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AQUAPONIC CORNER

On the sustainability of aquaponics

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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 sustainability 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 conclude that due to the different potential applications and settings for installing the technology, sustainability impacts need to be considered separately and that due the complexity within markets, value chains, communities, urban and rural infrastructure and policy settings, further research and data acquisition is needed to be able to assess all sustainability aspects.

Keywords – aquaponics, food production, sustainability, aquaculture, hydroponics

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Introduction

Assuring food security in the twenty-first century within sustainable planetary boundaries requires a multi-faceted agro-ecological intensification of food production and the decoupling from unsustainable resource use. 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 (Rockstörm et al. 2013). The new approach requires increasingly complex but still sustainable agricultural technologies that can raise crop yields on limited farmland, when water is getting scarce, and with little impact on climate and biodiversity (Pearson 2007). Food production within a sustainability framework requires ideas that exceed traditional innovation paradigms, acknowledging the complexity arising from sustainability (Leach et al. 2012; McIntyre, 2009; Pretty et al., 2010). In the field of food production, however, the multiplicity of relevant components makes it difficult to assess how much a technology or innovation contributes to sustainability (Elzen et al. 2015).

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) (Rakocy et al., 2004) (McMurtry et al. 1990; Lennard and Leonard 2006; Pilinszky et al. 2015; Palm et al. 2015) having its origins back in the 1970's (e.g. Naegel 1977; Sneed et al. 1975). 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 (Love et al. 2015). Its potential to improve sustainability is discussed in terms of food security and as an alternative to intensive fisheries or aquaculture, by effectively managing the food-water-energy-nexus (Kloas et al. 2015; Tisdell 1999).

Essential technical components of aquaponic systems are the fish tanks and plant grow 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 (Kloas et al. 2015; Bittsánszky et al. 2015). 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 (Sommerville et al. 2014). 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 (Sommerville et al. 2014). Aquaponic technology is considered to be ecologically friendly: it uses nonrenewable resources with very high efficacy as indicated by near zero-waste discharge (Sommerville et al. 2014). 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 (Junge et al. 2014), demonstrating ecological cycles and may serve as decorative elements at home or in public places. Moreover, the principle of combining fish and plant production can be implemented from low-tech level (Trang and Brix 2014) to a high-tech state-of-art system.

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 these are highly complex and interdependent (Tyson et al. 2011). In addition, the system inherently contains a toxic component: ammonia excreted by the fish (Bittsánszky et al. 2015). The somewhat contrasting requirements of fish, plants, and bacteria make it difficult to achieving maximum yield potentials (Kloas et al. 2015). 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 Kloas et al. 2015).

The food produced by aquaponics is fish and plants: the healthiest human diet according to current nutritional science (Sommerville et al. 2014). Recent publications on the sustainability of aquaponics (Tyson et al. 2011; Palm et al. 2014; Palm, Wehofsky, and Knaus 2014; Palm et al. 2015; Goddek et al. 2015; Kloas et al. 2015) 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. 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 sustainability 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 sustainability of aquaponics.

Sustainability 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 (Loomis et al. 2014; Carr et al. 2007; Jerneck and Olsson 2014; Klerkx et al. 2012). As a result of the lack of data, most publications look at partial aspects of sustainability 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 (Sommerville et al. 2014). As for other technologies, sustainability 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 sustainability scenarios.

The sustainability analysis of complex systems includes manifold approaches focused on different levels (technology, enterprise, business model types, value chain, target group, etc.) and different, sometimes multilayered sets of indicators and factors (Dunmade 2002; Dunmade 2014; Kriesemer and Virchow 2012). For example, in terms of agricultural technologies, the comprehensive review of Kriesemer and Virchow (2012) lists 18 economic, 51 environmental, 21 social, and 14 technical indicators. Since aquaponics is still developing quickly, 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 (Samuel-Fitwi et al. 2012). 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 for sustainability assessments in three application fields: urban agriculture, developing world aquaponics and industrial scale aquaponics.

Based on a literature review we will consider questions regarding economic, environmental and social sustainability, depending on the potential setting where aquaponics is implemented. We will not assess the sustainability of aquaponics *per se* but illustrate the diversity and complexity for research and practice lying ahead.

Environmental and economic sustainability

Today plant production and fish farming occupy vast regions of the surface of the Earth, and have a strong negative impact on the environment by inducing soil erosion, polluting the soil and groundwater by pesticides, fertilizers, and animal waste, production of greenhouse gases, and in many other ways (Goudie and Viles 2013, and references therein). 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 valuable 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 (FAO 2007). Both environmental and economic sustainability could be improved significantly by either formulating alternative fish feeds, and/or by reducing the fish meal and fish oil in the feeds (Tacon and Metian 2013; World Bank 2013). Also, the contamination of feeds 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 of fish, reduce yield and economic sustainability (Pietsch et al. 2013; Pietsch et al. 2015).

The cost of labor and energy are the main critical factors in European industrial greenhouse vegetable production. Aquaponics is a labor-intensive technology: 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 depend 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 (Al-Hafedh et al. 2008). In Europe and North America, where water is more abundant, the discourse of sustainability 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 fish and vegetables need to compete with conventionally grown products, the acceptance of the products by consumers remains to be studied.

Social sustainability

Aquaponics is already being used extensively in education in natural sciences at the primary and secondary school levels and also in vocational training (Junge et al. 2014; Graber et al. 2014). However, little has been done to assess social aspects (health, wellbeing, learning…) of education and demonstration projects (but see Junge et al. 2014). There are still problems regarding technical and school settings that need to be overcome before claiming that aquaponic units facilitate education in sustainability (Hart et al. 2013). Another social aspect with potential is community cohesion. However, the setup of such systems will be different to those for commercial urban or industrial production, so the sustainability 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 side (Junge, manuscript in preparation).

Sustainability aspects of aquaponics in urban environments

The greatest increase in worldwide human population will occur in urban areas. Food security and infrastructure will become a central issue and aquaponics may be one solution. Already today, many urban areas around the world face the challenge of a food supply infrastructure (e.g. so called "food deserts") (Beaulac et al. 2009). Aquaponics implemented either as professional urban agriculture or as community farming could help alleviate the 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 (Junge et al. 2014), interior greening (providing better climate in public buildings and homes), and as a unit in social institutions. In Italy, for example, a psychotherapy hospital implements aquaponics in rehabilitation for people after shock (Dr. Maurizio Borin, personal communication on April 24, 2015). In Hungary, a passive house aquaponic system is used as part of the housing for autistic people (Otto Olajos, personal communication on December 11, 2015).

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 (Vadiee and Martin 2012)), and local biomass cycles (re-use of nutrients).

Aquaponic operations installed in urban areas can meet the demands of consumers and thus achieve premium prices, which in turn allow fast return on investment (Edwards 2015). We have observed that several aquaponic businesses integrate the value chain vertically e.g. add 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 produce food in urban areas on a commercial scale are only beginning, hence sustainability information for decision makers is lacking. In the long run, there are many visions for urban areas in temperate zones that include building-based food production (Caplow 2009). However, these scenarios rely on increased technological and capital intensity (Kiss et al. 2015) that has to be assessed in the light of the development 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 sustainability of aquaponics.

To solve water problems in cities around the world, aquaponics can be incorporated into building concepts to enlargen the local water cycle (Haase 2015) or integrated into the matrix of the city (Viljoen et al. 2005). An example of integrating aquaponics into cities as a part of the blue-green structures is the Roof Water Farm concept (Million et al. 2014). However, quantitative data are still lacking for a comprehensive sustainability assessment of aquaponics in urban environments.

Sustainability aspects of aquaponics in developing countries

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 and vegetables improve nutrition (Tacon and Metian 2013). Aquaponics could help to increase food security (Ericksen 2008) and the food sovereignty. 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 und rural areas where nutrition deficits in terms of food variety and protein are most predominant (Little and Buniting 2015). However, under favorable climatic conditions (tropics and subtropics), aquaponic systems may be very simple, consisting of un-insulated outdoor units (low-tech). Little und Bunting (2015) state 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.

Sustainability aspects of aquaponics at industrial food production scale

As a rule of thumb, many aquaponic professionals agree that a production unit becomes profitable when the area dedicated to vegetable growth exceeds 1000 m^2. For large scale aquaponics (>1000 m^2), fish and vegetable produce compete with standard products from horticulture and aquaculture. There are currently no recognized certification systems or legislation to recognize the positive environmental externalities of aquaponics (Joly et al. 2015). However, some brands are either striving to develop their own labels (for example Sweet Water Aquapons) or to obtain Global G.A.P. Certification (http://www.globalgap.org/uk_en/) (Andreas Graber, personal communication in February 2016).

Energy for the system (pumps, aeration) can be supplied by the grid, with a built-in generator unit based on natural gas, or using photovoltaic energy. The dependence on external energy necessitates backup generators (using fossil fuel or biofuel) or batteries storing direct current for conversion to AC (Sommerville et al. 2014). Using renewable energy with photovoltaics improves energy efficiency, but also requires emergency equipment, thereby increasing costs (Kloas et al. 2015). Alternative energy systems and management strategies for large-scale horticultural production are in the development phase (Kuntosch et al. 2015). Water efficiency can be increased by incorporating rainwater or treated greywater, which is possible in temperate climate zones (Kloas et al. 2015) or by water reclaiming in arid areas.

From a life cycle perspective, there has been little discussion about the sustainability of materials used in aquaponics. One material that could be replaced yet successfully is the non-reusable rock wool (used as standard growing medium in hydroponics), or other recyclable materials used for growing beds. Adoption of these materials has to be balanced with economic viability and feasibility.

New zero-discharge or highly efficient systems require improved management skills and may pose a greater economic risk. Efforts should be made to identify economically feasible aquaponics based on energy, water and climate management regimes (Kloas et al. 2015).

In practice, aquaponics balances environmental benefits with economic risk by appropriate technical and business model designs. The risk of economic failure due to system failure has already been analysed to some extent for recirculation aquaculture systems (RAS), indicating the need for a skilled and intensive risk management for "total" system control (e.g. Rawlinson and Forster 2000).

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 sustainability: economic, environmental and social.

Our literature review demonstrates that due to the lack of data on operating commercial aquaponic systems in different environmental (climatic, social, and technological) conditions, a comprehensive sustainability 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 lying ahead is the simultaneous development of methodological approaches for technology-specific ex-ante and ex-post sustainability assessments while at the same time, the technology needs to spread in order to fully achieve the sustainability potentials promised by the advancement of the technology.

A co-development of technology, business models, and sustainability data generation could contribute 1) to achieve the multiple potentials of the technology, and 2) to develop sustainable food systems from production to consumption. Sustainability assessments could then enable policy makers, entrepreneurs and the general public to differentiate between food production systems with limited negative sustainability externalities.

However, this process ideally should begin soon if aquaponics is to have a chance of developing into a full-fledged alternative for food production. While an establishment of a comprehensive list of indicators, analogous to the one proposed for agriculture by Kriesemer and Virchow (2012) will be very important, we propose to implement an existing tool to assess the current environmental sustainability of aquaponics: i.e., life cycle analysis (LCA). LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 2006b). We suggest that the environmental impacts of aquaponics could be analyzed using Life Cycle Assessment based on ISO 14040 and ISO 14044 (ISO 2006a; ISO 2006b). The LCA can consider emissions and resource consumption for all relevant life cycle stages. Data for the foreground system have to be provided by the investigated operation, while background data can be assessed via appropriate databases (like the international ecoinvent database v3, Ecoinvent Centre, Zürich, Switzerland). For the modeling, a suitable simulation software has to be used (like for example SimaPro v8 LCA simulation software from Pré Consultants, Amersfoort, NL).

This procedure would allow a comparison of different aquaponic systems (or their parts), operated under different environmental conditions and social settings, which would allow for valid conclusions. Furthermore, it would indicate processes within the system that have the highest environmental impact and thereby allow to effectively improving the environmental performance of the product under consideration. Yet, for the economic and social sustainability 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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