Organic hydroponics
– efficient hydroponic production from organic waste streams

Introductory research essay
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Introduction

In conventional hydroponic production, the nutrient solution contains only dissolved inorganic salts, and organic content is avoided. On the other hand, organic waste streams contain high concentrations of plant nutrients in more or less organically bound form, which already are mineralized and solubilized to varying degree during e.g. wastewater treatment or anaerobic digestion for biogas production [1]. Because of environmental concerns regarding production of synthetic fertilizer and waste management, it is of interest to develop efficient food production systems, in which the advantages of hydroponic cultivation is combined with the large organic waste resources available, not least in urban areas with high population density and lack of cultivable land [2].

There is a need for research that thoroughly examine the possibilities of using various organic waste flows, such as anaerobic effluent from biogas production and aquaculture water effluent, for efficient food production in hydroponic systems [3,4]. The most extensive research in this area is the use of wastewater from aquaculture systems, in integrated recirculating systems for simultaneous production of fish and horticultural crops (aquaponics). Thus, the research and shared experience of aquaponic production systems are useful for comparisons with other existent and hypothetically possible hydroponic systems with organic fertilizers.

In this essay, the peer reviewed scientific literature on hydroponic systems based on organic waste as fertilizer source, is reviewed and different systems and approaches are compared. Reports from *the Food and Agriculture Organization of the United Nations* (FAO) and *the Swedish Board of Agriculture*, are also referred to.

In the sections focusing on different organic waste sources and their respective characteristics with regards to use in hydroponic production, tables of methods and results from the published papers, can be found. The sections are based on the organic waste sources that have been found in the literature on organic input hydroponics: (1) digestate, (2) aerobically treated organic waste (3) aquaculture wastewater, (4) municipal wastewater (5) vermicompost leachate (6) urine.

Definition of organic hydroponics

The term *organic* in the field of horticulture is problematic as it may refer to the use of a fertilizer with a high organic content, as well as the ideological idea of organic agriculture and the definition of organic agriculture as agriculture in which synthetic fertilizers and pesticides are not used, and in which various environmental issues are taken into account [5,6].

In the following text, the term *organic hydroponics* is defined as soilless cultivation in which an organic waste stream is used as nutrient solution. Although *organic input hydroponics* maybe would describe the situation more exact, the former term has been chosen for writing convenience.

In several cases of organic waste resources, the inorganic content can be high. Anaerobic effluent from biogas production (digestate) contains high amounts of inorganic plant nutrients, e.g. ammonium and potassium (see section on digestate), but the use of digestate in hydroponics is here defined as an organic hydroponics system, as the origin of the inorganic mineral content is a result of a biological treatment of an organic waste material.

Research questions

The area of hydroponics with organic fertilizer is vast and research within the field can therefore be based on many possible research questions and hypotheses. The organic hydroponic system that has been most thoroughly researched is aquaculture wastewater based system (aquaponics), with focus on varying aspects of the system such as effect on yield from nitrification, solution filtration and pH adjustment, or economic feasibility of small-scale and commercial-scale systems (see table 1 and section on aquaponics) [4,7–11].

The use of digestate in hydroponic cultivation is considerably less researched and research questions have mainly been focused on appropriate dilution rates, varying nitrate content in lettuce and effects from nutrient supplementation (see table 1 and section on digestate) [3,12,13].

In trials with wastewater as nutrient solution, research questions are in general focused on water treatment aspects, rather than quantity and quality of the produced crop (see table 1 and section on wastewater) [14–16].

Table 1. Examples of research questions and focus for hydroponics with organic fertilizer.

Organic fertilizer source	Research focus	Research question	Reference and journal
Aquaculture waste water (aquaponics)	Effect on yield from nutrient solution treatment	What is the effect of membrane filtration on nutrient solution quality parameters and how does it affect fish weight gain and specific plant growth rate, in a recirculating aquaponic system?	[11] *International Biodeterioration & Biodegradation*
Aquaculture waste water (aquaponics)	Crop physiological response to different EC and pH adjustments	How does typical aquaponic low EC-high pH conditions affect crop growth, yield and crop quality in an ebb-and-flood system, compared to high EC-low pH conditions, typically used in conventional hydroponics?	[10] *Scientia Horticulturae*
Aquaculture waste water (aquaponics)	Crop species effect on water quality parameters and GHG emission	How does cultivation of pak choi and tomato differ in effect on nitrogen use efficiency, N_2O emission and water quality parameters?	[17] *Bioresource technology*
Aquaculture waste water (aquaponics)	pH adjustment effect on GHG emission and plant nutrient content in the solution	What is the effect of different levels of pH on nitrogen use efficiency, nitrogen dynamics and N_2O emissions, in a recirculating aquaponic system?	[9] *Bioresource technology*

Aquaculture waste water (aquaponics)	Case study of input and input costs in relation to marketable biomass output	Is there a net profit for a small-scale DWC aquaponics farm producing various crops and tilapia, accounting for all input costs and sales at farmers market?	[4] *Aquacultural engineering*
Liquid fraction of digestate	Effects of different dilution levels and amino acid supplementation on yield and crop quality	How does different dilution levels of digestate and supplementation of glycine affect yield and nitrate content in lettuce in hydroponic media bed cultivation with digestate as nutrient source?	[13] *Acta Agriculturae Scandinavica*
Liquid fraction of digestate	Effects of dilution level, ammonia stripping and plant nutrient supplementation on yield	What treatments of digestate are necessary for good growth and satisfying yields of tomato and lettuce in a hydroponic system?	[18] *Water science and technology*
Effluent from aerobic mineralization bioreactor with organic fertilizer feedstock	Potential of aerobic mineralization for use of organic fertilizer in hydroponic production	Can fish-based soluble fertilizer be used in a hydroponic system if treated aerobically for mineralization of organic N to ammonium-N and nitrate-N? Is microbial inoculum necessary?	[19] *Soil science and plant nutrition*
Municipal wastewater	Treatment of wastewater and simultaneous production of marketable crop	Can cultivation of roses in a NFT system function as a sufficient purification system for small community urban wastewater effluent and provide marketable roses?	[16] *Water research*
Municipal wastewater	Microbial composition of hydroponic subsystem in treatment of wastewater	Is the nitrogen dynamics in wastewater treatment with hydroponics only due to aerobic ammonium oxidizing bacteria or are other microbial groups involved as well?	[20] *Journal of Environmental Engineering and Science*
Effluent from aerobic mineralization bioreactor with plant residue feedstock	Effect of mineralization bioreactor treatment on plant growth. Effect of filtration of effluent on plant growth.	Is the effluent from treatment of potato plant residue in an anaerobic mineralization tank, an efficient fertilizer in comparison to fertilization with Hoaglands solution and leachate from untreated potato biomass control? Does filtration of the effluent affect yield?	[21] *Advances in space research*

Overview of hydroponic cultivation and organic waste input

Several advantages and disadvantages of hydroponic crop production have been discussed in the scientific and grey literature. As can be seen in table 2, these traits concerns various aspects of horticultural practices, such as large-scale and small-scale production, environmental impact, high-tech and low-tech solutions, availability to arable soil, plant protection issues and production economy [22].

The recirculation of nutrient solution is a central advantage of hydroponic systems. This allows for increased water and nutrient use efficiency, prevents from leaching of eutrophying nutrients (N and P) and allows for increased control of pH and dissolved oxygen and thereby control of emission of e.g. ammonia and N_2O [9,22]. The use of organic fertilizers in soil crop production can lead to a leaching of nitrogen higher than with conventional mineral fertilization [23]. The use of organic fertilizers in soil cultivation can lead to deficiencies of Fe, Mn, B, Zn, Cu, Co and Ni due to very small increases of the soil pH [24]. The possibility to control and monitor an organic fertilizer based nutrient solution in a closed, recirculating hydroponic system, can lead to benefits with regards to nutrient use efficiency, as a result of reduced precipitation, reduced affinity to growing media particles, and no leaching.

Furthermore, the recirculation of nutrient solution in hydroponics is a prerequisite for the integration of a recirculating aquaculture system (RAS) [25,26].

Table 2. Advantages and disadvantages of hydroponic crop production in comparison to soil based systems.

+	-
Food production in non-arable lands, e.g. desert and arid areas, land with high soil salinity or contaminated soil, urban areas, polar regions	Fast spreading of waterborne plant pathogens, mainly species of *Phytophtora*, *Fusarium*, *Pythium*,
Food production for astronauts in space	High set-up cost
Appropriate for urban agriculture as it allows for food production without access to arable land and high yields in small spaces	Generation of waste plastic material and waste nutrient solution
Increased possibilities to avoid soil borne diseases through sterilization	Vulnerable to power outage
High nutrient use efficiency and small or non-existent nutrient leaching in recirculating systems	Need for specialized management knowledge
Reduced water loss in recirculating systems	Dependent on electricity
Educational purposes indoors and in areas with lack of arable lands	
High controllability of external factors, e.g. nutrient availability	
Reduction of agricultural practices such as tilling, weeding and watering	
Light weight NFT systems are suitable for roof-top farming, as they allow for small amounts of nutrient solution and no or nearly no substrate	
Allows a high degree of labour automation	
Appropriate for indoor farming which allows an increased degree of controllability with regards to temperature, lighting conditions and decreased spreading of plant pathogens and pests from the surrounding area	

[2,17,22,27]

Organic waste streams for hydroponic production

In following text, the most common organic waste sources for hydroponics are discussed and their use in hydroponic systems is reviewed. Methods and results from trials with each waste type in hydroponic systems, are summarized in table 3, 4 and 5.

Digestate (anaerobic reactor effluent)

During production of biogas through anaerobic digestion of organic wastes, a digestate with high plant mineral content is produced as a by-product [1]. Due to the high content of inorganic plant nutrients, the liquid fraction from solid-liquid separated digestate is suitable for use in hydroponic cultivation, after dilution to appropriate levels [12,28].

Several risks are associated with land applications of digestate: (1) ammonia emission due to high ammonia content and high pH of digestate (2) nitrous oxide emission (3) N leaching after oxidation of ammonia to nitrate in the field (4) biological contamination of human pathogens [3,29,30]. The use of digestate in recirculating hydroponic systems with pH adjustment through the addition of an acid or through the use of a nitrification bioreactor, may decrease the risk of emissions and nutrient leaching and subsequent acidification and eutrophication [3].

Furthermore, indoor hydroponics may be integrated with biogas production, as heating and CO_2-fertilization then are obtained from methane combustion, while the liquid digestate flows into soil-based or hydroponic system via sedimentation and nitrification subsystems [3,31,32]. Examples of such integration with hydroponic systems, have not been found in the literature.

Research results on digestate in hydroponic systems

Trials with crop production in digestate-based hydroponic systems are few, and mainly lettuce has been tested. Below follows a summary of published material on crop production in digestate hydroponics, found in scientific journals. Summary of methods and results of the trials are presented in table 3.

Lettuce (*Lactuca sativa*) grown in a NFT system with different levels of dilution of digestate from thermophilic digestion of poultry waste, had a root fresh weight not significantly different from control with inorganic hydroponic nutrient solution, when diluted to 100 mg/L ammonium-N [12]. Less dilution (200 and 300 mg/L ammonium-N) led to less growth. A following trial with 50, 100 and 150 mg/L ammonium-N, gave less yield than the previous trials [12].

Tomato grown in perlite and coir media (85% + 15%) and fertigated with digestate from the same source as in trials with lettuce described above, grew slowly and gave small yields [33]. High ammonium concentration and low magnesium concentration was found to be the main factors for inhibited plant growth. By stripping ammonia, replacing lost N with $Ca(NO_3)_2$ and adding $MgSO_4$, deficiency symptoms disappeared and satisfying fruit production was obtained, although lower than in inorganic control [33].

Lettuce grown in pots and fertigated with digestate diluted to 134 mg/L ammonium-N, produced significantly more shoot biomass in treatment supplemented with K_2HPO_4 and EDTA-Fe, in comparison to treatment with no supplementation [34].

Treatments with supplementation with only K_2HPO_4 or only EDTA-Fe did not have significantly higher fresh weight, in comparison to no supplementation. Nitrate leaf concentration varied depending on supplementation and was higher in treatments with added K_2HPO_4 and EDTA-Fe in the solution [34].

Lettuce grown in sand in trays and fertigated with digestate diluted to 120 mg/L and 146 mg/L ammonium, exhibited best growth in dilution to 120 mg/L and with glycine supplementation up to a total N concentration of 210 mg/L N [13]. Nitrate concentration in leaves was significantly lower in treatments with supplementation with glycine, in comparison to inorganic control and digestate with no supplementation [13].

In cultivation of lettuce in a hybrid NFT-ebb-and-flow system, digestate with 223 mg/L TAN was compared to nitrified and clarified digestate with 355 mg/L nitrate-N, with respect to ammoniacal-N, nitrate-N, orthophosphate-P and shoot fresh weight (SFW) [35]. The digestate used in the treatments was taken from the same batch. Shoot fresh weight in untreated digestate treatment was less than 10% of commercial solution control, while SFW of nitrified treatment was 70-75% of control. Furthermore, untreated digestate had a orthophosphate-P concentration of 182 mg/L while nitrified treatment had a orthophosphate-P of almost 0 in nitrified treatment, which was concluded by the authors to be due to bacteria phosphate uptake during nitrification and subsequent sedimentation of bacterial biomass [35]. Despite that nitrification had occurred, pH was 8,15 in nitrified treatment, which may have been a reason to P precipitation and subsequent low ortho-P concentration in the treatment.

In non-aerated DWC systems with chard (*Beta vulgaris subsp. vulgaris*) and different levels of dilution of digaste from mesophilic digestion of food and vegetable wastes, biomass production was up to 10% of that of control [36]. The authors concluded that the low growth was due to low concentration of dissolved oxygen and high concentration of ammonium.

Measurements in the scientific literature on digestate in hydroponics

The analysis in systems using digestate in a hydroponics, concerns several aspects of the system: (1) characteristics of the digestate before and after treatment, during crop growth and after harvest (2) growth parameters of the crop (3) quality of the harvested product.

Most research on digestate in hydroponics focus on the inorganic content of the liquid fraction of the digestate, and dilutions are normally based on initial ammonium concentration [12,13,33,34].

For analysis of crop production and plant growth, numbers of leaves, shoot fresh weight and root fresh weight are normally measured at harvest. In some cases, clorophyll content is measured as SPAD readings [13,34], and nitrate is measured in harvested crop for comparison of varying nitrate accumulation between treatments [13,34].

Table 3. Methods and results from trials with digestate in hydroponic production

Hydroponic system	Crop	Treatment	Comments	Result	Reference
NFT	Lettuce	Different dilution levels	pH adjustment with phosphoric acid	Dilution to 100 mg/L ammonium-N yielded similar to inorganic control	[12]
Fertigation in vermiculite media in pots	Lettuce	Supplementation of K_2HPO_4, and/or EDTA-Fe. Supplementation through foliar spraying or in nutrient solution	No pH adjustment	Supplementation with K_2HPO_4 *and* EDTA-Fe in nutrient solution, led to significantly higher biomass than other treatments	[34]
Fertigation in sand media in trays	Lettuce	Different dilution levels N supplementation with glycine to 210 mg/L total N	pH adjusted to 6,0	Biomass production was significantly higher in dilution to 120 mg/L NH_4^+ with glycine-N supplementation compared to 146 mg/L NH_4^+ with no supplementation	[13]
NFT ebb-and-flow hybrid	Lettuce	Nitrified digestate compared to untreated digestate	High pH in untreated and nitrified digestate (pH 7,4-7,9 and 8,15) High TAN in untreated digestate (223 mg/L) Orthophosphate-P concentration was near 0 in nitrified digestate No aeration in solution tank	70-75% of control SFW yield in nitrified digestate treatment Very low SFW in treatment with untreated digestate	[35]
NFT	Green mustard	Nitrified digestade, untreated digestate and inorganic control	Nitrification in moderately aerated tank inoculated with bark compost for microbial activity	SFW from nitrified treatment was not significantly lower than control, but significantly higher than untreated digestate treatment	[37]
Fertigatation in perlite+coir media in pots	Tomato	Ammonia stripping Nutrient supplementation with $Ca(NO_3)_2$ and $MgSO_4$.	pH adjustment with phosphoric acid Dilution to ammonia-N concentration equal to nitrate+ammonium-N in inorganic control	Replacing of ammonium with nitrate and supplementation with Mg, led to satisfying fruit yield	[33]
DWC	Chard	Different dilution levels	No aearation No pH adjustment	Yielded maxium 10 % of inorganic control	[36]

Unbalanced plant nutrient content in digestate

The high pH of digestate will lead to a high concentration of ammonia, rather than ammonium, and low plant availability of P, Mg and Fe. Adjustment of pH through the addition of an acid or through nitrification, can therefore be suspected to be necessary for optimal plant nutrient availability and avoidance of ammonia toxicity.

High pH during digestion leads to precipitation of phosphates and carbonates, e.g. struvite, calcium phosphate and iron carbonate [1], why digestate may be unbalanced with respect to P, Mg and Fe in relation to e.g. N and K, for optimal plant growth. Supplementation with mineral or organic fertilizer containing plant available P, Mg and chelated Fe to the digestate, has therefore been needed to acquire a balanced nutrient solution for optimized production in an organic hydroponic system (see table 3). This can be compared to aquaponic systems in which concentrations of K, Ca and Fe often are to low, why the recommendation is to add these separately to the system [25].

The plant nutrient content of a digestate varies depending on what substrate has been digested [1]. Supplementation with Mg in trials with tomato, led to a yield increase to a satisfactory level [33]. This may be due to low content of Mg in the liquid fraction of the digestate as a result of precipitation of Mg during digestion [1]. High K levels have been found in the liquid fraction of digestates derived from plant waste, and may lead to inhibition of Mg uptake when used in a hydroponic system. The K/Mg ratio in plant derived digestate from a large-scale mesophilic biogas plant, was 30:1 when untreated and 17:1 after nitrification [38]. In trials with poultry waste digestate, K/Mg ratio was 16:1 [33].

Risks with digestate

Spore-forming pathogenic bacteria, e.g. *Clostridium perfringens*, can survive mesophilic and thermophilic anaerobic digestion [39]. Faecal coliforms and *E. coli* have been found in digestate from mesophilic digestion, and were found 15 days after application of digestate to soil [39]. After 60 days, no faecal coliforms were detected in soil amended with digestate.

In the journal papers on digestate in hydroponics, generally no focus has been on the food safety aspect of the system, which is remarkable for trials on food production systems with waste derived fertilizer [3]. Most research is conducted from a wastewater treatment perspective, in which optimization of crop growth and quality, and thereby food safety issues, are of secondary importance.

Research on digestate hydroponics in China

Wen Ke Liu et al. (2009) have reviewed several papers published in Chinese, on yield and quality of vegetables produced in hydroponic systems with digestate. Economically feasible yields of lettuce, cucumber, pepper, tomato, water spinach (*Ipomea aquatica*) and malabar spinach (*Basella alba*) have been obtained in hydroponic systems with modified digestate solution [28]. Reports on soluble sugar content, acidity, amino acid and vitamin C content have been contradictory, while findings on significant plant nitrate content decrease, is consistent in all studies on digestate in hydroponics [28].

Conclusions on digestate based organic hydroponics

Research on the use of digestate in hydroponic systems have up to date mainly been conducted from a wastewater perspective, and has therefore in many cases not focused on optimizing of biomass production aspects in the tested systems. Focus has been on different levels of dilution, and over all plant nutrient levels in the solution has therefore been limited by highest concentration possible of ammonium/ammonia.

Furthermore, basic principles of hydroponics such as aeration for sufficient concentration of dissolved oxygen and pH adjustment, have not been adhered to in all experiments. It could be suspected that aeration would be of utmost importance for achieving sufficient oxygen uptake by plant roots in a digestate based nutrient solution, as competition in oxygen uptake from heterotrophic bacteria will be greater than when using a pure inorganic nutrient solution.

Nitrification through the use of a nitrification reactor is needed for production of ammonium sensitive crops such as tomato and cucumber. It could also be suspected to be necessary for reaching an optimized general plant nutrient concentration, as a decreased ammonium:nitrate ratio allows for smaller dilution of the digestate. Untreated liquid fraction of digestate can be appropriate for hydroponic production of short cultures that are not sensitive to high ammonium levels, such as lettuce.

Future research on digestate based hydroponics

The use of digestate as a fertilizer in general and specifically in hydroponic systems, needs to be further explored and several aspects remain to be researched further [3,28,40].

For a deepened understanding of hydroponic systems based on digestate fertilizer, the study of several different aspects of such a system would be useful: (1) food safety issues depending on digestate source and pre-treatment of digestate, (2) plant protection issues, (3) integrated bioreactor subsystems for improved growth and plant protection, (4) evaluation of the necessity of integrated mechanical filtration subsystems (5) comparison between digestates derived from different waste sources (6) nutrient supplementation (7) use of other by-products related to digastate and biogas production, such as supplementation with struvite and mineralization of solid fraction of digestate for use in a hydroponic system.

It has been argued that increasing fossil fuel prices, climate change and environmental pollution and subsequent increase in agricultural input cost will increase the interest of using digestate in domestic, small-scale biogas plant contexts [40]. It could therefore be argued that research on digestate in hydroponic systems of large scale, as well as small scale, is needed.

Aerobic bioreactor effluent

Trials with hydroponic systems based on effluent from aerobically treated organic waste, are found in papers by Shinohara et al. and in papers related to closed ecological systems for food production in space, promoted by NASA. Both research groups have produced hydroponic inorganic nutrient solutions through mineralization in aerated tanks.

Aerobic reactor for mineralization of fish-based soluble fertilizer and food waste

Fish-based soluble fertilizer has successfully been mineralized for use as hydroponic solution for cultivation of lettuce and tomato [19]. Inorganic nutrient solution with 210 mg L^{-1} nitrate-N and 8,3 mg L^{-1} ammonium-N was obtained by aerating a water mixture of 1,5 g L^{-1} fish-based fertilizer and 1 g L^{-1} bark compost, for 170 days. Shorter aeration time (33 days) but same proportions of fish-based fertilizer and bark compost inoculum, led to 164 mg L^{-1} nitrate-N and 9 mg L^{-1} ammonium-N [19].

Efficient mineralization of dried and milled food waste, was acquired with a similar method [41]. Food waste was added 1 mg a day for 4 days. Bark compost was put in fabric bag and was removed after nitrite-N concentrations was exceeding 0,5 mg L^{-1}. The solution was aerated for 64 days.

Lettuce grown in mineralized fish-based fertilizer solution, had a mean SFW significantly higher than lettuce grown with conventional hydroponic fertilizer [19]. Lettuce grown in mineralized food waste-based solution, had a SFW slightly lower than control, but was not significantly different [41]. Total fruit yields of tomato in mineralized fish based fertilizer and control, was not significantly different [19]. In treatment with conventional hydroponic fertilizer with addition of fish-based fertilizer that was not aerobically treated, lettuce performed well while tomato did not survive [19]. This was concluded to be due to high ammonium-sensitivity for tomato, while lettuce is tolerant to high concentrations of ammonium.

Aerobic reactor for mineralization of plant residue and subsequent NFT crop fertilization

For the development of regenerative food production for long term stays in space, NASA has conducted research on closed loop systems for the use of produced organic waste in hydroponic food production systems within a closed chamber, denominated Controlled Ecological Life Support System (CELSS) [42]. For mineralization of the obtained organic waste, e.g. inedible parts of potato plants, an aerobic bioreactor has been developed and tested for production of a nutrient solution for NFT food production [21,43]. The aerobic mineralization reactor has treated 6-12 L of bioreactor liquid with a solids loading <50 g/L and has functioned through the combined action of aeration and impeller stirring, in order to maintain sufficient concentration of dissolved oxygen and an optimized mineralization rate [43].

In trials with potato grown in NFT with aerobic reactor effluent fed with inedible parts of potato plant, potato tuber yield from treatments with effluent was equally high as or higher than yields from control with half-strength Hoalands solution [21]. Macronutrient content of potato plant derived aerobic effluent was: 70 mg/L NO_3-N; 6 mg/L PO_4-P; 39 mg/L K; 16 mg/L Ca; 10 mg/L Mg [21].

In contrast to digestate from anaerobic digestion, where the effluent in general is considered a by-product and the biogas is the primary product, the aerobic mineralization reactor in the CELSS projects referred to above, functions as a liquid compost in which the effluent is considered the primary product. As the aerobic mineralization process allow for simultaneous nitrification due to high pH and dissolved oxygen, the inorganic N content in aerobic effluent is mainly nitrate-N, while anaerobic effluent contains mainly ammonium-N [1,43].

Integration of anaerobic digestion, aerobic yeast production, nitrification and hydroponic subsystems

Anaerobic bioreactors with the purpose of producing yeast growth media and plant mineral solution in an integrated system, have been tested in research on CELSS [44,45]. The intention with such a system was to prevent methanogenesis in anaerobic bioreactor, in order to allow for subsequent aerobic yeast (*Candida ingens*) production with the partially digested waste. Effluent from the yeast reactor were then supplemented as needed for appropriate plant nutrient balance and used for NFT cultivation of potato with or without a nitrification pre-treatment [45]. Treatment with no nitrification yielded similarly to inorganic control, and the nutrient solution obtained from an integrated anaerobic digestion/aerobic yeast growth system, was concluded to be low in plant available nitrogen but useful as an acid buffer solution for use in hydroponic cultivation [45].

Aquaculture water (aquaponics)

The use of aquaculture wastewater in hydroponics is known as aquaponics and has gained considerable popularity since it started to evolve to its present form, in the late 1970s [46]. Aquaponics systems exist in many forms, and ranges from small hobby projects to larger commercial systems. It has been promoted by FAO as an appropriate cultivation method for small-scale domestic production, especially in areas of little availability of land, fertile soil and water [2]. The minimized use of water is a central advantage of aquaponics. According to FAO, several of the strategic goals of the organization can be associated with the use of small scale aquaponics – solutions for regional water scarcity, efficient use of resources and sustainable intensification of agriculture [2].

Aquaponic systems integrates methods developed from the hydroponics and the aquaculture industry and is influenced by ideas from permaculture and organic agriculture [46].

In an aquaponic system, hydroponic and aquaculture fish systems are parts of one recirculating system in which solids are continuously separated from the solution and ammonia oxidized to nitrate in a nitrification subsystem [25]. Additional subsystems for filtration, degassing and mineralization are sometimes included. Being a complex, integrated system, research on aquaponics need to take into consideration several aspects and how these factors impact the overall productivity and stability of the system (see table 1 and 4).

Supplementation of nutrients in aquaponics

Aquaculture wastewater has in general a low EC and low concentrations of K, P and Fe, when compared to conventional hydroponic nutrient solutions [10 25]. In trials with aquaponic systems supplementation of K, P, Mg, S and Fe [26], has been made in order to increase EC and plant nutrient availability of these nutrients.

Recommendations by Rakocy regarding nutrient supplementation, is addition of K and Ca in the form of KOH and $Ca(OH)_2$ in order to simultaneously increase pH [25].

Nitrification and subsequent pH adjustment in an aquaponics system

Due to constant ammonia excretion from fish gills, a proportional level of ammonia and nitrite removal is necessary in order to avoid toxic levels for the fish (levels above 0,5 mg/L NH_3) [7]. Therefore, a nitrification subsystem is included in aquaponic systems, either through a nitrification bioreactor or nitrification within media in media bed type aquaponics [25,47].

As ammonia removal is crucial for fish survival, pH in aquaponics systems are adjusted to close to pH 7, in order to compromise between optimal pH for nitrification (above pH 7,0) and optimal pH for hydroponic production (5,8-6,2) [7,25,48]. During nitrification pH decrease and needs therefore to be adjusted with a base. As described above, Rakocy et al. therefore recommends to add K and Ca as hydroxides [25].

Methods and results from research on aquaponics

Research on aquaponics has been conducted with regards to several aspects of an aquaponic system, e.g. comparisons of hydroponic subsystem, flow rate, comparisons of solution parameters depending on cultivated crop, emissions of N_2O, nitrogen dynamics, fish density and different transplanting and harvesting schemes (see table 4).

Among tested crops, lettuce is the most common crop for trials with aquaponics. In the articles listed in table 4, basil, tomato, cilantro, water spinach and pak choi have also been used as test crops.

Conclusions

The integrated aquacultural and horticultural production is based on a recirculating aquaculture system (RAS) in which the hydroponic subsystem absorbs ammonium, nitrate and mineralized waste from the fish, thereby avoiding toxic concentrations of accumulated fish waste in the system, most importantly ammonia. Nitrification of ammonia and mineralization of solids and dissolved organic molecules, are taken care of with various more or less advanced technical solutions, depending on what kind hydroponic system and what kind of bioreactors that are used. The various approaches for handling a recirculating organic waste stream within an aquaponic system, can hypothetically be applied to other sources of organic wastes and byproducts for use in a hydroponic system.

Various aspects of an aquaponic production system have been researched, and further research on those aspects would be applicable and of interest in other hydropnic systems based on organic waste input.

Table 4. Examples of methods and results from trials with crop production in aquaponic systems

Hydroponic system	Crop	Treatments	Comments	Result	Reference
Gravel media bed	Lettuce	(1) Flood and drain (2) Constant flow	TAN, NO_2^-, NO_3^-, PO_4^{3-}, EC, pH and DO was measured in nutrient solution	Harvest at 21 DAT (1) SFW: 113,4 g Yield: 4,34 kg m^{-2} (2) SFW: 130,0 g Yield: 4,97 kg m^{-2}	[49]
DWC	Lettuce	(1) Low fish density (2) High fish density (3) Hydroponic 1,7 dS m^{-1} pH 5,5	20 plants m^{-2} TAN, NO_2^-, NO_3^-, EC, pH and DO was measured in nutrient solution Chlorophyll content was measured with SPAD	Harvest 28 DAT (1) SFW: 118,6 g Yield: 2,37 kg m^{-2} (2) SFW: 135,3 g Yield: 2,71 kg m^{-2} (3) SFW: 142,2 g Yield: 2,84 kg m^{-2}	[26]
DWC (UVI system)	Basil	(1) batch aquaponic (2) staggered aquaponic (3) staggered in soil + cow manure	8 plants m^{-2} TAN, NO_2^-, NO_3^-, TDS, EC, pH and DO was measured in nutrient solution Feed input ratio for tilapia + basil was calculated	(1) SFW: 286 g Yield: 2,0 kg/m^2 (2) second harvest SFW: 327 g Yield: 2,4 kg/m^2 (3) second harvest SFW: 159 g Yield: 1,0 kg/m^2 (Dato from earlier hydroponic basil trials Yield: 6,25 kg/m^2)	[50]
DWC	Tomato	Flow rates (1) 4 L h^{-1} (2) 5 L h^{-1} (3) 6 L h^{-1}	NH_3, NO_2^-, NO_3^-, P, K, Ca and Mg was measured in nutrient solution	Yield increased with increased flow rate (1): 1,06 kg $plant^{-1}$ (3): 1,37 kg $plant^{-1}$	[51]
DWC with air space, no water aeration (aka Kratky method)	Pak choi Cilantro	(1) pak choi (2) cilantro (3) RAS (no hydroponic subsystem)	TAN, NO_2^-, NO_3^-, PO_4^- and DO was measured in nutrient solution Pak choi plant density was 20 plants/m^2	(1) 34 DAT SFW: 117±61 g/plant Yield: 2,5 kg/m^2 (2) Low survival and yield due to fungal infection NO_3^- and PO_4^- was significantly lower in aquaponic systems compared to RAS control	[52]
DWC	Water spinach (*Ipomea aquatica*)	(1) With membrane for increased filtration (2) Without membrane	TAN, NO_2^-, NO_3^-, pH, DO, BOD, COD, SS, transmembrane pressure, total bacterial count and turbidity was measured in nutrient solution	(1) 74 DAS SFW: 907,2 g (2) 74 DAS SFW: 680,8 g	[11]

Municipal waste water

Cultivation of plants for treatment of wastewater has been tested in hydroponic systems at different stages of the water treatment process and with varying sources of wastewater. The overall objective with hydroponic treatment of wastewater is to achieve a sufficient level of purification efficiency with respect to BOD_5, COD_{Cr}, suspended solids, N and P and reach concentrations below discharge standards, e.g. 15 mg/L BOD, 20 mg/L N and 0,5 mg/L P [14,16,53].

Yields from trials with hydroponic wastewater treatment

Cultivation of *Chrysanthemum cinerariafolium* in a NFT system with a mixture of urban stormwater and sewage waste water, gave sufficient purification for discharge of treated water and good yield and quality of pyrethrins for insecticide use [54].

In sufficiently aerated NFT systems with secondary treated wastewater and crop production of chard, low levels of nitrate in the waste water led to considerably lower yield than in treatments with commercial hydroponic fertilizer [55].

In cultivation of *Rosa hybrid* for production of saleable rose cut flowers in a NFT system with domestic waste water, quantity and quality of harvested product was not significantly different from cultivation with conventional fertilizer [16]. Purification efficiency of COD, BOD_5, suspended solids, total N and total P was concluded to be reached after 24 hours of recirculation, as a result of plant and bacterial uptake [16]. Equivalent results with respect to plant growth and purification efficiency, was achieved in a similar NFT system with *Datura innoxia* plant .

Cultivation of giant reed (Arundo donax) for biomass production in pig's waste, yielded similarly to soil grown plants, although P supplementation led to significantly higher yields, due to low P content and high pH in pig's waste solution [15].

Nitrification inhibition due to high organic loads

Under high organic loads, nitrification is hindered because of competition from heterotrophic bacteria [16,53]. Nitrification has observed to increase when BOD_5 levels have decreased below 45 mg/L [53].

Plant root biofilter effect

Plant roots provides habitats and high surface area for biofilm production for heterotrophic and nitrifying bacteria [14,16,53]. Hydroponic treatment of liquid waste therefore not only acts through plant uptake of N and P, but also indirectly by providing a beneficial environment for microbial colonization and activity, forming a biofilter in the root zone [14,16,53]. The nitrification rate in a hydroponic root zone biofilter have been found to be less effective than in other biofilm systems, although sufficiently high for sufficient N removal for tertiary wastewater treatment [14].

Table 5. Methods and results from trials with waste water and hypertrophic water in hydroponic production

Hydroponic system	Crop	Treatment	Comments	Result	Reference
NFT	Cut roses (*Rosa hybrida*) *Datura innoxia*	Treatment in NFT channels with and without plants Secondary treated waste water	Sufficient aeration for bacterial and plant growth, through 30 cm waterfall from NFT channel to nutrient tank (4-5 mg/L DO)	No significant difference in quantity nor quality of wastewater produced cut roses, in comparison to conventional control	[16,53]
NFT	*Chrysanthemum cinerariaefolium* for production of pyrethrins	NFT channel with and without plants Comparison between system behavior in winter, spring and summer	Water quality parameters were measured: pH, DO, SS, COD, BOD_5, Total N, Total P, inorganic nitrogen dynamics Plant growth, water content, flourescense pyrethrins production was measured	Purification to permitted levels of discharge was reached. Plant growth and pyrethrins production was not negatively affected by the water solution.	[54]
NFT	Lettuce	(1) undiluted (2) 1:1 dilution (3) 1:3 dilution (4) conventional nutrient solution Primary treated municipal wastewater	Concentration of P was considered limiting nutrient for plant growth and effluent quality Sufficient DO (5 mg L^{-1}) due to circulation in NFT system	Growth rate highest to lowest: (4) (2) (1) (3). Low K content was though to be limiting factor for (1) (2) and (3). Toxic fatty acid and metal content was thought to be limiting factor in (1).	[56]
NFT	Chard	Comparison to commercial hydroponic fertilizer	Sufficient aeration Low nitrate concentration	Yielded ~50% of control	[55]
Recirculating gravel bed system	Giant reed (*Arundo donax*) for biomass production	Comparison to soil grown plants without fertilization and between treatments with or without phosphoric acid supplementation. Pig's waste diluted to 5 dS m^{-1}.	Nutrient solution was replenished regularly in order to keep 5 dS m^{-1} in reservoir	Yielded similarly to soil grown plants in treatment without supplementation: 1,2-1,5 kg/m^2 DM Yielded significantly higher with P supplementation: 2,0-2,3 kg/m^2 DM	[15]

Multifunctionality of hydroponic wastewater treatment facilities

It has been concluded that the potential multifunctionality of a hydroponic wastewater tertiary treatment system, is an advantage compared to conventional biological and chemical water treatment techniques [14]. Beside the potential for crop production, attraction of visitors to innovative and visually interesting green technology treatment systems, can inspire to discussion on and eventually lead to a deepened understanding of waste production and management [14,16,53,54].

Vermicompost leachate

A research approach on hydroponic cultivation based on vermicompost leachate have only been found in a throrough report by Midmore et. al (2011), in which a number of factors influencing such an integrated food production system, has been tested. See section on *Small-scale hydroponics* and *Integration of waste producing component with hydroponic system* for comments on yield, system set-up and vermicompost integration with hydroponics.

Urine

The use of urine separating toilets is a means of facilitating the use and recycling of human excreta, as feces and urine have remarkably different characteristics with regards to plant nutrient content and COD [57–59]. Through the use of flush toilets, feces contaminate large amounts of water, meanwhile urine - which contains the major part of the soluble nutrients - is diluted to approximately 1:100 [57]. Consequently, separate and possibly decentralized handling of urine and feces can lead to reduced treatment and fertilizer costs, compared to centralized water-based sanitary systems [60].

Precipitation and nitrification methods for urine have been researched and developed, in order to handle issues with storing, transportation and spreading of large volumes of urine on farmlands [58,61–63]. These methods include struvite precipitation through the addition of magnesium of varying sources (including low cost and waste sources), nitrification in moving bed biofilm reactor, distillation with reduced air pressure, and ammonia stripping with subsequent absorption in sulphuric acid [61,62,64].

Hygiene issues are also central in the use of urine for agriculture purposes. Human urine have been considered safe regarding pathogenic organisms, after storage with pH control and elevated ammonia concentration as a result of hydrolysis [63,65]. The increasing ammonia concentration due to urine hydrolysis reduces pathogenic microorganisms. Concentrations of ammonia higher than 40 mM NH_3 (680 mg/L NH_3) in temperatures above 20 °C leads to a sufficient reduction of pathogens after less than 6 months, for use of urine in fertilization of food crops [65]. Storage at 34 °C with $[NH_3] > 40$ mM shortens the storage time significantly for safe use for food crops, and 2 months of storage at low temperature (down to 4 °C) is sufficient for use in non food crop production if $[NH_3]$ is above 40 mM during storage [65].

Urine in hydroponic production

In order to use urine in a hydroponic system, the nitrogen – which in fresh urine is found mainly as urea – needs to be converted to ammonia through hydrolysis. Conductivity can be used as a process indicator for urine hydrolysis, due to increasing ammonia concentration [66]. A minor fecal cross-contamination of collected urine from urine separation toilets, leads to infection of urease-positive bacteria (e.g. *Proteus*) from the feces, and thereby speeds up the hydrolysis process in comparison to hydrolysis of urine that has been sterilized or pretreated with centrifugation [66].

Urine pretreated with hydrolysis, induced partial struvite precipitation and ammonia stripping was used as nutrient solution in experiments with hydroponic cultivation of water spinach (*Ipomea aquatica)* in troughs without aeration [67]. Lettuce (*Lactuca sativa*), lawn (*Hydrocotyle sibthorpioides*) and golden pothos (*Epipremnum aureum*) were also tried, but did not grow sufficiently in the system. Water spinach is an aquatic species and may therefore be problematic as a representative crop for hydroponic food production, as food crops in general are terrestrial species [68]. When pretreated urine was diluted to 1:50 (initial [NH_4^+-N] = 17,62 mg/L), growth rate and leaf number were comparable to control with commercial fertilizer, lower dilution ratio led to plant growth inhibition, which was thought to be due to high NH_4^+-N and/or high salinity [67]. Initial nitrate levels were low in low dilutions of pretreated urine, but increased rapidly in 1:50 dilution [67]. As no nitrification pretreatment was applied, the low nitrification rate in lower dilutions could be due to inhibition of AOB and NOB due to salinity and ammonia/ammonium levels. There was a small accumulation of nitrite in some treatments, which indicates inhibition of NOB due to high ammonia levels.

Integration of microbial and mechanical subsystems in organic hydroponic systems

A hydroponic system that uses organic waste as a source for plant nutrients, require integration of microbial subsystem in order to make available plant nutrient ions through mineralization, and for conversion of ammonia to nitrate [19,21,33]. In order to obtain a nutrient solution with a low level of suspended solids, mechanical filtration may also be integrated in an organic hydroponic system.

Varying aquaponic set-ups from research trials, hobby and commercial systems, exemplify such integration through the use of nitrification bioreactors of different sorts, mineralization reactors, sedimentation tanks, filtering equipment etc. [11,25,69–71].

In the case of digestate, many methods are used for separating the digestate in a solid and liquid fraction [72]. Examples of integrated solids filtration subsystems for digestate based hydroponics, have not been found in the literature.

Depending on waste source and preparation of organic nutrient solution, integrated microbial and mechanical subsystems are needed to varying extent.

Integration of nitrification and mineralization subsystems in hydroponic system with digestate

When using digestate from biogas production, mineralization is reached to a high extent during anaerobic digestion, and plant nutrients that do not easily precipitate are maintained in the liquid fraction of the digestate [1]. Therefore, the liquid fraction of the obtained digestate is suitable for direct application in a hydroponic system when diluted to appropriate levels, especially in the case of lettuce production [12,13].

As methanogenesis is an anaerobic process, no nitrification occurs and the inorganic nitrogen in the digestate is therefore almost exclusively ammonia/ammonium [1]. In order to avoid ammonium toxicity, decreasing the ammonium:nitrate ratio and allowance of lower dilution levels of the digestate in order to obtain higher concentration of other plant nutrients, a nitrification subsystem can be incorporated [33,35]. Depending on initial levels of ammonium in relation to other plant nutrients in the digestate, ammonium stripping may also be of interest, in order to obtain a balanced level of plant nutrients [33]. In digestate from anaerobic digestion with only plant material, the ammonium concentration has been around 2500 mg/L (Analysis from Jorberga biogas plant, Sweden). From digestion of substrates with higher nitrogen content, e.g. animal manure, the obtained digestate will have higher ammonium concentrations [1].

During anaerobic digestion, phosphates, magnesium, calcium and ammonium easily precipitates as struvite and calcium phosphate due to high pH, resulting in lower concentration of these nutrients (except for ammonium) in the liquid fraction, compared to content of potassium and ammonium [18,1]. In order to utilize precipitated salts bound to the solid phase of the digestate, as well as plant nutrients not yet mineralized and bound in organic molecules, a mineralization reactor can make available these plant nutrients before adding the liquid to the hydroponic system. A mineralization bioreactor could hypothetically be integrated within the recirculating system, as is done in some hydroponic and aquaponic systems [19,70,71].

Nitrification and pH

The optimal pH for oxidation of ammonium and nitrite has been found to be 8,2 ± 0,3 for AOB (nitritation) and 7,9 ± 0,4 for NOB (nitratation), from empirical modeling based on nitrification batch experiments where the maximum specific substrate utilization of ammonium and nitrite was measured in treatments with different pH levels [48].

In aquaponic systems, pH of the nitrification subsystem does not only affect the nitrification efficiency, but also pH of the hydroponic and aquaculture production units within the recirculating system. In trials with aquaponic production of tilapia and cucumber, ammonia biofiltration through a perlite trickling filter gave a total ammoniacal nitrogen (TAN) removal of 19, 31 and 80 g * m^{-3} * day at pH 6,0; 7,0 and 8,0; respectively [7]. The TAN removal rate increased linearly while cucumber yield decreased linearly, with increasing pH from 6,0 to 8,0 in the abovementioned trials. (Tilapia vigor increased with increasing pH.)

Nitrite accumulation and aeration

Nitrite accumulation (partial nitrification) can be desirable in denitrification of effluents with high ammoniacal concentration, as it allows for direct denitrification of nitrites, which makes the denitrification process shorter and more cost-effective than via two-step nitrification. In nitrification for nitrate production for fertilizer purposes, nitrite accumulation must be hindered in order to obtain an efficient nitrification process. Nitrite accumulation can occur as a result of (1) high temperature (above 25 °C have led to higher specific growth rate for AOB than for NOB), (2) high pH and high concentration ammonia (3) low dissolved oxygen [73–75].

Aeration and dissolved oxygen in nitrification reactors

The aeration in a moving bed biofilm reactor allows for oxygen transfer to the liquid media and for movement and circulation of the biofilm carriers through proper air bubble distribution in the reactor. In reactors with continuous flow a dissolved oxygen (DO) concentration of 6,5-7,0 mg/L has been sufficient, while the sequencing batch biofilm reactor DO was varying along the feeding cycle [76].

Overload, ammonia loss and solids content in digestate

Overload of a nitrification reactor can occur when high concentration of free ammonia, due to high input of digestate and high pH, inhibits nitrifying organisms, and can easily be detected through pH measurement (slow or no pH drop) [77].

Ammonium and ammonia loss due to ammonia stripping and assimilation into microbial cells have been observed to be up to 27 % of the ammonium content [77].

In trials with nitrification of digestate from municipal organic wastes with an ammonium concentration of 1700 mg/L, sequenced batch reactors with activated sludge were fed once per day by exchanging ~1,5 % nitrified effluent to digestate. [77]. Within one feeding cycle pH dropped up to 3 units. Activated sludge reactors fed with pre-settled digestate had a steeper pH drop than unsedimented digestate, which was thought to be due to additional buffer capacity as a result of dissolution of the solids [77].

The sedimentation of digestate from organic municipal waste increased after nitrification in a sequence batch nitrification reactor [77]. It has been discussed that complete separation of liquid and solid fraction may have disadvantages, as solids in the digestate contribute to higher buffer capacity and additional plant nutrients [77].

Nitrification and subsequent pH drop and dissolution of solids, therefore could lead to higher P and Mg content of the liquid fraction during nitrification of digestate with mixed solid and liquid fraction. Nevertheless, high content of solids in aquaponic systems has an inhibiting effect on plant growth, as accumulation of sludge leads to anaerobic zones and higher heterotrophic bacterial acitivity, leading to decreasing levels of dissolved oxygen and risk for anaerobic production of toxic metabolites [11,25].

Mineralization with bioleaching

Various bacteria and fungi possess the ability to solubilize organically bound minerals via lowering of pH and solubilizing enzymes. In order to solubilize plant nutrients bound to suspended solids gathered from clarifiers and sedimentation tanks in aquaponic systems, bioleaching methods have been proposed [69].

Addition of 1 mol L^{-1} lactic acid to sludge from aquaculture production, led to an higher increase of P and Fe in the permeate, than addition of the same concentration of HCl [78]. This was thought to be due to a chelating effect of the lactic acid (as well as acetic acid). When comparing *Lactobacillus plantarum* with *L. buchneri* as bioleaching agents, *L. plantarum* in contrast to *L. buchneri* is a homo-lactic fermenter and therefore yields more acidity and consequently gives a higher degree of solubilizing activity [78].

Solid state fermentation with *Aspergillus niger* in a mixture of phosphate rock and agricultural waste (e.g. sugarcane bagasse or sugarbeet waste) can be applied as an environmentally sound means for efficiently solubilize phosphate [79]. Phosphate was also solubilized from cassava peels through solid state fermentation with *A. niger* and *A. fumigatus*, and led to significantly higher dry weight of pigeon pea (*Cajanus cajan*) when bioleached fertilizer was used as a biofertilizer in sandy loam soil [80].

Integration of waste producing component with hydroponic system

Aquaponics is an example of an integrated hydroponic system, where the organic waste production and treatment of the wastewater occurs within the system. Small-scale integrated systems with biogas production in greenhouse, where the use of on-site produced digestate fertilizer is combined with combustion of biogas for heating and CO_2 + fertilization of the greenhouse, have been applied in northern China [31]. This system has not included a hydroponic subsystem.

If a biogas reactor integration with a hydronic system is feasible, e.g. in cases of small-scale domestic bioreactors where soilless cultivation is of high interest due to water scarcity and/or lack of arable soil in an urban setting, such a system would benefit from being dimensioned from the organic waste input in the anaerobic digester. This would be similar to the principle of dimensioning the hydroponic subsystem to the fish feeding rate, or vice versa, in an aquaponic set-up [81,82]. The ratio of the mass fish feed input per day per plant growing area unit, has been denominated *feeding rate ratio* by Rakocy and could be applied to an integrated biogas reactor hydroponic system as follows [25]

$$\frac{\text{waste put in bioreactor per day}}{m^2 \text{ plant growing area}} = g\, d^{-1}\, m^{-2}$$

The feeding rate ratio for aquaponic production has been recommended to be 60-100 g d^{-1} m^{-2} as a general approximation and was experimentally determined to be 15-42 g d^{-1} m^{-2} under specified circumstances with african catfish and water spinach (*Ipomea aquatica*) [81,83]. With a standardized substrate, e.g. based on daily faeces and kitchen waste production in one household, similar ratio between biogas reactor feeding rate and area of hydroponic production in a biogas reactor hydroponic integrated system, could experimentally be determined. Similarly to the conclusions by Endut et al. concerning aquaponic systems, optimization of the components of such a system, is crucial for a maximized use of the plant nutrient content of the digestate [83]. Integration of nitrification reactor - and possibly a mineralization tank - with biogas reactor and hydroponic subsystem, would make justice to this kind of integrated system and show its eventual possibilities.

In trials with vermicompost leachate in hydroponic production of lettuce in pots and NFT-systems, vermicomposting of paunch and kitchen waste was integrated in a roof-top pak choi production system [84]. In comparison between off-batch production of leachate and integration of vermicomposts in the recirculating system, the latter was problematic as the nutrient solution paramaters (especially pH) was difficult to control [84]. Nevertheless, in both cases the vermicompost leachate production unit was a waste treatment subsystem integrated with hydroponic food production, and led to satisfying yields (see section on *Small-scale hydroponic system*).

Small-scale hydroponic systems and urban hydroponics

Advantages with hydroponic cultivation such as optimized use of cultivated area, indepence from arable soil, increased water and nutrient efficiency and higher yields, have been widely recognized in literature on urban farming [85–90]. The applicability of hydroponic technology in an urban horticulture setting, depends on material and energy availability and the grower's crop production experience. Small-scale, more or less simplified hydroponic systems and aquaponic systems have been promoted by FAO and *Rural Industries Research and Development Corporation* (RIRDC) in Australia [84,90].

Small-scale hydroponic systems

In small scale hydroponic systems with leachate from vermicomposting of paunch and kitchen waste in separate treatments, shoot fresh weight of pak choi was 80-100 % of inorganic control (see table 6) [84]. The most efficient roof-top system for vermicompost leachate hydroponics was (1) buffered with nitric acid (2) NFT rather than pot culture (3) off-line batch vermicompost leachate rather than integration of vermicompost in recirculating system [84].

A thorough guide on aquaponics popular science-biology as well as construction, maintenance and economics of a small-scale, 5 m^2-aquaponic system built from IBC containers and pvc-piping, has been published by FAO (see table 6) [2].

For hydroponic lettuce production in DWC without electricity, yields of 150-250 g per lettuce head have been achieved with non-floating polystyrene sheets in nutrient solution tanks with air space between net pots and nutrient solution surface [91,92].

Simplified hydroponics

Simplified hydroponic systems have been developed for easy management and construction from scrap material by non-professionals [85,90]. Simplification of hydroponic systems allows for wide dissemination in poor urban areas and have contributed to increased sustainability with regards to increased food and nutrition security, ecological waste management and generation of income for poor households [85,90].

Several systems for simplified hydroponics have been designed and tested in relevant locations, e.g. the *Garrafas* and *Caixa* systems in North-East Brasil, simplified floating systems in Peru and the "tube" hydroponics system in Uruguay [93–96]. These are not dependent on electricity.

The simplified hydroponic systems are recommended in the concept of microgardening, promoted by FAO, in which optimized cultivation in spaces of 1-10 m^2 is supposed to be taught at training and demonstration centres [90].

From trials with inorganic nutrient solutions, varying yields have been achieved (see table 6). Lettuce stands out as the most rentable option for growing for market purpose in simplified hydropoic systems [96].

Table 6. Examples of small-scale organic hydroponic systems and simplified hydroponic systems.

Hydroponic system	Yield or SFW mean
IBC-based aquaponic system Aquaponic system design designed from IBC tanks and PVC tubing. Three system versions: NFT, DWC and media bed. All versions occupies 5 m^2 in total, of which planted area is ~3 m^3. Fish tank is 1 m^3. Promoted by FAO. 2	Lettuce: 20 heads m^{-2} month-[1] Tomato: 3 kg m^{-2} $month^{-1}$ Fish: 2,5 kg m^{-3} $month^{-1}$
Vermiliquer roof- top hydroponic system NFT or pots with perlite. Nutrient solution from vermicompost leachate. Vermicompost leachate is circulated through the composts until appropriate EC level is reached. Thereafter the leachate is introduced to the hydroponic subsystem. pH is adjusted with nitric acid. 84	In the highest yielding test system Undiluted leachate SFW of pak choi 32 DAT Pot: 252,9 g NFT: 461,7 g Control: 563,3 g
DWC-system with air space and no aeration (Kratky-system) Tanks constructed from lumber and plywood is lined with 2 layers of 0,15 mm polyethylene plastic, are covered with polystyrene or plywood sheet supported by the sides of the tank. Seedlings are transplanted to 5 cm net pots supported by the tank cover. Nutrient solution level in tank should reach to 1-2 cm of net pots at transplantation and will decrease during plant growth, leading to a moist air zone and nutrient solution zone in the tank. 91,92	Lettuce SFW With air space: 220 g No air space (polystyrene sheet floating on nutrient solution): 178 g
Garrafas system (bottles system) 300 L nutrient medium tank. Nutrient flows at a rate of 2 L h^{-1} by gravity through 20 lines of 8 plastic 2 L bottles. Bottles are filled with substrate, e.g. burned rice hulls. Do not require electricity. Nutrient solution is manually refilled twice a day. 95	Lettuce 'Red comet' yield: 3,69 kg m^{-2} at 30 DAT. Soil grown lettuce in the same region yielded 2,25 kg m^{-2} at 40-50 DAT. Cherry tomato yield: 2,1 kg m^{-2}. Okra yield: 1,2 kg m^{-2}.
Caixa system (box system) Wooden container, ~1m^2 lined with waterproof plastic film and filled with substrate, e.g. coir. The container leans slightly letting excess nutrient solution drain to reservoir. Do not require electricity. 20 L Nutrient solution is manually refilled twice a day. 95	Cherry tomato yield: 3,1 kg m^{-2}. Okra yield: 1,3 kg m^{-2}.

Economic feasibility of organic hydroponic production

As mentioned above, peer-reviewed research on hydroponic systems with organic fertilizers, is relatively scarce. Needles to say, research on the economical feasibility and commercialization of such systems, neither is abundant. Focus has been on technical aspects of aquaponic and other organic hydroponic systems production [69]. However, there are within the field of aquaponics several examples of functioning commercial aquaponic systems and a few research papers on economical aspects of the systems have been published [4,8,46,69].
One study on a small-scale "residential/lifestyle farm" commercial system, found that vegetable production gave a net profit, but fish production did not [4]. Calculations were made from all input costs (energy, water and fish feed) and from sales on a local farmers market.
In a study based on an international survey for commercial aquaponics practitioners, it was found that (1) most commercial systems were small-scale with mostly direct sales to costumers (2) profitability was highest for operations with sales of non-food products related to aquaponics, as a complement to sales of the produced food (3) the majority of the systems had not been profitable the previous year as they were newly started operations [8].
It has been concluded that more research is needed on the economical feasibility of commercial aquaponic systems and for supporting the development of such operations [8,69].

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