas. At least in one phase (e.g. nursery phase) BFT has been used with great success in México, Brazil, Ecuador and Peru. For commercial-scale tilapia culture, farms in Mexico, Colombia and Israel are using BFT with productions around 7 to 30 kg/m^3 (Avnimelech 2015) (Fig. 12.5b). Additionally, this technology has been used (e.g. in Brazil and Colombia) to produce tilapia juveniles (~30 g) for further stock in cages or earthen ponds (Durigon et al. 2017). BFT has mainly been applied to shrimp culture and to some extent with tilapia. Other species have been tested and show promise, as noted for silver catfish (*Rhamdia quelen*) (Poli et al., 2015), carp (Zhao et al., 2014), piracanjuba (*Brycon orbignyanus*) (Sgnaulin et al., 2018), cachama (*Colossoma macropomum*) (Poleo et al., 2011) and other crustacean species such as *Macrobrachium rosenbergii* (Crab et al., 2010), *Farfantepenaeus brasiliensis* (Emerenciano et al., 2012), *F. paulensis* (Ballester et al., 2010), *Penaeus semisulcatus* (Megahed, 2010), *L. stylirostris* (Emerenciano et al., 2011) and *P. monodon* (Arnold et al., 2006). The interest in BFT is evident by the increasing number of universities and research centres carrying out research particularly in the key fields of grow-out management, nutrition, reproduction, microbial ecology, biotechnology and economics.

12.6.2 How does BFT Work?

Microorganisms play a key role in BFT systems (Martinez-Cordoba et al. 2015). The maintenance of water quality, mainly by the control of the bacterial community over autotrophic microorganisms, is achieved using a high carbon to nitrogen ratio (C:N) since nitrogenous by-products can be easily taken up by heterotrophic bacteria. In the beginning of the culture cycles a high carbon to nitrogen ratio is required to guarantee optimum heterotrophic bacteria growth, using this energy for its maintenance and growth (Avnimelech 2015). Additionally, other microorganism groups are crucial in BFT systems. The chemoautotrophic bacterial community (i.e. nitrifying bacteria) stabilizes after approximately 20–40 days and might be responsible for two-thirds of the ammonia assimilation in the system (Emerenciano et al. 2017). Thus, the addition of external carbon should be reduced and alkalinity consumed by the microorganisms must be replaced by different carbonate/bicarbonate sources (Furtado et al. 2011). The stability of zero or minimal water exchange depends on the dynamic interaction amongst communities of bacteria, microalgae, fungi, protozoans, nematodes, rotifers, etc. that will occur naturally (Martinez-Cordoba et al. 2017). The aggregates (bioflocs) are a rich protein-lipid natural source of food that become available 24 h per day due to a complex interaction between organic matter, physical substrate and large range of microorganisms (Kuhn and Boardman 2008; Ray et al. 2010). The natural productivity in a form of microorganisms' production plays three major roles in the tanks, raceways or lined ponds: (1) in the maintenance of water quality, by the uptake of nitrogen compounds generating in situ microbial protein; (2) in nutrition, increasing culture feasibility by reducing feed conversion ratios and a decrease in feed costs; and (3) in competition with pathogens (Emerenciano et al. 2013).

Regarding the water quality for the culture organisms, besides oxygen, excess of particulate organic matter and toxic nitrogen compounds are the major concern in the biofloc systems. In this context, three pathways occur for the removal of ammonia nitrogen: at a lesser rate (1) photoautotrophic removal by algae and at a higher rate (2) heterotrophic bacterial conversion of ammonia nitrogen directly to microbial biomass and (3) autotrophic bacterial conversion from ammonia to nitrate (Martinez-Cordoba et al. 2015). The nitrate available in the systems plus other minor and major nutrients accumulated over the cycle could be used as substrate for plant growth in aquaponic systems (Pinho et al. 2017).

12.6.3 BFT in Aquaponics

The application of BFT in aquaponic systems is relatively new, although Rakocy (2012) mentions a commercial pilot-scale project with tilapia. Table 12.2 summarizes key recent studies that have used BFT in aquaponic systems.

Overall, the results demonstrate that biofloc technology can be used and integrated in a fish or shrimp-plant production. BFT when compared to other conventional aquaculture systems (such as RAS) actually improved the plant and fish yields and promoted better plant visual quality (Pinho et al. 2017), but not in all cases (Rahman 2010; Pinho 2018). Pinho et al. (2017) observed that lettuce yields with the BFT system were greater compared to the clear-water recirculation system (Fig. 12.6). This is possibly due to the higher nutrient availability provided by the

Table 12.2 Recent studies around the world applying the BFT in aquaponic systems for different aquatic and plant species

Aquatic species	Plant species	Main results	References
Tilapia	Lettuce	Biofloc technology did not improve lettuce production as compared to conventional hydroponic solution	Rahman (2010)
Tilapia	Lettuce	Yield and visual quality of lettuce was improved using BFT as compared to clear-water recirculation system	Pinho et al. (2017)
Tilapia (nursery)	Lettuce	Plant performance (lettuce) using tilapia in a nursery phase (1–30 g) was negatively influenced by biofloc wastewater as compared to RAS wastewater after two plant cycles (13 days each). Plant visual aspects were better in RAS as compared to BFT	Pinho (2018)
Tilapia	Lettuce	The presence of filtering elements (mechanical filter and biological filter) positively affected the lettuce production in aquaponic systems as compared to treatment without filters using BFT	Barbosa (2017)
Tilapia	Lettuce	Low salinity (3 ppt) can be performed in aquaponics using BFT. Visual and performance parameters indicated that the purple variety had better performance than the smooth and crisped varieties	Lenz et al. (2017)
Silver catfish	Lettuce	The use of bioflocs in the aquaponic system may improve the productivity of lettuce in an integrated culture with silver catfish	Rocha et al. (2017)
Litopenaeus vannamei	*Sarcocornia ambigua*	The performance of marine shrimp *L. vannamei* was not affected by the *S. ambigua* integrated aquaponics production and also improve the use of nutrients (e.g. nitrogen) in the culture system	Pinheiro et al. (2017)

Fig. 12.6 Experimental aquaponics greenhouse comparing biofloc technology and RAS wastewater at Santa Catarina State University (UDESC), Brazil. (Source: Pinho et al. 2017)

higher microbial activity. However, this trend was not observed in the study by Rahman (2010), who compared effluent from fish culture in a BFT system to a conventional hydroponic solution in a lettuce production. In addition, Pinho

Fig. 12.7 High salinity halophyte *Sarcocornia ambigua* aquaponics production integrated with Pacific white shrimp *Litopenaeus vannamei* successfully applying biofloc technology at Santa Catarina Federal University (UFSC), Brazil. (Source: LCM-UFSC, Brazil)

Fig. 12.8 Aquaponics lettuce production integrated with tilapia using biofloc technology (left) and accumulation of suspended solids in lettuce roots (right). Barbosa (2017)

(2018) in a recent study observed that productive performance of lettuce in aquaponic system using tilapia in a nursery phase (1–30 g) was negatively influenced by biofloc wastewater as compared to RAS wastewater over 46 days. The variation in results identifies the need for additional studies in this area.

BFT can be used with low salinity water, e.g. with some varieties of lettuce (Lenz et al. 2017), and higher salinity waters can be used, e.g. with halophyte plant species such as *Sarcocornia ambigua* co-culture with Pacific white shrimp *Litopenaeus vannamei* (Pinheiro et al. 2017) (Fig. 12.7). Silver catfish *Rhamdia quelen* has also shown good potential for the integration of aquaponics with BFT (Rocha et al. 2017).

With BFT, the concentration of solids can severely affect the roots and impact nutrient absorption and oxygen availability. As a result, yields can be affected but also the visual quality of the plants (e.g. lettuces) which is an important criterion for consumers. With this in mind, solids management is an important subject for further studies where the impact of solids (particulate fraction and also dissolved fraction) in aquaponic systems when applying BFT is considered (Fig. 12.8). In addition, economic studies need to be undertaken to compare the costs involved of the various aquaculture and plant growing systems and to identify appropriateness relative to different locations and conditions.

12.7 Digeponics

Anaerobic processing of purposely cultivated biomass, as well as residual plant material from agricultural activity, for biogas production is a well-established method. The bacterially indigestible digestate is returned to the fields as a fertilizer and for building humus. Whilst this process is widespread in agriculture, the application of this technology in horticulture is relatively new. Stoknes et al. (2016) claim that within the 'Food to waste to food' (F2W2F) project, an efficient method for the utilization of digestate as substrate and fertilizer has been developed for the first time. The research team coined the term 'digeponics' for this circular system. Digeponics, in contrast to aquaponics, replaces the aquaculture part with an anaerobic digester, or, when comparing it to a three loop aquaponic system that includes an anaerobic, the aquaculture part is removed from the system, leaving two main loops, the digestion loop and the horticultural loop.

The required organic input that is provided in the form of the fish food to an aquaponic system is replaced with food waste from human food production for digeponics. The varying composition of nutrients in the input stream opposed to the well-known, constant and probably nutritionally optimized nutrient stream resulting from the fish feed will most likely call for a more strict nutrient analysis and management regime than that required in aquaponics.

The produced biogas, which mainly contains methane and carbon dioxide, can be utilized within the facility for electricity and heat production. The resulting carbon dioxide-rich exhaust gas can be used as a fertilizer directly in the greenhouse reducing emissions in comparison to classical biogas plants used in agriculture.

Since the 'fresh and untreated digestate in anaerobic liquid slurry (contains) plant toxic substances, a very high electrical conductivity (EC) and chemical oxygen demand (COD)' (Stoknes et al. 2016), it has to be treated to make it suitable for plant fertilization. Several methods of moderation have been examined within the F2W2F project. The relatively high EC of the digestate and the operational flexibility of a digester fed with low-cost food waste alleviate some of the tight coupling issues often attributed to coupled aquaponic systems (see Chap. 7). Thus digeponics may serve as an interesting alternative to aquaponics in situations where the aquaculture part represents a challenge. With respect to a three loop aquaponic system that already comprises a loop with an anaerobic digester, the inclusion of a food waste stream for organic input might represent an interesting future direction. The methane yield of aquaculture sludge is rather limited. A targeted inclusion of residual agricultural biomass with the aim of methane yield optimization could enhance overall performance.

12.8 Vermiponics and Aquaponics

It would be remiss in this chapter not to mention earthworms and their introduction into aquaponics, and thus this chapter concludes with a brief résumé of these detritivore invertebrates and their abilities to convert organic waste into fertilizer. It is said that worms and the way that they digest matter were of interest to Aristotle and Charles Darwin as well as the philosophers Pascal and Thoreau (Adhikary 2012) and they were protected by law under Cleopatra. Earthworms are valued in agriculture and horticulture as they are 'vital to soil health because they transport nutrients and minerals from below to the surface via their waste, and their tunnels aerate the ground' (National Geographic).

Modern vermiculture is attributed to Mary Appelhof, who in the early 1970s and 1980s produced a number of publications on composting with worms. Contemporary vermicomposting occurs on large and small scales with the objective of getting rid of organic waste and producing fertilizer in the forms of compost and 'worm tea'. Worm tea can be produced by soaking worm casts or by leaching the nutrients from the compost through wetting or natural wetting leachate from precipitation.

Vermiponics uses the worm casts of mainly red wriggler worms also known as tiger worms (*Eisenia fetida*) or (*E. foetida*) to provide nutrients in a hydroponic system. When worms are introduced into an aquaponic system, we suggest that the system is termed 'vermi-aquaponics' to differentiate the systems. It is thus the introduction of worms into the growing beds of the plant parts of an aquaponic system. It should be noted that vermi-aquaponics is in its infancy and mainly practiced by hobbyists and in research laboratories. The worms are introduced mainly into the plant growing media, usually gravel beds, where they can help to break down any solid waste from the fish and any detritus from the plants and additionally provide additional nutrients for the plants, and they can also be fed to carnivore fish. In most instances the beds are of a flood and drain type, so that the worms are not constantly under water.

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