Journal of Cleaner Production 180 (2018) 232–243

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Analysis of aquaponics as an emerging technological innovation system

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ARTICLE INFO

Article history:
Received 14 June 2017
Received in revised form
4 January 2018
Accepted 7 January 2018
Available online 28 January 2018

Keywords:
Aquaponics
Aquaculture
Hydroponics
Sustainable food production
Nutrient cycles
Sustainable technologies

ABSTRACT

Aquaponics is an approach of coupling two technologies: recirculation aquaculture (fish-farms) and hydroponics (soil-less cultivation of crops). While it is perceived as a way to contribute to more sustainable food systems, the technology is still in its infancy, with several challenges. This paper describes current conditions of development and identifies aspects that can promote or hinder future pathways. We focus our analysis on the EU, using Germany as an institutional case study, while also considering worldwide developments. We propose a framework to analyze aquaponics as an emerging technological innovation system at the interface between existing fish and plant production systems. The approach is explorative based on a literature review and interviews with experts. The main findings are that stakeholders have different views regarding the future development pathways, knowledge to manage complex systems in the long term is needed and it is still unclear how to design institutional conditions to deliver sustainable outcomes.

1. Introduction

1.1. The general context for the development of aquaponics: challenges for innovative and sustainable food systems

There is general agreement that environmental, social and economic challenges drive the need for new and improved solutions for food production and consumption systems (food systems). Increasing food demands cannot be sustained by additional exploitation of natural resources and land on the production side. On the consumption side, transformations are needed to improve food security in developing countries and the healthiness and sustainability of western diets in developed nations (e.g. climate mitigating food consumption; Schuetze et al., 2008; Binz et al., 2010; Garnett, 2011; van der Goot et al., 2016; Ashley, 2016). In general, an increase in the production and consumption of fish and vegetables could be a way to improve the sustainability of food systems.

Food production within a sustainability corridor requires innovations exceeding traditional paradigms, acknowledging the complexity arising from sustainability (Leach et al., 2012; McIntyre et al., 2009; Pretty et al., 2010). However, there is a lack of strategic knowledge about how to direct further activities to develop those food production technologies while maintaining their promise of sustainability and potential solutions for urgent questions (Elzen et al., 2014).

One strategy to create more sustainable food systems is to change the way food is being processed (van der Goot et al., 2016). Another strategic approach is to change food production technologies themselves, ideally accompanied by changes in consumer behavior. Aquaponics is considered a promising example, potentially contributing to sustainability. The sustainable production of fresh fish and vegetables using intensive technological cycle systems and higher consumption is interesting for the scientific

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https://doi.org/10.1016/j.jclepro.2018.01.037

community (e.g. Junge et al., 2017), policy makers (e.g. Van Woensel and Archer, 2015) and entrepreneurs (e.g. Love et al., 2014; Joly et al., 2015).

The combined production of fish and annual plants has been practiced since ancient times.[1] Yet modern day aquaponics, combining aquaculture and soil-less vegetable production (hydroponics) is still quite new and popular as an individual hobby in Europe and worldwide (Junge et al., 2017). It began to be used in the US and EU in the 1980s, however most fish and vegetables are still produced separately via aquaculture, hydroponics or land based vegetable production, in highly specialized technical, knowledge and capital-intensive production systems and value chains.

Currently, most aquaponics applications focus on research questions in aquaculture, hydroponics, water quality, microbiology and engineering. Nevertheless, policy makers and actors involved with the technology face difficulties in extracting practical guidelines for policy and business development since there are still many open questions beyond the technical aspects of engineering, and plant and fish production (Van Woensel and Archer, 2015). Those guidelines are especially desirable in the light of the precautionary principle (EEA, 2013) and the responsible research and innovation principles of the European Commission (EU, 2012). For new and emerging technologies, policy formulation principles can only be applied on the basis of information and, according to Leach et al. (2012) that information should help formulate direction, diversity and distribution for technology development pathways. However, sustainable technology development is characterized by uncertainties, high risks, huge investments and late returns on investments (Alkemade et al., 2007). Agricultural innovation needs to take an interdisciplinary perspective to capture the *"multi-dimensional and multi-level interplay"* (Joffre et al., 2017:129). The technological innovation systems (TIS) framework has been developed *"… for understanding the complex nature of the emergence and growth of new industries and a focus on analyzing obstacles to this process"* (Bergek et al., 2015: 52). Knowledge about emerging technological innovation systems can be obtained by analyzing their functions (Bergek et al., 2008; Hekkert et al., 2007; Alkemade et al., 2007), i.e., those activities that will contribute to achieve the aims of an innovation system. In its early phases, the aims of an innovation system are not "fixed", but rather arise from the expectations actors assign to the potential (not actual) technological performance (Alkemade and Suurs, 2012). We are currently lacking an overall conceptual and empirical understanding of aquaponics as a potentially emerging technological innovation system and its expectations and empirical insights into functional activities.

In this paper, we adapt the technological innovation system framework for an explorative interdisciplinary empirical analysis of the current developments of aquaponics. We understand aquaponics as a potential technology contributing to the development of more sustainable food systems. The aim of this paper is to conceptualise and empirically describe the current state of its development and, based on that, describe the functioning of the TIS that may explain current opportunities and obstacles for its development. We focus our analysis on the EU, using Germany as a case study, but also consider worldwide developments. The interdisciplinary perspectives of the authors have helped to connect natural sciences, agricultural economics and governance, technological and sectoral knowledge within the TIS perspective, to provide a comprehensive description about current transition processes in food systems.

First, we position our research as an explorative approach in the technological innovation systems literature (Bergek et al., 2008), relate it to the sustainability paradigm (Weber and Rohracher, 2012) and develop an operational research framework to capture the integrative aquaponics technology within the environment of fully developed technological innovation systems of greenhouse vegetable production and aquaculture. Our explorative approach allows to discuss current functions that can facilitate or hinder the further development of aquaponics as a technology potentially contributing to sustainable food systems.

1.2. Historical background

In general, the search for solutions contributing to sustainable food production and consumption pathways can be developed by (1) reducing meat consumption, (2) minimizing food waste and (3) changing production processes (van der Goot et al., 2016). Efficiently produced vegetables and fish (the main products of aquaponics production) can potentially contribute to improving production and consumption habits, although dietary habits also play a vital role (Thøgersen, 2017). In Europe, the world's leading fish import market, there are large differences in fish consumption among countries, with more fresh fish being consumed in Spain, UK, Italy and France. Salmon, cod, hake and mackerel are the most consumed fish species in the EU (EUMOFA, 2016). Food production systems are also very diverse, from local to global and cannot be directly compared to one another (Baritaux et al., 2016). As a consequence, there is no "one fits all" solution to change food production and consumption. Aquaponic systems are expected to contribute to sustainability issues in food systems in different settings – urban/rural, small scale/large scale, developed/developing countries (Junge et al., 2017), yet assessing their contribution to more sustainable food systems faces methodological and data availability challenges (König et al., 2016).

Sustainable food system development also needs to consider broader infrastructural aspects beyond technical and physiological matters of food production and consumption behavior. Currently, already more than 50% of the world population lives in cities. It is expected that this percentage will grow to approximately 60%, with a yearly increase of 1.7% until 2030 (UN, 2012). Many of cities are expected to grow significantly, with 37 urban agglomerations expected to become Megacities by 2025. At the same time, some cities are shrinking. Both growing and shrinking cities put pressure on the operation and management of conventional centralized infrastructure systems for energy, water and organic waste management (Gleick, 2002). Strategies for decentralized infrastructures are considered appropriate to address these developments (Schuetze et al., 2008; Binz et al., 2010), and aquaponics could contribute to urban cycling systems in terms of water, energy and food (Million et al., 2014). However, green space provision and food systems are not primarily organized within urban planning procedures, but rather within global-local value chains and are the result of the interplay of multiple actors and policy domains. (Re-) integration of food production into the city is discussed as a necessary element to achieve a circular urban metabolism (Benis and Ferrão, 2017; Tedesco et al., 2017). While urban agriculture cannot supply all of cities' needs, there is an inherent environmental logic and resilience within recognized historic models of incorporating urban food production, such as Johann von Thünen (1826, cited in Van der Schans and Wiskerke, 2012) and Howard (1902).

Modern aquaponics began with Jim Rakocy, with the first peer reviewed paper being published in 1981 (Rakocy and Allison, 1981). Mark McMurtry (McMurtry et al., 1990), from NC State University is acknowledged as the originator of aquaponics in the mid-eighties to early nineties, which he named Integrated AquaVegeculture

[1] The oldest examples are probably "chinampas" of the Aztecs, artificial islands in shallow lakes planted with crop. In the canals between these, fish were raised (Boutvelluc, 2007).