IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

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To cite this article: A Rizal *et al* 2018 *IOP Conf. Ser.: Earth Environ. Sci.* **137** 012098

IOP Conf. Series: Earth and Environmental Science **137** (2018) 012098 doi:10.1088/1755-1315/137/1/012098

The economic and social benefits of an aquaponic system for the integrated production of fish and water plants

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Abstract. Aquaponics is an evolving closed-system food production technology that integrates recirculating aquaculture with hydroponics. In this paper we give a brief literature overview of the benefit aspects of aquaponics by discussing its social, environmental, and economic impacts in different potential settings. The technology might be applied to commercial or community based urban food production, industrial scale production in rural areas, small scale farming in developing countries or as systems for education and decoration inside buildings. We concluded that due to the different potential applications and settings for installing the technology, benefit impacts need to be considered separately and that due the complexity, communities, urban and rural infrastructure and policy settings, further research and data acquisition is needed to be able to assess all benefit aspects.

1. Introduction

The lack of arable land area and degradation with water scarcity are some of the the current problems of agricultural production, especially in the most under developed areas with a scarcity of resources. This should make us re-evaluate the way in which food is produced. The consumer demand for fish has been increasing, but ocean fish catches continue to decline. Aquaculture, the cultivation of freshwater and marine plants and animals, is one of the fastest growing segments of Indonesian agriculture. The increase of farm-raised fish has lead to increased concern regarding discharges from those facilities.

Therefore, the treatment of fishery effluents needs to be considered when planning aquacultural production systems. However, it may be important to treat the nutrients in aquaculture effluents because the total nutrient mass loading can contribute significantly to environmental degradation, depending on the quality of receiving water. According to the current discourse, this involves an increase in productivity and resource use efficiency, solutions for small holder farmers, as well as a reduction in food waste [1].

Land-based recycle aquaculture facilities release dissolved nitrogen and phosphorus to the water environment, which contributes to the undesirable growth of macro and micro algae in the receiving waters. In land-based fish culture, water quality can be controlled by a high rate of either water exchange, which is costly; or water treatment and subsequent recirculation, which comes at a price. To offset treatment costs, the integration of aquaculture and plants offers an ideal solution to reduce nutrient discharge levels, increase profitability, and convert the excretion of fish culture into beneficial

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products. Aquaculture as a business requires a stable run of the cultivation system, maintaining all environmental factors under control. Aquaponics is a relatively new concept to modern food production methods and can provide answers to many of the above-mentioned problems.

Aquaponics, the combined culture of fish and plants in recirculating systems, has become increasingly popular. Aquaponic systems offer several benefits. Dissolved waste nutrients are recovered by the plants, reducing discharge to the environment and extending water use (i.e., by removing dissolved nutrients through plant uptake, the water exchange rate can be reduced). Minimizing water exchange reduces the costs of operating aquaponic systems in arid climates and heated greenhouses where water or heated water is a significant expense. Having a secondary plant crop that receives most of its required nutrients at no cost improves a system's profit potential. The daily application of fish feed provides a steady supply of nutrients to plants and thereby eliminates the need to discharge and replace depleted nutrient solutions or adjust nutrient solutions as in the case of hydroponics.

In this article we would like to illustrate this complexity by using the example of aquaponics as a rapidly emerging technology that integrates recirculating aquaculture with hydroponics (production of plants in nutrient solution, without soil) [2, 3, 4, 5, 6], having its origins back in the 1970's [7, 8]. Aquaponic food production is highly efficient, because it re-uses the nutrients contained in fish feed and fish feces to grow the crop plants in an ecological cycle [9].

Essential technical components of aquaponic systems are the fish tanks and plant growth beds, while dedicated biofilters and settlers are optional and depend on the configuration of the system. The microbial community is central for the catabolism of the organic matter contained in the feces and feed residues and for the conversion of the fish-generated ammonia to nitrate [10, 11]. Fully contained and climate-controlled aquaponic systems potentially operate under water conserving and contaminant-free conditions.

At its highest level, aquaponics is a technology-intensive, capital-intensive and knowledge-intensive method of food production that is discerned based on definitions such as horizontal *vs.* vertical, and open *vs.* recirculating [12]. Systems are characterized according to the way plants are supplied with nutrient solutions in the hydroponic systems, e.g., floating polystyrene foam sheets (floating raft), nutrient film technique (NFT), or media filled growth beds arranged horizontally or vertically, while fish are kept in standard recirculating aquaculture conditions. Aquaponic technology is considered to be ecologically friendly: it uses nonrenewable resources with a very high efficacy as indicated by near zero-waste discharge [12].

In addition to its value as a food production system, smaller aquaponic units can be great assets as teaching tools for a wide range of subjects [13], demonstrating ecological cycles and may serve as decorative elements in homes or public places. Moreover, the principle of combining fish and crop production can be implemented from a low-tech level to a high-tech state-of-art system [14].

Although the basic arrangement of an aquaponic system is apparently simple, involving only three kinds of living organisms: fish, beneficial bacteria, and plants, the interrelations between the three are highly complex and interdependent [15]. In addition, the system inherently contains a toxic component: ammonia excreted by the fish [11]. The somewhat contrasting requirements of fish, plants, and bacteria makes it difficult to achieve maximum yield potentials [10]. More research is needed to manage the cycling of nutrients (especially nitrogen and phosphorus), and pH levels so that aquaponics can be economically viable, which will also affect its overall sustainability (e.g. the ASTAF-PRO approach by [10]).

The food produced by aquaponics are fish and plants: the healthiest human diet according to current nutritional science [12]. Recent publications on the sustainability of aquaponics give a broad perspective on the technology, and conclude that these systems can be sustainably managed only with a thorough knowledge of the fish, bacteria, and plant components on both an individual and systems level [6, 10, 12, 15, 16, 17, 18,]. These authors indicate the problems with waste from the nitrogen cycle (e.g., the toxicity of ammonium) and the advantages of higher yields and reduced water use, and suggest avenues for future research, such as the integration of nutrient flows (availability of key macro and micronutrients), the need for technological advancements and fish feed alternatives. Unfortunately, other important benefit issues are often neglected such as resource scarcity, climate change and social aspects. We argue that the lack of reliable data and documented practice is the main knowledge gap to assess the benefit of aquaponics.

Benefit assessment of a new technology is a complex and data-intensive exercise, because in addition to the material and energy considerations, various environmental, societal and social factors have to be taken into account [19, 20, 21, 22]. As a result of the lack of data, most publications look at partial aspects of benefit and do not consider all "three pillars" – ecological, economic and social. Due to the numerous interdependencies within the technology and various application settings, the societal and social aspects are difficult to quantify [12]. As for other technologies, benefit assessment is typically a mixture of potential outcomes rather than a pure black or white answer, i.e., the use of the technology under different developmental, human, and climatic conditions will lead to different benefit scenarios.

The benefit analysis of complex systems includes manifold approaches focused on different levels (technology, enterprise, business model types, value chains, target groups, etc.) and different, sometimes multilayered sets of indicators and factors [23, 24]. For example, in terms of agricultural technologies, the comprehensive review of [24] lists 18 economic, 51 environmental, 21 social, and 14 technical indicators. Since aquaponics is still developing rapidly, we lack clear definitions, classifications and demarcations towards similar technologies. With regard to social aspects, there is ongoing discussion about how to qualitatively and quantitatively conceptualize and measure all aspects in indicators. The available impact assessment methodologies do not address the full range of specific activities and impacts of food systems and technologies, as discussed in a review for aquaculture [25].

Assessments are mainly ex-post, while in the case of aquaponic technology development ex-ante methods are needed. In the following paragraphs we briefly discuss the challenges of benefit assessments in three fields of application: urban agriculture, developing world aquaponics and industrial scale aquaponics. Based on a literature review we will consider questions regarding the economic, environmental and social benefist, depending on the potential setting where aquaponics is implemented.

2. Social Benefit

Aquaponics has already been used extensively in the education in natural sciences at the primary and secondary school levels and also in vocational training [26, 27]. However, little has been done to assess the social aspects (health, wellbeing, learning of education and demonstration projects [26]. There are still problems regarding technical and school settings that need to be overcome before claiming that aquaponic units facilitate education in benefit [28]. Another social aspect with good potential is community cohesion. However, the setup of such systems will be different to those for commercial urban or industrial production, so the benefit assessment would be different. There is probably a trade-off between technology and knowledge input (high-tech vs. low tech) on one side, and the potential for social impact on the other.

The greatest increase in worldwide human population will occur in urban areas. Food security and infrastructure will become a central issue and aquaponics may prove to be a solution. Even today, many urban areas around the world face the challenge of a food supply infrastructure (e.g. so called "food deserts") [29]. Aquaponics implemented either as professional urban agriculture or as community farming could help alleviate these food deserts. However, in urban settings, aquaponics can fulfill other functions besides food production. For example, it may serve as an educational tool in schools [26], interior greening (providing better climate in public buildings and homes), and as a unit in social institutions.

Aquaponics has the potential to be an integral part of the "blue and green" infrastructure of cities. It can be integrated into the local water cycle (using treated grey water and rainwater instead of freshwater), local energy flows (for example, the "watergy" concept [30]), and local biomass cycles (re-use of nutrients).

Aquaponic operations installed in urban areas can meet the demands of consumers and thus will attain premium prices, which in turn will allow fast return on investment [31]. We have observed that several aquaponic businesses integrate the value chain vertically e.g. adding services (such as catering, selling of equipment, system planning services), because production itself is not yet economically viable when compared to specialized horticulture or aquaculture. The development of short value chains, e.g. selling directly to consumers, restaurants or supermarkets, can also be a viable option. Approaches to food production in urban areas on a commercial scale are only the beginning; hence there is a lack of benefit information for decision makers. In the long run, there are many visions for urban areas in temperate zones that include building-based food production [32]. However, these scenarios rely on increased technological and capital intensity Hase [33] that has to be assessed in the light of the development of food prices and income. It is still unclear, however, how sustainable cities will be developed based on existing infrastructure, and how that will affect the benefit of aquaponics. To solve water problems in cities around the world, aquaponics can be incorporated into building concepts to enlarge the local water cycle Viljoen *et al*. [34] or integrated into the matrix of the city [35]. An example of integrating aquaponics into cities as a part of the blue-green structures is the Roof Water Farm concept [36]. However, we still lack quantitative data for a comprehensive benefit assessment of aquaponics in urban environments.

Aquaponics can be used to improve the livelihoods of households and communities. Fish is an important source of protein in low and medium income countries while vegetables improve nutrition [37]. Aquaponics can help to increase food security and food sovereignty [38]. However, the costs of modern aquaponic systems might exclude the poor from its potential benefits: The dependency on electricity and water might limit its use in unplanned urban sprawl and rural areas where nutrition deficits in terms of food variety and protein are most predominant [39]. However, under favorable climatic conditions (tropics and subtropics), aquaponic systems may be very simple, consisting of un-insulated outdoor units (low-tech). [39] states that very few inputs are needed for a basic unit (e.g. fingerlings and seeds). Yet these inputs are often locally limiting factors to food security. Depending on the specific conditions, aquaponics can provide a sustainable food source in low and medium income countries, especially where climate conditions are favorable.

3. Economic benefit

Today crop production and fish farming occupy vast regions of the Earth's surface and have a strong negative impact on the environment by inducing soil erosion; polluting the soil and groundwater by pesticides, fertilizers, and animal waste; the production of greenhouse gases; and in many other ways [40]. A combination of plant production and fish farming in closed aquaponic systems results in a significant reduction on the environmental impact. Aquaponic systems can be operated almost waste-free; therefore they have no measurable effects on the soil if no new area is consumed for installing aquaponics. Even the relatively small amount of waste produced (in the form of sludge) can be easily composted and converted to beneficial products.

The viability of industrial scale aquaponics depends on achieving efficient and high yield systems. Fish feed is the biggest cost factor in intense aquaculture [41]. Both the environmental and economic benefits could be improved significantly by either formulating alternative fish feeds, and/or by reducing the fish meal and fish oil in the feeds [36, 42]. Also, the contamination of feed with mycotoxins, which can originate from feed-borne ingredients or from bad storage conditions, is often overlooked, which is dangerous since they can cause many health problems to fish, reduce yield and economic benefits [43, 44].

The cost of labor and energy are the main critical factors in industrial greenhouse vegetable production. Aquaponics is a labor-intensive technology: the operation and maintenance of such systems generates employment and income, but also high labor costs, as the monitoring has to be performed daily, including weekends. The claims of nutrient and water efficient food production depends upon the extent of recycling/recirculation of the nutrients and water in the system. The water saving aspect, however, is expected to be most advantageous in areas with water scarcity [39]. In Indonesia, where water is more abundant, the discourse of benefit and alienation between consumers and producers as a result of highly specialized value chains opens economic potential for direct marketing aquaponic farms.

A basic requirement for an economically viable system is the acceptance of the products by consumers. Yet, as these fish and vegetables need to compete with conventionally grown products, the acceptance of the products by consumers remains to be studied.

4. Conclusions

Aquaponics, due to its integrative character and multiple application scenarios from high-tech to low-tech, is an atypical and complex food production technology. The complexity of the systems and their application in different settings potentially affects the delivery of all aspects of benefit: economic, environmental and social.

Our literature review demonstrates that due to the lack of data on the operation of commercial aquaponic systems in different environmental (climatic, social, and technological) conditions, a comprehensive benefit assessment is difficult. In addition, as of yet there are no reliable empirical data available on energy use, accidents, repairs, and social change pertaining to the technology. Prototypes used in research and development can only provide certain types of data, so more cooperation is needed with the few industrial operations to characterize appropriate and scalable indicators.

The challenge ahead is the simultaneous development of methodological approaches for technology-specific ex-ante and ex-post benefit assessments, while at the same time, the technology needs to spread in order to fully achieve the benefit potentials promised by the advancement of the technology. A co-development of technology, business models, and benefit data generation could contribute 1) to achieve the multiple potentials of the technology, and 2) to develop sustainable food systems from production to consumption. Benefit assessments could then enable policy makers, entrepreneurs and the general public to differentiate between food production systems with limited negative benefit externalities.

Furthermore, it would indicate processes within the system that have the highest environmental impact and thereby allow to effectively improve the environmental performance of the product under consideration. Yet, for the economic and social benefit aspects we see the need for conceptionalisation, empirical validation and operationalization and more data in order to inform the development of aquaponic technology with regard to delivering its potentials to contribute to sustainable food production.

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Acknowledgements
Thanks to Universitas Padjadjaran, Indonesia which funded the study of aquaponics, through Academic Leadership Grant program (ALG).