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Recovery of Nutrients from Fish Sludge as Liquid Fertilizer to Enhance Sustainability of Aquaponics: A Review

Hong Zhang[a], Yueshu Gao[a], Junyan Liu[a], Zhiyun Lin[a], Chew Tin Lee[b], Haslenda Hashim[b], Wei-Min Wu[c], Chunjie Li[a,*]

[a]School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b]School of Chemical & Energy Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Johor, Malaysia
[c]Department of Civil & Environmental Engineering, Center for Sustainable Development and Global Competitiveness, William & Cloy Codiga Resource Recovery Research Center, Stanford University, Stanford, CA 94305-4020, USA
cjli@sjtu.edu.cn

Aquaponics combines aquaculture with hydroponics by recirculating water in a closed loop. As an innovative environmental-friendly system, aquaponics is able to reuse available nutrient resource and minimize waste discharge. Current commercial aquaponics technologies only recycle liquid effluent but considerable amount of fish sludge is filtered out of the system as waste, and therefore, a great proportion of nutrients in the sludge has not re-utilized as resource. Recovering nutrients from fish sludge directly and reintroducing it into aquaponics as liquid fertilizer has become attractive because of environmental and economic benefits which enhance the sustainability of aquaponics. This article reviewed recent progress in aquaponic system with fish sludge management as resource, including the potential of recovering nutrients in fish sludge, methods for collection of fish sludge, and the nutrient recovery via the mineralization of fish sludge. The results indicate that the management of fish sludge can be optimized to ensure high efficiency of nutrient utilization in aquaponics. Effective collection and digestion of the fish sludge to generate nutrients are the key for successful nutrient recovery. The digestion of the concentrated sludge can be performed either in anaerobic reactors or aerobic reactors. Combining the collection of fish sludge with the conversion of solid nutrients in a single device is effective in achieving high nutrient recovery efficiency of aquaponic system. A modified biological aerated filter in the process is proposed for the filtration of fish sludge and the conversion of nutrients in aquaponics.

1. Introduction

An evolutional food production system which is intensified, highly productive and environmental-friendly is urgently required to satisfy the need of rapid urbanization (Li et al., 2018). Aquaponics, an integrated recirculating water system which combines aquaculture with hydroponics, is a promising approach for industrialized food production (Dong et al., 2020). It mainly composes of fish tanks, a mechanical filtration unit for solid removal, a biofilter for nitrification, a hydroponic unit and a UV disinfection unit. They form a closed loop and enable aquaculture effluent to provide fertilizer for the growth of edible plant. In turn, with the uptake of plant, water quality is improved and inhibitory metabolites, such as ammonia and nitrite can be removed, thus the effluent can flow back into aquaculture unit for reuse. The unique combination of two systems eliminates the weakness of both when running separately and bring some superior merits to aquaponics, such as obvious reduction in land use, efficient utilization of water and nutrients, high productivity and quality of fish and plants, and low pollutant discharge.

In aquaponics, fish feed, as the main input of nutrients, is partially assimilated to fish biomass, and converted to soluble excreta, solid faeces with various portion of uneaten/residual feed. The soluble components could provide macronutrients and micronutrients for plant. Fish sludge is composed of solid faeces and uneaten feed, and remains as suspended and precipitated solids. Strauch et al. (2018) indicated that 7.1–9.9 % of the fish feed input would finally be sediments. Cerozi and Fitzsimmons (2017) estimated that 25–35 % of the feed may remain in water as suspended solids. Once aquaculture wastes accumulated without proper treatment,

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they may lead to higher oxygen consumption, the production of toxins, eutrophication, and the blockage of plumbing and equipment (Fu et al., 2018). Fine particles may also get into gills of fish or coat on roots of plants, threatening their survival.

Solid waste management is essential for aquaponics. At present, only nutrient in liquid effluent is recovered in aquaponics while fish sludge is concentrated by mechanical filtration unit and then removed from the system as waste (Khiari et al., 2019). According to Cerozi and Fitzsimmons (2017), daily sludge discharged accounts for 5–20 % of the total volume of recirculating aquaculture system. The discarded sludge can be further treated by land field application, composting, or anaerobic digestion. Field application comes with high transportation cost due to the high water content of sludge (≥99.76%) (Strauch et al., 2018), incalculable loss of nutrients and severe environmental pollution. Composting has been accepted as a promising method of stabilizing solid waste. It converts sludge into humic substances with a significant reduction in volume and the stabilized end product can serve as solid fertilizer and soil conditioner. The shortcomings are long processing period and air pollution due to emission of ammonia and pollutant VOCs (Volatile Organic Compounds). Anaerobic digestion decomposes organic matters by anaerobic bacteria to generate methane as biogas energy resource and nutrients like ammonium and phosphate in liquid phase could be reused. Remaining digested sludge can also be used as fertilizer. It is limited by production of offensive odours, low by-products yield, high process variability, and decreased nutrients availability (Khiari et al., 2019).

The management of fish sludge remains an issue regarding on the nutrient recovery and enhancement of the efficiency in aquaponics. This paper introduces a new way of fish sludge management in aquaponics: recovering nutrients from fish sludge and reintroducing them into the system as liquid fertilizer. The potential of nutrient recovery in fish sludge, technologies for collection of fish sludge, and the nutrient mineralization are reviewed. A modified biological aerated filter is also proposed for both the filtration and the nutrient conversion of fish sludge.

2. Potential of nutrient recovery from fish sludge in aquaponics

As a closed loop of food production system, aquaponics is desired to fulfil zero discharge, eliminate negative environmental impact and enhance system sustainability. A great potential is to recover the nutrients of fish sludge into soluable form via mineralization and then reintroduce the obtained nutrient solution as recirculating water to provide liquid fertilizers for hydroponic plants (Goddek et al., 2019).

Aquaculture sludge contains large amounts of water, nutrients and energy, which should not be regarded as merely waste. According to Fu et al. (2018), 17 %, 3 %, and 62 % of residual feed and fish faeces are protein, fat and carbohydrates (based on dry matter). Most macronutrients and micronutrients that are essential for the plant can be obtained from aquaculture solid waste. Cripps and Bergheim (2000) mentioned that the sludge solids contain 7–32 % of the total nitrogen and 30–84 % of the total phosphorus of the wastewater. Goddek et al. (2019) noticed that among macronutrient, 6 % of the nitrogen, 18 % of the phosphorus, 6 % of the potassium, 16 % of the calcium, 89 % of the magnesium are contained in the sludge; while for micronutrients, 24 % of the iron, 86 % of the manganese, 47 % of the zinc, and 22 % of the copper were measured (based on dry matter). Phosphorus is more present in sludge (Delaide et al., 2017). Micronutrients like Cu, Zn and Mn are also mainly concentrated in solids (Strauch et al., 2018). More than 99% of N, P, Fe, Mn, Zn, Se, Co and Cr, 95–98% of K, 69–87% of Ca, 67–85% of Mg, 69–86% of S, 95–98% Mo, and 90–96% Cu are derived from fish feed (based on dry matter) (Strauch et al., 2018).

Nutrient recovery from fish sludge can also alleviate the problem of plant nutrient deficiency faced by aquaponics and save the cost of additional purchase of plant nutrients. According to the definition of aquaponics by EU Aquaponics Hub, no less than half of the nutrition that hydroponics needs should be provided by aquaculture tank. The existing system is far from meeting this requirement. It was found that most nutrients provided by the aquaculture effluent are insufficient compared with those in the nutrient solutions used by independent hydroponic systems (N: 70–164 mg/L, P: 5–40 mg/L, K: 120–280 mg/L, Ca: 80–140 mg/L, Mg: 40–60 mg/L, S: 60–130 mg/L, Fe: 2.0–6.0 mg/L, Mn: 0.4–1.0 mg/L, B: 0.2–1.0 mg/L, Cu: 0.01–0.1 mg/L, Zn: 0.04–0.08 mg/L, Mo: 0.01–0.4 mg/L). Therefore, the hydroponic products in aquaponics are restricted to leafy vegetables rather than fruit crops (Nozzi et al., 2018). Aquaculture effluent is generally deficient in phosphorus, potassium, calcium and micronutrients, especially iron, molybdenum and manganese (Delaide et al., 2017). If the nutrients obtained via fish sludge mineralization were added into aquaculture effluent, the concentrations of total nutrients available for plants would be effectively increased, and the deficiency of specific nutrients could be eliminated (Montanhini Neto and Ostrensky, 2015).

3. Technologies for collection of fish sludge

Collecting fish sludge effectively has a great significance to the recovery of nutrients. At present, the solid removal methods adopted by aquaponics are mainly those used in the recirculating aquaculture system (RAS) which include sedimentation, sieve separation, medium filtration and foam separation. Sedimentation works on the basis of the gravity of particles and the centrifugal force generated by the water flow rotation or the centripetal force generated by the secondary retention. Settling basins, tube or plate separators, centrifugal separators, and swirl separators are commonly used devices (Rakocy, 2012). Sedimentation requires lower energy consumption and operating cost but is time-consuming and manpower-consuming for it is bulky. Sieve separation traps solids by a sieve with a certain aperture base on the particle size and removes solids by backwashing. Drum filters are the most frequently used equipment. For suspended solids with particle size between 60-100 microns, the removal rate of rotary drum filters can reach 68–94 % when the inlet concentration is higher than 50 mg/L (Cheng et al., 2014). But the cost of drum filter is high, and the secondary crushing of large particles may be caused in the process, which reduces the efficiency (Cheng et al., 2014). Media filtration intercepts the suspended solids by the media such as quartz sand, ceramsite, anthracite, and polystyrene materials due to the pores formed. Sand and gravel hydroponic substrates are good alternative for solid waste removal as they intercept solids when aquaculture effluent flow through hydroponic bed and simultaneously decompose organic matters of the solid remained in the unit (Rakocy, 2012). Bed tillage or periodic media replacement is required from system water in case of the clogging of the media (Rakocy, 2012). Foam separation is a technique using the interface properties of surfactants and the bubbles generated to adsorb the solids. Foam separation needs less energy and has good performance on removing particles less than 10 microns or 50-90 microns, but can be limited by low concentration of organic matter and electrolytes (Shan et al., 2013).

The particle size and density of solid are two parameters in consideration of suitable separation technology for fish sludge. In the recirculating aquaculture system, the particle size distribution range of solid particles is relatively wide, from 3 to 300 microns, most of which are less than 20 microns, accounting for more than 47 % of the total weight of particles (Chen et al., 1993). Particles size over 100 microns are settleable solids, which are suitable for gravity sedimentation or using hydrocyclone; size under 100 microns are unsettleable solids and some of them may be further dispersed into fine particles with particle size smaller than 30 microns under the action of aquatic organisms and water power (Fu et al., 2018). Solids with particle size less than 60 microns are suitable for mechanical filtration or physicochemical methods (Zhang et al., 2008).

Combining the collection of fish sludge with the conversion of solid nutrients in a single equipment in aquaponics has been proposed by Zhang et al. (2020) and may be a trend. All the sludge collected in the filter can be further mineralized into soluable nutrients by activities of microorganisms, which can reduce nutrient loss to a higher degree and is highly-efficient in nutrient utilization.

4. The nutrient mineralization of fish sludge

Fish sludge can be mineralized into soluble and bioavailable nutrients that hydroponic plants can uptake either in anaerobic reactors or aerobic reactors with degradation by microorganisms (Delaide et al., 2018).

Anaerobic digestion has been regarded as a promising way to stabilize and reduce solid waste along with methane production. In recent years, it also has been evaluated with nutrient recovery. The anaerobic digestion produces less residual sludge than aerobic process (Gichana et al., 2018). It consumes less energy due to without aeration and can produce biogas to recover energy, which brings economic benefits. Continuously stirred tank reactor (CSTR), upflow anaerobic sludge blanket (UASB) reactor and membrane bioreactor are common reactors of anaerobic digestion (Mirzoyan et al., 2010). Goddek et al. (2018) investigated the mineralization performance of fish sludge from RAS in sequential UASB-EGSB reactors and recovered 26–71 % P, K, Ca, and Mg (based on dry matter) in the minimally acidic reactor. Delaide et al. (2018) found that among 2–35.8 % of phosphorus, calcium, magnesium and boron and among 5.7–21.9 % of copper, zinc and manganese (based on dry matter) were mineralized in anaerobic reactor for nutrient recycling in aquaponics. Anaerobic digestion faces some drawbacks, including long reaction period and strict requirements of conditions such as pH, temperature, salinity, mineral composition, carbon/nitrogen ratio (C/N), volatile fatty acids (VFAs) content and hydraulic retention time (HRT) (Mirzoyan et al., 2010). According to Strauch et al. (2018), TOC (Total Organic Carbon) in aquaculture sludge (366–416 g/kg·dm) is 36–42 % lower than that of typical matrix, and C/N is 1.1–3.8 times lower than the recommended value of anaerobic digestion. This reveals that it is necessary to adjust composition of the fish sludge before anaerobic digestion in order to ensure digestion performance, i.e., supplementing acids, carbon sources and bacterial suspension (Monsees et al., 2017).

Aerobic conversion of fish sludge decomposes organic matters and releases a variety of minerals, including all the macronutrients and micronutrients that plants need via activities of a variety of heterotrophic microorganisms (Khiari et al., 2019). Aerobic conversion has the advantage in dynamics compared with anaerobic reaction, especially in terms of TSS (Total Suspended Solid) and COD (Chemical Oxygen Demand) removal (Delaide et al., 2018). The production of VFAs, anaerobic secondary metabolites and other toxins to plants can also be avoided. At this point, aerobic conversion is more environmental friendly and safe due to the reduction in odour, greenhouse gas emissions and pathogens. Aerobic conversion shows higher nutrients capture abilities and less nutrient loss. Monsees et al. (2017) found that the concentration of nitrate in the aerobic reactors was reduced by 16 % compared to 97 % in the unaerated treatment. Aerobic digestion also increased the concentration of P and K by 330 % and 31 % within 14 d of incubation, while those under anaerobic treatment only had minor increase (Monsees et al., 2017). Delaide et al. (2018) also concluded better mineralization performances of P (54.25 %), Ca (64.95 %), Mg (57.49 %), B (62.98 %), Cu (21.79 %), Zn (24.60 %), Mg (13.18 %), Na (55.98 %) (based on dry matter) in aerobic reactors. Rakocy et al. (2007) showed concentrations of six of thirteen nutrients required by plant exceeded standard hydroponic values after aerobic mineralization of 29 d. The disadvantage of aerobic digestion is the high energy consumption due to continuous aeration, the management complexity and capital costs of the system. The growth rate of microorganisms under aerobic conditions is much faster than that under anaerobic conditions, thus a considerable amount of new biomass may be produced and accumulated in the reactor, which is not conducive to the reduction of solids (Delaide et al., 2018). In general, aerobic digestion may also be a promising approach for nutrient recovery from fish sludge in aquaponics (Monsees et al., 2017).

5. Modified biological aerated filter for nutrient recovery from fish sludge

Biological aerated filter (BAF) is a flexible and efficient bioreactor developed on the basis of European bioreactor (Wu et al., 2015). BAF is filled with granular media or porous media which can trap solids from water passing through. The large specific surface area of filter media also enable the growth of nitrifying bacteria and heterotrophic bacteria, which are responsible for the removal of ammonium and the degradation of organic compounds in water. For years, it has been used for treating industrial and municipal wastewater. Considering BAF integrates mechanical filtration with biofiltration, it may also perform well in the recovery of nutrients from aquaculture sludge after proper modification. The modified BAF should be capable of both the collection and the aerobic nutrient mineralization of fish sludge. Specifically, the BAF should quickly capture a large amount of sludge and then efficiently convert the sludge in nutrients without backwashing, thus reducing the nutrient loss at maximum and improving the operating efficiency with a compact footprint.

Recently, a new BAF which is modified based on the reactor reported by Zhang et al. (2020) has been proposed to fulfill the collection of fish sludge and the recovery of nutrients in one device. The reactor is composed of two columns connected by the flange (Figure 1a). The upperside column is transparent, which is used for observing the level of water. The downside column with filter materials inside is for the interception of sludge. The effluent is pumped into the BAF from the upperside column and then flows downward through the lowerside column. Three layers of perforated aerator, named high-level aerator, middle-level aerator and low-level aerator, are equipped in the lowerside column which is controlled by valves. The upper filter media will be blocked by the fish sludge first, resulting in the rise of water level in the upperside column. In this case, high-level aerator is opened, which alleviating the resistance of upper filter media. Meanwhile, the middle filter media intercepts fish sludge. Once the water level in upperside column is observed again, the middle-level aerator is opened and the lower layer of filter media work. Until the water level in upperside column rises again, the valve of effluent of BAF is then closed and the low-level aerator is also opened for nutrient conversion.

For industrial production, the BAF can be designed as: upperside column (height=0.4 m, diameter=0.12 m), made of plexiglass; downside column (height=0.9 m, diameter=0.3 m), made of polyvinyl chloride. In high density aquaculture (2–8 kg/m^3) with daily feed input accounting for 4 % of the fish weight, two BAFs may provide effective filtration for 20–30 d.

The selection of filter media in BAF is of great importance. Zhang et al. (2020) tested ceramsite with different lignocellulosic materials as filter media of BAFs and gained inspiring nutrient recovery efficiency for most macronutrients and micronutrients. The BAFs encountered constrains because of the biodegradation of lignocellulosic materials and nutrient loss. For small scale or home-based aquaponics, the retention rate of fish sludge can be improved by using sponge materials. For large scale or factory-based aquaponics, porous polyethylene floating balls which normally used in moving bed bioreactor (MBBR) are recommended.

A proposed aquaponic system with the modified BAF is shown in Figure 1b, which includes the fish tank, the sump with BAFs, the immobilized biofilm unit with polypropylene fibers (PF) and immobilized microbial granules (IMG) in separate compartments, the hydroponic unit, and the ultraviolet (UV) disinfection tank. In this system, the modified BAF intercepts fish sludge. The BAF is operated as a bypass circulation rather than full-flow filtration. Thus, it is inevitable that a portion of fish sludge flows via the whole system. In order to reduce the impact of the residual fish sludge, the unit with polypropylene fibers acts for the interception for the sludge. Immobilized microbial granules (IMG) are used for the conversion of ammonia nitrogen into nitrate. The flow rate of circulating water of the BAF is an important operational parameter. The faster the circulating rate is, the higher the efficiency of interception of fish sludge is, which is benefit for nutrient recovery, but more energy is consumed. In the proposed system, at least two BAFs are required to alternatively perform continuous operation: one is used for fish sludge collection (BAF-F) and another is for nutrient conversion (BAF-C). After the nutrient conversion period is ended in a BAF, the liquid solution flows from the BAF into the hydroponic system.

In this aquaponic system with BAFs, the nutrients that hydroponic plants need all come from fish tank. The system recovers nutrients effectively in a closed loop, thus is environmentally friendly and cost-effectively.

Future research should be performed for the improvement in the efficiency of nutrient recovery by investigating the mechanisms of nutrient balance and optimizing operational parameters of BAFs.

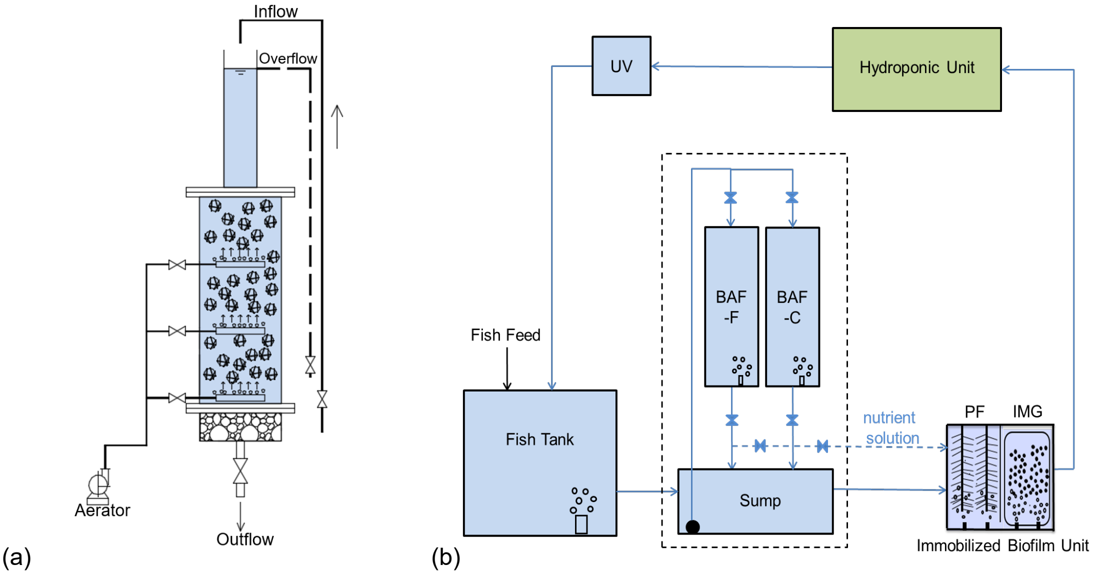

Figure 1: Schematic of (a) the modified BAF, and (b) aquaponics with modified BAFs

6. Conclusions

Aquaponics is desired to fulfil zero discharge, eliminate negative environmental impact and enhance sustainability of aquaculture with hydroponics. This system can be enhanced further via recovery of the nutrients of fish sludge and reuse of the treated water. Effective collection of fish sludge and efficient nutrient mineralization are crucial to solid nutrient recovery in aquaponics. Combining the fish sludge separation with nutrient conversion in a single device is an effective way. The digestion of the concentrated sludge can be performed in either in anaerobic reactors or aerobic reactors. A modified BAF is proposed to perform as both filter for sludge collection and bioreactor for nutrient conversion in order to fulfil nutrient recovery effectively in a closed loop, with environmental and economic benefits. Future research should be performed for the improvement in the efficiency of nutrient recovery by modifying device design and optimizing operational parameters for solid collection and sludge mineralization as well as investigating the mechanisms of nutrient balance.

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