Anaerobic Solid Waste Treatment in Aquaponics Enhance its Sustainability and Feasibility via Nutrient and Energy Recovery

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1. Introduction

Aquaculture has been one of the fastest growing agricultural sectors in the last 4 decades, supplying 80 million tons per year, which is > 50% of fish production. Fish feed application is typically about 1.5 times the production, accounting for nearly 120 million tonnes, and the resulting sludge ranges between 25 and 50% of applied fish feed (FAO, 2022). The escalating production of aquaculture sludge not only leads to significant economic losses in the industry but also poses a threat to water quality, the environment, and aquatic health, potentially causing ecological imbalance and global concern, necessitating effective treatment and management of this waste (Naylor et al., 2021). Anaerobic digestion (AD) has been suggested for sludge treatment and is often used to recover nutrients and energy through biogas production (Mirzoyan and Gross, 2013). More specifically, upflow anaerobic sludge blanket (UASB) reactors that operate with low suspended solids concentrations of less than 3% were demonstrated to perform well for fish sludge treatment. The resulting biogas can be combusted to produce electricity and heat, while the remaining nutrients in the supernatant can be applied as fertilizer or other products (Zhu et al., 2022b). The integration of aquaculture and hydroponics, called aquaponics, is a sustainable food production system in which plants are cultivated in the recirculating water from the fish tanks with the primary goal of reusing the nutrients contained in the uneaten fish feed and fish excretions to grow plants (Graber and Junge, 2009). Integrating anaerobic digestion into aquaponics for both fish sludge and plant waste offers a path toward a circular economy by enabling zero waste discharge and facilitating the recovery of nutrients and energy (Zhu et al., 2023).

The objectives of this study were to investigate the effects of pH and HRT on AD of fish sludge on a laboratory scale as well as to study long-term onsite AD of fish sludge and hydroponics plant waste in terms of substrate degradation efficiency and recovery of bioenergy and nutrients.

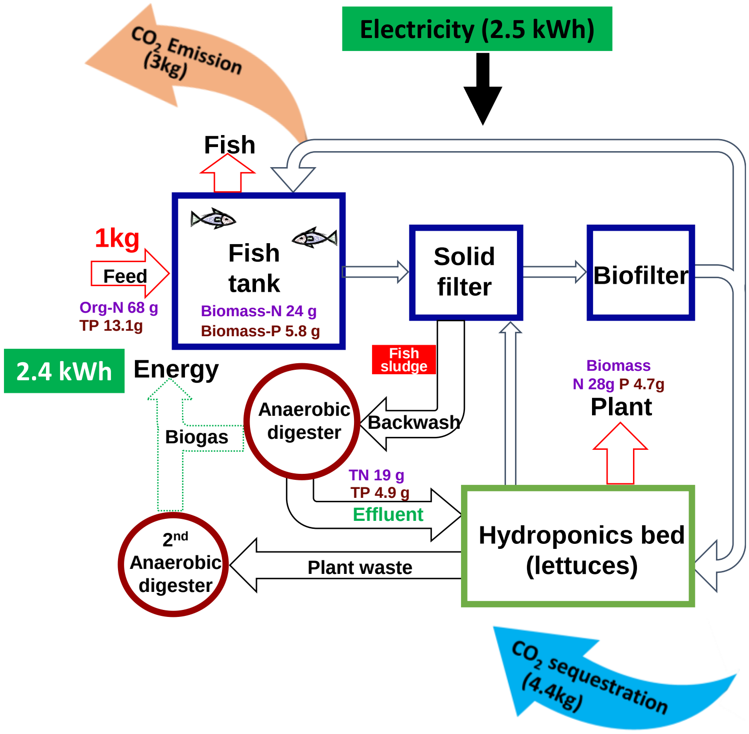
2. Materials and Methods

The laboratory scale set-up uses 1 L serum bottles containing 40g of dry fish sludge, 560 ml of tap water, and 200 ml of inoculum, leaving 200 ml as empty space. We conducted batch tests using a modified biochemical methane potential test, adjusting pH levels to 9, 8, natural (about 7), 6, and 5 with solutions of NaOH or HCl. Experiments ran for 10, 20, and 30 days, including control and blank samples, and were repeated three times. After sampling and pH adjustments, we removed oxygen by flushing it with nitrogen. The reactors were kept in a dark, warm (37°C) shaking incubator. The aquaponics system (Fig. 1) supported about 50 kg of fish in a 1 m^3 grow-out tank coupled with hydroponics units. Onsite 1.3 m^3 UASB reactor (height 2.5 m, radius 0.4 m) was used to treat the fish sludge, and a 'HomeBiogas' unit was used to anaerobically treat the hydroponics plant waste (e.g., roots and inedible leaves). Fish sludge was backwashed and pumped into the UASB reactor by a 0.06 m^3/h peristaltic pump (Boxer 4500, Uno) and plant waste was introduced manually twice a week. Gas and supernatant from both anaerobic reactors were sampled and analyzed. In addition, water, fish, and plants from aquaponics were sampled routinely and analyzed for a wide range of physical and chemical parameters (Zhu et al., 2022a).

3. Results and discussion

The biogas production in the laboratory scale reactors under natural pH treatment increased more than the production in other pH treatments ($p < 0.05$) with 132±6 L biogas /kg-VS after 30 days. At 20 days HRT, the VFA yield reached a maximum of 272 ± 30 mg/L, and increasing HRT from 20 to 30 days gained no significant additional VFA yield. The production of VFA was affected by pH and was significantly higher under alkaline conditions. At pH 8.0, the VFA production reached 306 ± 21 mg/L. The VFA mainly consisted of acetic acid followed by propionic, n-butyric, and i-valeric acids. The highest batch nutrient product was observed for the lowest pH 5.0 and longest HRT 30 days. Maintaining a pH below 5 significantly enhanced nutrient mineralization and mobilization, enabling the recovery of about 25% of phosphorus, potassium, and calcium from the sludge.

The volume of biogas produced in the UASB reactor averaged 0.9 m^3/ kg-VS. The methane concentration in the biogas averaged 74.5%, sufficient for direct generator use. High and stable TOC and VS digestion efficiency over time, which averaged 92.8% and 97.6%, respectively, were also observed. Supernatant TN concentration averaged 142 mg/L, of which TAN accounted for 90%. Of the TP input, 66 ± 6 % was released into the supernatant, which resulted in an average TP concentration of 36 ± 5 mg/L. Similarly, all the important macronutrients and micronutrients needed for plant growth, such as K, Ca, Fe, Zn, Mn, Cu, and B, were found in the supernatant. VFA concentration in the supernatant was 148 ± 62 mg/L, and can potentially chelate metals, enhancing their availability over extended periods in the oxidizing environment characteristic of plant growth conditions (Zhu et al., 2023). In the aquaponics system coupling with UASB and plant waste reactors, 33% N and 37% P of the feed and 71% water were recovered from fish sludge via UASB reactor, which led to total nutrient utilization efficiency of 76% N and 80% P in the aquaponics. This system had 1.6 times higher plant productivity, used 2.1 times less water, and saved 96% of the overall energy consumption per kg of feed compared with previous reports for "traditional aquaponics." Net CO_2 sequestration of about 4.4 kg plants-C for 3 kg system-C emission was observed, minimizing the environmental footprint.



4. Conclusions

Anaerobic digestion (AD) of aquaponics solid wastes plays a pivotal role in waste management, sustainability and feasibility of aquaculture systems. Key findings include efficient biogas production with methane concentrations suitable for direct energy generation, substantial nutrient recovery from fish sludge and plant waste, and improved nutrient utilization efficiency. The system not only achieved typical fish production and high lettuce yields but also exhibited considerable water and energy savings compared to traditional methods. Additionally, the study underscores the potential for this integrated approach to significantly reduce the environmental footprint of aquaculture systems, contributing to circular economy goals and highlighting its feasibility for zero-waste, off-grid operations.

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