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Prospect of Aquaponics for the Sustainable Development of Food Production in Urban

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Aquaponics refers to a system that combines aquaculture (raising aquatic animals like fish) with hydroponics (cultivating vegetable plants in water) in a symbiotic environment. This system has great potential as a new industrialised food production approach to meet the needs of rapid urbanisation. An evolutional food production system with high productivity and low resource consumption is desirable. Aquaponics is designed based on excellent ecology recycling system, i.e. the food residues and metabolic products in the effluent of aquaculture are pollutants to the environment; they are also the source of nutrients that can be converted and mineralised via microbial treatment and eventually up taken by plants in the hydroponics section. The effluent of hydroponics section is then recycled as clean water for the aquaculture section. Home-based aquaponics (HA), factory-based aquaponics (FA) and building-based aquaponics (BA) are the typical forms of aquaponics for different urban development. The sustainability of aquaponics practices is evaluated using the “triple-bottomline” approach, which requires assessment of impacts on environmental, economic and societal systems. There is a lack of systematic research and modelling work reported on aquaponics, especially in terms of ecological manipulation. Understanding the conversion of the pollutants in the combined system is essential to achieve the optimal manipulation of ecology for optimal system operation. Future work will focus on the production of pollutants in aquaculture, the conversion and degradation of the pollutants in the microbial treatment section, and uptake of organic nutrients and inorganic salts in the hydroponics section. Development of a model, capable of describing the release of pollutants, conversion and uptake of nutrients and the production of metabolic products, is desirable. The model could be developed based on the mass balance of nutrition, productivity of fish and plants and the environmental factors. The aquaponics system could be simulated and analysed using this model so as to provide an optimal system for the design and implementation of different type of aquaponics.

1. Introduction

Global food production faces great challenges in the future due to the growing population, decreasing arable land, risks of contamination of soil, water and air, and extreme weather caused by climate change (Eigenbrod and Gruda, 2015). Today, over 50 % of the world population live in cities. Increased urbanisation causes a shift in the demand for food in cities. More people prefer fresh vegetables, fruits and white meat such as fish and shrimp, rather than red meat and grains. Food production infrastructure will be more productive and sustainable in the future. Sustainable urban food production needs to address environmental challenges, fulfil societal needs and provide economic welfare (Eigenbrod and Gruda, 2015).
Aquaculture could significantly enhance the supply of food products in the future (Little et al., 2016). In 2014, the total world production by all fisheries was 158 Mt, 44.1 % of that produced by aquaculture (FAO, 2016). About 60 % of these aquaculture activities occurred in freshwater systems; 88 % of all aquaculture products

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were produced in Asia, including 62 % in China (FAO, 2016). Rapid global expansion of the aquaculture industry has caused many environmental issues, such as water pollution (Edwards, 2015), ecosystem degradation (Ottinger et al., 2016), and disease outbreaks (Liu et al., 2017), suggesting that this expansion may not be sustainable (Li et al., 2011). In this case, recirculating aquaculture system (RAS) attract concern and will be well developed in the future.

Urban agriculture represents an opportunity for improving food supply, health conditions, local economy, social integration, and environmental sustainability (Orsini et al. 2013). Vegetable production is the most significant component of urban food production which contributes to global food security. Soilless systems are especially suitable for urban areas due to their light weight and their sustainability in terms of resource efficiency. In hydroponic systems (a subset of soilless culture), vegetables are grown in water that contains minerals and nutrients needed by the plants. This makes an exact dosage and application of nutrients possible. It has potential for year-round production if controlled. High volumes of food are produced in a small space. The main disadvantage of hydroponics is that the production highly depends on costly manufactured/mined fertilisers.

Based on the development of aquaculture (especially RAS) and hydroponics, aquaponics is proposed and has been developed for several decades. It shows a promising prospect for sustainable development of food production in urban. Aquaponics is an environmentally friendly, natural food-growing method that harnesses the best attributes of aquaculture and hydroponics without the need of discard any water or filtrates and avoid the use of chemical fertilisers. It has the potential for higher yields of produce and protein with less demand on labour, land, chemicals and water usage. Being a controlled system, it combines a high level of biosecurity with a low risk of disease and external contamination, without the need for fertilisers and pesticides. It is potentially a useful tool for overcoming some of the challenges of traditional agriculture including freshwater shortages, climate change and soil degradation. Aquaponics works well in places where the soil is poor, and water is scarce, for example, in urban areas, arid climates and low-lying islands.

In this paper, the concept and the state-of-the-arts of aquaponics are introduced. Three kinds of aquaponics are proposed for the future development. The sustainability assessment for aquaponics is summarised. The future research directions for aquaponics are also proposed.

2. Concept of Aquaponics

Aquaponics is a symbiotic integration of two mature food production disciplines: (i) aquaculture, the practice of fish farming; and (ii) hydroponics, the cultivation of plants in water without soil. Aquaponics combines the two within a closed recirculating system (Thorarinsdottir, 2015). An aquaponics system filters the nutrient-rich effluent through an inert substrate containing plants. Bacteria metabolise the fish waste, and plants assimilate the resulting nutrients, with the purified water then returning to the fish tanks. The result is the value-added products such as fish and vegetables as well as lower nutrient pollution into watersheds (Figure 1).

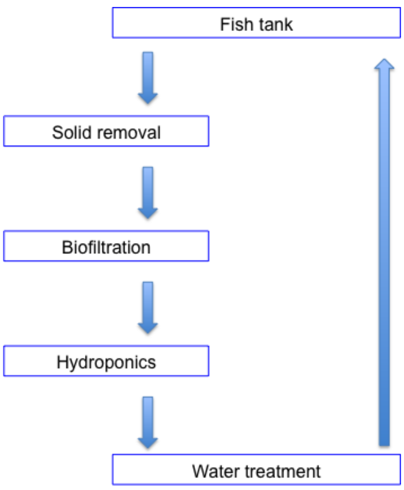

Figure 1: Diagram of water cycle in aquaponics system

Aquaculture is defined as “the cultivation of aquatic animals and plants, especially fish, shellfish and seaweed, in natural or controlled marine or fresh water environment” (Thorarinsdottir, 2015). Traditional aquaculture operations are generally classified as extensive, semi-intensive, or intensive according to the species stocking density and amount of feed applied to the system. The most recent development in aquaculture is the recirculating aquaculture system (RAS), which is a technique where fish are raised, in large, densely stocked tanks (not natural bodies of water). Stocking densities as high as one pound of fish per gallon of water has been successfully achieved. RAS is capital intensive, energy intensive and risky. The main disadvantages of RAS are the risk from the high packing densities and the need for oxygen-rich water. The aeration depends on the system powered with electricity. Lack of oxygen in less than one hour due to the power fail will result in millions of fish killed. The other disadvantage of RAS is the amount of fish waste produced, and the waste disposal. Fish produce waste through their respiration process, mostly in the form of ammonia. They also produce solid waste through their digestive process. Another source of waste is the excess and uneaten food that sinks to the bottom of a fish tank. All wastes are harmful by-products and can be removed from the fish tanks by filtration methods (mechanical, chemical and biological) (Thorarinsdottir, 2015).

Hydroponics is a method for cultivating plants without soil, using only water and chemical nutrients (Thorarinsdottir, 2015). Most of the greenhouse tomato, basil and lettuce production in North America employs hydroponic growing techniques. Four common aquaponics systems are media filled, flood and drain, nutrient film technique, and floating raft systems. Media filled systems use a media in which plant roots are grown. Fish waste is collected in the medium and is processed by the bacteria present in it. The need for a biofilter and separate settling tank can be avoided. In the flood and drain system, plant roots are soaked in a concentrated nutrient solution until the solution has been drained. This procedure can be repeated several times a day to supply the plants with the necessary nutrients. This system does not require a medium for the roots. Nutrient film technique relies on the plant roots being exposed to a thin sheet of nutrient water, which runs through a pipe. This technique relies on the need for the water to reach the bottom layer of the roots. The remaining layer of the roots is portioned off to allow for a sufficient oxygen supply. In this system, the biofilter becomes critical as there is no medium for bacteria to be sustained. In floating raft system, the plants are grown on floating rafts, most commonly made of styrofoam. The plants are suspended by nets, and the roots are allowed to extend into the water. In this system, the nutrients tend to become less concentrated and therefore higher feeding rates for the fish are needed. The water still needs to be circulated, and a biofilter may be required (Thorarinsdottir, 2015).

Compared with aquaculture and hydroponics, aquaponics exhibits the improvement in the following aspects: (1) expensive chemical nutrients are replaced by less expensive fish feeds; (2) water in hydroponics systems needs to be discharged periodically, as the salt and chemicals build up to levels that have become toxic to the plants. In the aquaponics system, a natural nitrogen balance can be achieved without the need to replace water (water is added due to the evaporation from leaves); (3) easy to maintain an aquaponics system; (4) aquaponics are more productive; (5) aquaponics are organic due to the natural ecosystem.

3. State-of-the-art of aquaponics

In the last century, aquaponics began in areas that are limited in fresh water (such as Australia) and other arid regions (such as the US Virgin Islands) with the growing population and increasing demand for food. The movement in Australian initially focused on small-scale food production and that in the University of the Virgin Island on the commercial levels of production to create a viable industry (Thorarinsdottir, 2015).

The aquaponics research led by Dr. Jim Rakocy at the University of the Virgin Islands (UVI) began in the late 1970´s and has been active for more than thirty years. It has a globally recognised aquaponics education program. The scientists gave the inspiring layout of several commercial systems in the US, which were also built by several growers and researchers worldwide. The aquaponics system developed at UVI is a raft hydroponic system and the aquaculture part focus is on tilapia production (Thorarinsdottir, 2015).

Aquaponic systems are being developed in many European countries (such as Spain, Italy, Denmark, German, Iceland, Norway, Switzerland and Slovenia). Most of them are small hobby or research units. In recent years a few semi-commercial pilot units have been put to the tests, which provide excellent information for the future developments (Thorarinsdottir, 2015).

Three kinds of aquaponics, i.e., the home-based, factory-based and building-based aquaponics system are proposed to be developed for the future food production in the urban area.

3.1 Home-based aquaponics (HA)

Home-based (or backyard) aquaponics (HA) is the small scale and self-sufficiency devices that produced food products for local consumption. This type of aquaponics can be enjoyed by many people as a hobby and an opportunity to spend time (just like home gardening). HA is much suitable for schools, hospitals, hotels, prisons, supermarkets, and shopping malls as ideal settings. In the developing countries, self-sufficiency through HA can be vital for a family's survival. In the developed countries, HA is also decrease the risk of obesity and unhealthy diets due to both the quantity and the quality of protein, fruit and vegetable uptake were increased significantly by home activities (Somerville et al., 2014).

3.2 Factory-based aquaponics (FA)

Factory-based aquaponics (FA) is an industrial (large-scale) food production system that is intended for international trade and subject to the regulations of the receiving market. Either fresh water aquaponics or seawater aquaponics can be developed as FA mode. Seawater aquaponics may exhibit more economic benefits for seafood production and the low-salinity or high-salinity marine plants are used (Waller et al., 2015). Energy efficiency of cultivation facilities is a very important parameter for the success, and food productivity is also another parameter to evaluate cost-effectiveness. The FA could reduce operational costs by increasing fish productivity and harvest of vegetables. To date, the largest factory aquaponics system reported is only 6,000 m^2 that was established in Spain, producing up to 125 t of tilapia, 15 t of tomatoes, 6 t of strawberries and up to 50,000 salads per year (Thorarinsdottir, 2015).

3.3 Building-based aquaponics (BA)

Building-based aquaponics (BA) is a medium-scale infrastructure. The idea behind BA is from the innovative forms of green urban architecture that aim to combine food, architecture, production, and design to produce food on buildings in urban areas (Specht et al. 2014). BA may increase food production by exploiting new locations for cultivation. The BA concept is to integrate food production (fish and vegetable) into existing building infrastructures in order to save resources and achieve high resource efficiency (Specht et al. 2014). BA is to create entities linking food production and buildings with multiple uses of waste resources (e.g., waste water, waste heat, organic waste) to establish a resource saving system. BA systems use the combined effort of agricultural production and buildings and create an integrated whole within the protected environment of a building (Specht et al. 2014), including the integration of greenhouses into urban buildings and the vertical farming with buildings for food production purposes. Building-based aquaponics (BA) will be promising to be a new green urban architecture in the future. It should be pointed out that BA is still a futuristic type of aquaponics, which is of great complexity to combine with the future building system.

4. Sustainability assessment for aquaponics

In the future, aquaponics has the potential to support economic development and enhance food security and nutrition through efficient resource use and become an additional means of addressing the global challenge of food supply. However, commercial aquaponics is not appropriate in all locations, and many start-ups have failed. Before investing in large-scale systems, operators need to consider all factors carefully, especially the availability and affordability of inputs (i.e. fish feed, building and plumbing supplies), the cost and reliability of electricity, and access to a significant market willing to pay premium prices for locally produced, pesticide-free vegetables. Aquaponics combines the risks of both aquaculture and hydroponics, and thus expert assessment and consultation are essential (Goddek et al., 2015).
The preliminary qualitative comparison of the three kinds of aquaponics system was summarised in Table 1. The sustainability of aquaponics practices is evaluated using the “triple-bottomline” approach, which requires assessment of impacts on environmental, economic and societal systems (Pusnik et al. 2014). As a whole, these three aspects were summarised as follows.

Table 1: Qualitative comparison of the three kinds of aquaponics system

Types	Initial costs	Annual costs	Fish production	Vegetable production	Environmental benefits	Social benefits	Economic benefits
HA	Low	Low	Low	Low	Low	High	Low
FA	High	High	High	High	Medium	High	High
BA	High	High	Medium	Medium	High	High	Medium

4.1 Environmental Impacts

Aquaponics is expected to provide several potential benefits for environment, such as eco-effective architecture and urban landscapes, reducing food miles and transport emissions, use and recycling of water resources, energy consumption and production, recycling of organic waste, new landscape opportunities etc. at the same time. However, some limitations for the environmental impacts may be considered for future research and development, including technical constraints, lack of experience and bias in food system research etc. Some researchers considered that small scales of aquaponics have potential to be highly sustainable, while larger scales are more likely to create adverse impacts, such as high use of fossil fuels, additives and medicaments; degraded water quality and habitat destruction; and fish disease. The initial capital investment of aquaponics is large, and so they may not be feasible for producers in the developing countries (Specht et al. 2014).

4.2 Social Impacts

Aquaponics has the potential to provide learning and education facilities for children and adult city-dwellers and help bridge the gap between consumers and producers. The social potentials show the following aspects: (1) improving community food security; (2) provision of educational facilities; (3) as a design inspiration; (4) providing a source of relatively cheap protein; (5) important to low-income individuals in both developing and developed nations; (6) better working condition. Meanwhile, the limitations for social impacts are as follows: (1) lack of acceptance of soil-less growing techniques; (2) exclusionary practices and disparities; (3) food quality and health risks; and (4) the mental health implications for workers (Specht et al. 2014).

4.3 Economic Impacts

In terms of potential economic advantages, bringing food production to urban areas is supposed to bring public benefits and commodity outputs, which are as follows: (1) urban food production as an economic advantage for urban areas; (2) potential products and yields; (3) allows for the utilisation of unemployed labour and land; (4) using the waste stream of an aquaponics system to create biogas by anaerobic digestion to power a natural gas to provide for the total energy needs of an aquaponics system. There are also unanswered economic questions in the field of investment and financing. At this early stage of development, investment costs are too high and economic feasibility has not been exhaustively investigated, while secondary benefits are difficult to quantify. The physical capacities of only a small number of cities have been investigated and the results are not transferable (Specht et al. 2014).

5. Future research direction for aquaponics

It is important that architects, city planners, biologists, economists, engineers, and environmental scientists work closely with horticulturists in the future. To date, neither systematic research results nor modelling about the aquaponics, especially in terms of ecological manipulation. Understanding the conversion of the pollutants in the combined system is essential to achieve optimal manipulation of ecology for system operation.

The future work will focus on the production of pollutants in the aquaculture section, the conversion and degradation of the pollutants in the microbial treatment section, uptake and adsorption of organic nutrients and inorganic salts in the hydroponics section (Figure 2). A model, capable of describing the release of pollutants, conversion and up taking of nutrients and the production of metabolic products is significant based on the mass balance of nutrition, productivity of fish and plants as well as environmental factors, is desirable. The aquaponics system will be simulated and analysed using this model and will facilitate excellent design and implementation.

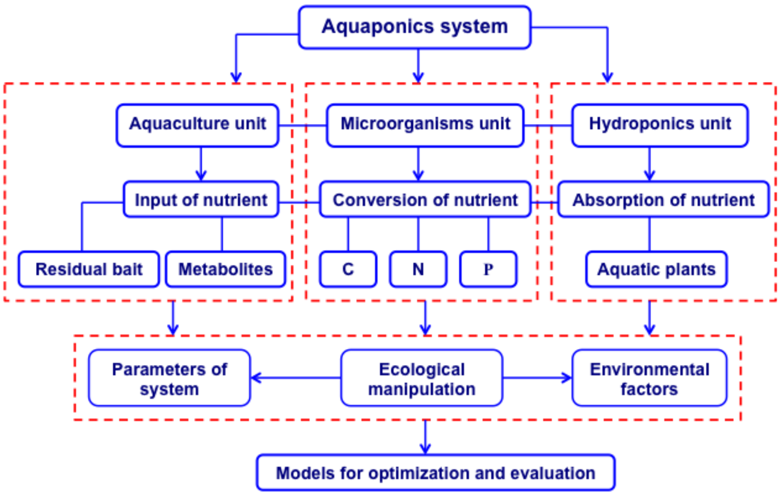

Figure 2: Framework for the future research of aquaponics system

6. Conclusions

Aquaponics exhibits the prospect for the sustainable development of food production in urban. It can serve as an essential element of sustainable urban infrastructure in the smart city. Home-based aquaponics (HA), factory-based aquaponics (FA) and building-based aquaponics (BA) are the typical forms of aquaponics for different urban development. Aquaponics have a high potential to fulfil all three sustainable criteria, namely environmental, social, and economic aspects. Impact assessments on these three aspects are anticipated. It is still a rather new concept for food production.

Future work will focus on the system modelling for the input of the nutrient in the aquaculture section, the conversion and degradation of the pollutants in the microbial treatment section, organic nutrients and inorganic salts uptakes in the hydroponics section. The relevant model is significant for the optimisation and design of different aquaponics system.

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