



RESEARCH ARTICLE

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Utilization of Aquaculture Effluent as an Organic Fertilizer to Improve Soil Fertility and Cassava (*Manihot esculenta* Crantz) Yield

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Abstract

This study evaluated the potential of aquaculture effluent as a liquid organic fertilizer to enhance soil fertility and cassava (*Manihot esculenta* Crantz) productivity. Conducted in Blang Berandang Village, West Aceh Regency, the experiment employed a Randomized Complete Block Design (RCBD) with six treatments: a control (0% effluent), inorganic fertilizer, and four effluent concentrations (25%, 50%, 75%, and 100%), each replicated four times. Measured variables included soil chemical properties (pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium), plant growth parameters, and tuber yield. Results indicated that the aquaculture effluent was rich in nutrients, containing 35.2 mg L⁻¹ nitrogen, 12.6 mg L⁻¹ P₂O₅, and 22.4 mg L⁻¹ K₂O, with a C/N ratio of 3.6. Effluent application significantly improved soil physicochemical properties, raising soil pH from 5.5 to 6.9 and organic carbon from 1.25% to 2.45%. Furthermore, total nitrogen, available phosphorus, and exchangeable potassium levels increased in proportion to effluent concentration. The 75% effluent treatment yielded the optimal results, producing a plant height of 135.4 cm and a tuber weight of 4.12 kg per plant—a 90% increase compared to the control. These findings demonstrate that aquaculture effluent significantly enhances soil fertility and cassava productivity relative to untreated controls. Consequently, its utilization offers a sustainable, eco-friendly strategy for integrated aquaculture-agriculture systems, contributing to increased crop production while mitigating environmental impacts associated with aquaculture waste.

Keywords: Agricultural Wastewater Reuse, Circular Agriculture, *Manihot esculenta* Cultivation, Nutrient Recycling, Sustainable Crop Production

1. Introduction

Agriculture plays a crucial role in ensuring national food security and maintaining ecosystem sustainability. However, agricultural and aquaculture systems are often managed independently, leading to inefficient resource use. One of the major concerns is the discharge of nutrient-rich wastewater from aquaculture systems, which is often released into the environment without proper utilization (Al-Wabel et al., 2024; Campanati et al., 2022a; FAO, 2024; Saliu & Oladoja, 2021). Integrating aquaculture and agriculture through an Integrated Aquaculture–Agriculture System (IAAS) offers an effective strategy to improve nutrient recycling, enhance soil fertility, and promote sustainable agricultural production (Turlybek et al., 2025; Verma et al., 2023).

Aquaculture effluent typically contains organic residues from feed and fish excretion, as well as essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K), along with micronutrients including calcium (Ca), magnesium (Mg), and zinc (Zn) (Devi et al., 2024; Hleibieh et al., 2026). These nutrients indicate that aquaculture wastewater has considerable potential for use as a liquid organic fertilizer (Ahuja et al., 2020; Al-Wabel et al., 2024; Van Tung et al., 2021; Zhang Hong et al., 2021).

The makeup of these nutrients in this farming byproduct makes it a useful asset that can serve as liquid organic fertilizer (LOF), offering both ecological safety and positive effects. Studies have indicated that employing LOF sourced from farming refuse can improve the physical,

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chemical, and biological aspects of dirt, increase the work of microbes, and decrease the need for manufactured fertilizers (Idaryani et al., 2024; Kurnianta et al., 2021; Riddech et al., 2025; Shi et al., 2023).

Employing liquid organic fertilizer made from fishery refuse on farmland presents a twofold benefit: it increases how well resources are used and simultaneously reduces air contamination from tossing waste into water bodies (Fitriani et al., 2017; Haryanta & Widya, 2024; Sa'adah, 2025). Furthermore, the elements existing as dissolved ions such as ammonium (NH_4^+), nitrate (NO_3^-), and phosphate (PO_4^{3-}) are readily absorbed by plants, particularly when they are in the rapid growth phase (Kodithuwakku et al., 2024; Ma et al., 2026; Passos et al., 2023; Shen et al., 2011). Several scientific investigations have shown that using discharge water from fish farms promotes the growth of crops such as grain, maize, and green produce (Al-Wabel et al., 2024; Kaab Omeir et al., 2020; Kanazoe et al., 2025). Merging fish farming with crop cultivation has demonstrated a nearly 40% improvement in the application of water and nutrients compared to older approaches (Afiya R.S.).

The Cassava plant (*Manihot Esculenta* Crantz) is an important national commodity, providing another source of carbohydrates and serving as a feedstock for the bioenergy industry (Anyanwu et al., 2015; Mohidin et al., 2023; Rozi et al., 2023; Scaria et al., 2024; Silva et al., 2025). Nevertheless, cassava output at the cultivation stage remains low, around 25-30 tons per hectare, which is considerably below the maximum potential yield of better varieties, which can reach 40 tons per hectare or more. A primary factor contributing to this diminished output is the decline in soil fertility due to extensive use of chemical fertilizers and a decrease in organic matter in the soil. Small amounts of HCN and substantial starch levels indicate that cassava has strong potential for cultivation in marginal and dry regions when appropriate, environmentally friendly management practices are applied (Bilong et al., 2022; Hafif et al., 2024; Kintché et al., 2017).

Previous studies have demonstrated the potential use of aquaculture wastewater as an alternative nutrient source in agricultural systems (Al-Wabel et al., 2024; Campanati et al., 2022b; Tabrett et al., 2024). Aquaculture effluent generally contains considerable amounts of nitrogen (N), phosphorus (P), and potassium (K) derived from fish feed residues and metabolic waste, which can improve soil nutrient availability and enhance crop productivity (Al-Wabel et al., 2024; Diatta et al., 2023; Zhang et al., 2023). For instance, irrigation with aquaculture wastewater has been reported to significantly increase soil nutrient concentrations and improve plant growth due to the presence of both macro- and micronutrients in the effluent. Similarly, research on crop production systems showed that aquaculture effluent can support plant growth and partially

substitute conventional fertilizers by recycling nutrients within integrated farming systems (Chiquito-Contreras et al., 2022; Fruscella et al., 2025; Kimera et al., 2021; Lopchan Lama et al., 2025; Oguntade et al., 2026).

Several experimental studies have evaluated the use of aquaculture wastewater in agriculture on various crops. For example, Diatta et al. investigated the combined use of catfish aquaculture wastewater and inorganic fertilizers in tomato cultivation and reported improvements in plant growth and biomass production when wastewater was integrated with balanced nutrient management. Other studies also reported that aquaculture wastewater irrigation could improve soil nutrient status and enhance crop yield while reducing the need for synthetic fertilizers (Al-Wabel et al., 2024; Fruscella et al., 2025; Guo et al., 2023; Nair et al., 2025; Obijianya et al., 2025; Saleh et al., 2025).

However, most previous studies have primarily focused on horticultural crops such as tomato and papaya, and limited research has explored the use of aquaculture wastewater for cassava cultivation, particularly in integrated aquaculture–agriculture systems in tropical marginal soils. Moreover, previous studies often evaluated wastewater irrigation alone or in combination with chemical fertilizers, whereas the potential of aquaculture wastewater as a liquid organic fertilizer (LOF) for improving soil fertility and cassava productivity remains underexplored.

Therefore, the novelty of this study lies in evaluating the application of aquaculture effluent as a liquid organic fertilizer for cassava (*Manihot esculenta* Crantz) cultivation, specifically focusing on its effects on soil chemical properties and cassava productivity under an integrated farming system. This research also provides a sustainable waste-management strategy for aquaculture operations, promotes nutrient recycling, and improves agricultural productivity on low-fertility soils.

Considering these circumstances, this study aims to evaluate the potential use of aquaculture wastewater as a liquid organic fertilizer to improve soil fertility and enhance the productivity of Adira-1 cassava (*Manihot esculenta* Crantz). The utilization of aquaculture effluent is expected to provide an environmentally friendly strategy for managing aquaculture waste while promoting sustainable crop production on marginal soils. Furthermore, this research contributes to the development of an integrated aquaculture–agriculture system that supports nutrient recycling, improves resource use efficiency, and strengthens sustainable food production systems.

2. Material and Methods

This study was conducted during a single cassava growing season from April 2024 to April 2025 at an experimental field located in Blang Berandang Village, West Aceh Regency, Aceh Province, Indonesia (4.143° N; 96.125° E), at an elevation of approximately 15 m above

sea level. Laboratory analyses were conducted for both chemical and biological soil properties, in addition to assessing nutrient levels within the fish effluent at the Soil Science Laboratory located at Universitas Teuku Umar. Selecting this particular research spot resulted from assessing terrain characteristics appropriate for nearby agricultural workers and the ease of monitoring the deployment of the fish processing water.

The components used for this investigation include local or better cassava seed kinds, such as the Adira 1 version, measuring twenty to twenty-five cm long cuttings. Water effluent from nearby fish ponds, housing species such as catfish, tilapia, or carp, is collected in advance for its intended purpose. Typical mineral fertilizers, such as NPK 15-15-15, urea, or ZA, are also brought in for contrasting purposes, dosed according to local recommendations.

Moreover, groundwater or clear water intended for irrigation is used as a baseline, alongside various agents to test the ground and water in the lab. These agents include sulfuric acid, potassium dichromate, Kjeldahl reagent, Olsen's solution, 1 M ammonium acetate, various enzyme agents, chloroform for microbial testing, extraction buffer, and a glucose mixture.

The apparatus utilized involves fieldwork implements such as hoes, plows, measuring threads, meters, GPS devices, plot markers, and treatment nameplates. For assessing plants, tools include measuring tapes, calipers, digital scales, and leaf-area-measuring tools. Ground examination tools include soil drills, ring samplers, ovens, 2 mm filters, pH meters, and electrical conductivity meters. Furthermore, lab instruments such as Kjeldahl apparatus, spectrophotometers, ovens, muffle furnaces, incubators, centrifuges, soil enzyme analyzers, and accessible TOC analyzers are used. Work safety protocols are upheld by using gloves, safety goggles, and typical laboratory attire.

This research uses a random design, the Complete Block Design (RCBD), with four replicates to reduce the effects of land differences. When there are two factors, such as wastewater concentration and fertilizer type, a factorial design is used within the RCBD. For the single factor layout with the waste water concentration treatment, there are six different treatments: T0, which is the control (regular water without fertilizer), T1, standard inorganic fertilizer for comparison, T2, 25% waste water (1:4 dilution), T3, 50% waste water (1:1 dilution), T4, 75% waste water (3:1 dilution), and T5, 100% waste water without any dilution. Each treatment was repeated four times, making a total of 24 experimental plots, each measuring 5 m by 5 m, with a spacing of 1 m and a buffer of 2 m between blocks. Cassava is planted with a spacing of 100 cm by 80 cm, resulting in approximately 20 to 25 plants per plot.

Effluent is applied regularly using manual watering or

irrigation systems, adjusted to the plant's nutrient needs, while inorganic fertilizers are applied according to the recommended dosage for different cassava varieties. Plant maintenance includes activities such as weeding, loosening the soil, and controlling pests, and these are done the same way across all treatment areas. The data collected includes the physical, chemical, and biological properties of the soil before and after treatment, plant growth (such as height, stem diameter, and number of leaves), and the yield of fresh and dry tubers per plot. Data analysis was carried out using ANOVA, followed by Duncan's or Tukey HSD post hoc tests, Pearson correlation analysis, optimal effluent dose regression, and optional multivariate analysis, such as PCA, with differences considered significant at $\alpha = 0.05$.



Figure 1. Flow diagram of research implementation

Water samples were collected from three locations in the ponds for testing pH, electrical conductivity, total suspended solids, biochemical oxygen demand, chemical oxygen demand, ammonium nitrogen, nitrate nitrogen, total nitrogen, phosphate phosphorus, potassium, calcium, magnesium, sodium, chloride, heavy metals (lead, cadmium, copper, zinc), and pathogens (optional). The initial soil samples (0–20 cm and 20–40 cm) were tested for texture, pH, organic carbon, total nitrogen, available phosphorus and potassium, cation exchange capacity, bulk density, porosity, and microbial biological parameters.

The treatment is applied using the effluent at the correct concentration, either once a week or every two weeks, through an irrigation hose or by manual watering. The amount of solution used is adjusted according to the needs of the plants, such as 10 liters per square meter, depending on nutrient levels. Inorganic fertilizer (T1) is

applied at the recommended rate for each cassava variety. Control (T0): well water only.

Laboratory and field tests were conducted to assess how applying fishery wastewater affects soil properties and cassava plant growth. Wastewater samples were tested for several key factors. These included pH level, electrical conductivity, biochemical oxygen demand, chemical oxygen demand, total suspended solids, nitrogen content in different forms like ammoniacal nitrogen, nitrite nitrogen, and total nitrogen, as well as levels of phosphorus, potassium, calcium, magnesium, and heavy metals such as lead, cadmium, copper, and zinc. Microbial indicators were also checked when needed. Meanwhile, soil samples were tested for their physical properties, including texture, bulk density, and porosity. They were also checked for chemical properties like pH, organic matter, total nitrogen, available phosphorus and potassium, and cation exchange capacity. Additionally, biological properties were examined, including microbial biomass, basal respiration, and enzyme activity (dehydrogenase, phosphatase, and fluorescein diacetate). In the field, plant growth is measured by assessing plant height, stem thickness, leaf number, and yield of fresh and dried tubers. All the data were analyzed to understand how soil characteristics, available nutrients, and plant growth and yield responses change across different treatments. The goal was to evaluate how effectively fishery wastewater can be used as a liquid organic fertilizer that is environmentally friendly and sustainable.

Data normality test (Shapiro–Wilk) dan homogenitas (Levene). If the data doesn't meet the assumptions, a transformation is applied, such as a log or a square root. Analysis of variance (ANOVA) is used for each variable response variable with the model:

$$Y_{ij} = \mu + B_i + T_j + \epsilon_{ij}$$

Table 1. Nutrient Content in Fishery Wastewater

No	Parameter	Unit	Result	Criteria fertility
1	pH	-	7.4	Neutral
2	Temperate	°C	28.3	Ideal microorganisms
3	BOD ₅	mg/L	36.5	Moderate
4	COD	mg/L	64.8	Moderate
5	Total N	mg/L	35.2	High
6	P ₂ O ₅	mg/L	12.6	Moderate
7	K ₂ O	mg/L	22.4	High
8	Ca	mg/L	18.7	Moderate
9	Mg	mg/L	9.5	Moderate
10	Na	mg/L	14.2	Moderate
11	Fe	mg/L	1.8	Safe
12	Mn	mg/L	0.54	Safe
13	C-organic	mg/L	128.6	High
14	Ratio C/N	-	3.6	Low

Note: Fertility criteria based on (FAO, 2021) and (Mansyur et al., 2021).

3.2. Post-Treatment Soil Analysis (After Harvest)

Post-harvest soil analysis revealed significant increases

BiB_iBi = block effect, T_jT_jT_j = treatment effect, ϵ_{ij} = error. Analysis of variance (ANOVA) was performed to determine the effects of the treatments on the observed variables. When significant differences among treatments were detected, Duncan’s Multiple Range Test (DMRT) was applied at a 5% significance level ($p \leq 0.05$) to compare treatment means. Pearson correlation analysis was conducted to evaluate the relationships between soil chemical properties and cassava yield. In addition, regression analysis was performed to determine the optimal dose of aquaculture effluent for cassava productivity.

All statistical analyses were carried out using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Statistical significance was determined at $p \leq 0.05$.

3. Results and Discussion

3.1. Chemical Analysis of Fishery Wastewater (Effluent)

At the Faculty of Agriculture's Laboratories, the Soil and Water Chemistry Laboratory analyzed air fisheries wastewater using standard procedures (SNI 6989.57:2008 and APHA, 2017). Samples were collected at a depth of ±20 cm below the water's surface from a catfish farming pond called *Clarias gariepinus gariepinus*). According to the investigation, the macro- and micronutrient content is high enough to sustain plant growth. Phosphorus (P₂ O₅) 12.6 mg/L, potassium (K₂ O) 22.4 mg/L, and nitrogen (N) 35.2 mg/L demonstrated potential effluent as a natural liquid organic fertilizer. Ratio A low C/N (3.6) suggests that the organic matter in the effluent is breaking down swiftly, ensuring that nutrients are available sooner.

While dissolved organic matter quickly decomposed to support soil microbial activity, the high levels of N, P, and K indicated that the effluent could support vegetative development and the filling of cassava tubers. Rapid decomposition ensures that nutrients are available more quickly.

in pH, organic carbon, total nitrogen, available phosphorus, and available potassium with increasing effluent dose. An

increase in pH from 5.4 (control) to 6.7–6.9 at effluent doses of 75–100% occurs because alkaline cations (Ca^{2+} , Mg^{2+} , K^{+}) neutralize hydrogen ions (H^{+}) in the soil exchange complex (Table 2). The rise in organic matter and

the availability of cations enhance cation exchange capacity (CEC), improve soil structure, and boost microbial activity, thereby increasing the availability of nitrogen, phosphorus, and potassium to plants.

Table 2. Post-Treatment Soil Analysis (After Harvest).

Parameter	Unit	T0	T1	T2	T3	T4	T5	criteria
pH (H_2O)	-	5.5	5.8	6.0	6.4	6.7	6.9	Slightly sour–neutral
C-organik	%	1.25	1.40	1.85	2.15	2.38	2.45	Moderate
N-total	%	0.12	0.14	0.18	0.22	0.25	0.27	Moderate–high
P	mg/kg	9.0	11.3	13.8	16.5	18.4	19.7	Moderate–high
K-dd	$\text{cmol}(+)\text{kg}^{-1}$	0.35	0.42	0.58	0.71	0.84	0.87	Moderate–high
KTK	$\text{cmol}(+)\text{kg}^{-1}$	14.9	15.4	16.2	17.1	17.8	18.1	Moderate–high

Note: Soil chemical properties were analyzed at the Soil Science Laboratory, Faculty of Agriculture, Universitas Teuku Umar, Aceh, Indonesia. The experiment used a randomized complete block design (RCBD) with six treatments and four replications (24 soil samples). Values are the meaning of four replications.

3.3. Vegetative Growth and Yield

Effluent from fisheries raised the plant height from 90.3 cm (T0) to 139.6 cm (T5). The stem diameter rose from 17.8 mm to 25.2 mm, and the number of leaves increased from 18.2 to 32.9 with the highest dose of effluent. This growth enhancement is attributed to the presence of nitrogen, phosphorus, potassium, and organic matter in the effluent, which supports vegetative development, photosynthesis, and the formation of plant tissues.

It looks like Table 3 shows that increasing the amount of wastewater used for irrigating cassava plants really makes a big difference in how well they grow. When plants get taller, have thicker stems, and produce more leaves, it means the wastewater is supplying enough nutrients for them to build up their plant parts. Nitrogen is key for making chlorophyll and leaves, while phosphorus and potassium help with stem growth and strong roots. The best results came from the highest treatment level (T5), suggesting that the plants can effectively use the nutrients from wastewater without any signs of excess or harm.

This taller growth in plants basically shows that using that fishery wastewater as a liquid organic fertilizer, or

POC, really works. It's giving them the main nutrients they need, like nitrogen, phosphorus, and potassium, which are super important for them to grow their leaves and stems. Nitrogen, in particular, is a big deal because it helps build up those plant parts through making proteins and chlorophyll (Anas et al., 2020; Fathi, 2022; Guan et al., 2025; Jaiswal & Dakora, 2025; Leghari et al., 2016; Muhammad et al., 2022; Yang et al., 2025; Zayed et al., 2023). When plants get enough nitrogen, they can photosynthesize better, which means they grow faster and taller.

Potassium and calcium in fish farm wastewater are believed to be important for cell wall formation and strengthening plant stems (Burstrom, 1968; Harika et al., 2024; Meena et al., 2022; M. Wang et al., 2013). Potassium helps move sugars from photosynthesis around the plant and keeps cells plump, while calcium helps make plant cell walls more robust. Nitrogen in this wastewater promotes the growth of new shoots and leaves, and phosphorus is key for developing new tissue. Since photosynthesis occurs in leaves, having more leaves means a larger surface area for capturing sunlight, which in turn leads to greater plant growth (Fang et al., 2023; Mridha et al., 2025).

Table 3. Vegetative Growth

Treatment	Plant Height (cm)	Stem Diameter (mm)	Number of Leaves (strands)
T0	90.3 ± 5.6 d	17.8 ± 1.2 d	18.2 ± 2.0 d
T1	104.7 ± 6.2 c	19.4 ± 1.4 c	22.1 ± 2.3 c
T2	114.9 ± 5.8 c	21.2 ± 1.5 c	25.3 ± 2.4 c
T3	124.6 ± 5.5 b	22.9 ± 1.3 b	27.9 ± 2.5 b
T4	134.8 ± 5.3 a	24.5 ± 1.2 a	30.8 ± 2.7 a
T5	139.6 ± 5.1 a	25.2 ± 1.1 a	32.9 ± 2.8 a

Note: T0 = control treatment (water without fertilizer); T1 = recommended dose of inorganic fertilizer; T2 = 25% aquaculture wastewater; T3 = 50% aquaculture wastewater; T4 = 75% aquaculture wastewater; T5 = 100% aquaculture wastewater. Values represent mean ± standard deviation of four replications. Different letters within the same column indicate significant differences among treatments according to Duncan's Multiple Range Test (DMRT) at the 5% significance level ($p \leq 0.05$).

The findings revealed that tuber weight increased from 2.15 kg per plant in the control group (T0) to 4.25 kg per plant in the T5 group. The best results were seen at T4, which used 75% effluent. The tubers' dry weight also

increased, from 32.6% to 37.7%. This suggests that the tubers were of higher physiological quality and contained more starch.

Table 4 shows that using fishery effluent significantly

boosts cassava yields. It makes a big difference in the number of tubers per plant, the total yield per acre, and the tuber dry weight. This jump in yield suggests that the nutrients from the effluent are doing a great job helping tubers grow and fill out properly. The T4 treatment was the most effective, yielding a substantial increase comparable to T5. This indicates that using 75% effluent provides enough nutrients for the plants. On top of that, the organic matter and key nutrients in the effluent also help improve soil structure and microorganism activity. This, in turn, makes nutrient uptake more efficient, thereby positively affecting the overall quality of the tubers, as evidenced by their high dry weight.

The increase in tuber bulk implies that fishery wastewater's nutrient supply assists in both tuber formation and final size. Nitrogen (N) promotes plant development and raises the output of energy-making compounds, while phosphorus (P) and potassium (K) support tuber growth by controlling how cells multiply, how sugars move, and how starch is made (Cao et al., 2025; Jiaying et al., 2022; H. Wang et al., 2024).

This pattern of climbing tuber amounts agrees with what (2023) found in maize, which uses sewage water as

liquid plant food, showing a 75% jump in seed output compared to control teams. The buildup of solid material inside manioc roots is much influenced by how well the light-capturing process works and the path of sugars from the foliage toward the roots. The mineral element potassium (K) present in used water plays a vital role in this sequence, since K helps move the captured light energy toward storage areas and speeds up root bulking.

Based on the study using ANOVA and the 5% DMRT test, giving wastewater at a rate of up to(T4) resulted in improvement compared with the untreated group and the lower. Yet, raising the use from 75% to 100% (T4 → T5) caused no meaningful difference whatsoever. This indicates that applying 75% wastewater provides the necessary nutrients for cassava without introducing excessive unwanted elements. Using too much wastewater may cause a buildup of ammonia salts and nitrogen substances, which could actually reduce how well plants absorb nutrients (Ahsan et al., 2022; Da Silva Cuba Carvalho et al., 2018; Hashmat et al., 2021). Therefore, implementing 75% wastewater use is recommended for both farming and environmental appropriateness.

Table 4. Harvest Results

Treatment	Tuber Weight per Plant (kg)	Tuber Yield (Ton/ha)	Tuber Dry Weight (%)
T0	2.15 ± 0.14 D	17.8 ± 1.1 d	32.6 ± 1.5 d
T1	2.86 ± 0.17 C	22.6 ± 1.3 c	34.1 ± 1.3 c
T2	3.25 ± 0.19 C	26.1 ± 1.5 c	35.4 ± 1.4 bc
T3	3.72 ± 0.22 B	29.9 ± 1.7 b	36.8 ± 1.2 ab
T4	4.18 ± 0.25 A	33.9 ± 1.8 a	37.5 ± 1.1 a
T5	4.25 ± 0.27 A	34.4 ± 1.9 a	37.7 ± 1.0 a

Note: T0 = control (water without fertilizer); T1 = recommended inorganic fertilizer; T2 = 25% aquaculture wastewater; T3 = 50% aquaculture wastewater; T4 = 75% aquaculture wastewater; T5 = 100% aquaculture wastewater. Values represent mean ± standard deviation (SD) of four replications under a randomized complete block design (RCBD). Different letters within the same column indicate statistically significant differences among treatments according to Duncan's Multiple Range Test (DMRT) at the 5% significance level ($p \leq 0.05$).

These results suggest that runoff from fishing operations increases both plant growth and the size and quality of cassava roots. The double effect of this wastewater, serving as a quick source of nourishment and improving ground quality, argues for putting into practice a combined farming method using both fish farming and cassava growing.

4. Conclusion

Aquaculture wastewater is rich in essential nutrients (N, P, and K) and exhibits a low C/N ratio, suggesting its potential as a readily available liquid organic fertilizer for cassava cultivation. Wastewater application significantly improved soil chemical properties, including pH, organic carbon, total nitrogen, available phosphorus, cation exchange capacity (CEC), and potassium levels, with the

most pronounced effects observed at 50–100% concentrations. Cassava vegetative growth parameters—specifically plant height, stem diameter, and leaf number—increased progressively with higher wastewater doses, demonstrating the effective support of nutrient supply for vegetative development. The maximum cassava yield was achieved at 75% wastewater concentration (Treatment 4), resulting in the highest tuber weight and indicating the potential for partial replacement of inorganic fertilizers. Therefore, aquaculture wastewater is recommended as a viable alternative organic fertilizer for cassava cultivation, with an optimal application rate of approximately 75%.

Acknowledgements

Thank you can also be conveyed to the parties who assist in the implementation of this independent research.

References

- Afiya, R. S. (2024). Harmony in agriculture: Integrating horticulture and fish farming for sustainability. *Chronicle of Aquatic Science*, 10(1), 74-84. <https://doi.org/10.61851/coas.v1i10.07>
- Ahsan, M., Nafees, M., Amin, M., Nawaz, F., Tufail, A., Sardar, H., Shokralla, S., Mahmoud, E. A., El-Sabrou, A. M., & Elansary, H. O. (2022). Nutrients uptake and accumulation in plant parts of

- fragrant *Rosa* species irrigated with treated and untreated wastewater. *Plants*, 11(9), 1260. <https://doi.org/10.3390/plants11091260>
- Ahuja, I., Dauksas, E., Remme, J. F., Richardsen, R., & Løes, A.-K. (2020). Fish and fish waste-based fertilizers in organic farming - With status in Norway: A review. *Waste Management*, 115, 95-112. <https://doi.org/10.1016/j.wasman.2020.07.025>
- Al-Wabel, M. I., Almutari, M. M., Ahmad, M., Al-Swadi, H. A., Ahmad, J., & Al-Farraj, A. S. F. (2024). Impacts of aquaculture wastewater irrigation on soil health, nutrient availability, and date palm fruit quality. *Scientific Reports*, 14(1), 18634. <https://doi.org/10.1038/s41598-024-68774-0>
- Anas, M., Liao, F., Verma, K. K., Sarwar, M. A., Mahmood, A., Chen, Z.-L., Li, Q., Zeng, X.-P., Liu, Y., & Li, Y.-R. (2020). Fate of nitrogen in agriculture and environment: Agronomic, ecophysiological and molecular approaches to improve nitrogen use efficiency. *Biological Research*, 53(1), 47. <https://doi.org/10.1186/s40659-020-00312-4>
- Anyanwu, C. N., Ibetu, C. N., Ezeoha, S. L., & Ogbuagu, N. J. (2015). Sustainability of cassava (*Manihot esculenta* Crantz) as an industrial feedstock, energy, and food crop in Nigeria. *Renewable Energy*, 81, 745-752. <https://doi.org/10.1016/j.renene.2015.03.075>
- Bilong, E. G., Abosolo-Angue, M., Nanganoa, L. T., Anaba, B. D., Ajebesone, F. N., Madong, B. A., & Bilong, P. (2022). Organic manures and inorganic fertilizers effects on soil properties and economic analysis under cassava cultivation in southern Cameroon. *Scientific Reports*, 12(1), 20598. <https://doi.org/10.1038/s41598-022-17991-6>
- Burström, H. G. (1968). Calcium and plant growth. *Biological Reviews*, 43(3), 287-316. <https://doi.org/10.1111/j.1469-185X.1968.tb00962.x>
- Campanati, C., Willer, D., Schubert, J., & Aldridge, D. C. (2022a). Sustainable intensification of aquaculture through nutrient recycling and circular economies: More fish, less waste, blue growth. *Reviews in Fisheries Science & Aquaculture*, 30(2), 143-169.
- Campanati, C., Willer, D., Schubert, J., & Aldridge, D. C. (2022b). Sustainable intensification of aquaculture through nutrient recycling and circular economies: More fish, less waste, blue growth. *Reviews in Fisheries Science & Aquaculture*, 30(2), 143-169. <https://doi.org/10.1080/23308249.2021.1897520>
- Cao, W., Sun, H., Shao, C., Wang, Y., Zhu, J., Long, H., Geng, X., & Zhang, Y. (2025). Progress in the study of plant nitrogen and potassium nutrition and their interaction mechanisms. *Horticulturae*, 11(8), 930. <https://doi.org/10.3390/horticulturae11080930>
- Chiquito-Contreras, R. G., Hernandez-Adame, L., Alvarado-Castillo, G., Martinez-Hernandez, M. D. J., Sánchez-Viveros, G., Chiquito-Contreras, C. J., & Hernandez-Montiel, L. G. (2022). Aquaculture-Production system and waste management for agriculture fertilization-A review. *Sustainability*, 14(12), 7257. <https://doi.org/10.3390/su14127257>
- Da Silva Cuba Carvalho, R., Bastos, R. G., & Souza, C. F. (2018). Influence of the use of wastewater on nutrient absorption and production of lettuce grown in a hydroponic system. *Agricultural Water Management*, 203, 311-321. <https://doi.org/10.1016/j.agwat.2018.03.028>
- Devi, N. L., Singh, A. H., Nongthombam, J., Kumar, S., & Chaudhary, K. P. (2024). Fish waste compost-A fertilizer for organic agriculture. *Journal of Experimental Agriculture International*, 46(11), 778-785. <https://doi.org/10.9734/jeai/2024/v46i113098>
- Diatto, A. A., Manga, A. G. B., Bassène, C., Mbow, C., Battaglia, M., Sambou, M., Babur, E., & Uslu, Ö. S. (2023). Sustainable production of tomato using fish effluents improved plant growth, yield components, and yield in northern Senegal. *Agronomy*, 13(11), 2696. <https://doi.org/10.3390/agronomy13112696>
- Fang, X., Yang, Y., Zhao, Z., Zhou, Y., Liao, Y., Guan, Z., Chen, S., Fang, W., Chen, F., & Zhao, S. (2023). Optimum nitrogen, phosphorus, and potassium fertilizer application increased chrysanthemum growth and quality by reinforcing the soil microbial community and nutrient cycling function. *Plants*, 12(23), 4062. <https://doi.org/10.3390/plants12234062>
- FAO. (2021). *Fish waste management*. FAO. <https://doi.org/10.4060/cb3694en>
- FAO. (2024). *Integrated agriculture-aquaculture: An efficient use of resources*. FAO. <https://doi.org/10.4060/cd1412en>
- FAO. (2025). *Small ponds make a big difference: Integrating fish with crop and livestock farming*. FAO. <https://openknowledge.fao.org/server/api/core/bitstreams/fec9445-f288-44e5-8c0e-557115082e9d/content/x7156e03.htm>
- Fathi, A. (2022). *Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: A review*. <https://doi.org/10.5281/zenodo.7143588>
- Fitriani, M., Marsi, M., Susanto, R. H., & Dewi, S. (2017). The effect of organic liquid fertilizer application on fish pond's water quality at the reclaimed Indonesian tidal lowland. *Aquacultura Indonesiana*, 17(2), 75. <https://doi.org/10.21534/ai.v17i2.63>
- Fruscella, L., Kotzen, B., Paradelo Perez, M., & Milliken, S. (2025). Investigating the effects of fish effluents as organic fertilisers on basil (*Ocimum basilicum*). *Applied Sciences*, 15(3), 1563. <https://doi.org/10.3390/app15031563>
- Guan, C., Zhang, D., & Chu, C. (2025). Interplay of light and nitrogen for plant growth and development. *The Crop Journal*, 13(3), 641-655. <https://doi.org/10.1016/j.cj.2025.01.005>
- Guo, H., Liao, L., Zheng, Z., Xu, J., Wei, Q., Chen, P., & Wang, K. (2023). Evaluating the effects of aquaculture wastewater irrigation with fertilizer reduction on greenhouse tomato production, economic benefits, and soil nitrogen characteristics. *Phyton*, 92(12), 3291-3304. <https://doi.org/10.32604/phyton.2023.044051>
- Haffif, B., Pujiharti, Y., Yani, A., Sjafrina, N., Asnawi, R., Wibowo, N. A., Frediansyah, A., Nurida, N. L., & Dariah, A. (2024). Improving cassava cultivation as an industrial raw material on acid soil in Indonesia. In A. Frediansyah (Ed.), *Cassava-Recent updates on food, feed, and industry*. IntechOpen. <https://doi.org/10.5772/intechopen.109709>
- Harika, N., Verma, A. K., Krishnani, K. K., Hittinahalli, C. M., Reddy, R., & Pai, M. (2024). Supplementation of potassium in aquaculture wastewater and its effect on growth performance of basil (*Ocimum basilicum* L.) and *Pangasianodon hypophthalmus* in NFT-based aquaponics. *Scientia Horticulturae*, 323, 112521. <https://doi.org/10.1016/j.scienta.2023.112521>
- Haryanta, D., & Widya, S. A. (2024). Liquid organic fertilizer (LOF) as a waste processing strategy to support increasing crop production: A review. *Journal of Applied Plant Technology*, 3(2), 106-119. <https://doi.org/10.30742/65vppg22>
- Hashmat, S., Shahid, M., Tanwir, K., Abbas, S., Ali, Q., Niazi, N. K., Akram, M. S., Saleem, M. H., & Javed, M. T. (2021). Elucidating distinct oxidative stress management, nutrient acquisition, and yield responses of *Pisum sativum* L. fertigated with diluted and treated wastewater. *Agricultural Water Management*, 247, 106720. <https://doi.org/10.1016/j.agwat.2020.106720>
- Hleibieh, M., Hanc, A., Michal, P., & Hrebeckova, T. (2026). Composting and vermicomposting of fish sludge with egg boxes and lettuce wastes with the addition of eggshells: Impacts on chemical properties, nutrient availability, and safety. *Agronomy*, 16(4), 473. <https://doi.org/10.3390/agronomy16040473>
- Hochman, G., Hochman, E., Naveh, N., & Zilberman, D. (2018). The synergy between aquaculture and hydroponics technologies: The case of lettuce and tilapia. *Sustainability*, 10(10), 3479. <https://doi.org/10.3390/su10103479>
- Idaryani, I., Fadwiwati, A. Y., Bananiek, S., Budiayati, E., Dianawati, M., Sugiartini, E., Wulanningtyas, H. S., Fatmawaty, A., & Yapanto, L. (2024). Effect of liquid organic fertilizer (LOF) on the growth, yield, and economics of maize (*Zea mays* L.) in South Sulawesi, Indonesia. *Transactions of the Chinese Society of Agricultural Machinery*, 55(3). <https://doi.org/10.62321/issn.1000-1298.2024.03.05>
- Jaiswal, S. K., & Dakora, F. D. (2025). Maximizing photosynthesis and plant growth in African legumes through rhizobial partnerships: The road behind and ahead. *Microorganisms*, 13(3), 581. <https://doi.org/10.3390/microorganisms13030581>
- Jiaying, M., Tingting, C., Jie, L., Weimeng, F., Baohua, F., Guangyan, L., Hubo, L., Juncai, L., Zhihai, W., Longxing, T., & Guanfu, F. (2022). Functions of nitrogen, phosphorus, and potassium in

- energy status and their influences on rice growth and development. *Rice Science*, 29(2), 166-178. <https://doi.org/10.1016/j.rsci.2022.01.005>
- Kaab Omeir, M., Jafari, A., Shirmardi, M., & Roosta, H. (2020). Effects of irrigation with fish farm effluent on nutrient content of basil and purslane. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, 90(4), 825-831. <https://doi.org/10.1007/s40011-019-01155-0>
- Kanazoe, M. F., Keita, A., Yamegueu, D., Konate, Y., Sawadogo, B., & Boube, B. (2025). Integrating fish farming into runoff water harvesting ponds (RWHF) for sustainable agriculture and food security: Farmers' perceptions and opportunities in Burkina Faso. *Sustainability*, 17(3), 880. <https://doi.org/10.3390/su17030880>
- Kimera, F., Sewilam, H., Fouad, W. M., & Suloma, A. (2021). Efficient utilization of aquaculture effluents to maximize plant growth, yield, and essential oils composition of *Origanum majorana* cultivation. *Annals of Agricultural Sciences*, 66(1), 1-7. <https://doi.org/10.1016/j.aas.2020.11.002>
- Kintché, K., Hauser, S., Mahungu, N. M., Ndonga, A., Lukombo, S., Nhamo, N., Uzokwe, V. N. E., Yomeni, M., Ngamitshara, J., Ekoko, B., Mbala, M., Akem, C., Pypers, P., Matungulu, K. P., Kehbila, A., & Vanlauwe, B. (2017). Cassava yield loss in farmer fields was mainly caused by low soil fertility and suboptimal management practices in two provinces of the Democratic Republic of Congo. *European Journal of Agronomy*, 89, 107-123. <https://doi.org/10.1016/j.eja.2017.06.011>
- Kodithuwakku, K., Huang, J., Doolette, C. L., Mason, S., Boland, J., Lehto, N. J., & Lombi, E. (2024). Plant responses to nitrate and ammonium availability in Australian soils as measured by diffusive gradients in thin-films (DGT) and KCl extraction. *Geoderma*, 449, 116997. <https://doi.org/10.1016/j.geoderma.2024.116997>
- Koutroubas, S. D., Antoniadis, V., Damalas, C. A., & Fotiadis, S. (2023). Municipal sewage sludge effects on maize yield, nitrogen use efficiency, and soil properties. *Journal of Soil Science and Plant Nutrition*, 23(1), 1209-1221. <https://doi.org/10.1007/s42729-022-01115-0>
- Kurnianta, L. D., Sedijani, P., & Raksun, A. (2021). The effect of liquid organic fertilizer (LOF) made from rabbit urine and NPK fertilizer on the growth of bok choy (*Brassica rapa* L. subsp. *chinensis*). *Jurnal Biologi Tropis*, 21(1), 157-170. <https://doi.org/10.29303/jbt.v21i1.2426>
- Leghari, S. J., Wahocho, N. A., Laghari, G. M., HafeezLaghari, A., MustafaBhabhan, G., HussainTalpur, K., Bhutto, T. A., Wahocho, S. A., & Lashari, A. A. (2016). Role of nitrogen for plant growth and development: A review. *Advances in Environmental Biology*, 10(9), 209+.
- Lopchan Lama, S., Marcelino, K. R., Wongkiew, S., Surendra, K. C., Hu, Z., Lee, J. W., & Khanal, S. K. (2025). Recent advances in aquaponic systems: A critical review. *Reviews in Aquaculture*, 17(3), e70029. <https://doi.org/10.1111/raq.70029>
- Ma, H., Liu, S., Zhao, Q., Liu, Y., Song, S., Shi, L., Li, H., & Shi, W. (2026). Increasing the nitrate-to-ammonium ratio improved plant growth and nitrogen uptake in pineapple seedlings. *Frontiers in Plant Science*, 16, 1754688. <https://doi.org/10.3389/fpls.2025.1754688>
- Mansyur, N. I., Pudjiwati, E. H., & MurtiLaksono, A. (2021). *Pupuk dan pemupukan*. Syiah Kuala University Press.
- Meena, L. L., Verma, A. K., Bharti, V. S., Nayak, S. K., Chandrakant, M. H., Haridas, H., Reang, D., Javed, H., & John, V. C. (2022). Effect of foliar application of potassium with aquaculture wastewater on the growth of okra (*Abelmoschus esculentus*) and *Pangasianodon hypophthalmus* in recirculating aquaponic system. *Scientia Horticulturae*, 302, 111161. <https://doi.org/10.1016/j.scienta.2022.111161>
- Mohidin, S. R. N. S. P., Moshawih, S., Hermansyah, A., Asmuni, M. I., Shafqat, N., & Ming, L. C. (2023). Cassava (*Manihot esculenta* Crantz): A systematic review for the pharmacological activities, traditional uses, nutritional values, and phytochemistry. *Journal of Evidence-Based Integrative Medicine*, 28, 2515690X231206227. <https://doi.org/10.1177/2515690X231206227>
- Mridha, D., Lamsal, B., & Antonangelo, J. A. (2025). Nanotechnology in agriculture: Innovations for sustainability and greenhouse gas mitigation—A review. *Science of The Total Environment*, 995, 180065. <https://doi.org/10.1016/j.scitotenv.2025.180065>
- Muhammad, I., Yang, L., Ahmad, S., Farooq, S., Al-Ghamdi, A. A., Khan, A., Zeeshan, M., Elshikh, M. S., Abbasi, A. M., & Zhou, X.-B. (2022). Nitrogen fertilizer modulates plant growth, chlorophyll pigments, and enzymatic activities under different irrigation regimes. *Agronomy*, 12(4), 845. <https://doi.org/10.3390/agronomy12040845>
- Nair, C. S., Manoharan, R., Nishanth, D., Subramanian, R., Neumann, E., & Jaleel, A. (2025). Recent advancements in aquaponics with special emphasis on its sustainability. *Journal of the World Aquaculture Society*, 56(1), e13116. <https://doi.org/10.1111/jwas.13116>
- Obijanya, C. C., Yakamercan, E., Karimi, M., Veluru, S., Simko, I., Eshkabilov, S., & Simsek, H. (2025). Agricultural irrigation using treated wastewater: Challenges and opportunities. *Water*, 17(14), 2083. <https://doi.org/10.3390/w17142083>
- Ogutade, O. A., Taofeek, A. A., Olagunju, S. O., Abifarin-Adegbenro, R. O., Odelana, T. B., Adewale, R. O., Sule, S. O., & Ojetayo, T. A. (2026). Influence of fishpond wastewater irrigation in enhancing soil mineral nutrition and uptake by cockscomb (*Celosia* spp. L.). *Journal of Hazardous Materials: Organics*, 2, 100009. <https://doi.org/10.1016/j.hazmo.2025.100009>
- Passos, L. P., Reis, P. R. C., Lima, L. C. R. D. S., Souza Sobrinho, F. D., & Silva, J. C. J. D. (2023). Comparative effects of ammonium and nitrate ions on growth and uptake of multiple elements of ruzigrass. *Journal of Plant Nutrition*, 46(14), 3370-3384. <https://doi.org/10.1080/01904167.2023.2205439>
- Rautaray, S. K., Sinhababu, D. P., Das, P. C., & Kaledhonkar, M. J. (2025). Integrated crop-fish farming system improves land and water productivity in a flood-prone lowland. *CABI Agriculture and Bioscience*, 0015. <https://doi.org/10.1079/ab.2025.0015>
- Riddech, N., Ngo, M. N., Boonlue, S., Dongsansuk, A., Santanoo, S., & Theerakulpisut, P. (2025). Physical and chemical properties evaluation of liquid organic fertilizers (LOFs) and their effects on promoting rice growth. *Sustainability*, 17(7), 3087. <https://doi.org/10.3390/su17073087>
- Rozi, F., Elisabeth, D. A. A., Krisdiana, R., Adri, A., Yardha, Y., & Rina, Y. (2023). Prospects of cassava development in Indonesia in supporting global food availability in future. In P. Kaushik (Ed.), *Advances in root vegetables research*. IntechOpen. <https://doi.org/10.5772/intechopen.106241>
- Sa'adah, T. T. (2025). Physicochemical properties of liquid organic fertilizer from a mixture of fish waste and coffee grounds. *International Journal of Multidisciplinary Research and Analysis*, 8(1). <https://doi.org/10.47191/ijmra/v8-i01-19>
- Saleh, M., Salehi, M., Khanaki, S., Ebrahimian, H., Liaghat, A., Mousavi, S. M., Pashapour, S., & Ashrafi, A. (2025). Effects of treated wastewater irrigation on soil properties, nutrient uptakes, and crop yields of agronomic crops under different crop rotations. *Agricultural Water Management*, 316, 109585. <https://doi.org/10.1016/j.agwat.2025.109585>
- Saliu, T., & Olojoja, N. (2021). Nutrient recovery from wastewater and reuse in agriculture: A review. *Environmental Chemistry Letters*, 19(3), 2299-2316.
- Scaria, S. S., Balasubramanian, B., Meyyazhagan, A., Gangwar, J., Jaison, J. P., Kurian, J. T., Pushparaj, K., Pappuswamy, M., Park, S., & Joseph, K. S. (2024). Cassava (*Manihot esculenta* Crantz)—A potential source of phytochemicals, food, and nutrition—An updated review. *eFood*, 5(1), e127. <https://doi.org/10.1002/efd2.127>
- Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W., & Zhang, F. (2011). Phosphorus dynamics: From soil to plant. *Plant Physiology*, 156(3), 997-1005. <https://doi.org/10.1104/pp.111.175232>
- Shi, Y., Niu, X., Chen, B., Pu, S., Ma, H., Li, P., Feng, G., & Ma, X. (2023). Chemical fertilizer reduction combined with organic fertilizer affects the soil microbial community and diversity and yield of cotton. *Frontiers in Microbiology*, 14, 1295722. <https://doi.org/10.3389/fmicb.2023.1295722>
- Silva, S. D. O., Mafra, A. K. C., Pelissari, F. M., Rodrigues De Lemos, L., & Molina, G. (2025). Biotechnology in agro-industry: Valorization of agricultural wastes, by-products, and sustainable

- practices. *Microorganisms*, 13(8), 1789. <https://doi.org/10.3390/microorganisms13081789>
- Tabrett, S., Ramsay, I., Paterson, B., & Burford, M. A. (2024). A review of the benefits and limitations of waste nutrient treatment in aquaculture pond facilities. *Reviews in Aquaculture*, 16(4), 1766-1786. <https://doi.org/10.1111/raq.12921>
- Turlybek, N., Nurbekova, Z., Mukhamejanova, A., Baimurzina, B., Kulatayeva, M., Aubakirova, K. M., & Alikulov, Z. (2025). Sustainable aquaculture systems and their impact on fish nutritional quality. *Fishes*, 10(5), 206. <https://doi.org/10.3390/fishes10050206>
- Van Tung, T., Tran, Q. B., Phuong Thao, N. T., Vi, L. Q., Hieu, T. T., Le, S., Tuan, N. Q., Sonne, C., Lam, S. S., Hai, L. T., & Le, Q. V. (2021). Recycling of aquaculture wastewater and sediment for sustainable corn and water spinach production. *Chemosphere*, 268, 129329. <https://doi.org/10.1016/j.chemosphere.2020.129329>
- Verma, A. K., Chandrakant, M. H., John, V. C., Peter, R. M., & John, I. E. (2023). Aquaponics as an integrated agri-aquaculture system (IAAS): Emerging trends and future prospects. *Technological Forecasting and Social Change*, 194, 122709. <https://doi.org/10.1016/j.techfore.2023.122709>
- Wang, H., Yang, Y., Yao, C., Feng, Y., Wang, H., Kong, Y., Riaz, U., Zaman, Q. U., Sultan, K., Fahad, S., & Deng, G. (2024). The correct combination and balance of macronutrients nitrogen, phosphorus, and potassium promote plant yield and quality through enzymatic and antioxidant activities in potato. *Journal of Plant Growth Regulation*, 43(12), 4716-4734. <https://doi.org/10.1007/s00344-024-11428-2>
- Wang, M., Zheng, Q., Shen, Q., & Guo, S. (2013). The critical role of potassium in plant stress response. *International Journal of Molecular Sciences*, 14(4), 7370-7390. <https://doi.org/10.3390/ijms14047370>
- Yang, Z., Yan, H., Liu, H., Yang, L., Mi, G., & Wang, P. (2025). Enhancing crop nitrogen efficiency: The role of mixed nitrate and ammonium supply in plant growth and development. *Biology*, 14(5), 546. <https://doi.org/10.3390/biology14050546>
- Zayed, O., Hewedy, O. A., Abdelmoteleb, A., Ali, M., Youssef, M. S., Roumia, A. F., Seymour, D., & Yuan, Z.-C. (2023). Nitrogen journey in plants: From uptake to metabolism, stress response, and microbe interaction. *Biomolecules*, 13(10), 1443. <https://doi.org/10.3390/biom13101443>
- Zhang, H., Gao, Y., Liu, J., Lin, Z., Lee, C. T., Hashim, H., Wu, W.-M., & Li, C. (2021). Recovery of nutrients from fish sludge as liquid fertilizer to enhance sustainability of aquaponics: A review. *Chemical Engineering Transactions*, 83, 55-60. <https://doi.org/10.3303/CET2183010>
- Zhang, J., Akyol, Ç., & Meers, E. (2023). Nutrient recovery and recycling from fishery waste and by-products. *Journal of Environmental Management*, 348, 119266. <https://doi.org/10.1016/j.jenvman.2023.119266>