Literature Review on Aquaponics as Commercial Food Production and suggestions for improvements to the Matthaei Aquaponics system

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Abstract:

This paper is a review of the body of literature related to the implementation of commercial aquaponics. This review was conducted after issues with an experimental aquaponics system developed into an interest in the relationship between the issues identified with the aquaponics system in the experiment and the issues identified with commercial aquaponics in the literature in the literature. Previous research on the development and commercialization of aquaponics does exists and overs a diversity of topics. This research is gaining in its importance as the FAO has identified a need to improve the sustainability of the methods used to produce fish products. Commercial aquaponics if developed properly could fill this need in the food system. In this analysis the review was conducted using Citation Network Explorer and Visualization of Similarities Viewer which allowed the researchers to narrow in on the literature within the aquaponics field specifically focused on commercial aquaponics systems. It was found that there is broad coverage of the issues related to commercial aquaponics; however, the technology remains complex and expensive, there is little cross pollination of research within the field focused on commercialization, and there is a lack of understanding of both consumer and producer priorities which limits the applicability of the system designs in the food system. Developing solutions aimed at reducing the complexity and costs of commercial systems, integrating research from all of the identified areas of interest, and identifying consumer and producer priorities could be used to develop more appropriate system designs, increase ethe adoption of commercial aquaponics, and increase the resilience of the production systems.

Introduction:

The goal of this paper is to conduct a systematic review of the body of literature on commercial aquaponics. Additionally, the review is aimed at providing recommendations for increasing the applicability of the body of knowledge and to aid in increasing the adoption of commercial-scale aquaponics. Aquaponics is defined as a production system that combines aquaculture and hydroponic food production through water recirculating between the two adjoined subsystems (Naegel, 1977). This creates a system where nutrients produced by the aquaculture component are utilized by the hydroponic component (Naegel, 1977). In the 2020 State of Fisheries and Aquaculture Report; aquaculture is highlighted as one of the fastest-growing agricultural fields, surpassing many aquatic capture sectors including algae, freshwater fish, and mollusks: with aquaculture contributing 46.0 percent of production from 2016 to 2018 (FAO, 2020). In this same report, a need is identified for technologies and practices that “foster the sustainable use of resources” and reduce waste as necessary for addressing climate change and securing a future for the aquaculture sector (FAO, 2020). We argue that the necessary developments in the field create a niche for commercial aquaponics. We also argue that aquaponics addresses sustainable development goal 12 (responsible consumption and production) as there is little to no use of agrichemicals, high efficiency of nutrient use, and reduced waste outputs from the production of food products in aquaponics production (Rackocy, 2012; Suhl, 2016; and Blidariu, 2011).

The foundational research on aquaponics was conducted from the late 1970s to the early 2000s with the main body of research expanding around 2010 (Junge, 2017; Figure 6). Aquaponics systems function through nutrient, mineral, and water flows between the aquaculture and hydroponic subsystem (Goddek, S.D., 2015) In these systems fish effluent and feed provide essential nutrients to the system which are processed by bacteria transforming nutrients into a bioavailable state, which is then uptaken by the plants (Goddek, S.D., 2015). This creates a synergy in the system where the inputs and outputs from the aquaculture sub-system provide the nutrients for the hydroponics sub-system, which in turn treats the water to be habitable for the aquaculture sub-system. In Blidariu et al. (2011) and Delaide (2016), it is argued that the associated reductions in effluent discharge and use of chemical pesticide and herbicide combined with higher water and nutrient use efficiency amounts to the creation of a more sustainable, aquacultural production practice. However, there is a continued push towards more efficient and sustainable production practices within the aquaponics field (Goddek, 2015). In this paper the authors argue that further improvements must be made in the energy use efficiency and other consumptive use efficiencies in aquaponics to achieve sustainable production (Goddek, 2015).

In Robertson (2015) it is suggested that sustainable agriculture needs to address economic, social, and environmental concerns. The concerns are defined as follows:

- Economic Sustainability: addresses the continuity of producing goods and services where the benefit exceeds the cost in dollar value and the externalities associated with production;

- Social Sustainability addresses justice, equity, health, and other associated welfare concerns;
- Ecological Sustainability is summarized as the system's ability to maintain ecosystem services essential for the continuation of life (Robertson, 2015).

The goals of the development of aquaponics have been in line with this definition; however, the primary focus has been on developing economic and ecological sustainability (Milicic, 2017).

Background:

Our interest in commercial aquaponics was driven by an interest in sustainable agricultural practices which developed into an experiment with aquaponics at the University of Michigan Matthaei botanical gardens at the University of Michigan. Understanding our experience with this system is essential as the recommendations for the literature review are influenced by the knowledge gained through this experience, and the information gathered in the literature review allowed for the development of recommendations for improvements to the experimental system. An initial experiment with aquaponics was conducted at the Matthaei Botanical Gardens, which was terminated due to operational issues with system operation related to design changes, the Covid-19 pandemic, and fish illness. After the termination of this experiment, we developed a desire to understand what could be done to improve the system that we had operated, and how our experience with the system might overlap with the gaps in research in the commercial aquaponics literature.

Sustainability Without Borders Aquaponics System:

Sustainability Without Borders at the University of Michigan had been operating an aquaponics system used in research conducted by Frost (2019). The initial goal of our operation of this system was to conduct a life cycle assessment of the system under different management practices in the hydroponic component and to create an estimated return on investment for the experimental system. Our goal was to determine if the system was both sustainable and suited for public operation. The experiment with this system was unsuccessful and led to the development of the commercialization literature review. The operation of this system informed and focused our review of the literature toward understanding the commercial application drivers and barriers.

System design:

The system used a 2:1 gravel media bed to rearing tank ratio (Frost, 2019). The system was composed of wooden frames, with waterproof lining, vinyl pipe, gravel media, and water three pumps. The pumps were used as an inflow to the aquaculture tank, an inflow to the hydroponics grow bed, and an overflow safeguard from the aquaculture tank. The system was originally designed with 3-inch hard PVC drainpipes which made the system difficult to navigate and highly inaccessible, these pipes were replaced with 1.5-inch vinyl tubing which created greater accessibility around the system. Float switches were also added to the system as a method to prevent water loss due to overflow. The gravel beds were operated as a continuous flow system due to issues with siphons observed in Frost, 2019.

System Management:

The Covid-19 pandemic interrupted standard operating procedures by reducing our access to the aquaponics system. Before the pandemic feeding checks were provided twice per day and the fish were hand-fed. Health checks occurred once daily. Water quality checks were provided once per day using a multimeter. Water was added daily at less than 10% of system volume. Feed was added to the system as suggested by the supplier with feed consumed in approximately 5 minutes by the fish. Weekly water quality checks were delayed during the first 3 weeks of the experiment due to issues with the calibration of the photometer used for nutrient testing. Dissolved oxygen was monitored using the multimeter.

After the covid-19 pandemic shutdowns, feeding and health checks both occurred once daily. Fish were fed by an auto-feeder calibrated to provide the appropriate volume of feed. Basic water quality checks with a multimeter were performed once daily. Full water quality testing was not required to continue the experiment and the area of the campus farm used for chemical disposal was restricted making nutrient testing unavailable for the experiment. The hydroponics system was operated using an intercropped planting of hydroponic bell peppers and Salanova Green Butter Lettuce. The peppers were ordered from Johnny's seeds and the Salanova lettuce was donated by the University of Michigan campus farm.

Management issues:

During system operation, multiple issues were encountered. First, the reduced flow capacity in the smaller pipes led to a large reduction in the system's excess flow capacity, this created the conditions for 2 overflows despite preventative measures being taken. An initial overflow of water occurred early on in system operation, with no detrimental effects on system function as it was caught early. A second overflow occurred later in the summer from issues with algae build-up in the outflow pipes from the wooden gravel bed. We are unsure if this overflow was related to health issues experienced by the fish in the experiment. These overflows did result in significant water additions to the system which did exceed our 10% of system volume daily cap.

Pest infestations were experienced (Aphid and Spider Mite) on the pepper plants. These were likely caused by a lack of physical barriers to the entry of insects in the greenhouses at the UM campus farm. Both infestations were treated successfully with integrated pest management.

In late June and early July there were monitoring equipment malfunctions. The malfunctions were exacerbated by delays associated with supply chains, associated with Covid-19, resulting in the delivery of replacement components. Fish became ill and the system began losing 1-2 fish per day. Issues with identifying the cause of fish deaths occurred due to covid restrictions on access to the system and other areas in the campus farm. After the beginning of fish deaths, potential issues with ammonia, nitrite, and chloramine were identified. After the end of our experiment a black-grey sludge was identified in the grow bed and the sump tank which could indicate issues with sulfate-reducing bacteria which create hydrogen sulfide which can be harmful to fish and the system operator.

Attempted solutions:

After identifying two fish deaths in the systems the veterinary staff at the university was contacted. We continued working with veterinary staff from the time of contact to the end of the experiment, which ended after the loss of 50% of the fish stock. During this period the campus farm provided a special exemption for chemical disposal near the system so that full water quality testing could begin. Water treatments for Ammonia, Nitrite, and Chloramine were applied to reduce the potential for harm from water quality. Dissolved oxygen was identified as being low, aerators were added to the system to increase the DO content. The observed low DO was identified as a faulty sensor on the multimeter used in daily water checks. Additionally, the water source was changed from Ann Arbor city water to reverse osmosis water provided by the campus farm to prevent the addition of chloramines.

Results from Operation:

Due to the deaths of tilapia and the overall termination of the experiment data was not collected on the value of production, the mass of fish produced, the energy use, or any valuations from the operation. The mass of crops produced during the operation of the system was quantified. Lettuce was successfully harvested twice (31 heads and 41 heads respectively) with a total edible biomass of 15.05 lbs. The peppers were harvested continuously, with a drop in the rate of harvest during the attempted system recovery. The peppers produced 72.02 lbs of fruit biomass with 45.21 lbs being considered edible as there was loss due to overripening during the attempted system recovery. The initial harvest of lettuce was donated to members of the SEAS community and the remaining produce from the system was donated to the South-West Detroit Environmental Vision Cadillac Urban Farm to support ongoing food security efforts during the Covid-19 pandemic. Through this experience we also learned that under the current design, the system was not suitable for public use as we could not guarantee that our experiences with operation would not happen again without a redesign.

Literature Review Methods:

The citation network analysis software, CitNetExplorer (Citation Network Explorer) developed by van Eck and Waltman was used to begin our analysis of the commercial aquaponics literature (2014). The developers state that the software was designed “for analyzing and visualizing direct citation networks”. CitnetExplorer is intended to explore the citation linkages between individual publications and other associated attributes (Publication year, citation score, etc.) (van Eck N. a., 2014). The data analyzed in CitNetExplorer was exported from the *Web of Science* database for all papers related to the search term “aquaponics”. In this analysis, the network science tools offered by the software were utilized to determine the different groups of research within the aquaponics literature. We utilized the clustering tool which uses a combination of network science algorithms that determine the “relatedness” of papers and establishes clusters or “topics” based on the determined relatedness (van Eck N. a., 2014). A visual representation of the full citation network divided into groups is provided in figure 1 in the appendix.

Within the clustering tool the resolution is a variable in the relatedness algorithm used to determine the “level of detail at which clusters are identified” with a greater number of clusters appearing at higher resolutions (van Eck N. a., 2014). The strength of the resolution tool is dependent on the number of papers included in the file used for analysis (van Eck N. a., 2014). Due to a relatively low number of papers in our exported *Web of Science* data, resolutions from 1.00 to 2.00 were tested at a step of 0.05. A resolution of 1.50 was determined to be optimal as it was concluded that the five resulting groups seemed homogenous as determined by a review of titles and top cited publications.

The drill down tool was utilized on the group which was most related to the goal of our analysis, the barriers to commercialization of aquaponics. The drill down tool enabled us to restrict our analysis to only the papers within this cluster. Using the clustering tool again and a resolution of 1.50, 5 subgroups were identified within the commercialization group. In this stage of our analysis, the top 6 papers within each group were analyzed for content and research topics along with an analysis of abstracts and titles from the rest of the group allowing us to identify the niches in the research within the body of literature related to commercial aquaponics.

The *Web of Science* file information for each sub-group was exported for analysis in Visualization of Similarities (VOS) viewer. VOS viewer is software that uses mathematical matrices to place objects into visualizations by weighting the degree of similarity to other matrix components with the distance between objects representing the associated relatedness (van Eck N. a., 2006). The function of this software is similar to CitNetExplorer; however, VOS viewer can be used to create clusters of components using co-occurrence data in the papers which is useful for analyzing keyword networks (van Eck N. a., 2006). In this review, the keywords of each sub-group were analyzed using full counting and 2 co-occurrences per keyword as the minimum threshold for inclusion in our analysis. The use of 2 co-occurrences ensured that at least 2 papers had utilized the keyword. This helped to limit the number of keywords analyzed and ensure that only keywords utilized multiple times were included in the analysis. The keyword analysis was used to add additional depth to our understanding of the foci of each sub-group in the citation network.

Results:

Initial Analysis:

The main groups identified in our initial analysis of the aquaponics literature are:

Table 1: Initial Analysis Groups

Initial Analysis Groups Identified	
Group Name	Number of Publications in group
Nutrient Cycling	137

Nitrogen Cycling	52
Microbial Content	30
Novel Improvements to system design	29
Commercialization*	118

**focus of our analysis.*

The nutrient cycling group was determined to focus broadly on how nutrients are processed in aquaponics systems and the factors that could improve this process, primarily using new technologies or improving pre-existing technologies (Graber, 2009; Lennard, 2006; and Tyson, 2011). The nitrogen cycling group was determined to have a major interest in the factors that influence the transformation and uptake of nitrogen in aquaponics systems using various management techniques (Hu, 2015; Zou, 2016; and Wongkiew, 2017). The microbial content group focused broadly on the role of microbes in aquaponics systems and how to improve system function as it relates to promoting beneficial microbes while managing harmful microbes (Goddek, S.S, 2016; Schmautz, 2017; and Pantanella, 2015). The novel improvements group focused broadly on technical and managerial improvements to system function analyzing the benefits of using alternative technologies like plant-based feed, systems modeling, and various species of crops (Medina, 2016; Karimanzira, 2016; and Moya, 2014). Visual representations of these groups are provided in the appendix, Figures 6 - 11.

Commercialization:

In the initial analysis, this group was identified as focusing on the scale, profitability, and people involved in aquaponics systems (Love D.F., 2015; Love D.C., 2014). An expanded interest in commercial aquaponics was identified in the CitNetExplorer visualization, beginning around 2012 (Figure 12). This group also analyzed the technical, social, environmental, and economic challenges to the growth of aquaponics as a vector for sustainable food production (Goddek, 2015). Within this group, 5 sub-groups were identified and characterized as follows:

Table 2: Commercialization Sub-groups

Commercialization Sub-groups Identified	
Group Name	Number of Publications in Group
Technical Improvements	43
Factors influencing the scalability of commercial aquaponics	25
Economics of Aquaponics	17
Novel System Design	17
Limiting Factors to social acceptance	12

The technical improvements to aquaponics sub-group discussed a multitude of design and managerial improvements to aquaponics systems focused on increased productivity (Goddek S. D., 2015; Martins, 2010; Delaide, 2016; Van Rijn, 2013; Rakocy, 2012; and Goddek S.

E., 2016). The major foci of the technical improvements from this group were aimed at improving the economic efficiency; disease management; waste and nutrient loading; and overall productive capacity of aquaponic systems. Furthermore, the VOS viewer analysis of the papers within the group identified 7 keyword clusters focused on design-based solutions to concerns related to: energy, nutrient, and economic sustainability; different system design concepts; expansion of productive capacity; solids removal; negative environmental externalities; yield and nutrient concentrations; and the use of dynamic systems modeling (Figure 1). This group of literature broadly concludes that there is potential for intensification, but a greater understanding of the optimal operating conditions is necessary for efficient, successful, and sustainable intensification of aquaponics. The keyword clusters further identify the areas of interest in this group as heavily related to improving our understanding of the optimal conditions within aquaponics systems as it relates to the efficiency of the use of inputs.

Within the focus on the internal system mechanisms, several factors were highlighted repeatedly as essential for improving the internal system function within this group: the feed conversion ratio, biofiltration and mineralization, pH, pest and disease control, energy consumption, and the rate of innovation. Improvements to the feed conversion ratio (FCR) are necessary for greater efficiency in the utilization of the feed input (Martins, 2010). Suggested improvements to the feed conversion ratio centered optimization of water quality for the fish, using optimal feeding techniques and feed composition, and fish optimal to the system design (Van Rijn, 2013; Martins, 2010; and Goddek S.E., 2016). Improved biofiltration and mineralization are required to improve dissolved nutrient concentrations in aquaponics systems and reduce the loss of nutrients through sludge removal (Goddek, S.D, 2015). Recommendations for improving nutrient release through biofiltration and mineralization are the use of sludge thickening technologies, denitrification reactors, improved FCR, optimizing Biofilter design for the system (Martins, 2010; Van Rijn, 2013; Delaide, 2016; and Rackocy, 2010). pH balance is an interesting issue within this group, as fish, plants, and bacteria in the system have different optimal pH (Goddek, S.E., 2016). Solutions for this issue include the use of lime-beds to balance pH near 7 or decoupling system components so that pH can be adjusted prior to use in each sub system (Goddek, S.D., 2015; Goddek, S.E., 2015). Pest and disease management is difficult in aquaponics due to restrictions on the use of agrichemicals as the addition of these chemicals is likely to harm the overall health of the system and render the outputs of the system inedible (Rackocy, 2010). Primary recommendations for improved management biological controls, such as predators, and physical barriers (Rackocy, 2010 and Goddek, S.D., 2015). Recirculating aquaculture systems, of which aquaponic is a sub-set, are described as highly energy intensive systems with energy use 40-60% higher than conventional aquaculture which could make aquaponics inaccessible (Martins, 2010 and Goddek, S.D., 2015). In this group it is recommended that alternative energy sources are utilized to reduce dependency on fossil fuels and designing systems to flow using gravity instead of pumps (Martins, 2010 and Goddek, S.D., 2015).

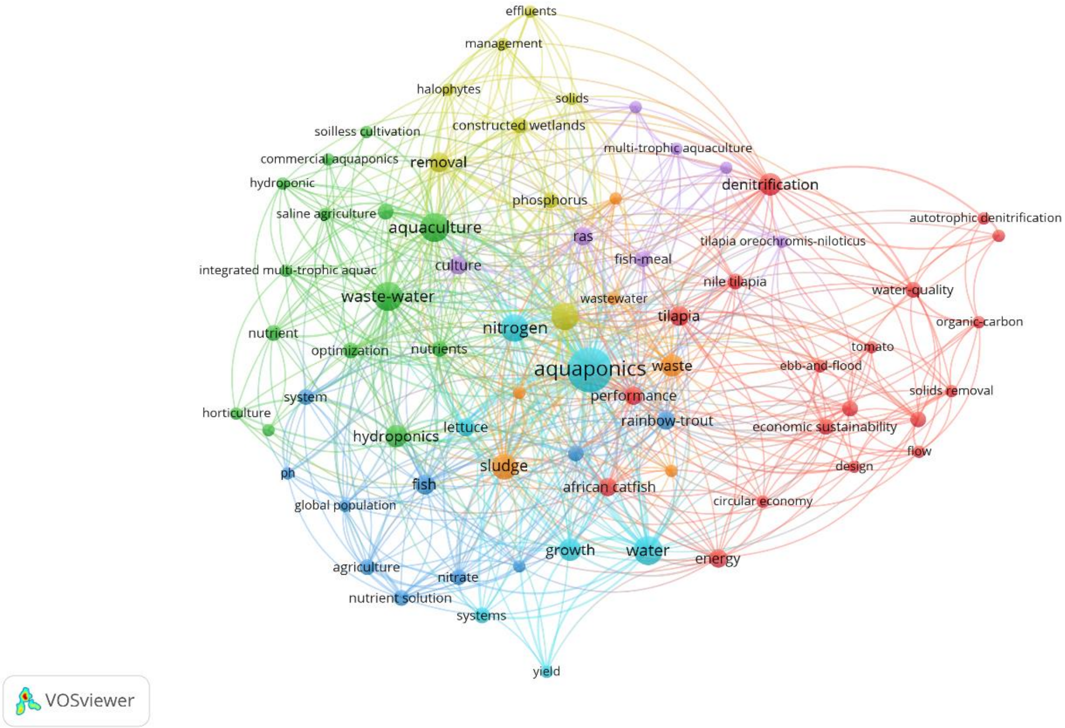

Figure 1: Keyword Network for Technical Improvements Sub-group

The factors influencing the scalability of commercial aquaponics systems sub-group was noted to have foci on the design and environmental challenges for scaling up aquaponics, the ability to integrate into current aquaculture systems, and the composition of the practitioners of aquaponics (Love, 2015; Love D.F., 2014; Love D. U., 2015; Naegel, 1977; Blidariu, 2011; and Lewis, 1978). This group discusses the role of practitioner priorities, environmental, geographic, and political conditions on the design and scalability of aquaponics systems. The VOS viewer analysis identified 5 clusters focused on scalability concerns related to: system performance under renewable energies; the quality of produce; the relationship between commercial aquaponics and food security; the sustainability of aquaponics; and bacterial diversity and water quality (Figure 2). The group broadly concludes that a greater understanding of the factors influencing the adoption of aquaponics must be developed especially with regard to the role of internal system function and the systemic context of system operation such as stakeholder priorities, markets, and environmental conditions. The keywords in this group identify a broad focus on improving the design of and outputs from aquaponics in ways that make easier scaling up the adoption of the production system.

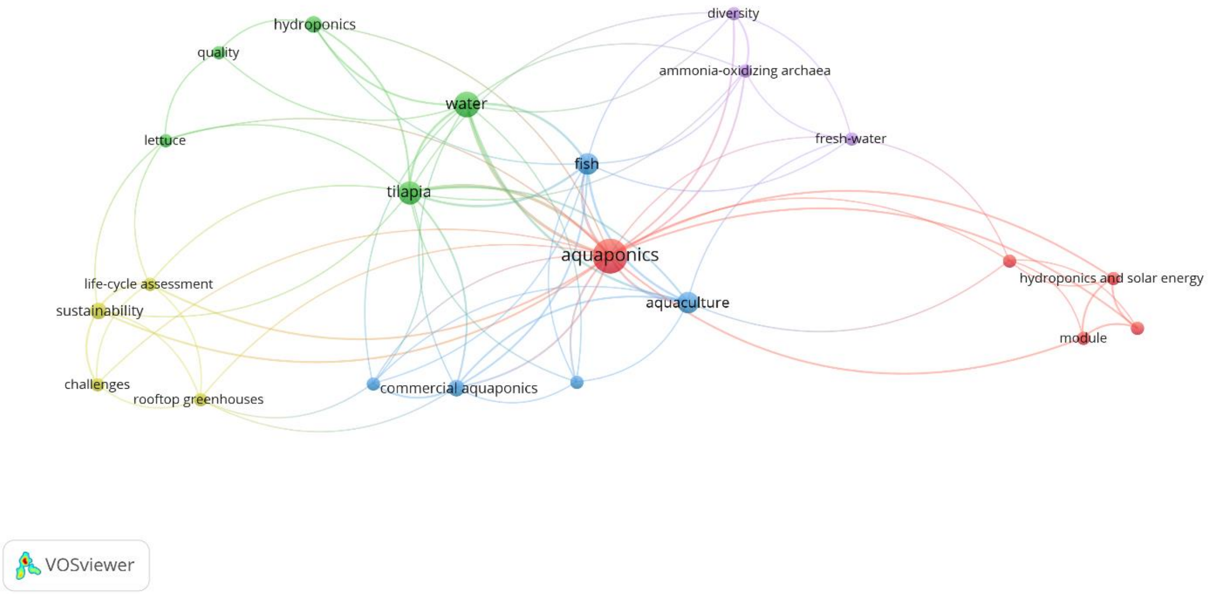

Figure 2: Keyword Network for Scalability Sub-group

The economics of aquaponics systems sub-group was identified as addressing some of the above concerns related to the economic feasibility of the production practice (Tokunaga, 2015; Rupasinghe, 2010; Bailey, 1997; Bosma, 2017; Vermeulen, 2013; and Bailey D. F., 2017). This group sought to develop an understanding of the economic feasibility of aquaponics production systems in both local and international contexts. The VOS viewer analysis of this group only identified two keyword clusters within the group, one focused on the economics of aquaponics and the other with a focus on aquaculture as a commercial enterprise (Figure 3). Within this group, papers that evaluated aquaponics on a small scale indicated that these production systems are profitable and have a role to play in the food system, the larger-scale analysis of aquaponics suggests that aquaponics is suboptimal in the context of the European food system (Tokunaga, 2015; Bosma, 2017; and Vermeulen, 2013). This group appears to suggest that aquaponics may only have a niche role to play in the food system dependent on external, market-based variables and not the productive capacity of the system alone. The keyword analysis further suggests that this group has primary interests in the external economic factors that influence the success or failure of commercial aquaponics systems.

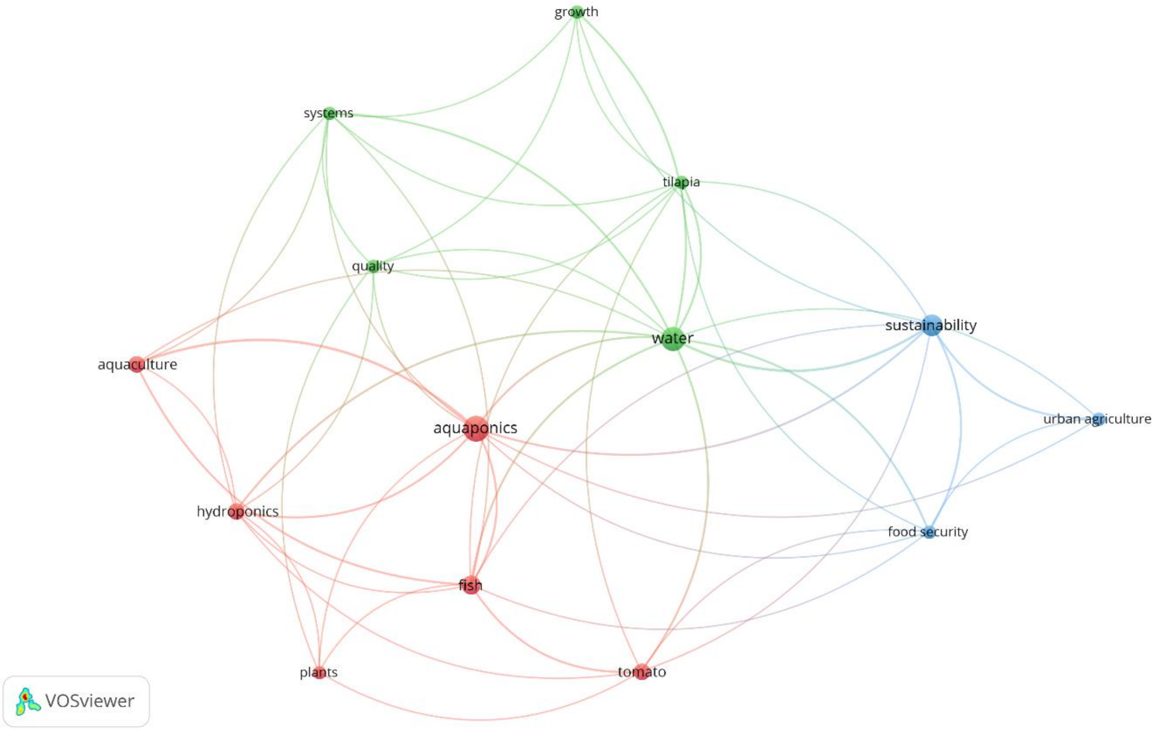

Figure 3: Keyword Network for Economics Sub-group

The novel system design sub-group was identified as discussing alternative system designs and management practices (Kloas, 2015; Suhl, 2016; Timmons, 2010; Villarroel, 2016; Sommerville, 2014; and Monsees, 2017). The papers analyzed primarily discussed aquaponics in a European context with a heavy discussion of the potential utility of the “aquaponics system for emission-free tomato and fish production in greenhouses” or “ASTAF-PRO” system design (Kloas, 2015; Suhl, 2016; Villarroel, 2016; and Monsees, 2017). Other papers within the group highlighted other alternative system designs including vertical agriculture and marine aquaponics. The VOS analysis identified three clusters, general system design; design for product quality; and interest in the sustainability and food security of urban aquaponics systems (Figure 4). This group broadly concludes that there is a wide variety of use-values from aquaponics, beyond traditional single recirculating freshwater aquaponic systems. The keyword analysis highlights an interest in this group related to increasing the efficiency of aquaponic systems generally, while also designing for specific contexts not addressed by traditional aquaponic system designs.

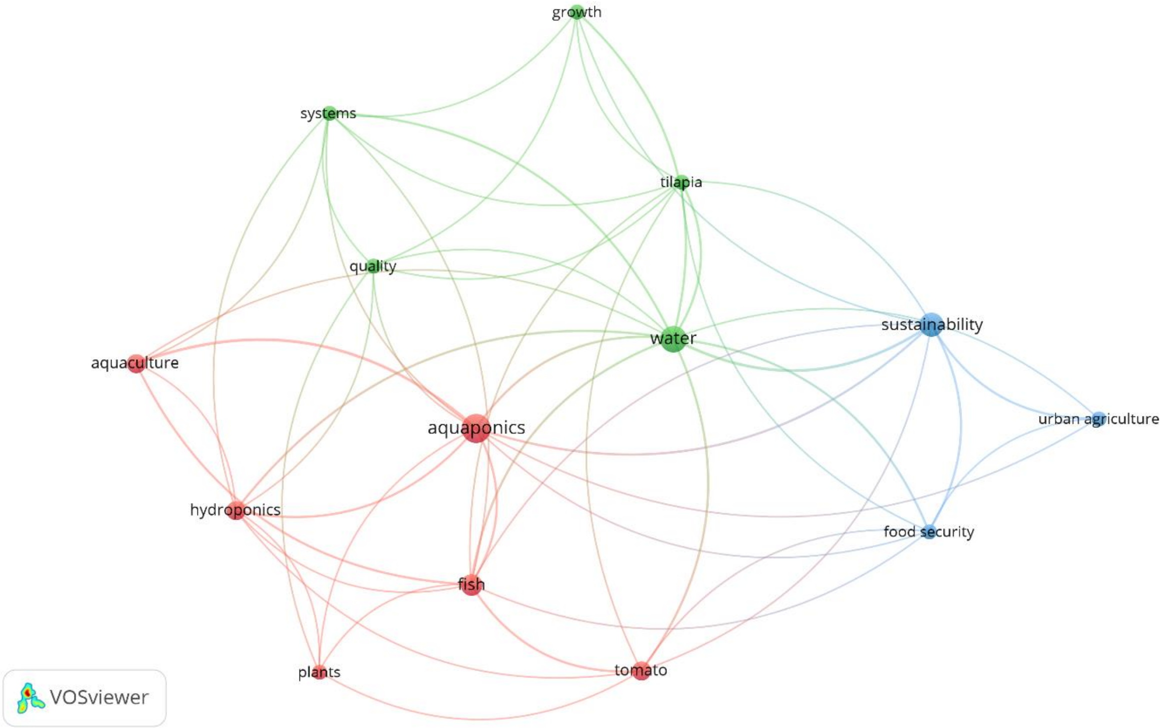

Figure 4: Keyword Network for Novel System Design Group

The limiting factors to social acceptance sub-group was identified as focusing on issues related to lack of awareness that is limiting consumer interest in aquaponics products and the overall adoption of aquaponics as a commercial venture (Junge, 2017; Sommerville, 2014; Dos Santos, 2016; Milicic, 2017; Pilinszky, 2015; and Pollard, 2017). The group focuses on consumer concerns, an overly generalized definition of aquaponics, low consumer awareness, managerial difficulties, and exclusionary policy gaps. The VOS viewer analysis of the group identified 3 clusters: aquaponics as sustainable food production, consumer perception of aquaponics, and consumer interest in aquaponics (Figure 5). The group broadly concludes that greater effort must be applied to raising consumer awareness of aquaponics, increasing the ease of management for practitioners and eliminating policy gaps that are exclusionary to the production practice. The keyword analysis for this sub-group further identifies a heavy interest in consumer priorities as they relate to aquaponics as well as interest in promoting aquaponics as a sustainable method of food production.

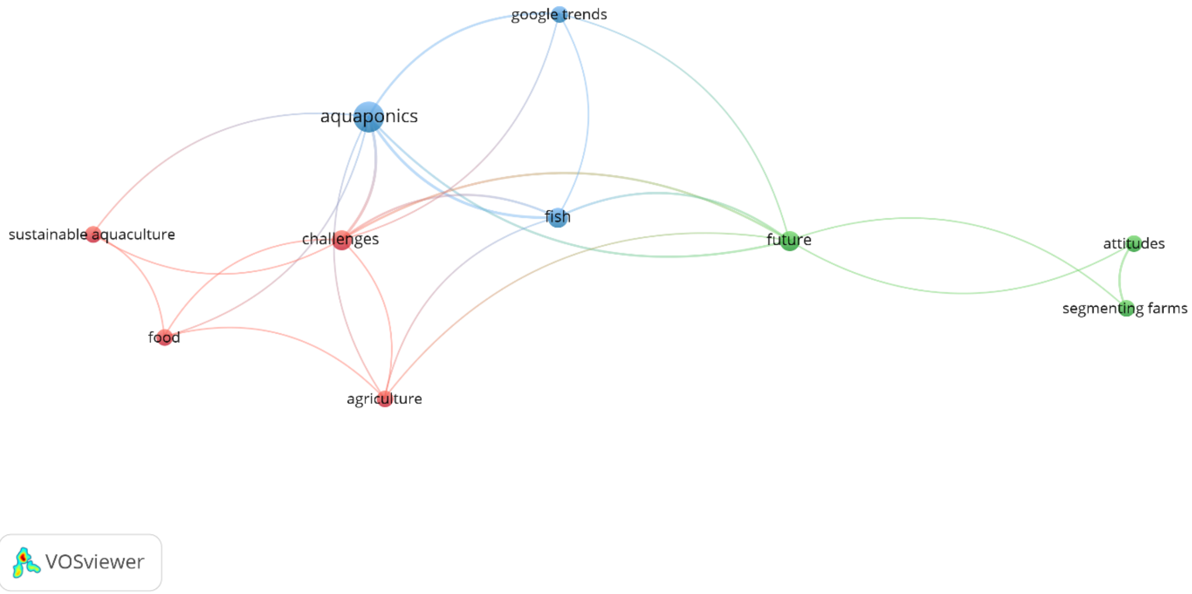

Figure 5: Keyword Network for Social Acceptance Group

Discussion:

Suggested research on Commercial Aquaponics:

Based on our analysis there is a high degree of focus on improving water quality and nutrient management in aquaponics systems, yet this does not address the only concerns related to the improvement of these production systems. A major concern related to the scalability of aquaponics is the ability to combat pests and diseases that may enter the system as there are heavy restrictions on these management practices (Goddek, 2015). There was an argument in the literature that the development of aquaponics safe pesticides and disease management techniques are essential to reduce the barriers to entry into the field and reduce the complexity of management (Pilinszky, 2015). In Monsees (2017) it is argued that decoupled aquaponics systems present an opportunity to use pest and disease management techniques that might otherwise be unavailable in traditional aquaponic system designs due to the ability to segregate the systems during the treatment period. We recommend that further development of the ability to quarantine system components as it relates to pest and disease management is necessary. Greater ease of pest and disease management would also increase the accessibility of aquaponics as current pest and disease management techniques require a high capital input for prevention as current treatments are prohibitively expensive and can be harmful to overall system health (Sommerville, 2014).

In many of the papers analyzed the aquaponics systems are studied in a vacuum as if the system is independent from external influences. We argue that this is problematic because a greater understanding of how aquaponics functions in the broader context of the food system is necessary to understand what niches might exist for the production system. This is best represented by the disparities between the viability of aquaponics as an alternative production practice in the context of food systems specific to Hawaii, the Philippines, and Europe (Vermeulen, 2013; Tokunaga, 2015; and Bosma, 2017). To improve our understanding of the role of aquaponics in the food system we recommend further study of aquaponics in a systemic context at local, regional, national, and international scales. A greater understanding of the systems that affect aquaponics at various scales would aid in understanding the context in which aquaponics can be successful. An expanded understanding of the niches available to aquaponics can also aid in the development of priorities-based system design. We argue that this is useful due to the context dependencies of successful aquaponics systems and the role producer and consumer priorities play in the social acceptance and economic success of aquaponics systems (Sommerville, 2014; Love, D.F., 2015; and Milicic, 2017).

Many of the above aquaponics studies analyzed commercial aquaponics in the context of a single owner-operator system which has high knowledge and labor burdens for practitioners, limits the diversity of the system and requires larger production scales to meet the needs of the market (Tokunaga, 2015; Bailey, 1997; Bosma, 2017). To address this assumption, alternative management structures including cooperative, or community management of multiple small-scale aquaponics systems should be studied. This is recommended due to the arguments in the literature that aquaponics can be built out for multiple contexts and that it is uniquely suited for an urban environment in which small-scale production can be useful (Goddek, 2015). We argue that alternative management structures might improve the appropriateness of the technology for local production which has been discussed as desirable (Bosma, 2017 and Tokunaga, 2015). We also argue that these management structures would reduce the barriers to entry for system development through increasing access to human capital thus reducing the individual labor and educational requirements for operation. We also argue that these management structures could allow for greater specialization as it relates to knowledge of system components. Furthermore, developing community centered management systems could expand interest in aquaponics generally as consumers have been noted to have more positive associations with the practice if they are connected to the producers (Millicic, 2017).

Additionally, greater attention should be paid to who is practicing aquaponics and why. The demographic composition and goals of aquaponics practitioners are noted to be influential in the design and success of aquaponics systems due to the role that practitioners play in establishing the priorities for production (Love, D.F. 2015; Love, D.C., 2014; and Villarroel, 2016). These studies indicate that there are few commercial practitioners with many individuals involved in aquaponics being educators, hobbyists, and NGOs. Developing a greater understanding of who the commercial producers are, what drives interest in commercial aquaponics, and what factors drive the profitability of these systems will provide necessary context to researchers seeking to expand the adoption of commercial aquaponics and aid in the further development of optimal system designs.

Recommendations for the SWB System at the Matthaei Botanical Gardens:

When addressing recommendations specific to alterations made to the Matthaei system our attempt at creating a physically accessible system harmed the health of the system overall. This harm was caused by multiple overflows despite preventative measures taken. This is likely caused by the reduction in excess flow capacity caused by using pipes at a significantly smaller diameter than the initial design. In a redesign, custom-sized flexible vinyl tubing should be ordered to keep the intended physical accessibility. An alternative could be the use of platforms and elevated surfaces which provide greater accessibility in terms of height. The operated system design was inaccessible to shorter individuals and proved challenging even for taller individuals when attempting to harvest fish and crops.

We also recommend the integration of a mechanical filter into the current design of the Matthaei system. This recommendation is given due to the high labor cost of emptying effluent from gravel beds (Rackocy, 2012). While gravel beds can be used as a mechanical filter on their own the addition of a separate mechanical filter can be useful as it will separate the wastes before the gravel beds allowing the gravel beds to function as the biofilter and grow bed (Sommerville, 2014). This alteration would increase the materials and energy cost of system operation by eliminating the ability to use gravity as a driver of flow in this design unless additional alterations were made. However, we argue that the potential to prevent the accumulation of effluent in the gravel beds is of greater concern. Especially in this system due to the likelihood of anaerobic or anoxic zones developing in the accumulated effluent potentially promoting the growth of sulfate-reducing bacteria.

Our third recommendation is the integration of an activated charcoal filter as described in Sommerville, 2014. These filters can be used to prevent the accumulation of unwanted chemicals in the aquaponics system by filtering them out before addition. This recommendation was developed out of concern for the potential accumulation of chloramines in the system related to the two overflow events. A surplus tank with an activated charcoal filter could have allowed for greater water additions with less risk of introducing high quantities of chloramines found in the Ann Arbor Drinking water which can be harmful to fish health.

Our last recommendation is to have secondary testing equipment on-site in case of emergency or issues with the accuracy of the primary equipment. There are cheap options for easy-to-use water quality testing equipment such as the API Freshwater Master Test Kit that can be kept as a backup in case of primary equipment malfunction. These test kits were used by veterinary staff when visiting the system and verified that nutrients were not out of range as expressed by our equipment; however, this equipment could have provided additional use-value as an alternative to the more noxious chemicals used in testing by the photometer, especially with access to the disposal site being restricted.

Conclusions:

Several foci were identified within the body of literature on commercial aquaponics. The foci were: Technical Improvements to aquaponics; Factors influencing the scalability of commercial aquaponics; Economics of Aquaponics; Novel System Design; Limiting Factors to social acceptance. The technical improvements sub-cluster identified internal optimization as essential for the continued development of the production practice. The scalability sub-cluster identified understanding the priorities of producers and the contexts in which systems function optimally as necessary for further adoption of commercial systems. The economics group established a need to understand how various scales of both aquaponics systems and food systems impact the success of commercial systems. The novel systems sub-cluster identified a need to expand the use values for the production practice through non-traditional systems designs as a method for expanding the utility of the production system and increasing the role of commercial aquaponics in the food system beyond the scope of traditional systems. The social acceptance sub cluster noted that the success of commercial systems is dependent on public interest in the outputs of these systems, and that increased public awareness is essential to expand both the consumer and producer base.

The groups identified above highlight a need to understand and optimize the internal and external systems affecting the successful operation of aquaponics systems. However, these groups generally highlight these as independent variables. Understanding the interaction between both the internal and external systemic factors that affect the success of aquaponics is essential for further improvements to system function and increased adoption of the production practice. Market success of commercial aquaponics requires greater improvements on the efficiency of the system; however, improvements to only the internal systems without acknowledging the external systems related to culture and the life of operators will result in sub-optimal performance. To develop optimal system design requires and understanding of both consumer and producer priorities and the success of the system in the market requires public interest. Furthermore, additional research should be focused on reducing barriers to entry to aquaponics production by working to simplify system operation. We propose that reductions in the costs associated with entry into the field and developing a simplified operation that accounts for the internal and external factors influencing success the adoption of aquaponics as a production practice will expand. Additionally, by accounting for both the internal and external pressures on aquaponics systems can be designed with greater resilience to these pressures.

As it relates to the Matthaei aquaponics system, these are all points of change that were identified as potential preventative measures during the attempted recovery of the failing system. Our recommendations are focused on maintaining system integrity and reducing the potential for harm to the system. Despite a focus on the internal function of the system our recommendations have been developed in response to both internal and external pressures with the intention of preventing a similar experience with the same system design. These recommendations have also been made in an attempt to address these issues at low-cost and without increasing the complexity of operation. Our suggested improvements to the Matthaei system and suggestions for the advancement of commercial aquaponics research further improve the responsibility of the production system through focusing on improvements aimed at welfare for both the animals in the system and the operators. The refocus toward welfare and accessibility also builds on the social sustainability of commercial systems which was indicated to be lacking when compared with the economic and environmental sustainability of the systems. Furthermore, working to increase the accessibility and adoption of commercial aquaponics systems can aid in addressing the broader need to increase the responsibility of production the aquaculture industry as described by the FAO and in addressing the sustainability concerns related to responsible production and consumption outlined in Sustainable Development Goal 12.

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Appendix 1: Citation Networks

Figure 6: Citation Network of Full Network

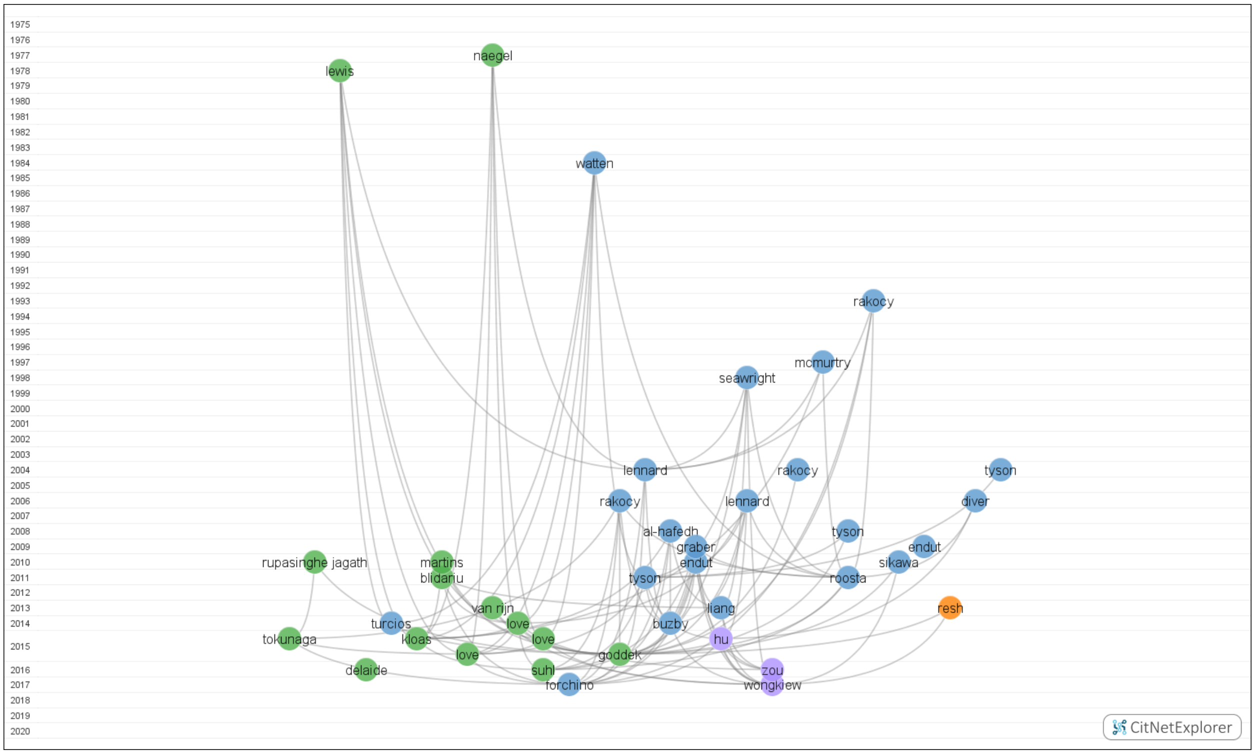


Figure 7: Citation Network of Group 1: Nutrient Uptake

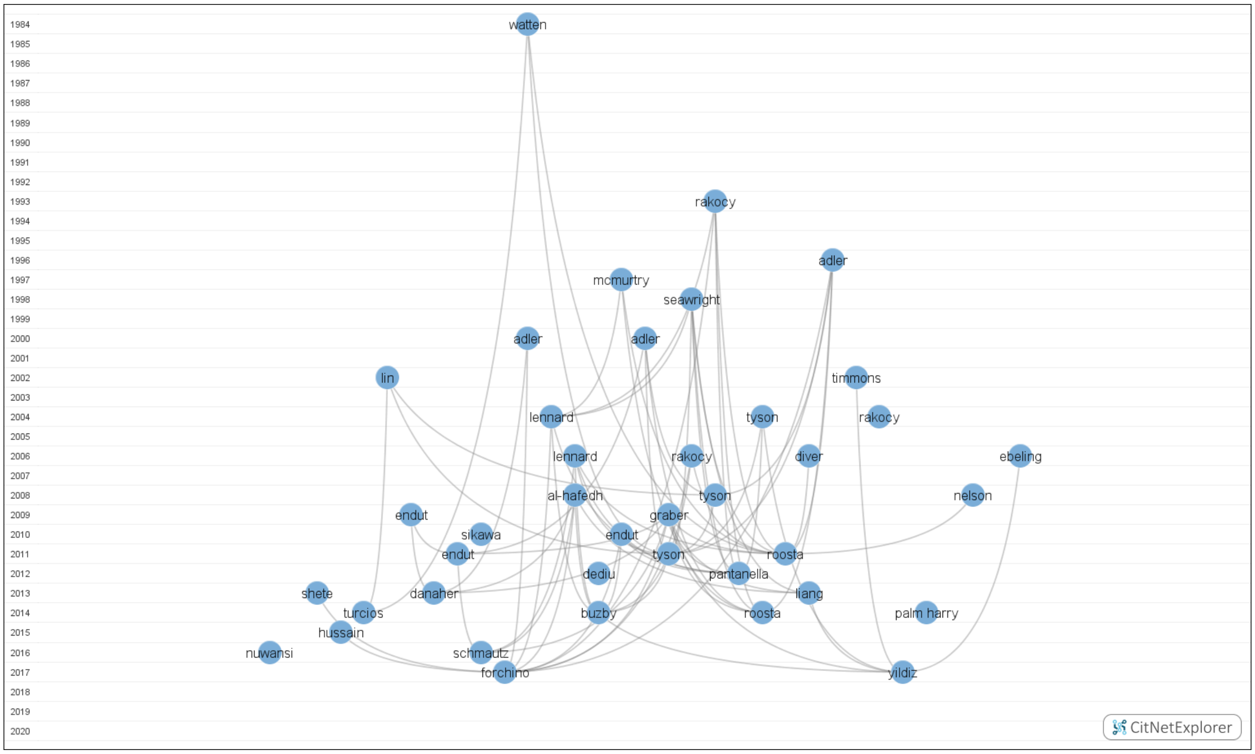


Figure 8: Citation Network of Group 2: Commercialization

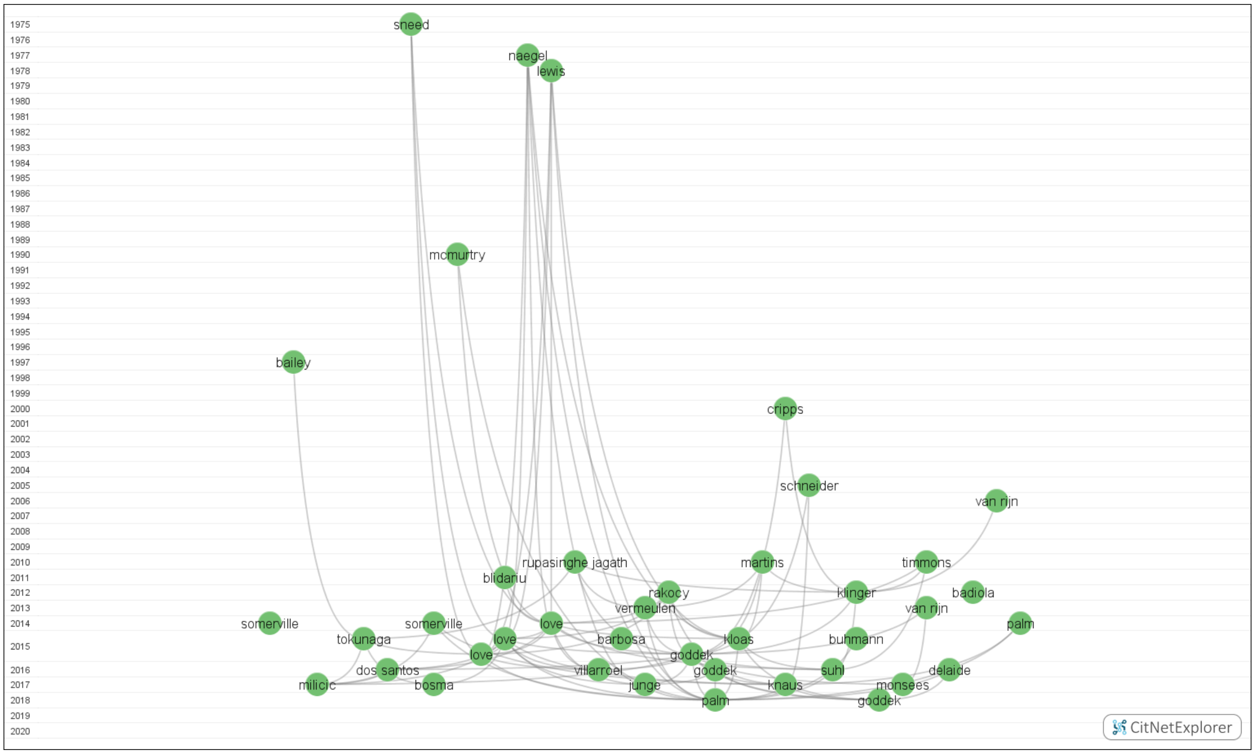


Figure 9: Citation Network of Group 3: Nitrogen Cycling

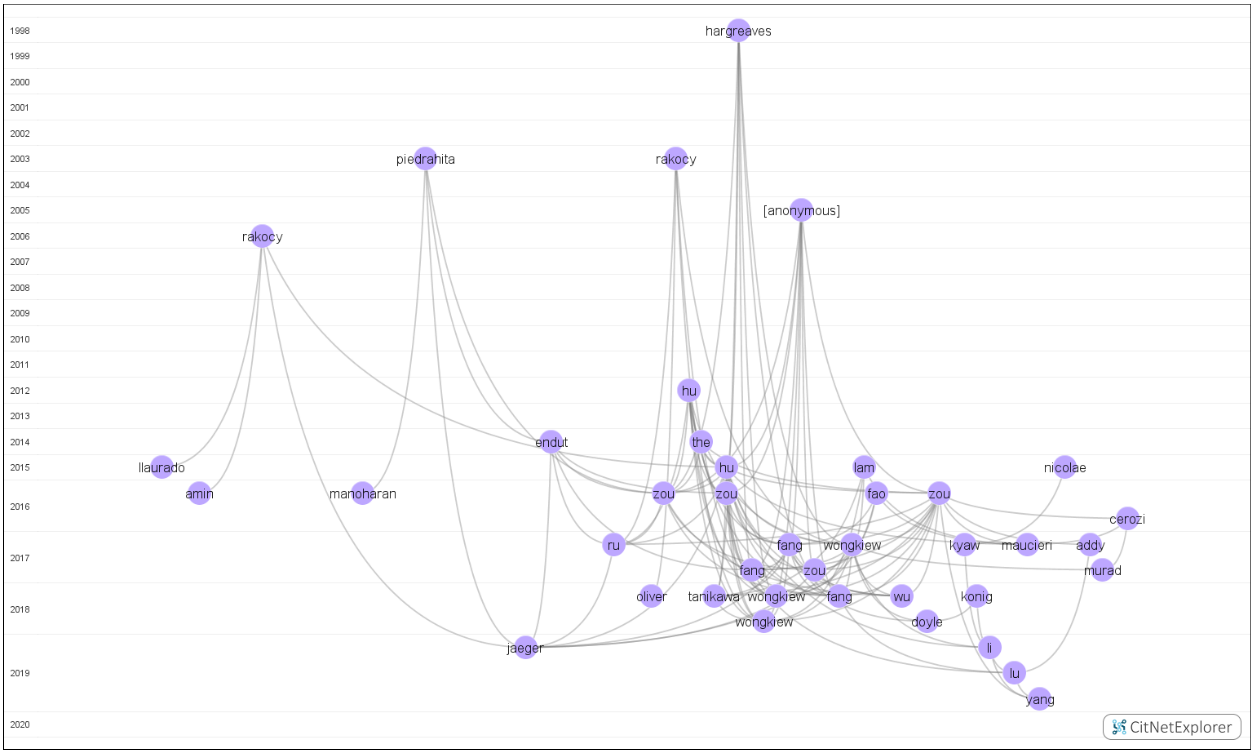


Figure 10: Citation Network of Group 4: Microbial Content

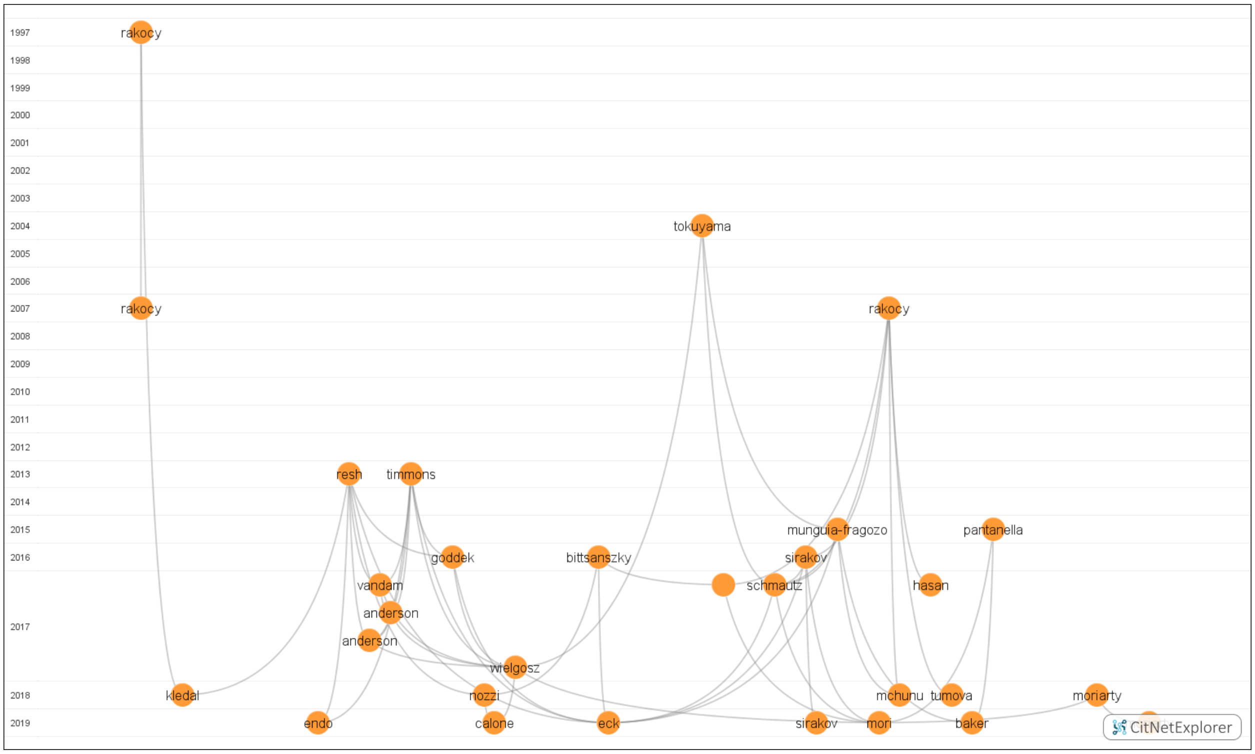


Figure 11: Citation Network of Group 5: Microbial Content

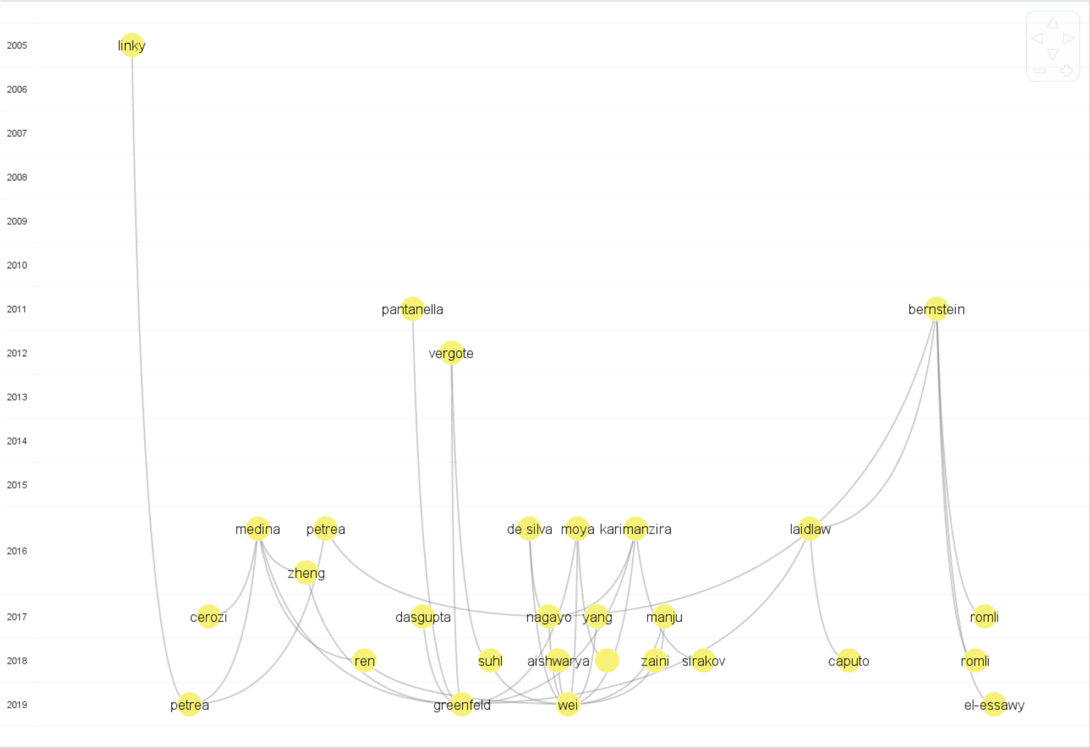


Figure 12: Commercialization Group with Sub-Groups:

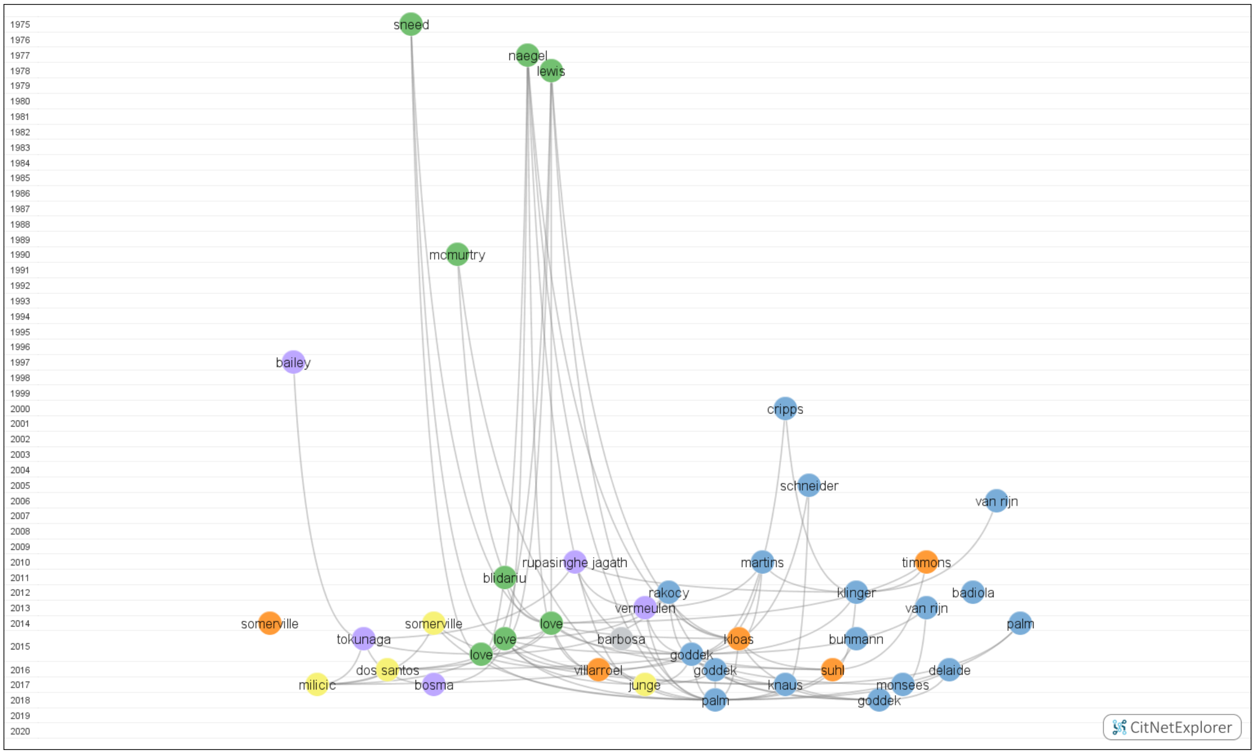


Figure 13: Technical Improvements Sub-Group Citation Network:

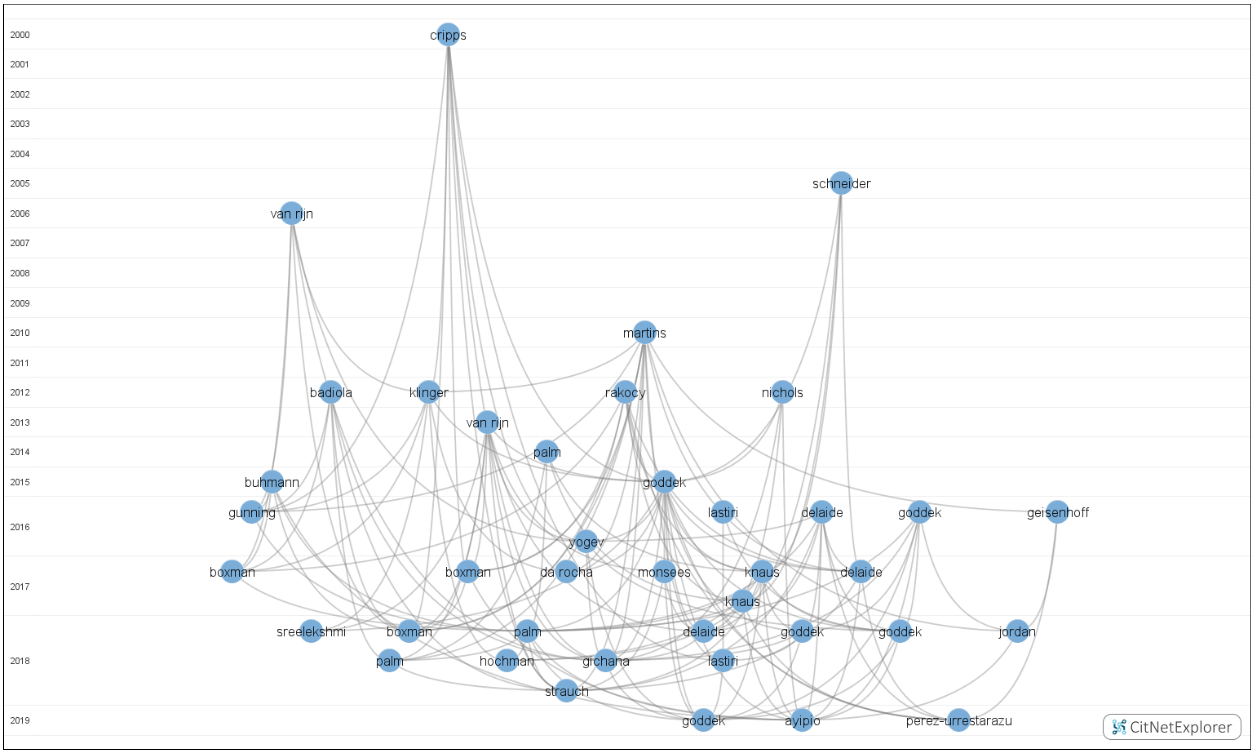


Figure 14: Scalability Sub-Group Citation Network:

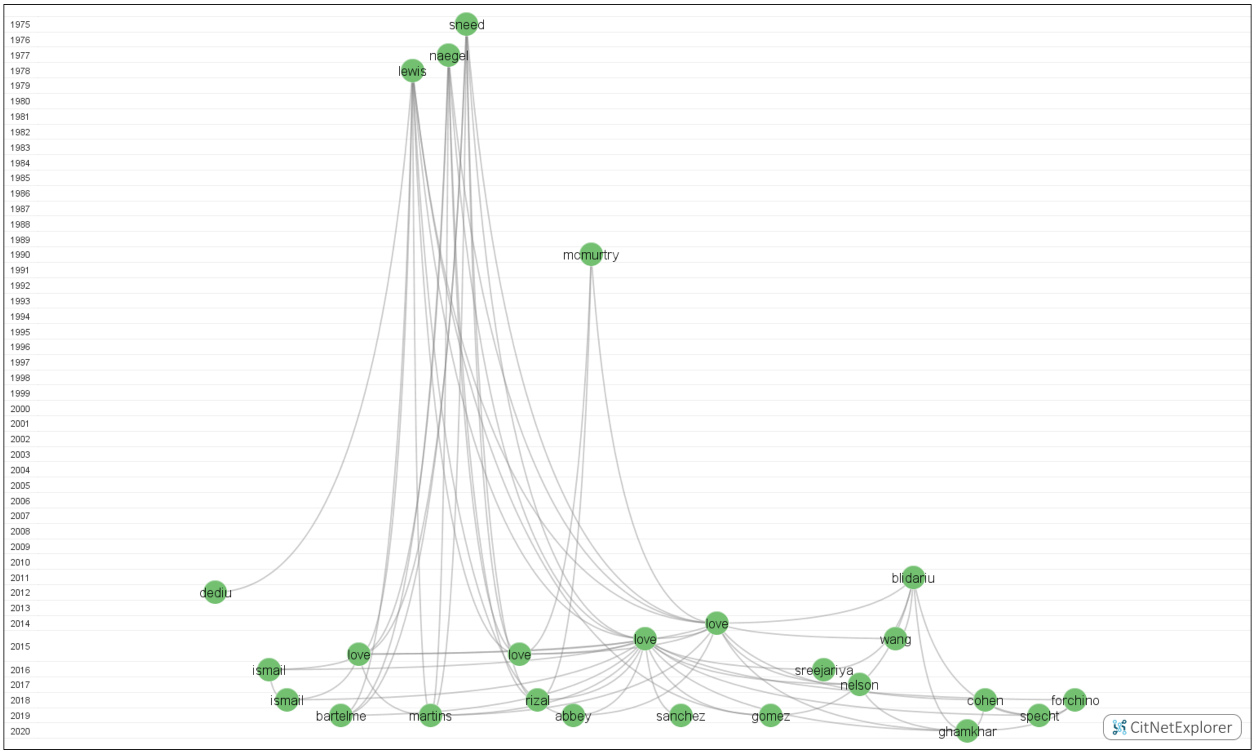


Figure 15: Economics Sub-Group Citation Network:

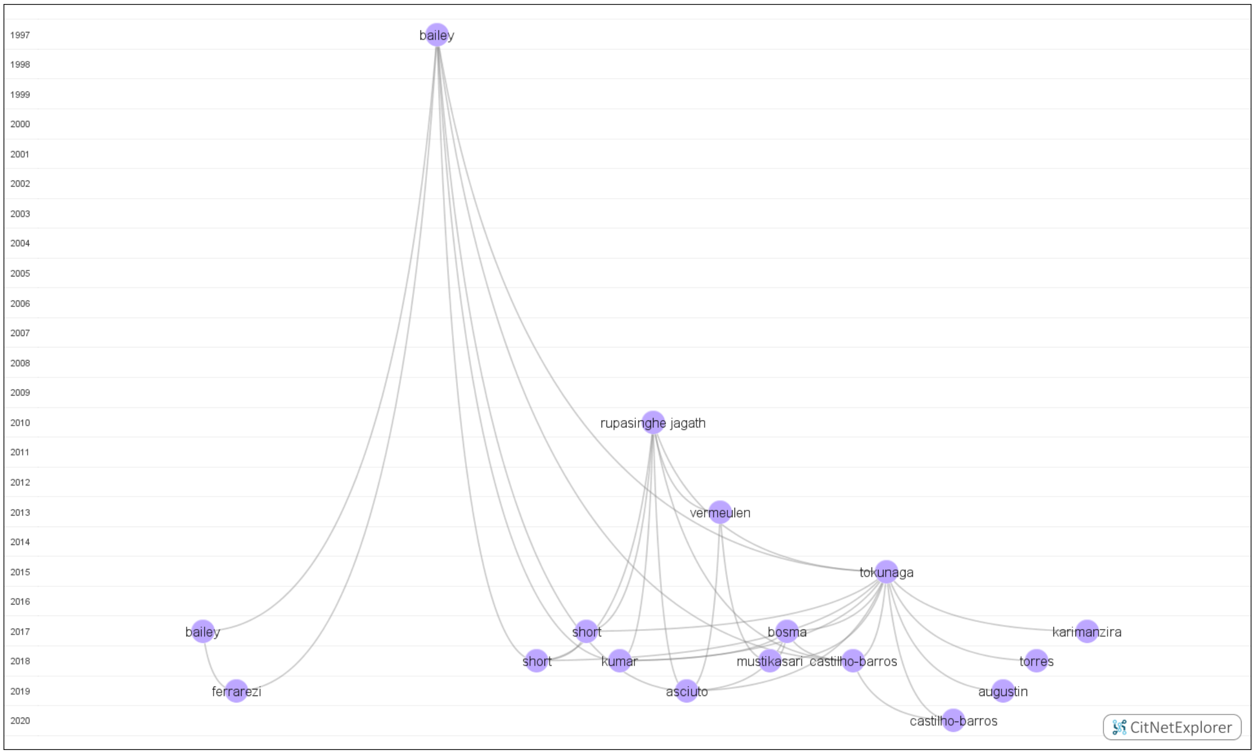


Figure 16: Novel Systems Design Sub-Group Citation Network:

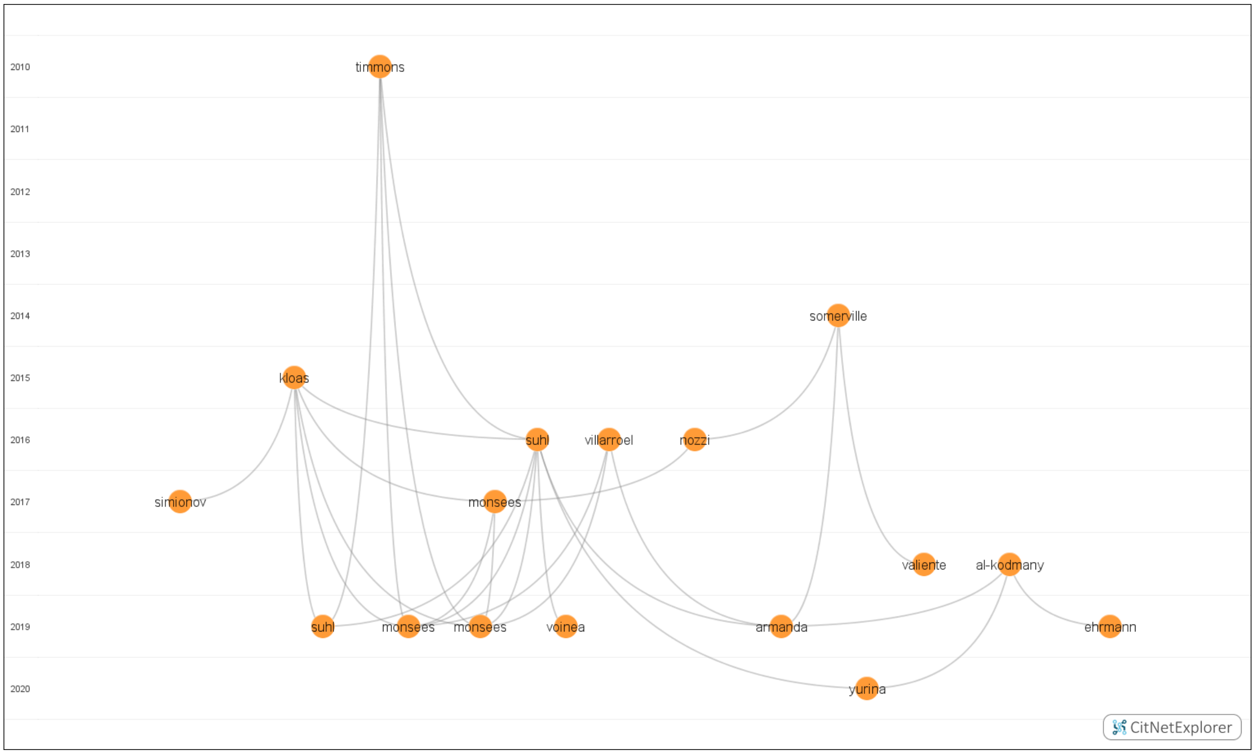
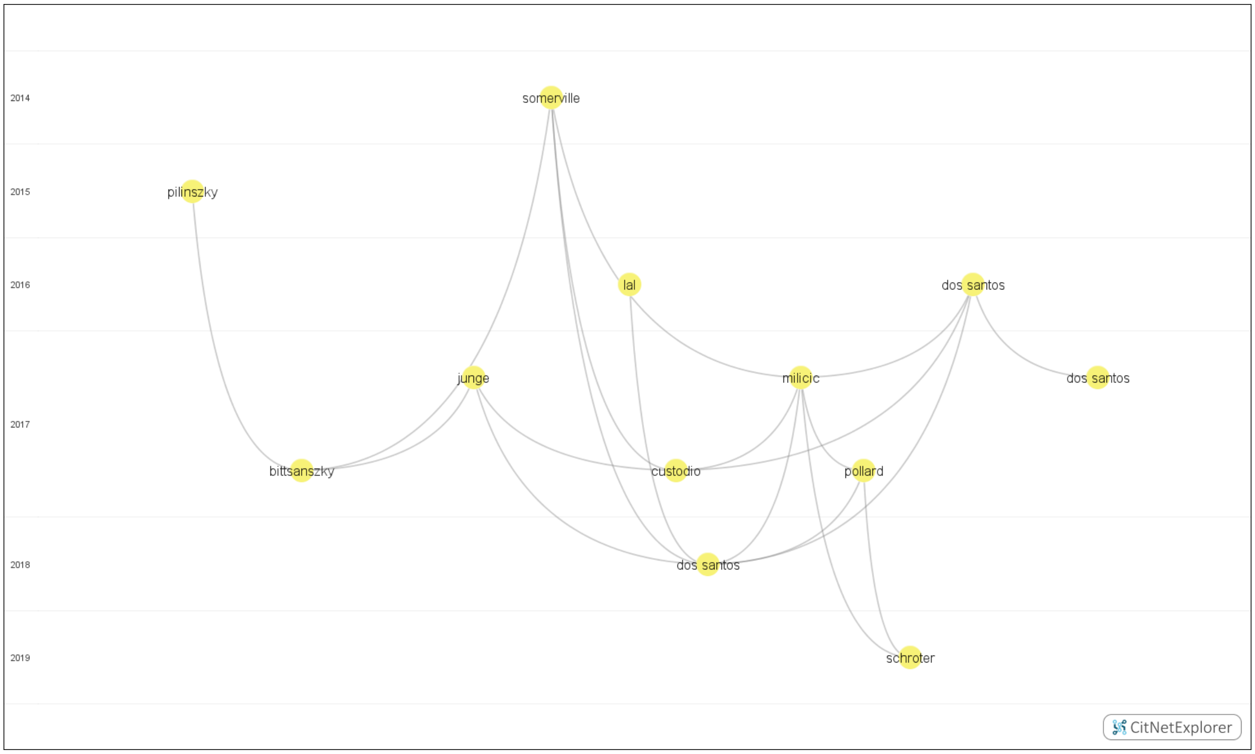


Figure 17: Social Acceptance Sub-Group Citation Network:



Appendix 2: Aquaponics system harvest data

Figure 18: Sustainability without borders aquaponics system:

Description: Left is the aquaculture component of the system, Center is one design for the gravel-based hydroponics components, right is the alternative design for the gravel hydroponics component, unseen to the front is the sump tank which is inset into the ground and spans the tanks from left to right.

Table 3: Lettuce harvest data from aquaponics experiment

Lettuce			
First Harvest		Second Harvest	
Planted	Harvested	Planted	Harvested
40 Plants	31 Plants	45 Plants	41 Plants
With roots and Rockwool (lbs)	Without Roots and Rockwool (lbs)	With roots and Rockwool (lbs)	Without Roots and Rockwool (lbs)
0.4	0.2	0.1	0.04
0.2	0.1	0.2	0.1
0.4	0.4	0.1	0.04
0.4	0.4	0.1	0.06
0.4	0.2	0.2	0.1
0.6	0.4	0.2	0.1
0.4	0.4	0.3	0.2

0.6	0.4	0.4	0.2
0.6	0.4	0.4	0.2
0.4	0.2	0.2	0.1
0.4	0.4	0.2	0.06
0.4	0.2	0.3	0.1
0.4	0.4	0.3	0.2
0.4	0.2	0.4	0.2
0.4	0.2	0.3	0.2
0.4	0.4	0.3	0.2
0.6	0.6	0.1	0.05
0.4	0.2	0.2	0.07
0.6	0.4	0.2	0.1
0.6	0.4	0.2	0.1
0.4	0.2	0.3	0.2
0.4	0.4	0.3	0.2
0.4	0.4	0.4	0.2
0.4	0.4	0.2	0.1
0.4	0.4	0.2	0.1
0.6	0.4	0.2	0.08
0.6	0.4	0.3	0.1
0.4	0.4	0.2	0.1
0.4	0.4	0.3	0.2
0.4	0.4	0.1	0.02
0.4	0.4	0.1	0.03
		0.3	0.2
		0.2	0.1
		0.2	0.1
		0.4	0.2
Total			
Total Yield Weight		Total Edible Yield Weight	
22.2		15.05	

Table 4: Pepper Harvest Data from aquaponics experiment

Peppers		
Edible Produce (lbs)	Inedible Produce (lbs)	Plants (lbs)
0.23	7.41	0.31
0.68	19.4	0.5
0.59		0.57

21.91		2.8
21.8		7.42
		6.5
		3.7
		10.9
		8.6
		13.9
		12.7
45.21	26.81	67.9
Total Food Biomass	Total Plant Biomass	
72.02	26.81	

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