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Enhancing Nutrient Recovery Efficiency through a Novel Dual-loop Aquaponic System Coupling Main Stream and Side Stream: a Review

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Aquaponics is a combination of recirculating aquaculture systems and hydroponics, which is in line with industrialization and urbanization. Typical coupled aquaponic systems use a single-loop mode to recover dissolved nutrients, while nutrient-rich aquaculture sludge is discharged, leading to a low nutrient recovery efficiency and low crop yield. Balancing the ideal conditions for aquaculture units, hydroponic units, and biofilters is difficult because of the different nutrient and environmental requirements. A decoupled aquaponic with an additional sludge treatment loop and distillation loop has been developed to overcome the shortcomings of single-loop aquaponics, but the symbiotic relationship is weakened, and the economic feasibility is challenged. In this paper, a novel dual-loop aquaponic system, coupling the main stream and side stream, is proposed for the recovery of both dissolved and solid nutrients. Nutrient conversion and nutrient losses in the main stream and side stream were discussed. The performance of aerobic and anaerobic mineralization of aquaculture sludge are compared, and a newly developed phototrophic bioconversion of aquaculture sludge based on the pre-treatment of anaerobic or aerobic solubilization is analyzed. It can be concluded that the dual-loop aquaponic system facilitates nutrient recovery from aquaculture sludge through an optimized symbiotic relationship in the main and side streams. The phototrophic bioconversion of aquaculture sludge simultaneously obtains biomass nutrients and mineral nutrients, enhancing the nutrient recovery efficiency of carbon, nitrogen, and phosphorus.

1. Introduction

Aquaponics is the integration of aquaculture and hydroponics and achieved the simultaneous production of plants and fish. It represents an industrialized food production approach in line with urbanization (Goddek et al., 2019). Typical aquaponic systems use a single-loop mode to recover dissolved nutrients (Figure 1), while the nutrient-rich aquaculture sludge (feces and uneaten feed) is discharged after mechanical filtration, thus preventing the roots of hydroponic systems from clogging and the deterioration of water quality. Dissolved organic matter and ammonium in the effluent of aquaculture unit are converted by microbes in the biofilter into nutrients (nitrate and phosphate) that are available for plants in hydroponics. Clean water from the hydroponics is recycled for the aquaculture unit. Symbiotic relationships between animals, plants, and microbes play important roles in nutrient recovery (Goddek et al., 2019). However, finding trade-offs among the conditions of aquaculture units, hydroponic units, and biofilters, such as pH, temperature, and nutrient concentrations, remains difficult (Baganz et al., 2022).
One challenge encountered in single-loop aquaponic systems is determining how to improve nutrient recovery efficiency. Nutrient levels are insufficient in single-loop aquaponic systems compared with those in hydroponic nutrient solutions because dissolved nutrients released from aquaculture unit are limited by the number of animals and the feed used (Goddek et al., 2019). The concentration of nitrogen and phosphorus in aquaponics were found to be much less than those in hydroponic solutions (three times and ten times) (Graber and Junge, 2009). The EU Aquaponics Hub regulations state that at least 50 % of the nutrients supplied should originate from aquaculture feed in an aquaponic system (Palm et al., 2018). Among the fish feed ingested by fish (over 95 %), 20 – 30 % of the nutrients of carbon and nitrogen are assimilated by the fish for growth, while the rest is

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released into the water, mainly as ammonia and organic solids (fish sludge) (Zhu, 2023). The aquaculture sludge is concentrated via mechanical filtration and removed from the system. It contains valuable nutrients, including macronutrients (N, P, S, K, Mg, and Ca) and micronutrients (Fe, Mn, Mo, Zn, Cu, and B), which are essential for plant growth. If aquaculture sludge is converted into a nutrient solution and provided with nutrients available for plants in hydroponics, the yield would be improved, increasing economic viability. Research on aerobic and anaerobic mineralization (Yogev et al., 2016) has been conducted to extract nutrients trapped in fish sludge. However, the integration of nutrient solutions into aquaponic systems has been limited owing to the difficulty of incorporating the ideal conditions for aquaculture and hydroponics units in a single loop.

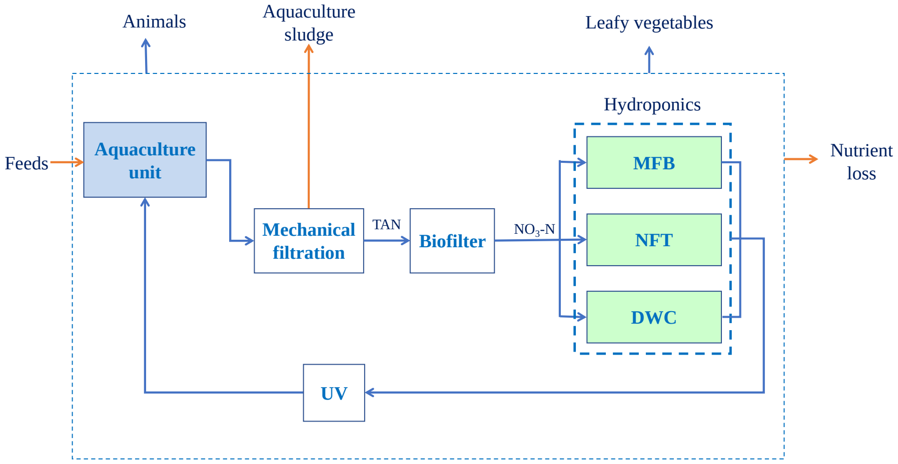

Figure 1: Diagram of single-loop aquaponics system (MFB—media filled beds; NFT—nutrient film technique; DWC—deep-water culture; UV—ultraviolet)

To overcome the shortcomings of single-loop aquaponics, decoupled aquaponics or on-demand coupled systems have been developed by decoupling aquaculture unit and hydroponic units to optimize the growth conditions of both animals and plants (Goddek et al., 2019). In decoupled aquaponic systems, aquaculture sludge is mineralized through aerobic and anaerobic digestion to obtain nutrients available for plants. Multi-loops, including the aquaculture sludge treatment loop, are used to improve the nutrient recovery efficiency and the distillation loop to reduce the risks to animal health. In a decoupled aquaponic system, desalination technology is used to concentrate nutrients for plants in hydroponics, reducing the need for additional fertilizers, and thermal distillation technology is used to recover the evaporated water resource, in which a major factor, that is, the rate of water replacement, is determined by the amount of this part of water (Goddek et al., 2019). The better utilization capacity of decoupled aquaponic systems ensures optimal plant growth (Goddek et al., 2019). Decoupled aquaponics are challenged economically owing to them requiring more infrastructure. Moreover, the weaker symbiotic relationship of decoupled systems deviates from the concept of aquaponics.
It is important to enhance the nutrient recovery efficiency of aquaponic systems by optimizing the symbiotic relationships between each unit. In this paper, a novel dual-loop aquaponic system that couples the main and side streams is proposed for this purpose.

2. Concept of dual-loop aquaponic system

A dual-loop aquaponic system facilitates the recovery of dissolved nutrients at low concentrations in the main stream, as well as the recovery of nutrients contained in fish sludge after bioconversion in the side stream (Figure 2).
Main-stream (in green in Figure 2) aquaponics are basically the same as single-loop aquaponics and include fish tanks, mechanical filtration, main-stream biofilters, and main-stream hydroponics. In the main stream, the nutrients dissolved after mechanical filtration of the effluent from a fish tank are converted by the microbes in the biofilter, especially from ammonium to nitrate. Water with a low concentration of nutrients enters hydroponics (main stream) and is taken up by leafy vegetables. Meanwhile, the water with residual nutrients at low concentrations from the side stream is also returned to the main stream.
The side stream (in yellow in Figure 2) focuses on nutrient conversion from aquaculture sludge and reuse. Aquaculture sludge concentrated via mechanical filtration is transformed into a nutrient solution through bioconversion (aerobic and anaerobic mineralization, or phototrophic bioconversion), which contains high concentrations of organic matter, ammonium, and phosphate. The subsequent side-stream biofilter is

responsible for the degradation of organic matter and the conversion of ammonium to nitrate, eventually obtaining high concentrations of nutrients that meet the nutrient requirements of fruiting vegetables in side-stream hydroponics, such as tomatoes and strawberries. After utilization, the effluent of the side-stream hydroponics returns to the main-stream hydroponics, supplementing the water resource for the aquaculture unit. Dual-loop aquaponic systems differ from decoupled aquaponics systems with two loops or multi-loops in that the aquaculture and hydroponic units are not decoupled. They recover a high concentration of nutrients produced from aquaculture sludge based on the diverse ecological composition. In dual-loop aquaponic systems, the symbiotic relationships in the main and side streams play an important role in nutrient conversion and reuse, and recirculating water serves as the medium for nutrient transportation. Leafy vegetables in main-stream hydroponics and fruiting vegetables in side-stream hydroponics ensure water quality and enhance economic profits.

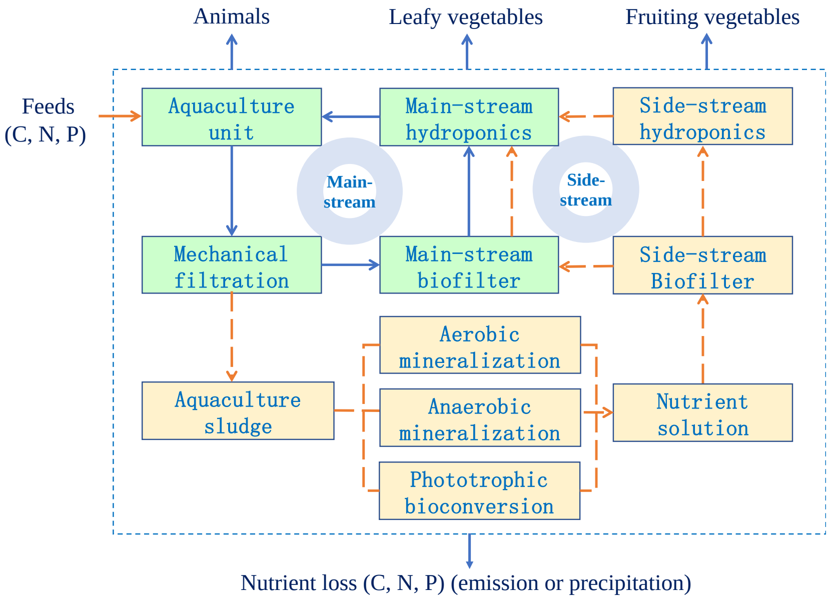

Figure 2: Dual-loop aquaponics system with main stream (in green) and side stream (in yellow)

3. Nutrient recovery in dual-loop aquaponic system

Nutrient recovery in a dual-loop aquaponic system involves two aspects: the main stream for nutrient conversion and the recovery of dissolved nutrients, and the side stream for nutrients in aquaculture sludge. The origins of nutrients, the nutrient conversion, and the nutrient loss warrant attention.

3.1 Nutrient recovery in main stream

In main stream of a dual-loop aquaponic system, nutrient (C, N, and P) input mainly originates from the aquaculture feeds, such as the classical fish feed containing organic carbon (40 % – 45 %), organic nitrogen (6 % – 8 %), and organic phosphorus (1.2 %) (Zhu, 2023). Proteins are the main source of nitrogen in fish feed. The content of protein in fish feed is different owing to the different categories of fish reared, such as approximately 55 % for carnivorous fish and approximately 25 % for herbivorous or omnivorous fish (Zhu, 2023). As mentioned previously, the assimilation of nutrients (C and N) for fish growth accounts for 20 % – 30% of the fish feed ingested by fish; the rest is excreted into the water as ammonia and organic solid waste. The dissolved nutrients are readily available for plant uptake, while aquaculture sludge (residual feed and solid feces) has a negative impact on water quality and needs to be removed from the system.
The dissolved nutrients in the effluent of an aquaculture unit must be converted by a biofilter (main stream) to remove residual organic matter and transform ammonium to nitrate. Ammonium is excreted through the gills, whereas organic nitrogen is excreted through urine and feces (Wongkiew et al., 2017). The presence of organic matter impacts nitrification because heterotrophic bacteria, owing to the degradation of organic matter, are highly competitive over nitrifiers such as ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB). From this point, the main-stream biofilter should be designed with the first compartment filled with media (such as filamentous polypropylene fibers) to intercept particulates and decompose organic matter (mainly organic nitrogen) (Li et al., 2019). The subsequent compartment is responsible for nitrification, in which immobilized

microbial granules are the best choice for achieving high ammonium conversion at low concentrations (Gao et al., 2021).
Despite the low concentration of nutrients in the main stream, nutrient loss occurs, e.g., nitrogen loss caused by denitrification, anaerobic ammonium oxidation, and ammonia volatilization. Nitrogen loss of 25 % – 60 % was found during denitrification by Hu et al. (2015) and Zou et al. (2016).
In summary, the main stream in dual-loop aquaponics plays an important role in ensuring the water quality of aquaculture units, but low nutrient levels lead to low nutrient recovery efficiency; in this case, only leafy vegetables are suitable for planting.

3.2 Nutrient recovery in side stream

The side stream of a dual-loop aquaponic system serves to recover nutrients from aquaculture sludge after mechanical filtration via the conversion of organic solids. The nutrients in fish sludge account for 40 % of the input fish feed (Yogev et al., 2016). Specifically, 6 % of the N, 18 % of the P, 6 % of the K, 16 % of the Ca, 89 % of the Mg, 24 % of the Fe, 86 % of the Mn, 22 % of the Cu, and 47 % of the Zn in fish feed enter fish sludge (Rafiee and Saad, 2005).
Aerobic mineralization (Seo et al., 2017) and anaerobic mineralization (Yogev et al., 2016) are commonly used methods to achieve mineral nutrients for plant growth (Figure 2). In addition, phototrophic bioconversion is perspective in the recovery of carbon, nitrogen, and phosphorus, owing to the simultaneous achievement of biomass nutrients for aquaculture animals and mineral nutrients for plants (Xia et al., 2022).

3.2.1 Nutrient recovery by aerobic mineralization of aquaculture sludge

Through aerobic mineralization, the organic matter in aquaculture sludge is decomposed by heterotrophic organisms, and ammonium is converted by AOB and NOB, which produce CO_2, macronutrients (N, P, S, K, Ca, and Mg), and micronutrients (Fe, Mn, Zn, Cu, B, and Mo).
Nutrients obtained via aerobic mineralization are beneficial for subsequent applications. Aerobic mineralization is superior to anaerobic mineralization because of its high kinetics but inferior in terms of energy requirements, resulting in the consumption of carbon resources and carbon dioxide release. Meanwhile, large amounts of biomass byproducts are produced, which increase the cost of post-treatment. During the process of aerobic mineralization, the pH increases at the stage of ammonification, while it decreases at the stage of nitrification, for which alkalinity should be added to adjust the pH to 7–7.5 when the pH is below 6.5.
A medium can be used to enhance the efficiency of aerobic mineralization, such as sponge media which is made of polyurethane foam(Gao et al., 2021), as well as polyhedral hollow spheres made of polypropylene.

3.2.2 Nutrient recovery by anaerobic mineralization of aquaculture sludge

Anaerobic mineralization includes four stages: hydrolysis, fermentation/acidogenesis, acetogenesis, and methanogenesis (Mirzoyan et al., 2010). During the hydrolysis stage, organic solids are solubilized by hydrolytic enzymes, which are rate-limiting and have low kinetics. During fermentation (acidogenesis), soluble organic substances are converted to volatile fatty acids (VFAs) by acidogenic bacteria, producing ammonia, CO_2 and H_2S. During acetogenesis, VFAs are digested by acetogens to produce acetic acid, CO_2 and H_2. Methane is produced by two types of bacteria during methanogenesis. Most of the methane (approximately 70%) is produced by acetotrophic archaea from acetate, and the rest is produced by hydrogenotrophic archaea (30%), with hydrogen and carbon dioxide being used to produce the methane. Anaerobic mineralization produces mineral nutrients and biogas, and it has the advantage of low cost and is beneficial for carbon recovery owing to the production of biogas. However, the nutrient solution after anaerobic mineralization requires further treatment to remove toxic substances for plants.
The main factors influencing the anaerobic mineralization of aquaculture sludge include temperature, pH, loading rate, C/N ratio, hydraulic retention time, and VFA content. A low pH is beneficial for mobilizing nutrients in decarbonized sludge. An upflow anaerobic sludge blanket reactor, expanded granular sludge bed, and anaerobic membrane bioreactor exhibit excellent performance in the mineralization of fish sludge (Goddek et al., 2019).

3.2.3 Nutrient recovery by phototrophic bioconversion of aquaculture sludge

Phototrophic bioconversion is a promising method of improving the nutrient recovery efficiency of aquaculture sludge in aquaponics (Xia et al., 2022). It uses anoxygenic phototrophic bacteria (APB), a diverse collection of organisms containing bacteriochlorophylls and carotenoids. They grow using energy from light and a variety of organic/inorganic electron donors, and they perform anoxygenic photosynthesis without evolving oxygen (George et al., 2020). APBs include four main categories: purple non-sulfur bacteria (PNSB), purple sulfur bacteria, green non-sulfur bacteria, and green sulfur bacteria (GSB) (Frigaard, 2016). In wastewater treatment, PNSB, such as *Rhodospirillum*, *Rhodomicrobium* and *Rhodopseudomonas*, exhibit excellent metabolization ability (Capson-Tojo et al., 2020). Three catabolic pathways were involved: photosynthesis, fermentation, and aerobic respiration. The metabolic products depend on the light–oxygen conditions, as well as the categories of electron acceptors and electron donors (Sakarika et al., 2020).

APB has advantages in resource recovery because of its high protein content and the production of multiple value-added substances, such as bacteriochlorin, carotenoids, coenzyme Q10, 5-aminolevulinic acid, indole-3-acetic acid, and polyhydroxyalkanoates (Cao et al., 2020). These substances are beneficial to both animals and plants in aquaponics (Sakarika et al., 2020). Through phototrophic bioconversion, the obtained biomass nutrients can be utilized by aquaculture animals as food, which is beneficial for the recovery of carbon and nitrogen resources. The remaining mineral nutrients can be utilized by plants in hydroponics (Figure 3).

Nutrients contained in aquaculture sludge provide fundamental substrates for APB growth. However, APBs cannot utilize substances with high molecular weights. Therefore, these substances must be converted into small molecular substances. Thus, pre-treatment, defined as solubilization (under anaerobic or aerobic conditions), is imperative to solubilize organic solids and transform large molecular substances into small molecular substances. According to the research by Xia et al. (2023), VFAs, especially acetic acid and propionic acid produced by anaerobic solubilization were found to be highly available for APB growth. In their study, anaerobic solubilization was superior to aerobic solubilization, yielding more soluble chemical oxygen demand (by 2.1 times) and more total VFAs (by 3.7 times). Under light-anaerobic conditions, the phototrophic bioconversion with the effluent of anaerobic solubilization as the substrate showed the highest yield of APB biomass and achieved a 54.1 % carbon recovery efficiency (in terms of COD), as well as 44.8 % and 91.3 % nutrient recovery efficiencies for N and P.

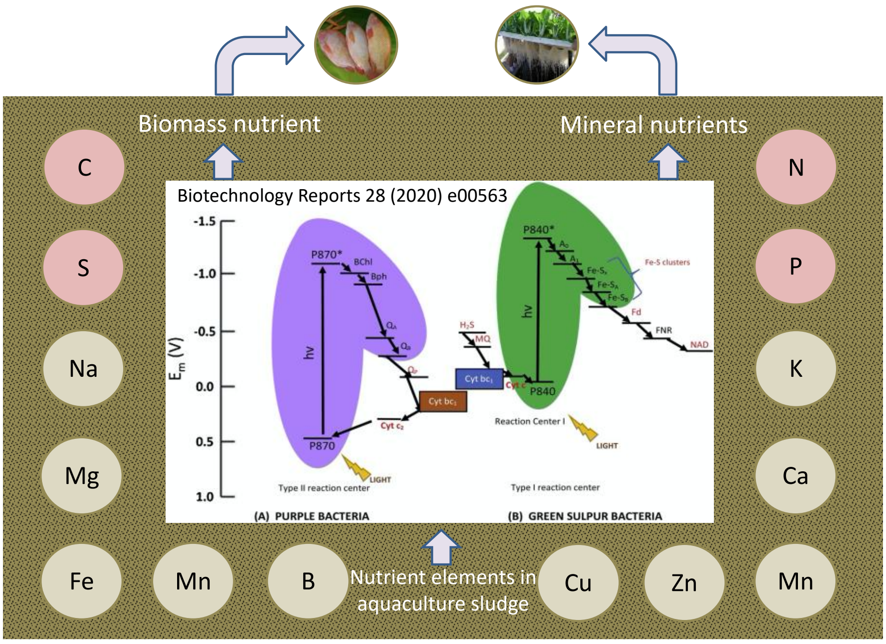

Figure 3: Schematic of the phototrophic bioconversion for the nutrients in aquaculture sludge

4. Conclusions

A typical single-loop aquaponic system is challenged in satisfying high nutrient recovery efficiency and obtaining a compromise between the ideal conditions of each unit, while, decoupled aquaponics with additional sludge treatment and distillation loops are limited by a weakened symbiotic relationship and economic feasibility. In this study, a novel dual-loop aquaponic system coupling the main and side streams is proposed to recover dissolved and solid nutrients. Nutrient conversion and nutrient losses in the main stream and side stream are discussed, mainly focusing on the aerobic and anaerobic mineralization of fish sludge as well as on the phototrophic bioconversion of aquaculture sludge based on pre-treatment with anaerobic or aerobic solubilization. It is concluded that the dual-loop aquaponic system improves nutrient recovery of aquaculture sludge due to the enhanced symbiotic relationships through coupling the main stream and side stream. The phototrophic bioconversion of fish sludge achieves biomass nutrients and mineral nutrients simultaneously, enhancing the nutrient recovery efficiency of carbon and nitrogen, and phosphorus.

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