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Towards commercial aquaponics: a review of systems, designs, scales and nomenclature

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Abstract Aquaponics is rapidly developing as the need for sustainable food production increases and freshwater and phosphorous reserves shrink. Starting from small-scale operations, aquaponics is at the brink of commercialization, attracting investment. Arising from integrated freshwater aquaculture, a variety of methods and system designs has developed that

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focus either on fish or plant production. Public interest in aquaponics has increased dramatically in recent years, in line with the trend towards more integrated value chains, greater productivity and less harmful environmental impact compared to other production systems. New business models are opening up, with new customers and markets, and with this expansion comes the potential for confusion, misunderstanding and deception. New stakeholders require guidelines and detail concerning the different system designs and their potentials. We provide a definitive definition of aquaponics, where the majority (> 50%) of nutrients sustaining the optimal plant growth derives from waste originating from feeding aquatic organisms, classify the available integrated aquaculture and aquaponics (open, domestic, demonstration, commercial) systems and designs, distinguish four different scales of production (≤ 50, > 50–≤ 100 m^2, > 100–≤ 500 m^2, > 500 m^2) and present a definite nomenclature for aquaponics and aquaponic farming allowing distinctions between the technologies that are in use. This enables authorities, customers, producers and all other stakeholders to distinguish between the various systems, to better understand their potentials and constraints and to set priorities for business and regulations in order to transition RAS or already integrated aquaculture into commercial aquaponic systems.

Keywords Aquaponic farming · Aquaponic systems · Circular economy · Definition · Integrated aquaculture systems · Nomenclature · Scale of operation · System design

Introduction

The combinations of fish and plant cultivation in integrated aquaculture systems date back to the early development of aquaculture in China about 2000 years ago. Modern aquaponics, or the combination of fish and soilless plant production systems, can be traced back to the first known hydroponic cultivation of various plants in the effluent from catfish holding tanks by Sneed et al. (1975, cited in Lewis et al. 1978), designed as a single-pass system without biofiltration. Naegel (1977) for the first time combined the production of the fish species *Tilapia mossambica* and *Cyprinus carpio* in a recirculation aquaculture system (RAS) with iceberg lettuce and tomatoes under hydroponic raft cultivation without the addition of special plant nutrients. This first fully closed or coupled aquaponic system already included biofiltration, a sedimentation tank and a sludge return with denitrification in a bypass, enriching the process water to 1200 mg NO_3/l during the first 7 weeks. Subsequent early closed aquaponic systems were designed by Lewis et al. (1978), Watten and Busch (1984) and Rakocy (1989) as well as presented as 'Integrated Aqua-Vegeculture System' by Mark McMurtry and Doug Sanders in the 1980s (Diver 2006).

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Aquaponics has received considerable more attention in recent years, as can be seen in the increasing number of publications in the scientific literature from approximately 5 in 2010 to approximately 35 in 2014 (Junge et al. 2017). This form of cultivation is considered one of the most efficient and sustainable animal protein production systems. Fish, in general, require less feed per kilogram added growth than all other agricultural animal products such as beef, mutton and goat (Tilman and Clark 2014), and in aquaponics, feed loss and fish waste can be reused and converted into valuable plant biomass. Additionally, in terms of water efficiency, aquaponics is potentially more efficient than the current stand-alone systems of conventional recirculating aquaculture systems (RAS) and hydroponics. According to Lennard and Leonard (2006), water is replaced (not exchanged) in aquaponics only to account for the water lost through plant-mediated evapotranspiration, where evaporative loss was the main mechanism. Palm et al. (2014a) had a daily water input of 5.77% and a water removal rate of 1.37% during cleaning in a closed ebb-flow substrate aquaponics system for Nile tilapia (*Oreochromis niloticus*) combined with tomatoes (water loss 4.4%), and Knaus and Palm (2017a) demonstrated a daily water replacement of 1.48% and a water removal rate of 0.26% (water loss 1.22%) in a more efficient system with Nile tilapia and African catfish (*Clarias gariepinus*) combined with herbs. Lennard and Leonard (2004) replaced 2.43–2.86% in a closed aquaponics with Murray cod (*Maccullochella peelii peelii*) and Green oak lettuce (*Lactuca sativa*), and Naegel (1977) added 2–3% of water daily to the system, mainly due to loss of water by evaporation, overspill and the disposal of excess sludge.

In general, aquaponic systems combine RAS for fish and hydroponics for plant production (Goddek et al. 2015). Essential elements are fish-rearing tanks, solid removal components (mechanical filtration, e.g. clarifiers, microscreens), biofilters (nitrification unit), a hydroponic component and a sump (Rakocy 2012; Somerville et al. 2014). According to Rakocy et al. (2010) and Somerville et al. (2014), aquaponics can be categorized from *mini*-, *hobby*- and *backyard* installations to *small*-, *semi*- and *large commercial* systems. However, all types have different variations and adaptations that relate to different types of site and local conditions.

A main weakness in the development of larger scale aquaponic systems is the economic sustainability in comparison to stand-alone systems (RAS, hydroponics) and the different factors (e.g. energy use) that influence economic failure or success. This area is crucial but sadly under researched. Initial studies either suggested negative outcome in terms of cost benefits (Vermeulen and Kamstra 2012; Stadler et al. 2015) or positive outcomes in the future (Goddek et al. 2015). Love et al. (2015a) who summarized aquaponic systems, with particular reference to the USA, discussed the wide range of production systems, where approximately 31% had the potential ability to attain profitability or economic sustainability. The companies that had the best prognoses were those that also distributed materials (system components) and services know how. The recent rise in interest in aquaponics by researchers, companies and the public is however undermined by disparate perceptions concerning ecological benefits and economic needs. Similar to RAS technology, investment costs, e.g. in state-of-the-art greenhouse technology can be high, resulting in possible economic constraints and even the loss of invested capital. Consequently, better guidelines and explanations concerning the different systems and their potentials, as well as the risks arising from different component usage and system designs, are urgently needed.

A first summary of aquaponics guidelines (The EU Aquaponics Hub, COST Action FA1305) reported different aquaponic systems, from research units to *large-scale* commercial operations (Thorarinsdottir et al. 2015). Inasmuch as aquaponics has a wide range of applications according to the degree of commercialization (domestic vs. commercial) and possible plant cultivation techniques, there is still no general system design recommendations. The objectives of this review is thus to summarize the current state of the knowledge on component use and system design, as well as the resulting classification of the currently available aquaponic systems, demonstrating the given limitations brought about by the type and scale of the system. This facilitates the development of a standardized nomenclature which is proposed in order to distinguish between integrated aquaculture, aquaponics and aquaponic farming, considering the wide variation in system designs according to the component use and scale of operation. Different categories of coupled and decoupled aquaponics are compared, and future developments of both systems are discussed.

Integrated aquaculture systems

Aquaculture is the farming of aquatic organisms, including fish, molluscs, crustaceans or other invertebrates such as echinoderms, ascidians, polychaetes and aquatic plants. Farming implies some sort of intervention in the rearing process to enhance production, such as regular stocking, feeding, protection from predators, etc. Farming also implies individual or corporate ownership of the stock being cultivated (FAO 1988). Integrated aquaculture systems are defined as the concurrent or sequential linkage between two or more farming activities, one of which is aquaculture. For example, integrated aquaculture can be defined as the integration of another (secondary) species (fish, plants or algae) into a system that benefits from the main targeted species (e.g. fish). Such systems date back to the early development of aquaculture in SE Asia, in China, in the Eastern Han Dynasty, 25–220 AD (Kangmin 1988; Fernando 1993), where carp and rice field production were combined benefitting both. As described by Lu and Li (2006), the ecological principles such as mutualism and symbiosis are achieved by linking the food web with benefits for fish, plants and microbes in a rice-fish culture. Contemporary integrated aquaculture systems have high variability in the use of resources and are found in many geographic regions, even under brackish or marine conditions. There are four different kinds of integrated production systems (Fig. 1) that all combine the use of water and the integration of a secondary or several species that benefit from each other.

There are different forms of rice-fish systems, irrigated, rain fed, deep-water and coastal systems (Dela Cruz et al. 1992). The most used component is the field area, where the fields contain a sump to concentrate fish for harvesting with a cover to protect the fish from excessive temperatures (Kangmin 1988). Rice fields may also be built in terraces with good opportunities for water flow. In modern times, a more mechanized form of rice-fish cultivation was developed

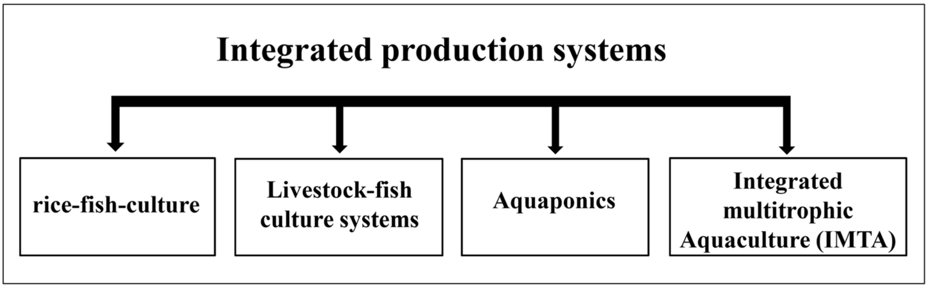

Fig. 1 Overview of integrated production systems, rice-fish culture and livestock-fish culture systems, aquaponics, integrated multitrophic aquaculture (IMTA)

with the use of fertilizer, pesticides, herbicides and irrigation facilities on a large scale in most continents (Fernando 1993). Today, rice fields are also used to treat the effluent water of fish aquaculture in which the rice fields receive the nutrient-enriched water, before the filtered water is drained into the natural water effluents such as small rivers or other drainage systems.

Livestock-fish culture systems combine livestock, such as goats, with catfish pond aquaculture in which the cages for the livestock are built over the fish ponds, and the excrements of the goats are used as fertilizer to increase algal and fish growth (e.g. Little and Muir 1987; Mukherjee et al. 1992). This is also done with chickens, ducks as well as pigs.

Aquaponics can also be considered a land-based integrated aquaculture system in which the effluent water is used for soilless plant cultivation. The aquatic organisms can be keep in monoculture, polyculture (polyponics = multiple fish species use in aquaponics in the sense of Knaus and Palm 2017b) or under integrated multitrophic aquaculture conditions. Modern aquaponic systems use technological components to recirculate the water in the fish production unit and to perform solid removal. However, after more than 40 years of development, a wide variation of systems exists, that necessitates a careful reconsideration of its terminology.

Integrated multitrophic aquaculture (IMTA) is the most current form of species integration within aquaculture production systems and was originally developed for raising marine organisms (Soto 2009). In IMTA, species are combined that utilize different trophic levels and, in combination, they can minimize nutrient output into the environment or even become extractive (Chopin et al. 2001; Troell et al. 2003, 2009; Palm et al. 2017). The main goal is to feed the less developed (more primitive) species of organisms from the feed remnants of higher level aquaculture species and their metabolic end products in order to exploit the actual input resource of fish feed efficiently and sustainably, whilst at the same time reducing negative waste outputs into the environment. IMTA usually combines fish, mussels and algae (different types of seaweed). The boundaries between IMTA (in the sea) and aquaponics (on land) can be unclear, for example in the implementation of a freshwater IMTA system with aquaponic production conditions (Bakhsh and Chopin 2012) or the concept of aquaponics as a land-based freshwater IMTA system for keeping the aquatic organisms, combining the aquaculture production (e.g. fish, crayfish, molluscs, etc.) with the hydroponic production of aquatic plants (explained in Gunning et al. 2016) (also known as FIMTA = freshwater IMTA according to Bakhsh et al. 2015). Similarly, combinations of aquaponics with marine water resources (described as "saltwater aquaponics" in Gunning et al. 2016) have also become known, combining saltwater fish with brackish water or salt loving plants (halophytes) such as *Salicornia dolichostachya*, *Tripolium pannonicum* (Buhmann et al. 2015; Waller et al. 2015) or *Sesuvium portulacastrum* and *Batis maritima* (Boxman et al. 2017). For these cases, Gunning et al. (2014) coined the term MARAPONIC systems, as exemplified by the production of *Salicornia europaea* (marsh samphire) in combination with *Oncorhynchus mykiss* (rainbow trout) under marine water conditions. With the use of saline water production environments under desert conditions, only a small number of brackish water aquaponic systems are known. Kotzen and Appelbaum (2010) and Appelbaum and Kotzen (2016) tested different conventional herbs (e.g. basil, mint) and vegetables (e.g. tomato, aubergine) for production in arid regions. The difference compared to freshwater aquaponic systems was the higher conductivity level up to 6800 μS/cm, considered to be moderately saline, which is often found in arid regions.

Aquaponic terminology

Aquaponics is a hybridized name conflated from aquaculture and hydroponics. Based on classical closed systems (see above), it combines the farming of aquatic organisms (FAO 1988) with water-based terrestrial plant culture (Lennard 2015). The suffix 'ponics' in hydroponics as well as aquaponics comes from the Greek 'ponos' for work, and thus, the term aquaponics is unfortunate as it really translates as 'waterwork' which does not adequately describe what the system really is and what it does. However, farming is an important word and concept here, as aquaculture farms aquatic organisms and there is legal ownership of the facilities who can claim ownership of production. Without ownership, fish production falls under fisheries and fishing which is something totally different logistically and legally. This general concept of farming must also be applied to aquaponics where the fish or other aquatic organisms are at the centre of the production system.

The term aquaponics has thus far been used by different authors, mainly to denote the combined culture of fish and plants in an aquatic environment (Lennard 2015). The practice originated from aquaculture production systems and the attempt to reuse and reduce the nutrients in the effluent waters (Sneed et al. 1975, cited in Lewis et al. 1978; Naegel 1977). Aquaponics was first defined by Rakocy (2012) as encompassing recirculating aquaculture systems (RAS) that incorporate the production of plants without soil, as earliest presented by Naegel (1977). In such systems, mainly non-toxic nutrients (P, NO_3) and organic matter as by-products from the primary cultured species (e.g. fish) are used to grow plants, which may be of aquatic or terrestrial origin.

Lennard (2015) defined aquaponics as "*A system of integrated, tank-based, aquatic-animal (fish) culture and hydroponic plant culture wherein the majority of nutrients required for plant growth arise from wastes derived from feeding fish.*" The organisms involved were designated as the initial user (i.e. the fish that consume the initial nutrient source, the feed), the intermediate converter (the bacteria) and the tertiary user (the plants). Originally, derived from classical coupled systems, the fish waste was entirely used to produce plants with a maximized and efficient use of the nutrient source (fish feed) having the positive effect of reducing nutrient discharges compared to conventional aquaculture. According to Lennard (2015), at least 80% by weight (and often more) of the nutrients required for optimal plant growth are derived from fish waste alone. Modern aquaponics often use additional fertilizers to supplement nutrients missing from the fish feed for the plants. Therefore, aquaponics so far includes a wide range of systems from complete recirculating units that only use the fish feed as a nutrient source (closed or coupled aquaponics) to separated aquaculture and hydroponic units (decoupled aquaponics) with significant nutrient addition and water control. Adopted from Lennard (2015), referring optimal plant growth to comparable cultivation practices in use, and considering the most recent research results of increasing importance to selectively add nutrients into the commercial systems to achieve the required plant product quality, and as a result of the COST Action FA 1305—'EU Aquaponics Hub', we alter and expand the definition as follows:

> '*Aquaponics is a production system of aquatic organisms and plants where the majority (> 50%) of nutrients sustaining the optimal plant growth derives from waste originating from feeding the aquatic organisms*'.

A classical aquaponic system consists of three main units: (1) the aquaculture unit comprising fish tanks, (2) filtration system comprising sludge removal devices (e.g. sedimenter) and optional biofiltration (e.g. trickling filter) and (3) a hydroponic component for the plant production including deep water culture (DWC), nutrient film technique (NFT), ebb-and-flow tables and drip systems. Naegel (1977) already included an additional sludge return with denitrification in a bypass. The fish-rearing unit can be operated from low to very high stocking densities in single tanks or combining different aquatic species under polyponics or following the concept of a freshwater IMTA. The plant cultivation can also range from a few plants to intensive hydroponic production systems. To maintain maximum water quality, the waste removal device must be adapted to cover increasing productivity, so that aquaponic systems can vary from extensive to highly intensive. However, simple technical solutions are also feasible through the use of near-natural surface waters (ponds) as opposed to highly engineered intensive aquaponic production systems with complex greenhouse technology. Thus, the agro-technical production principle ‘aquaponics’ offers highest variability in system design compared to other integrated production systems.

Aquaponic systems design

Open pond aquaponics

Open pond aquaponics has been developed in East Asia and often utilizes catfish (e.g. *Clarias* sp.) or tilapia (*Oreochromis* sp., Pantanella 2008). Most commonly produced fish species are herbivorous carps (grass carp—*Ctenopharyngodon idella*, silver carp—*Hypophthalmichthys molitrix*, bighead carp—*Hypophthalmichthys nobilis*), tench (*Tinca tinca*), pike larvae (*Esox lucius*), pike perch (*Sander lucioperca*) fry, catfish (*Silurus glanis*) fry production and African catfish (*Clarias gariepinus*) summer production in outdoor ponds (Horváth et al. 2002). Open pond aquaponics is a very cost-effective method of integrating the production of fish and plants. Very few technical and energy-driven components are used, including a minimal use of water pumps, water flow and aeration (Fig. 2). The main component is usually an artificial pond stocked with one or more fish species (mono/polyculture). Additional fertilizers can be added to the pond to enhance plant growth. Most often, a raft system for plant cultivation is installed directly on the pond surface. The plant roots therefore depend directly on the nutrient-enriched pond water. They are often stocked in batch cultivation and serve the direct sales market or are only for home use (Table 1). In Bangladesh, experimental pond polyculture with pangasius (*Pangasius hypophthalmus*) and tilapia (*Oreochromis mossambicus*) is used to produce okra (*Abelmoschus esculentus*), water spinach (*Ipomoea aquatica*), pudina (*Mentha arvensis*), brinjal/eggplant/aubergine (*Solanum melongena*), tomatoes (*Lycopersicon esculentum*), giant taro (*Alocasia macrorrhiza*) and Indian red spinach (*Basella rubra*) on bamboo pond rafts with varying results (Roy et al. 2013; Salam et al. 2013). Within these experiments, rafts can cover up to 4% of the total pond area, and only pudina production showed good results and was profitable.

In Thailand, an experiment using stocked hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) in a pond was described by Sikawa and Yakupitiyage (2010) with comparisons of water substrate filtration using different aggregates (styrofoam, sand and gravel). Lettuce (*Lactuca sativa*) yield was best when using the sand substrate (followed by gravel) and showed an even higher harvest when the nutrient water was filtered via an external affiliated mechanical and biological cleaning unit. The external filtration of the pond water reduced total

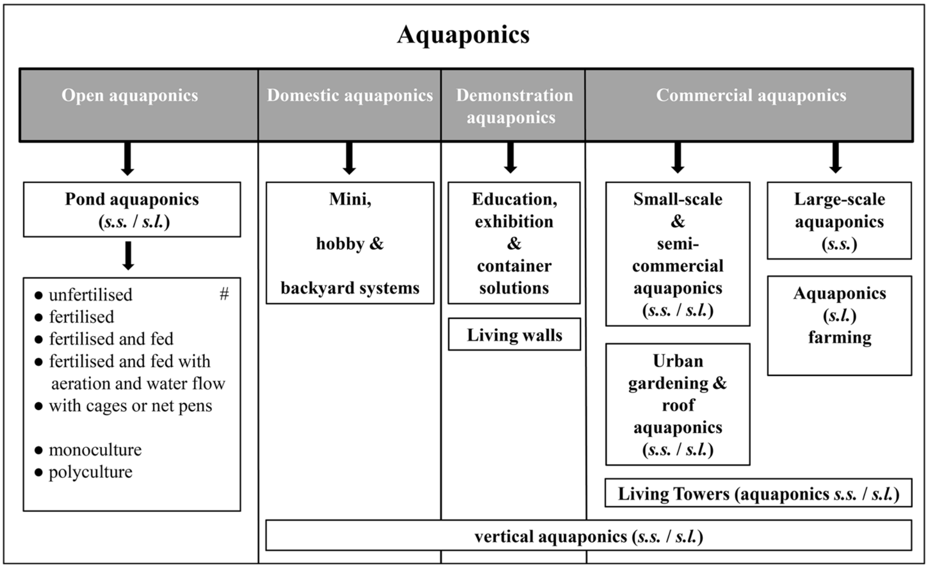

Fig. 2 Classification of aquaponic systems according to system and design into the four main categories: open, domestic, demonstration and commercial aquaponics (*s.s.* sensu stricto, *s.l.* sensu lato). The # sign identifies those adopted from Stickney (1994) from various types of aquaculture and Horváth et al. (2002) from carp and pond fish culture

suspended solid content by 61%, demonstrating the advantage of using an external cleaning unit in pond aquaponics.

In Slovenia, a land-based aquaponic system was described by Klemenčič and Bulc (2015) with the use of common carp (*Cyprinus carpio*) under extensive fish stocking densities as a pilot operation of aquaponics under field conditions. The system consisted of two 36-m^3 ponds (one control), a treatment system located outside the pond (water was pumped in recirculation)

Table 1 Aquaponic systems with markets used, fish rearing principles and main plant culture principles (modified after Rakocy et al. 2010; Somerville et al. 2014). DWC, deep water culture; NFT, nutrient film technique

Aquaponics system	Markets	Fish rearing principle	Main plant culture principle
Open aquaponics	Home use/direct sales	Batch[a]	Hydroponics and substrate based
Domestic systems (mini/hobby/backyard-coupled)	Home use/direct sales	Batch	DWC, NFT, ebb-flow, media bed
Demonstration aquaponics (e.g. living walls-coupled)	Education, exhibition	Batch	DWC, NFT, ebb-flow, media bed, aeroponic, vertical
Commercial aquaponics and aquaponics farming			
Small/semi-commercial systems (coupled or decoupled)	Retail/wholesale	Batch/staggered[b]	DWC, NFT, ebb-flow, drip, aeroponic, vertical, substrate/soil
Large-scale systems (coupled or decoupled)	Wholesale	Staggered	NFT with full nutrient management, substrate/soil

[a] Batch = rearing of one fish population or one fish age group

[b] Staggered (after Rakocy 2012) = rearing of more than one fish age group with intensification of fish production over the whole year

with a lamellar settler, a roughing filter and a vertically constructed wetland filled with expanded clay and planted with tomatoes (*Lycopersicon esculentum*). The growth of carp was better in combination with the aquaponics, and the tomato harvest was high (38.4 kg/m^2 wet weight). This land-based pilot aquaponic system clearly demonstrated the possibility of integrated production under field conditions with only little effort in the system design. Due to the favourable cost structure of such pond systems, this type of aquaponics should be more closely studied in the future.

Domestic aquaponics

Domestic aquaponic systems correspond to classical aquaponics where mainly fish is jointly cultivated with plants in closed or coupled systems. They include *mini* and *hobby installations* that can generally be characterized by the use of small fish tank volumes, extensive stocking densities and small plant areas (Fig. 3). In terms of general system design and component use, they have in common that they usually include only a single fish reservoir (e.g. aquarium) or tank and a small hydroponic unit (*mini-system*) with a total maximum area of approximately 2 m^2. They may include ornamental fish, and in their simplest form, the plants float directly on the water surface of the aquarium or fish tank. Extended versions separate the aquaculture unit from the hydroponic unit by pumping the nutrient-enriched water to the hydroponic unit (Fig. 3a). These systems usually use internal aquarium filters purchased from aquarium suppliers.

Larger systems may also contain a sedimentation unit and a sump with the expansion of functional recirculating components. In such *hobby installations*, water flows by gravity towards a small-sized sedimenter followed by the plant cultivation area, mostly using substrate systems (media beds), and then it flows into the sump (Fig. 3b). From the sump, the water is

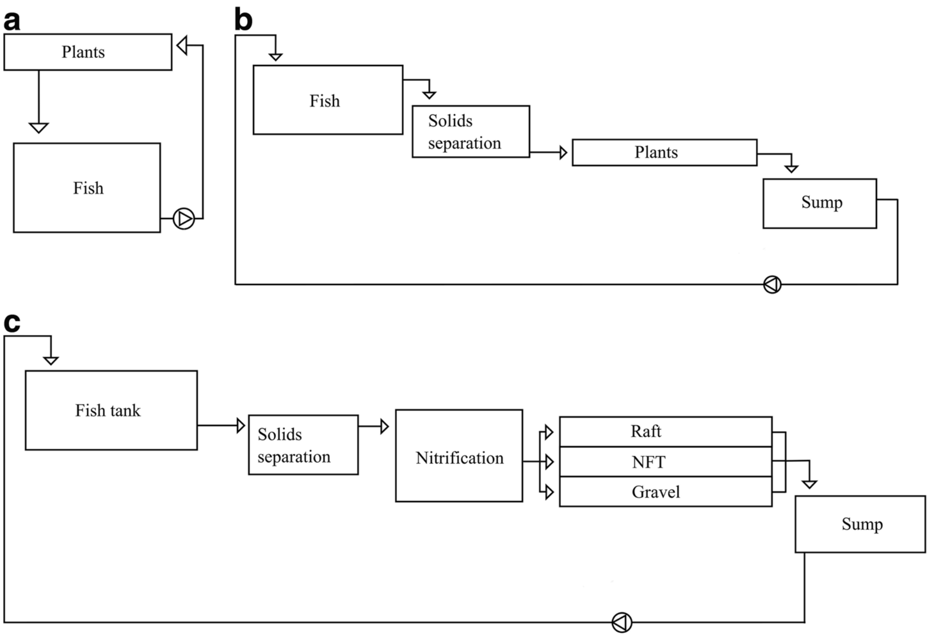

Fig. 3 Overview of different domestic aquaponic system designs. **a** Mini-system. **b** Hobby system. **c** Backyard aquaponic system (NFT, nutrient film technique; Raft, floating raft; Gravel = media bed substrate system)

pumped back with the help of a single pump into the fish tank. Additional aeration by air pumps or spray bars is often required to maintain fish growth and health. The space requirement does not exceed 2–3 m^2 to a maximum of 10 m^2, and the fish are often kept as fishkeeping instead of targeting production. As an indoor system, it can produce throughout the year.

Domestic constructions with the purpose of fish and plant production for human consumption are described as *backyard aquaponics* and are frequently built by enthusiasts. In the literature, experimental setups of this size also firm under small-scale aquaponics due to a lack of proper definition. These systems use larger sized fish tanks, may be several tens of m^2 in size (Malcolm 2007, Fig. 3c), but do not exceed 50 m^2 where the water circulation within a unit still can be achieved with a single pump. Occasionally, airlift pumps are used where air is pumped into a pipe located in the sump. This has the effect of pushing up the water in the pipe and thereby getting rid of the need for a water pump. The method is cost effective and on the whole cheaper than pumping. *Backyard aquaponics* can be equipped with a larger sedimenter and biofilter as cleaning units and different hydroponic subsystems (Tables 1 and 2). In the northern hemisphere, production is limited to the spring, summer and early autumn period when the water heating allows significant production.

Domestic aquaponics have been most frequently installed in urban *backyards*, often located in domestic scale greenhouses attached to a house or located away from the house in a garden. Other systems are found on urban rooftops for the better use of the incident light for production with an area of 20 to 50 m^2 per house (de Vries and Fleuren 2015) or, in general, for improved use of urban areas (Kotzen 2012). They have extensive stocking densities in common, resulting in a low feed input per day and a reduced rate of suspended solids and nutrients in the process water. On a 25-m^2 production area, Palm et al. (2014b) produced fish biomass of 13 kg (biomass weight gain) in about 92 days of production with significant numbers of cucumbers, tomatoes and basil. The hydroponic units usually consist of media bed substrate

Table 2 Scale of aquaponic operations, with focus on developed countries (DWC, deep water culture = floating raft; NFT, nutrient film technique)

	Domestic	Small-scale/semi-commercial	Intermediate/large-scale commercial for business and industry
Site area	≤ 50 m^2	> 50–≤ 100 m^2	> 100–≤ 500, > 500 m^{2a}
Aquaculture unit	Single tank	Few tanks (1–4[b])	Full recirculation aquaculture system
Fish rearing principle	Batch, extensive	Batch/staggered, extensive to intensive	Staggered, intensive
Biofilter	No/yes	Yes	Yes
Pumps	No/single	Backup, bypass systems	Multiple, bypass systems
Degree of mechanization	Low	Medium	High
Hydroponic subsystem	DWC, NFT, ebb-flow media bed	DWC, NFT, ebb-flow planting table, drip, aeroponic, vertical	DWC, NFT with full nutrient management, ebb-flow planting table, drip irrigation, soil (farming)
Plant culture principle	Batch	Batch/staggered	Staggered/intercropping
Cultivation period	Spring to autumn/year-round	Spring to autumn/year-round	Year-round
Decoupled	No	No/yes	No/yes

[a] modified after Love et al. (2015a)

[b] Rakocy (2012)

systems (e.g. gravel), which also serve as a biofilter (Rakocy et al. 2006; Tyson et al. 2008; Somerville et al. 2014), but sometimes smaller NFT installations (e.g. by using perforated drainpipes) and DWC (raft) systems are also possible. Known advantages of the use of media beds are the biofilter characteristics with biofilm formation and nitrifying bacteria, mineralization and the reuse of organic substrates for soil cultivation of crops through composting (Somerville et al. 2014). Lennard and Leonard (2006) demonstrated benefits of green oak lettuce (*Lactuca sativa*) gravel bed cultivation in contrast to raft and NFT systems with a 20% less efficient nitrogen removal rate of the NFT system and reduced biomass gain of lettuce.

Another positive potential is the incorporation of worms (vermiponics) into the aggregate. Vermiponics usually use tiger worms (*Eisenia fetida*) in ebb and flow systems. The worms help to remove any decaying material from the plants, and their own waste is a fertilizer for plants. Additionally, the worms can also be used as part of the fish diet when removed from the gravel and fed to the fish. One disadvantage is the accumulation of suspended solids on the aggregates, such as gravel, sand, perlite or clay, and an overload of these suspended solids can have a negative impact on fish feeding activities and the solid removal component stability (Rakocy 2012). Therefore, the size of such media beds filled with, for example, a gravel substrate is limited due to the difficultly in moving and cleaning them, the abrasion of plants by gravel particles and the high potential for clogging of suspended solids. Other negative aspects include the formation of anaerobic zones, the comparatively high labour input for washing and managing the substrates (Somerville et al. 2014) and a fairly limited production of fish and plants. This limits their application for commercial purposes (Table 1). Descriptions of the *backyard aquaponics* type are found in Watten and Busch (1984), Kotzen and Appelbaum (2010), Palm et al. (2014a, b), Palm et al. (2015), Morgenstern et al. (2016) and Knaus and Palm (2017a, b).

***Small-scale* and *semi-commercial* systems**

Small-scale aquaponic systems are characterized by a technical expansion of functional components and production areas compared to domestic installations. These systems are built for retail market (Table 1) purposes (farmers' markets and stands, Love et al. 2015a) and use a larger area and one or several larger sized fish tanks and plant units (Table 2). The use of more than one fish tank and hydroponic subunits allows staggered but not necessarily continuous fish and plant production to harmonize nutrient flow over a longer period. To optimize fish and plant output, these systems require mechanical (sedimenter) and biological (biofilter) filtration units, and they can use different hydroponic subsystems, such as DWC (raft), NFT techniques or ebb-and-flow tables (Fig. 4a, Table 2). Still using gravity to distribute the fish process water to the plant units, at the minimum, a single pump (with a backup pump system to avoid fish loss in case of breakdown) is required to circulate the water between the filters, fish tanks and/or the combined fish and plant units. Because of the small size of less than 100 m^2 and lower investment costs, production is mainly restricted to the spring, the summer and the early autumn period in the northern hemisphere to minimize energy costs (Table 2). However year around production in small greenhouses is possible. From the production point of view, small-scale aquaponics was identified with a lettuce output of 50–500 heads by Somerville et al. (2014).

Small-scale aquaponics still often use media bed systems with a variety of substrates (but mainly gravels) for plant cultivation. One problem is the management of the substrate, with transport and cleaning (as it is awkward and heavy) so that the maximum area for plant production becomes limited (Rakocy et al. 2006). Due to this problem, gravel media beds are only common in the small-sized aquaponics (also see *backyard aquaponics*). Sand was described as an excellent

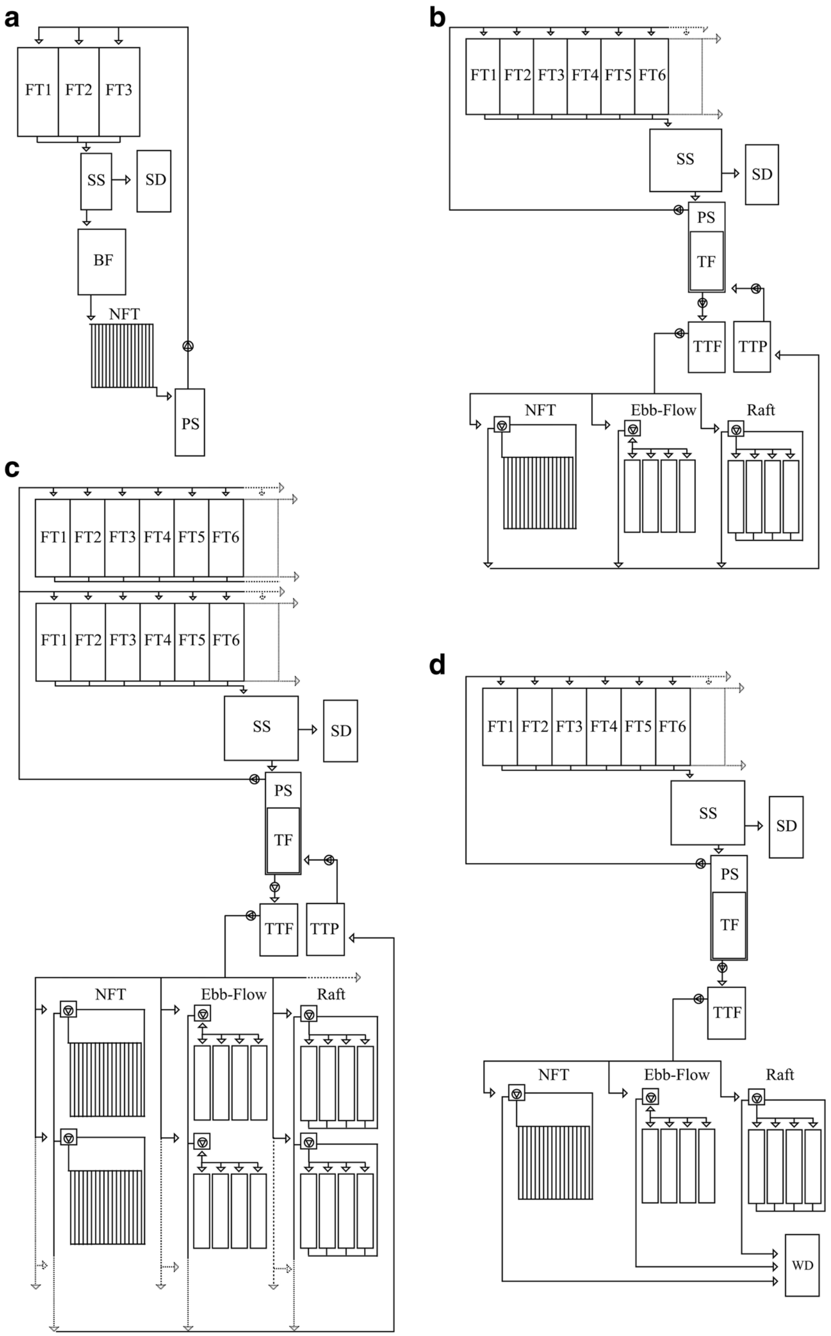

Fig. 4 Scale of aquaponic systems. **a** Small-scale system. **b** Semi-commercial system. **c** Large-scale system. **d** Scheme of a decoupled aquaponic system (FT, fish tank; SS, solids separation; SD, solids disposal; PS, pump-sump; BF, biofiltration; TF, trickling filter; NFT, nutrient film technique; Ebb-Flow = planting tables; Raft = floating raft troughs; TTF, transfer tank fish process water; TTP, transfer tank plant process water; WD, water discard)

substrate for plant growth. However, problems with clogging were described by McMurtry et al. (1990, 1997) and Rakocy (2012). To resolve this problem, a coarse grade of sand can be used to reduce the clogging capacity of the media beds. Other substrates that can be used in media beds are perlite (Rakocy et al. 2006), the light expanded clay aggregate LECA™ (Graber and Junge 2009), volcanic gravel/pumice (tuff or tufa), limestone gravel, river bed gravel, recycled plastic such as plastic bottle caps (held submerged with a layer of gravel), and organic substrates such as coconut fibre, sawdust, peat moss, and rice hulls (Somerville et al. 2014). Despite some problems, media bed systems offer certain advantages in plant production and system stability. The effects of nutrient accumulations, such as phosphorus, in media beds (gravel substrate) were reported by Palm et al. (2015) as a reservoir for demand-induced nutrient uptake by plants in a backyard-sized system. Other advantages which are also found in small-scale NFT and raft systems include the very low labour input during a balanced run of the system (steady state according to Palm et al. 2014a), low energy consumption due to the single pump and gravity-driven water flow and very low water exchange rates.

Small-scale aquaponic systems mark the further development of domestic systems with an expansion of the production area, the fish tanks and the hydroponic units, and they can still be constructed technically by non-professionals. Due to their technically relatively simple design, these systems have been widely used and described in the literature, e.g. in Watten and Busch (1984), Essa et al. (2008), Ako and Baker (2009), Simeonidou et al. (2012), Villarroel et al. (2011) and Love et al. (2015b). With a total size less than 50 m^2, some of them represent backyard systems or even hobby installations belonging into domestic aquaponics. Small-scale *aquaponic systems* are also found on rooftops in urban areas as described in Somerville et al. (2014). Roof gardens using aquaponics is a special form of urban use, increasing the value of urban areas and rooftops.

Semi-commercial aquaponic ventures operate between small-scale and large-scale production systems with a high degree of mechanization. They define the beginning of commercial production for the retail market (Table 1), as distinguished from domestic and small-scale use. According to the characteristics mentioned above, sites can have a production area lower than 100 m^2 (Table 2) as described for commercial ventures by Love et al. (2015a). From the production point of view, semi-commercial aquaponics was identified with a lettuce output of 500–2500 heads by Somerville et al. (2014). The 'FishGlassHouse' at University of Rostock (Germany) has an output of approximately 1200 basil, mint or other crops per experiment with the use of 100-m^2 hydroponic production area and about 90-m^2 area for fish production, targeting the retail market. Producing warm water African catfish (*Clarias gariepinus*) under intensive cultivation, the output reaches about 2–4 t fish per annum.

Semi-commercial aquaponics can use more than a single pump, besides gravity, to circulate the water, may include bypass systems (multi-loop) and require higher investment costs (Table 2). The fish production uses RAS technology suited to the selected species with increasing numbers of fish tanks (Fig. 4b). The effluent water has high nitrate concentrations (resulting from the higher fish stocking density) and is oxygenated inside the biofilter. The nutrient-enriched process water is connected to the hydroponic units, which may be differentiated into DWC (raft), NFT, ebb-and-flow tables, aeroponics or a combination of different subsystems. System design alterations depend on the location and specific regional conditions, making both coupled and decoupled systems feasible (Table 2). Ebb and flow tables were developed for conventional hydroponic commercial garden specialists (Raviv and Lieth 2008) and adapted to aquaponics. Additionally, drip irrigation techniques (Raviv and Lieth 2008) can be used for semi-commercial systems. However, the investment and maintenance costs can be high as each plant is connected to the drip irrigation system with a pipe and a terminal dripper, which feeds the nutrient-enriched water from a central water reservoir by pumping.

Semi-commercial ventures require additional consideration concerning system stability, fish health and microbe control inside the system. Aiming for a higher plant yield, the principle of culturing plants has developed more complex technology, such as climatic and environmental control (CO_2 greenhouse enrichment), the use of water monitoring tools, waste and sludge management, effective biofiltration and solids removal devices, power backup systems and biosecurity, as well as pest management. They are therefore usually based in greenhouses and require employees skilled in aquaculture and plant cultivation techniques (Somerville et al. 2014). They also require sufficient energy and may be connected to alternative energy supplies. Intermediate between small-scale aquaponics and large-scale commercial operations, semi-commercial aquaponic products can be sold to both retail and wholesale markets (Table 1). Semi-commercial aquaponic ventures are especially suitable for regional markets and depend on the marketing advantages of aquaponic-produced products (e.g. marketed and sold as being aquaponics, i.e. being unique and 'sustainable'), as compared with conventionally produced ones, compensating for higher production costs.

Large-scale (intermediate) commercial aquaponic operations

Large-scale commercial aquaponic operations seek a maximum production output of fish and plants. They require high investment costs and management skills, and they operate with a high degree of mechanization including computerization and monitoring of water quality. They are located within climatically controlled greenhouses, and because of climate control with high energy consumption, they often utilize alternative energy sources. Methods for a maximum yield can mainly be achieved through increasing the numbers of plants cultured per growing area, the selection and efficient use of hydroponic subsystems and the use of a maximum stocking density of fish or other aquatic animals. Large-scale aquaponics produce predominantly for indirect markets like grocery stores, restaurants, institutions and wholesalers (Love et al. 2015a) (Table 1).

In order to increase the number of cultivated plants and to achieve the best possible quality, management protocols for different crops must be met. In hydroponics, the number of plants cultivated per square meter is a main factor in intensification (e.g. Goddek et al. 2015). The number of plants for large-scale operations was described as being > 2500 lettuce heads per annum in Somerville et al. (2014). However, depending on the location, higher value plants such as herbs and tomatoes are the focus of the operation. The average site area for large-scale production was described by Love et al. (2015a) with 0.01 ha (100 m^2), but commercial operations can have land areas above 500 m^2 as seen in the UVI system (US Virgin Islands, Rakocy 2012) or in the FishGlassHouse at the University of Rostock (Germany, Herde and Wild 2015; Palm et al. 2016). Considering that aquaponics' larger scale ventures are increasing, it is apparent that there is a need to readjust the scale descriptors. The examples noted above producing 2500 lettuce heads or over an area of 100 m^2 only produce an average of around 7 lettuces per day. We thus propose that systems between 100 and 500 m^2 are termed intermediate-scale commercial operations and anything above 500 m^2 is considered to be large scale (Table 2).

In large-scale commercial aquaponics, intensive RAS technology is used to increase the yield of fish products, including delivery throughout the year. The use of multiple rearing units with staggered production is a recommended method for large-scale operations (Rakocy et al. 2006; Rakocy 2012; Fig. 4c). A minimum of four fish tanks for rearing different ages or size ranges of fish is useful to optimize fish production, marketing and sales. In line with intensive staggered fish production, plants can also be cultured by staggering planting at suitable intervals or simultaneously using intercropping principles with short-cycle plants, such as herbs and leafy vegetables with year-round producers, such as mint or basil or other woody herbs which can be cut and which regrow and can be cut again at various intervals (Rakocy 2012). Commercial operations can use many and different hydroponic subsystems to increase the plant harvest. Several methods are commonly found, including DWC (raft) (Love et al. 2015a), and NFT, as well as techniques adopted from conventional hydroponics, ebb-and-flow tables or drip irrigation technology (Table 2). In contrast to small-scale aquaponics, the use of media beds is not recommended due to a higher management input (Rakocy 2012) and also due to greater health control restrictions.

The higher fish stocking density in intensive aquaponics is associated and is required with an improved removal of waste and sludge. As was described by Junge et al. (2017), sludge separation increases water quality, and the efficiency of resource use can be increased through the theoretical integration of a biodigester unit or an anaerobic nutrient remineralization component (ANRC) with an upflow anaerobic sludge blanket (UASB) reactor (Goddek et al. 2016). Controlling the sludge concentration in the nitrification tank to a mixed liquid suspended solids (mlss) value of 1 g/l, a dissolved oxygen content of over 4 mg O_2/l, a daily load of about 3 g BOD_5/kg fish and a sludge amount of 400 g mlss in the aeration tank of 400 l with the help of a sludge return bypass, Naegel (1977) achieved a daily sludge load in the nitrification tank of less than 0.2 g BOD_5/g mlss, securing a complete oxidation of all nitrogenous compounds. To optimize fish and plant output, the degree of mechanization has to be adapted. Automatic climate and environmental control, quality monitoring of fish and plants, water monitoring tools, management for waste and sludge with solid removal devices and biofiltration, power generator backups, biosecurity, fish welfare and water quality monitoring equipment are recommended (Somerville et al. 2014). The reuse of water with cold traps, biogas systems and photovoltaic systems constitute special arrangements for highly engineered large-scale operations, especially for temperate climatic zone (Kloas et al. 2012). This type of large-scale aquaponics is often operated using the decoupled principle whereby the aquaculture unit is physically separated from the hydroponic unit (Thorarinsdottir et al. 2015). Fish effluent water is not circulating through all units, but is used as the basis of nutrient enrichment with the addition of conventional hydroponic fertilization. Figure 4d shows a scheme of a large-scale decoupled aquaponic facility with the separation of the aquaculture unit and the hydroponic subsystems, wherein the fish effluent water flows in one direction only from the aquaculture unit to the hydroponic unit. The nutrient-enriched process water (fertilizer + fish nutrient water) circulates in the hydroponics unit. The nutrient solution from the fish can thus be adapted with added hydroponic nutrients as required for different plant species. However, in order to be termed aquaponics, following the definition of the aquaponic production principle noted above, the majority (> 50%) of nutrients sustaining the optimal plant growth must derive from waste (effluent water, solid and sludge removal) originating from feeding the aquatic organisms. Large-scale decoupled aquaponic systems have the advantage of better disease management of fish and plants and show good growth values. These facilities have been described, e.g. by Kloas et al. (2015), Karimanzira et al. (2016) or Suhl et al. (2016) and are in the test phase in Germany, Spain and China (INAPRO 2017).

Examples of large-scale aquaponic systems

Large-scale aquaponic systems are currently under development, and published examples of these systems are still rare. A first modern commercial up-scaled system was developed at the

University of Virgin Islands (UVI) Aquaponic System and designed by James Rakocy from preliminary investigations that began in the 1980s (Rakocy 1989). It was developed to produce different species of plants as part of a coupled system. The final large-scale commercial system, with an area above 500 m^2, consisted of six hydroponic tanks (Fig. 5b) (30.56 m in length, 11.35 m^3) and four fish rearing tanks and was used as a standard system by Al-Hafedh et al. (2008) and with a reduced number of plant growing troughs also by Savidov (2004).

A 'semi-closed loop' (coupled) aquaponic system was described by Graber et al. (2014) and was partly reported by Schmautz et al. (2016) regarding the aquaponic research and

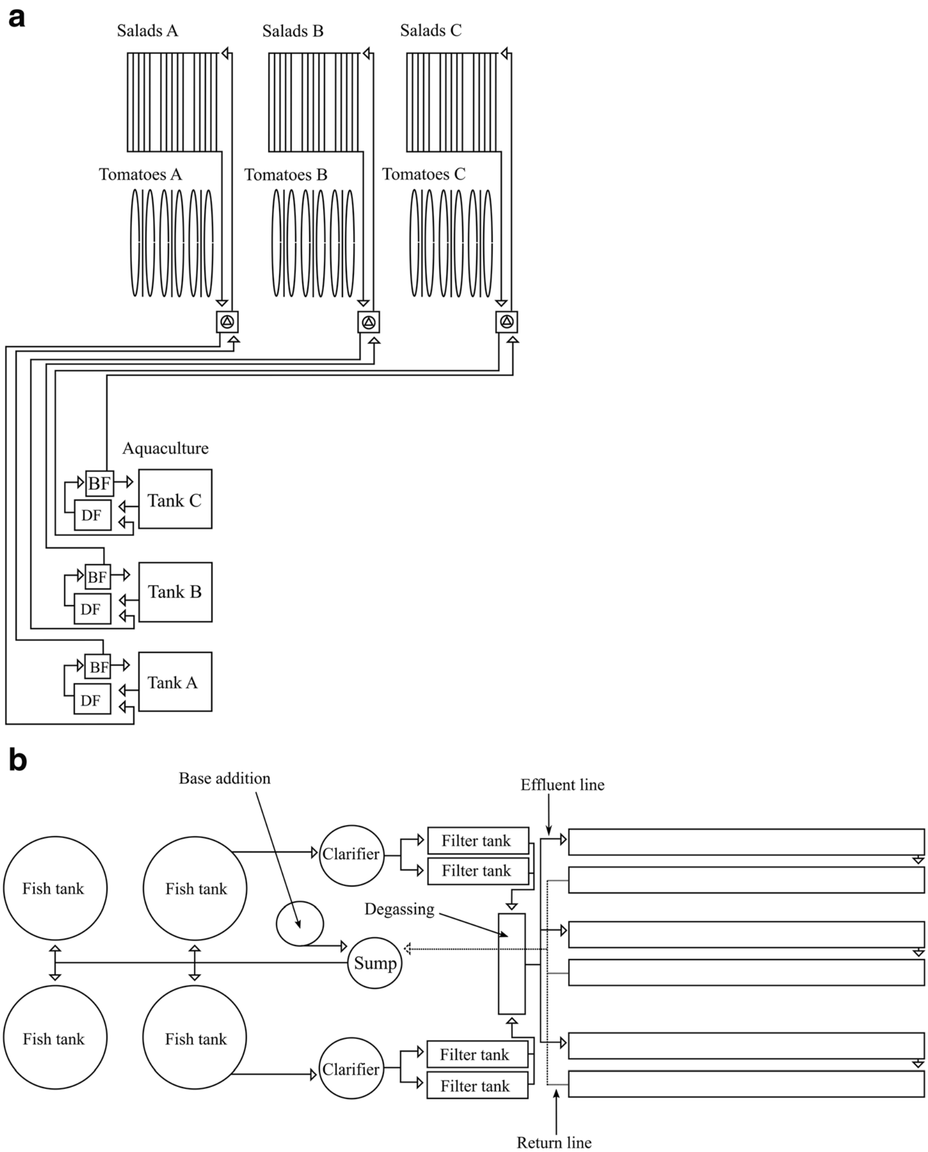

Fig. 5 **a** Semi-coupled ZHAW system (Graber et al. 2014). **b** UVI commercial RAFT system (Rakocy 2012). BF, biofilter (nitrification); DF, drum filter (solids separation)

training facility at ZHAW in Waedenswil, Switzerland (Fig. 5a). Three identical recirculating aquaculture systems are connected to hydroponic production units comprising three channels for production of tomatoes and three modules with five channels for NFT and a total production area of 292 m^2. A central sump connects the aquaculture and hydroponic units, with the backflow from the plants to fish units periodically managed by an electronic control unit.

The FishGlassHouse, a contemporary facility which can be managed as a coupled as well as a decoupled aquaponic system, was built in August 2015 on the campus of the University of Rostock (Germany), Faculty of Agricultural and Environmental Sciences, Department of Aquaculture and Sea-Ranching (Fig. 6, Palm et al. 2016). With an aquaculture unit of 300 and 600 m^2 of plant cultivation area (100 m^2 water transfer area), it generally uses ebb-and-flow planting tables with a range of gravel substrates, DWC (raft) and NFT systems. The hydroponic subunits (six hydroponic cabins), using tables or rafts, are interchangeable or can be used in combination in the same hydroponic cabin or coupled in different cabins. They can also be used with a decoupled production design. The FishGlassHouse in its current set up thus represents a hybrid between coupled and decoupled aquaponics and, under full production, would reach a large-scale aquaponic operation.

Future commercial aquaponic systems may reach up to several 10.000 m^2, similar to hydroponic farms in The Netherlands. A new trend for large-scale aquaponic ventures is the use of different types of subunits for the plants. Thus, for example, ebb-and-flow planting tables with a high load of potted crops, such as herbs, medicinal and ornamental plants, are becoming increasingly important due to the better nutrient supply, bioactive environment in planting pots and following the already established product demand by the customers. However, the production method of potted crops not necessarily applies soilless plant production. It consequently does not fall under the soilless plant cultivation principle of aquaponics (see below, aquaponics sensu stricto). This also concerns fish farmers that collect the effluent water to supply soil-planted crops with nutrients. We herewith use the term aquaponic farming (aquaponics sensu *lato*) for this activity (Fig. 2).

Special aquaponic system design constructions

Aquaponic system design varies considerably, and thus, the designs change as they are developed for the variability in different environments. Newer forms of aquaponics include vertical gardens and living wall components originating from hydroponic design and may be located as part of roof farming (Fig. 2). Thus, a new trend in aquaponics uses vertical systems (mainly in urban areas) which can maximize the production output by using the vertical space that is usually not utilized in production units/greenhouses. Vertical aquaponics can use hydroponics such as DWC, NFT, ebb and flood or growing towers with aeroponics (Pattillo 2017) and can also be developed for home or interior production as small 'cupboard'—systems as described in Wilson (2015) for fresh food in urban homes and urban food service establishments. Love et al. (2015a) noted that one third of commercial aquaponic producers (29%) used vertical towers which are similar to NFT but equipped with vertical trays or tubes for plant cultivation. The general advantage of vertical systems is found in better use of space and greater design possibilities (Fernández-Cañero et al. 2015).

There are a lot of different vertical aquaponic system designs which use technically different vertical/horizontal combined hydroponic components and a fish production unit. For example,

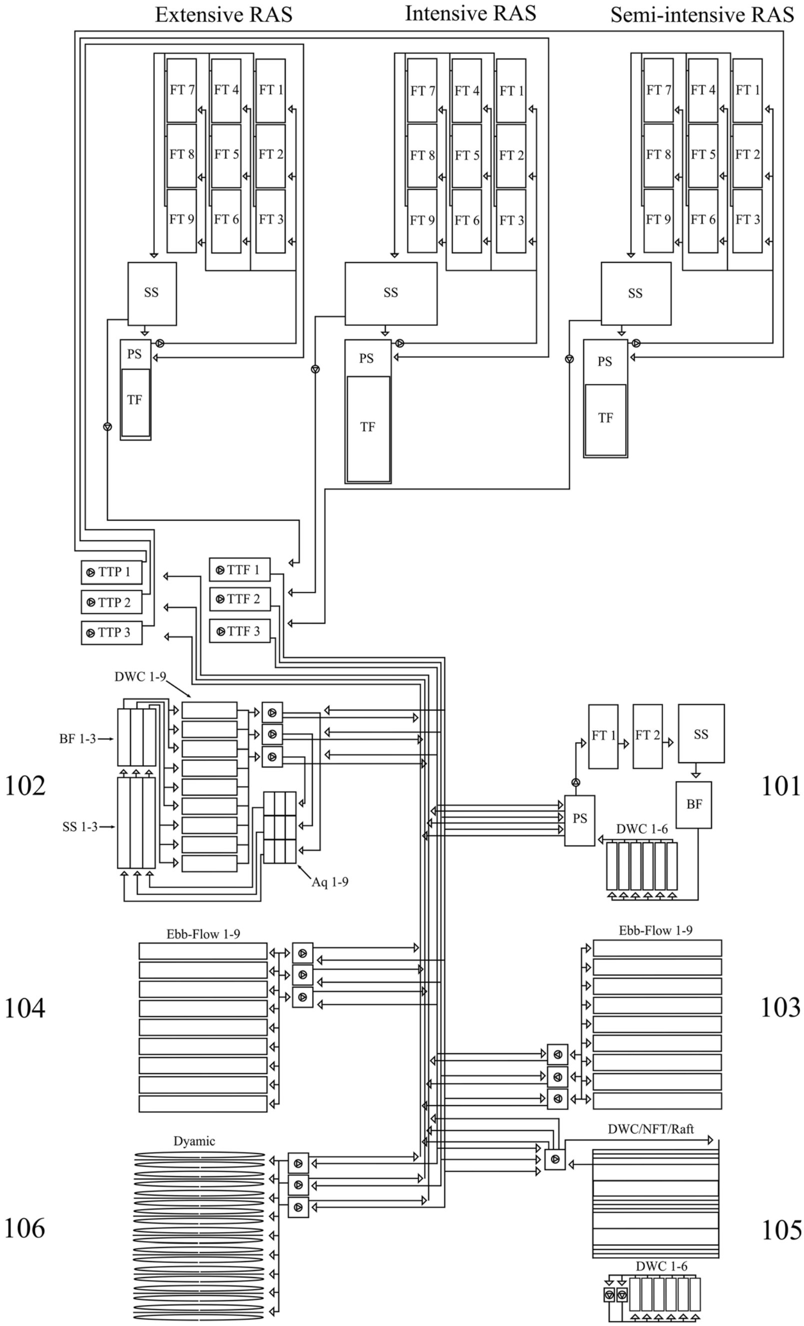

Fig. 6 FishGlassHouse at University of Rostock with aquaculture units (extensive, semi-intensive and intensive RAS) and hydroponic cabins (101-106), Germany (Palm et al. 2016) (FT, fish tank; SS, solids separation; PS, pump-sump; TF, trickling filter; BF, biofilter; NFT, nutrient film technique; TTF: transfer tank fish process water; TTP, transfer tank plant process water; Aq, Aquarium; DWC, Deep water culture; Ebb-Flow = planting tables; Raft, floating raft troughs)

Giacomantonio (2012) described a self-sustaining vertical aquaponic micro-farm with the combination of aquaculture, hydroponics, solar, wind and battery technologies. The system is constructed by a scaffolding parabolic arch support structure which contains an active medium (grow mat) on which the plants are cultured. A further development of this system is described under Giacomantonio (2013) for the production of decorative and/or food plants. The vertical garden is mounted on a cylinder, which is connected to a motor and can adjust the plants optimally to the sunlight. Both systems have a very low water requirement compared to conventional plant cultivation and can be used externally or internally, using growing towers. Growing towers were described by Pattillo (2017) as vertical hollow elements, through which nutrient-rich RAS water flows, moistening the roots through a kind of rain. Within the tower, substrates can be stored which, however, should be flushed more frequently due to clogging.

Another form of vertical plant cultivation is described in the so-called living walls, which are often used in architecture providing ecological and environmental benefits in urban areas (Perini et al. 2013). These green vertical systems were developed for energy saving purposes in buildings (evaporative cooling, shadowing) like green facades with climbing plants or include plants that are placed in perforated panels or geotextile felt thereby supporting the vegetation (e.g. Perez et al. 2011). Living walls can also be used in aquaponics as a further development of the original form with food-producing properties, but there are only a small number of investigations. An important component in living walls is the choice of substrates for plant cultivation. Experiments by Kotzen and Khandaker (2017), at the University of Greenwich, London, showed that for aquaponic production in living walls coconut fibre and mineral wool were the best growing media for basil (*Ocimum basilicum*), spinach (*Beta vulgaris*) and chicory (*Cichorium intybus*). Another type has been described by Gumble (2015) with a rotating living wall prototype, wherein the plant cultivating substrate rotates over the vertical axis. This invention of the rotating living wall seems to be of interest in the future but must be adapted for aquaponic production.

Aquaponics has also moved onto the roofs of buildings and can be part of green roof infrastructure and urban agriculture especially in high-density urban areas where local food production is being encouraged. Aquaponics has already been successfully installed on a number of roofs in various cities around the world, with Urban Farmers AG (2017) Switzerland, the Netherlands and in the USA or 'die Urbanisten e.V." (2017) Dortmund (Germany). The system design generally corresponds to the regular aquaponic system design of various production scales with a recirculating aquaculture unit and NFT or DWC (raft) systems for plant cultivation. De Vries and Fleuren (2015) have developed a spatial typology of urban agriculture according to size. Domestic aquaponics can be organized on a privately owned roof with an area of 20–50 m^2 per house. Professional roof garden aquaponics require roofs between 500 and 1.500 m^2. Thus, even roof top aquaponics illustrates variability of the production areas and system design components.

Many designers and planners are looking to the future to provide healthy local food with all the benefits this brings in reducing food miles, reducing the carbon and ecological footprint of products and providing food security. Vertical farming and roof top agriculture which can include aquaponics is envisaged as a key way to implement this vision. Vertical farming was defined by Kalantari and Tahir (2016) as a system of commercial farming (plants, animals and other life forms), which are by artificially stacked vertically above each other. This integration of agricultural culture or farming into the architectural landscape of urban regions leads to the production of foodstuffs within individual buildings or building complexes. The 'living tower', described by Scott (2009) as a building that integrates agriculture in a single tower, combines living walls and roof-top farming in an urban environment. There are even more radical visions to enable farming (and aquaponics) in skyscrapers through the sustainable use of human, animal and plant waste resulting in a self-sufficient long-term production. Hence, the living tower is considered as a closed unit with a complete recirculation of water. The benefits of production in a living tower are continuous indoor year round production, very low transportation costs, low degree of disease susceptibility, complete water recycling, high production efficiency versus conventional farming and recycling of plant and human waste for energy production, water recovery and nutrient recovery (e.g. through a methane digester) (e.g. the 'Living city' by Scott 2009; the 'Dynamic Tower' by David Fisher, 'Aberrant Agriculture' by Scott Johnson or the '2020 Tower' by Kiss and Cathcart Architects: in Scott 2009). Living towers and indeed vertical cities where all the functions of a city are contained within a building or building cluster are, however, visions that are at the conceptual stage. However, if and when they get implemented they are most likely to include aquaponics as part of the food production system and would be fully integrated into the buildings' water, energy and waste management systems.

Nomenclature of aquaponic systems

Aquaponic production systems cultivate aquatic organisms, in particular those species that require constant feed supply such as fish, amphibians, crustaceans and other invertebrates. The nutrients provided from the excretions of these organisms are utilized to support plant growth. This nomenclature incorporates the production of algae, soilless plant cultivation, gardening plants and crops (Table 3).

As a result of the historic development of aquaponics, and following the definition by Rakocy (2012), aquaponics encompasses the farming of aquatic organisms that incorporate the production of plants without soil. This applies to the hydroponic production of plants by using effluent waters or nutrients that originate from the farming of aquatic organism. According to the new definition of aquaponics, altered from Lennard (2015), the majority (> 50%) of nutrients sustaining the optimal plant growth must derive from waste originating from feeding the aquatic organisms. Consequently, aquaponics in the narrower sense (aquaponics (*s.s.*) or sensu stricto) is restricted to the hydroponic principle without the use of soil or substrates such as sand or gravel. Newest integrated aquaculture systems combine fish with algae production, either macro-algae inside separate tanks or microalgae inside photo-bioreactors. In both cases, the production process is without any soil-like substrates and herewith falls under the concept of aquaponics (*s.s.*). Because the term aquaponics has been already widely applied and is most likely to remain, it should therefore be restricted to the soilless plant cultivation without any substrate in the sense of Rakocy (2012) and other authors.

Aquaponics in the wider sense (aquaponics (*s.l.*) or sensu *lato*) is found in indoor and outdoor substrate aquaponics, which includes horticulture techniques for the production of herbs or gardening plants and the crop production in agriculture, also under the use of conventional soil cultivation techniques. It utilizes the mineralization processes, buffer and nutrient storage function of the different substrates. Because these activities are common horticulture and agriculture practices, we herewith introduce the term aquaponic farming for these activities.

Based on the purpose and function of the known aquaponic systems, it is possible to distinguish among the four main categories, open pond, domestic, demonstration and commercial aquaponic systems (Fig. 2). 'Open pond aquaponics' contains all aquaponic system design variants, which use free surface waters such as lakes or ponds combined with an on-pond or on-land hydroponic component. Ponds are regarded as human-made surface waters

Table 3 Aquaponic nomenclature (DWC, deep water culture; NFT, nutrient film technique; *s.s.*, sensu stricto; *s.l.*, sensu lato)

Product	Algae	Soilless plant cultivation	Gardening plants	Crops
Concept	Aquaponics (*s.s.*)	Aquaponics (*s.s.*)	Aquaponics (*s.l.*)	Aquaponics (*s.l.*)
Industrial activity	Biotechnology	Hydroponics	Horticulture	Agriculture
Production	Industrial	Domestic to industrial	Domestic to corporate	Farms
Scale	Demonstration/commercial	Demonstration/small-scale /semi-commercial/commercial	Demonstration/small-scale /semi-commercial/commercial	Commercial
Technology	Algae reactors	Various subsystems	Various systems	Various systems
Systems	Liquid	DWC, NFT, ebb and flow, drip, aeroponics	Substrate	Substrate and soil
Nomenclature	Aquaponics	Aquaponics	Aquaponic farming	Aquaponics farming
Definition	The majority (> 50%) of nutrients sustaining the optimal plant growth derive from waste originating from feeding the aquatic organisms[a]			

[a] Altered after Lennard (2015)

and examples include the well-known carp ponds, fertilized or not or aerated, in monoculture or polyculture, respectively, under extensive and semi-intensive production (Horváth et al. 2002). Open pond aquaponics can also include the production of marine species, when using nutrients from semi-intensive to intensive fish production (shrimp culture) in coastal ponds or cages, similar to the IMTA system design, but with a hydroponic component on land. Systems with or without soil are possible (aquaponics *s.s.* and *s.l.*).

'Domestic aquaponics' (Fig. 2) includes all types of aquaponic system designs used for private purposes such as *mini*-, *hobby*- and *backyard* systems. A variety of fish species, especially ornamental fish species, can be used, which are produced primarily for the purpose of human interest (*mini-systems*, *aquarium aquaponics*) or for private home production (*hobby*, *backyard systems*, Table 1). These systems can be installed in urban areas with a high housing density. Vertical aquaponics, also represented in other categories, can be classified here as a system for private use (Fig. 2). Systems with or without soil for the plant production are possible (aquaponics *s.s.* and *s.l.*) (Table 3).

Demonstration aquaponics (Fig. 2) have been built to represent food chain use in aquaponic production systems. These include, for example, aquaponic demonstration units in school classrooms or industry workshops. Here, the principle of sustainable resource fish and plant production is explained. Demonstration aquaponic systems can be used as, for example, living walls in exhibitions or industrial buildings (Wilson 2015). Aquaponics can also be used in architecture to embellish the human environment. In this case, a commercial benefit is not striven for. The combination of aquaponics and architecture in the artistic sense or as a component of structures is under development. Vertical aquaponics can be used here as a demonstration but without the aim of a high production output. Again, systems with or without soil for the plant production are possible (aquaponics *s.s.* and *s.l.*).

Commercial aquaponic systems, including small-scale to semi-commercial (> 50–≤ 100 m^2), urban gardening, roof aquaponics, living towers and vertical aquaponics, have a wide range of applications. Systems with or without substrate or soil for the plant production are possible (aquaponics *s.s.* and *s.l.*) (Fig. 2). Intermediate-scale (between 100 and 500 m^2) and especially large-scale (> 500 m^2 up to several ha) commercial operations clearly show the trend towards industrialized production (Table 2), with a high degree of mechanization. There are attempts to combine commercial hydroponic plant production with effluents and nutrients originating from aquaculture. If the plant production under the hydroponic principle utilizes more than 50% of the plant required nutrients for optimal growth from the aquaculture unit (according to the definition either from effluent waters or from other wastes), the entire production still falls under aquaponics (*s.s.*). On the other hand, the direct application of aquaculture-derived nutrients for plant and crop production in substrate or soil is also possible (aquaponic farming). Brod et al. (2017) applied dried fish sludge on agricultural land and achieved a relative agronomic efficiency compared with mineral fertilizer of 50-80%. Below the threshold of 50%, production can still considered to be following the aquaponic concept towards a circular flow economy; however, the products result from biotechnology, hydroponics, horticulture or agriculture (Table 3).

Thus, according to the presented nomenclature, all forms of aquaponics unite the use of more than 50% of nutrients from fish effluents for optimal plant growth, either directly from the effluents or through recovery from the solid waste. Consequently, in aquaponics, any form of plant cultivation is possible irrespective of the technical design of the hydroponic unit. We are aware that a minimum level of nutrient reuse requires new methods to identify this threshold. We therefore suggest that to distinguish aquaponics from regular farming, the nutrients from the aquaculture effluents or other wastes allow 50% of the intended yield obtained through regular farming practices of the respective crop (relative agronomic efficiency according to Brod et al. 2017), either solely under hydroponics (aquaponics *s.s.*) or with the use of substrates (aquaponic farming). This assures the public and customers that the product is from aquaponics and not from regular hydroponics or other farming systems. The posited nomenclature applies to all forms of integrated aquaculture and plant systems where the fish rearing and plant production units do not fall under freshwater or marine fisheries. When applying this nomenclature, all forms of aquaponics can be unequivocally placed (see Fig. 2, Table 3), independent from the cultivated organisms or the scales of production.

Future developments and research needs

Aquaponics can be considered a contemporary and ecologically sustainable agricultural production system that supports the development of a recycling economy. It can be integrated into the existing value chains, either coming from the aquaculture or the plant production side. However, a successful transfer of the often smaller sized systems into commercial applications requires a wide range of skills and research needs.

There are many different aquaponic systems in use (Tables 1 and 2, Figs. 3, 4, and 5). Whilst the system components may vary according to scale, the functions and applications remain more or less constant, around the world. However, climatic factors can and will determine the types of fish and vegetables grown as well as the general construction. Thus, for example, it is unlikely that Arctic char (*Salvelinus alpinus*) or trout will be grown in the Caribbean as it is too hot and it would be too costly to keep water and air temperatures low. The climate will influence the arrangement of system components, for example, shading or cooling under intensive natural light conditions or the requirement for indoor production in the temperate climate zone of the northern hemisphere with different plant yields throughout the year (e.g. Knaus and Palm 2017a, b). Advantages have been demonstrated in aquaponic facilities with a relatively stable climate and optimum temperatures for fish and plant production, such as those found in the Caribbean Virgin Islands (Rakocy 1989) or in the Canary Islands (Spain). In the US Virgin Islands, the plants are grown outdoors in direct sunlight, whilst the fish are located under shade structures. In the northern hemisphere, systems need protection in greenhouses especially during the cold winter months, where with heating and lighting production occur the whole year round. However, greenhouses in warmer Mediterranean areas will require cooling during the hotter months. This variability demonstrates that the location of the aquaponic system is of tremendous importance, generalizations and comparisons are difficult to make, and the sustainability of the commercial systems depends on local adaptations and preconditions.

One of the key current debates in aquaponics centres around coupled and decoupled systems. However, both stand alongside each other, because they rely on different production principles and also target different markets (Tables 1 and 2). Consequently, they have different research needs and problems to be addressed. Coupled systems (often single pump or single-loop systems) require relatively stable conditions for fish and plant production and are often technologically limited due to their smaller size and lower investment costs. Their future development lies in the numerous small-scale to medium-sized semi-commercial ventures, driven by the increasing demand for locally and regionally produced healthy and sustainable food products where there may be limited water supply and space and where investment costs need to be low. In these systems, an optimum selection of fish, polyponics (in the sense of Knaus and Palm 2017b) and plant species (also intercropping) is necessary to be sustainable, where the chemo-physical characteristics and nutrient dynamics are balanced. However, due to nutrient constraints, up-scaling of such systems seems to be limited to a certain size.

Decoupled aquaponic systems (several pumps or multiple-bypass/loop systems) may be considered as a variation of horticulture, where the plants are the main focus and where the nutrient fish water is enhanced to provide the optimal nutrient conditions and leading to high growth rates (Delaide et al. 2016). Because the RAS systems, also in the form of integrated multitrophic aquaculture (IMTA), and the hydroponic system run independent and require different optimal water conditions (e.g. pH), decoupled large-scale commercial operations require higher investment costs and water monitoring as this is in two systems. The commercial running of decoupled systems needs to be a focus of future investigations. However, because these systems also could function solely as horticulture in cases in which not enough effluent water or fish waste can be provided through the aquaculture unit, public surveillance and control of these systems (over 50% of the nutrients originate from the aquatic organisms) is required in order to distinguish and market the products from aquaponic (*s.s.*, *s.l.*) production.

Aquaponic farming combines aquaculture with the farming of plants and crops in substrate or soil. There is so far no research carried out on how to measure the influence of the aquaponic waste onto the plant performance in comparison to regular farming practices. This is urgently needed in future research. Within coupled systems, nutrient remineralization processes and the impact of the RAS water on plant growth, including the possibly central position responsible microorganisms, are not yet understood and need urgent consideration. They are already known to play an important role in the ammonium cycle. Promising studies have shown plant productivity in aquaponics as high as in hydroponics despite lower concentrations in NPK. Such phenomena could be attributed to beneficial micro-organisms for plant nutrition. They also might play also an important role in natural control of plant pathogens.

Additionally there are numerous areas which also require research and development. It is evident that fish species that allow high stocking densities will be especially important, necessitating efficient management of nutrient flow and solid removal. Because solid removal is decisive for the water quality, fish welfare and nutrient availability in coupled and decoupled aquaponics (*s.s.*) as well as for aquaponics (*s.l.*) farming, new technologies might support the better reuse of aquaculture wastes. Other important issues to be addresses are pest control and the effects of different feed and nutrients on plant and fish health and product quality. Still the future development of these systems towards commercial systems depends on market acceptance, future retail prices and the ability of the systems and management to be adapted to a wide range of different local conditions.

Future developments include special aquaponic systems, such as vertical aquaponics, urban gardening and roof aquaponics, living walls and living towers (Fig. 2). There is great speculation and vision of what our future cities will look like and be able to produce, and in this respect, much more work is required to integrate aquaponics as part and parcel of these visions. Whilst today, research is focused on vertical aquaponics and living walls as special components, these are most likely to become part of integrated systems which are combined into our smart city environments. Much work has yet to be done in integrating water harvesting and management, water re-use, energy supply and waste management. It is important to stress that this is likely to be part of the future, where continuous supply is managed sustainably to meet increasing market demands especially as cities grow. In order to achieve this, there needs to be considerable research in the set-up and design of vertical aquaponics, with particular interests in plant cultivation substrates and the technical possibilities, e.g. rotating growing systems which orient to sunlight.

Conclusions

Aquaponics is coming of age. This can be readily seen in the rapid growth in small scale and larger practice as it is in research. This paper has been written in response to this maturation as it is crucial to take stock of the different types of aquaponic systems especially for those about to plunge into the field and in particular those considering entering into commercial scale aquaponic production and farming.

Aquaponic systems vary considerably in scale and sophistication which are usually related. It is possible to distinguish between main categories: 'open pond aquaponics', 'domestic aquaponics', 'demonstration aquaponics' and 'commercial aquaponics (intermediate or large-scale)'. Of all the systems, open pond aquaponics' strongly contrasts to the other systems, as they are relatively simple and usually open to the elements. All other aquaponic systems utilize components, derived from conventional intensive aquaculture systems (RAS) and techniques of soilless plant cultivation (hydroponics). As aquaponic systems increase in size and production areas towards commercial systems, technology increases and becomes more complicated especially due to the need for using and treating the aquaculture waste. The attitude and cultivation principles of the aquaculture unit and hydroponics unit differ in their intensive use. This requires adaptation of the simple media-bed substrate systems on domestic aquaponics to NFT or ebb-and-flow tables on large-scale systems, and the development of coupled into decoupled systems. However, both are meant for different purposes, allow decentral production of highly valuable and sustainable food and nowadays find representatives in commercial aquaponics.

This paper has illustrated the breadth of aquaponic types, which includes those that incorporate traditional hydroponic plant production systems such as NFT, DWC (raft), table substrate ebb and flow and drip systems as well as aeroponics and the incorporation of vertical systems. The largest systems (large-scale) mostly use DWC (raft) or NFT-growing systems as using gravel increases maintenance and labour costs. The main principle of aquaponics is that water from the aquatic organisms is used to grow the plants. However, we maintain that aquaponics requires that more than 50% of the nutrients for plant growth (agronomic efficiency), either from the process waters or from the solids removal, originates from culture of fish or other aquatic organisms. We, the authors of the paper and the members of COST Action FA1305, 'The EU Aquaponics Hub', propose the following definition of aquaponics as follows:

> '*Aquaponics is a production system of aquatic organisms and plants where the majority (> 50%) of nutrients sustaining the optimal plant growth derives from waste originating from feeding the aquatic organisms*'.

According to this new nomenclature, aquaponics in the narrower sense (aquaponics (*s.s.*) or sensu *stricto*) is restricted to the hydroponic principle without the use of soil or substrates such as sand or gravel. Below the threshold of 50% nutrient use, a production still can be considered following the aquaponic concept towards a circular flow economy; however, the products still originate from conventional biotechnology, hydroponics, horticulture or agriculture. Finally, we also propose that according to this nomenclature, aquaponic systems that are combined with the conventional substrate or soil cultivation of crops are also possible, contrary to earlier definitions of aquaponics, and should be termed '*aquaponic farming*' (aquaponics (*s.l.*) or sensu *lato*) as the produce is as 'natural' as horticulture or field grown crops. This is of relevance also for larger commercial scales where products are marketed and produced for wider sale. With the suggested nomenclature, all aquaponic categories from '*open pond aquaponics*' to large-scale commercial systems are covered because of the clear origin of the process water or solid waste originating nutrients from farming aquatic organisms.

As aquaponics starts to become better known and produce is being sold in larger quantities, the consumer needs to know that aquaponic farm sourced produce is safe, healthy and that it can be considered organic if grown with organic fish feed and with no added non-natural chemicals, unlike large-scale hydroponic produce which is mostly grown with non-organic nutrient solutions. Aquaponic farming has to be much more sensitive in terms of plant crop protection as additives can affect the fish, and thus, plant problems are treated organically without harming the aquatic organisms. The consumer is about to be confronted with the choice of purchasing produce, say lettuce or tomatoes, grown/farmed in soil, grown/farmed organically in soil, grown hydroponically and grown/farmed aquaponically. The consumer needs to know that aquaponic vegetables and fish are grown using a sustainable method with only natural inputs and are unlike hydroponically grown vegetables which usually use inorganic nutrients. As noted, commercial-scale aquaponics requires a different level of technology and operation to function successfully, but it also needs for the public to understand that aquaponic produce exists in order to be healthy food that is more sustainable and environmentally friendly.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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