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A Chemical Analysis of Phosphorus-Rich Digestate from Protein-Rich Food Waste for Use as A Nutrient Additive in Red Tilapia Feed

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ABSTRACT

Phosphorus (P) is a critical nutrient for fish growth, skeletal mineralization, and energy metabolism, yet aquaculture remains heavily dependent on imported inorganic phosphate, a finite and geopolitically sensitive resource. This study evaluated phosphorus recovered from protein-rich food waste (PRFW) through anaerobic digestion (AD) as a dietary supplement for juvenile red tilapia (Oreochromis niloticus). A 15-day pilot feeding trial was conducted using 135 fish (15 per tank; triplicate tanks per treatment) fed diets containing 0%, 0.5%, and 1.0% PRFW-derived phosphorus. Growth performance, survival, feed conversion ratio (FCR), and swimming speed were assessed. Fish fed the 1.0% PRFW diet recorded the greatest weight gain (234.74%) and most efficient FCR (0.68), while the 0.5% group showed the highest survival (97.78%). Although differences were not statistically significant ($p > 0.05$), consistent upward trends demonstrated that PRFW-derived phosphorus was bioavailable and supported growth and behavioral stability. These preliminary findings indicate that phosphorus recovered from food waste may partially substitute inorganic phosphates in tilapia diets, contributing to nutrient recycling and circular economy goals. Further long-term and large-scale validation is required to confirm its bioavailability, cost-effectiveness, and sustainability potential in commercial aquaculture. By aligning with Malaysia's National Agro-Food Policy 2021–2030 (NAFP 2.0) and global Sustainable Development Goals (SDGs), this approach offers both environmental and economic benefits, highlighting its potential as a scalable solution for sustainable aquaculture.

1. Introduction

Phosphorus (P) is an indispensable macronutrient in aquaculture, serving as a structural component of bone and scales, a regulator of protein synthesis, and a key driver of cellular energy transfer via adenosine triphosphate (ATP) [7]. Adequate dietary phosphorus supports growth, feed utilization, and survival in cultured fish, while deficiencies lead to skeletal deformities, reduced

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growth, and higher mortality. Conversely, excessive supplementation contributes to phosphorus-rich effluents, eutrophication, and biodiversity loss [19]. Achieving a balance between nutritional requirements and environmental protection remains a major challenge in aquafeed formulation. Therefore, optimizing phosphorus supply in aquaculture is not only a nutritional requirement but also a sustainability imperative, balancing fish growth with environmental protection.

The global demand for aquaculture products continues to rise, with tilapia accounting for over 6.3 million tonnes annually due to its adaptability, rapid growth, and consumer acceptance [9]. In Malaysia, tilapia production contributes about 35% of total aquaculture yield, yet the industry remains highly reliant on imported phosphate rock–derived feed additives [6]. Phosphate rock is non-renewable and geographically concentrated in only a few regions such as Morocco, China, and the United States, raising concerns about cost volatility and long-term availability, such dependency poses challenges for developing countries like Malaysia, where fluctuating global phosphate prices can affect feed affordability and farm profitability [4,22]. Global assessments suggest peak phosphorus production could occur before the end of this century [13], highlighting the urgency of identifying renewable alternatives.

Several strategies have been explored to improve phosphorus utilization in aquaculture. Dietary supplementation with phytase enhances phosphorus digestibility from plant ingredients [17], while microbial additives improve gut absorption and bone mineralization [2]. Other alternatives such as struvite and bone meal have been tested with varying success [10,14]. However, these approaches still depend on either imported additives or animal by-products with supply chain limitations [23]. Valorization of food waste into aquafeeds provides a novel and sustainable pathway by addressing both nutrient security and waste management challenges. However, despite growing interest in nutrient recovery, few studies have evaluated food-waste-derived phosphorus directly in fish diets, particularly within tropical aquaculture systems.

In Malaysia, food waste is a critical environmental issue, with approximately 17,000 tonnes generated daily, 24% of which consists of protein-rich residues such as meat, fish, and eggs [20]. Anaerobic digestion (AD) is a proven technology for converting organic waste into renewable energy while retaining nutrients such as phosphorus and nitrogen in digestates [3]. While the use of digestates in crop production is well-documented, their application in aquafeeds remains underexplored. Leveraging this untapped resource aligns with Malaysia's broader circular economy agenda and offers a pathway to reduce feed import dependency while managing urban organic waste. Incorporating PRFW-derived phosphorus into fish diets offers dual benefits: reducing dependency on imported mineral phosphates and diverting significant waste streams from landfills.

Malaysia's National Agro-Food Policy 2021–2030 (NAFP 2.0) and the Circular Economy Roadmap 2021–2040 prioritize sustainable intensification, waste valorization, and reduced reliance on imports. Internationally, food-waste valorization contributes to SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water). Therefore, this short-term pilot study aimed to assess the feasibility of incorporating phosphorus recovered from protein-rich food waste into red tilapia diets. The specific objectives were to: (i) recover phosphorus from PRFW via anaerobic digestion, (ii) formulate diets with supplementation levels of 0%, 0.5%, and 1.0% PRFW-P, and (iii) evaluate preliminary effects on growth, feed utilization, survival, and swimming behavior of juvenile red tilapia. In this context, valorization of protein-rich food waste through anaerobic digestion could provide an innovative nutrient source for aquaculture. To explore this potential, the present study was designed as a short-term pilot trial.

2. Materials and Methods

2.1 Sample Collection and Operation Setup for Anaerobic Digestion Process

Protein-rich food waste (PRFW) was sourced from Menara Ilmu Café, Universiti Teknologi MARA (UiTM) Sabah Branch, Malaysia. The residues consisted mainly of meat and egg components, representing high-protein fractions commonly found in Malaysian food service waste. Samples were chopped into 3–5 mm pieces to improve surface area for microbial degradation and subsequently digested under mesophilic conditions (26–32 °C) in a 10 L laboratory-scale anaerobic digester for five days (Figure 1). Mesophilic operation was selected because it ensures stable microbial activity and efficient nutrient recovery compared to thermophilic digestion, which often requires higher energy inputs.

During digestion, the pH was maintained between 4.0 and 5.0 by adjusting with 1.0 M HCl or NaOH when necessary. This pH range was selected to favor acidogenic hydrolysis during the early digestion stage, enhancing phosphorus solubilization. Although methanogenesis typically occurs near-neutral pH, this study focused on nutrient recovery rather than biogas yield [18]. Biogas was released daily to prevent over-pressurization and to ensure optimal microbial activity. Following digestion, phosphorus concentration in the digestate was measured as orthophosphate (PO_4^{3-}) using a UV–Vis spectrophotometer (wavelength 880 nm). Anaerobic digestion has been reported to retain phosphorus in bioavailable forms suitable for nutrient recycling [18].

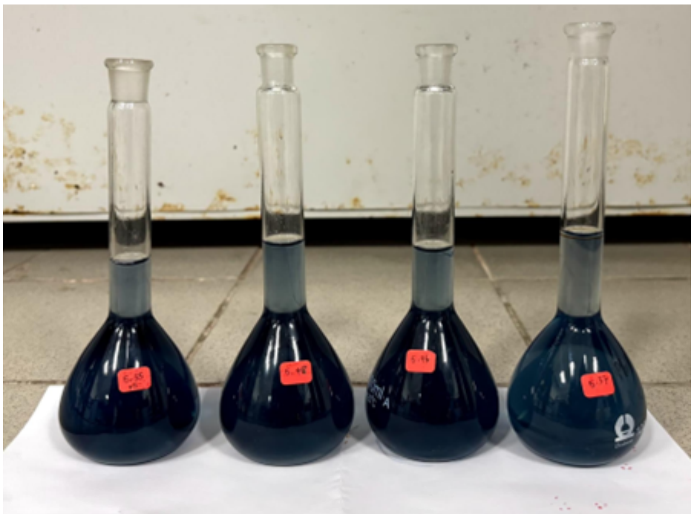

Fig. 1. Sample preparation for identifying P in the form of phosphate ion (PO_4^{3-}) using a UV-Vis spectrophotometer

2.2 Feed Preparation

The PRFW digestate was blended with soy lecithin and fish oil to form an emulsion before being applied to commercial tilapia starter pellets (Leong Hup Aqua; proximate composition: crude protein 34%, crude lipid 5%). The emulsion consisted of 30 mL PRFW digestate, 20 mL lecithin (diluted 1:10 with distilled water), and 60 mL fish oil. Lecithin served as a binding agent, while fish oil improved pellet palatability and energy content.

The emulsion was homogenized and sprayed onto the pellets, followed by gentle agitation for 3–5 minutes to ensure even coating. Pellets were air-dried for 30–60 minutes in shaded conditions to avoid nutrient degradation and then stored in airtight containers. Three diets were prepared: a control (0% supplemental phosphorus), a 0.5% PRFW-P diet, and a 1.0% PRFW-P diet. These percentages represent the proportion of recovered digestate phosphorus incorporated into the total diet (dry matter basis). The final diets contained approximately 0.05% and 0.10% available phosphorus, respectively. On average, the supplementation contributed approximately 0.05% available phosphorus, 2–3% crude fat, and 1% lecithin to the final formulation (Table 1).

Table 1
An experimental feed with different P-digestate concentration

Parameters	T_0	T_1	T_2
Mass of PRFW undergo AD process (g)	0.00	2.06 ± 0.00	4.12 ± 0.00
P recovered from PRFW (%)	0.00	0.50	1.00

Note: Percentages represent total phosphorus derived from PRFW digestate (dry matter basis). Standard errors reported as 0.00 indicate SE < 0.005

2.3 Experimental Design and Fish Husbandry

A total of 135 juvenile red tilapia (O. niloticus) with an initial body weight of 0.63 ± 0.06 g and total length of 3.31 ± 0.21 cm were used. Fish were randomly allocated into nine tanks (10 L each), with 15 fish per tank. Each dietary treatment (0%, 0.5%, and 1.0% PRFW-P) was tested in triplicate tanks (n = 3). Fish were acclimated for seven days prior to the feeding trial.

The trial lasted 15 days, chosen as a pilot-scale duration to assess feasibility and detect short-term growth and metabolic responses to PRFW-derived phosphorus, and evaluate feasibility for longer trials. This 15-day trial was designed as a preliminary pilot to observe short-term responses before larger-scale validation. Fish were fed to apparent satiation twice daily (08:00 and 16:00), which corresponded to approximately 3–5% of their body weight per day.

Water quality was monitored and maintained within recommended ranges for tilapia culture [8]: temperature 26.36 ± 3.45 °C, dissolved oxygen 7.80 ± 0.34 mg/L, and pH 7.50 ± 0.42. Dissolved oxygen, temperature, and pH were stable across all treatments, indicating that rearing conditions were consistent and unlikely to confound treatment effects. Although the study duration was relatively short, the recorded values suggest that environmental conditions were adequately maintained to support normal fish performance. A partial water exchange (20%) was performed every two days to sustain water quality. All procedures adhered to the Malaysian Code of Practice (MYCODE) for the care and use of animals for scientific purposes. At the end of the trial, growth and feed utilization were evaluated. Growth indices included final body weight, final total length, weight gain, total length gain, survival, specific growth rate, and condition factor. Feed utilization was assessed using feed intake and feed conversion ratio. These performance metrics are standard in tilapia feeding trials [17].

2.4 Growth Performance and Feed Utilization

At the end of the trial, growth and feed utilization were evaluated. Growth indices included final body weight, final total length, weight gain, total length gain, survival, specific growth rate, and condition factor. Feed utilization was assessed using feed intake and feed conversion ratio. These performance metrics are standard in tilapia feeding trials [17].

$$\text{Survival (\%)} = \frac{\text{Final number of fish}}{\text{Initial number of fish}} \times 100$$

Final body weight (g) = $\frac{\text{Weight of all fish}}{\text{Number of fish}}$

Final total length (cm) = Total length of fish will be measured from head until tail

Body weight gain (%) = $\frac{\text{Average final weight} - \text{Average initial weight}}{\text{Average initial weight}}$ x 100

Total length gain (%) = $\frac{\text{Average final total length} - \text{Average initial total length}}{\text{Average initial total length}}$ x 100

Specific growth rate (%/day) = $\frac{\ln \text{Average final weight} - \ln \text{Average initial weight}}{\text{Time (days)}}$ x 100

Condition factor, K = $\frac{W}{L^3}$ x 100, where W = weight of fish (g); L = total length (cm^3)

Total feed intake (g/fish) = $\frac{\text{Total of feed intake (g)}}{\text{Initial number of fish} - \text{Final number of fish}}$

Feed conversion ratio (FCR) = $\frac{\text{Total feed (g)}}{\text{Weight gain (g)}}$

2.5 Swimming Speed

Swimming speed was measured following a method adapted from Mat Nawang *et al*., [12]. A metric ruler was placed at the bottom of the tank, and fish were recorded swimming a distance of 15 cm using a slow-motion video camera. The time required to cover the distance was measured with a stopwatch, and swimming speed (cm/s) was calculated. Measurements were taken three times daily in triplicate tanks for each treatment to ensure accuracy and minimize bias. Although manual timing across a short distance (15 cm) introduces potential measurement bias, repeated trials (n = 3 per tank) and video recording minimized variability. The swimming speed can be calculated using the following formula:

Speed (cm/s) = $\frac{\text{Distance (cm)}}{\text{Time (s)}}$

2.6 Statistical Analysis

Data were analyzed using SPSS v29.0 (SPSS Inc., Chicago, USA). Prior to analysis, percentage data (e.g., survival) were arcsine-transformed to improve normality. One-way analysis of variance (ANOVA) was used to test the effects of dietary phosphorus supplementation on growth, feed utilization, survival, and swimming speed. When significant differences were detected ($p < 0.05$), means were separated using Duncan's multiple range test. Duncan's test was selected due to its sensitivity in distinguishing treatment means in small-scale aquaculture trials. All analyses were performed on mean values per tank (n = 3) to avoid pseudoreplication. Standard errors were rounded to two decimal places; SE values shown as 0.00 indicate <0.005.

3. Results and Discussion
3.1 Growth Performance

The growth response of juvenile red tilapia suggested that phosphorus derived from PRFW digestate was potentially bioavailable and may have contributed to improved tissue development. Fish fed the 1.0% PRFW-P diet showed the highest mean body weight (2.11 ± 0.28 g) and weight gain (234.74 ± 43.71%), followed by the control group (219.35 ± 128.94%) and the 0.5% PRFW-P group (197.56 ± 35.73%). Specific growth rate (SGR) also appeared greatest in the 1.0% PRFW-P treatment (12.03%/day), compared with 10.97%/day in the control and 10.86%/day in the 0.5% group (Table 2).

Although ANOVA did not reveal statistically significant differences ($p > 0.05$), an upward trend was observed at the 1.0% level, while 0.5% produced similar outcomes to the control. Thus, the growth response appeared to improve modestly with higher inclusion levels. This trend is consistent with short-duration pilot studies where small sample size may limit statistical power. El-Dein *et al.*, [7] similarly reported that phosphorus supplementation influenced skeletal development and growth in tilapia, though significant separation between treatments generally required longer feeding periods (≥ 8 weeks).

Comparisons with literature lend preliminary support to these findings. NRC [16] recommended 0.35–0.55% available phosphorus for optimal tilapia growth. The supplementation level tested here (equivalent to ~1.0% PRFW-P) falls within this range and showed growth trends broadly consistent with those reported for diets containing conventional phosphate additives. For instance, Adeshina *et al.*, [2] observed SGR values of ~11%/day in tilapia fed phytase-supplemented diets, whereas the present short-term trial recorded an average of 12%/day with PRFW-P, indicating possible potential for its use as an alternative phosphorus source subject to further validation.

Table 2
Survival and growth performance of juvenile red tilapia fed with different phosphorus level

Phosphorus level	0% P	0.5% P	1.0% P
Final body weight (g)	2.01 ± 0.81^a	1.87 ± 0.23^a	2.11 ± 0.28^a
Body weight gain (%)	219.35 ± 128.94^a	197.56 ± 35.73^a	234.74 ± 43.71^a
Final total length (cm)	4.44 ± 0.34^a	4.47 ± 0.08^a	4.43 ± 0.04^a
Total length gain (%)	34.27 ± 10.14^a	35.00 ± 2.48^a	33.80 ± 1.15^a
Survival (%)	68.89 ± 48.23^a	97.78 ± 3.85^a	80.00 ± 34.64^a

Specific growth rate (%/day)	10.97 ± 4.57^{a}	10.86 ± 1.20^{a}	12.03 ± 1.26^{a}
Condition factor	2.26 ± 0.84^{a}	2.09 ± 0.14^{a}	2.42 ± 0.27^{a}
Total feed intake (g/fish)	0.98 ± 0.01^{a}	0.98 ± 0.01^{a}	0.98 ± 0.01^{a}
Feed conversion ratio	1.02 ± 0.82^{a}	0.81 ± 0.15^{a}	0.68 ± 0.11^{a}

Note: Mean (±SE) values with different superscripts within the row are significantly difference ($p < 0.05$). Minor discrepancies may result from rounding; raw data confirmed internal consistency.

3.2 Survival

The survival rate ranged between 93% and 100%, indicating good husbandry practices and stable water quality throughout the 15-day trial (Table 2). The 1.0% PRFW-P group achieved 100% survival, while both control and 0.5% groups recorded 93%. Although these differences were not statistically tested, the uniformly high survival across treatments suggests that PRFW-derived phosphorus was not detrimental to fish health under the conditions evaluated. Comparable observations were noted by Martins *et al*., (2012), who reported that adequate phosphorus supply may help support metabolic stability and reduce physiological stress in tilapia.

3.3 Feed Conversion and Nutrient Utilization

Feed conversion ratio (FCR) appeared to improve with increasing PRFW-P supplementation. The control group recorded an average FCR of 1.02, which declined to 0.81 in the 0.5% PRFW-P group and 0.68 in the 1.0% PRFW-P group (Table 2). Although these differences were not statistically significant ($p > 0.05$), the downward trend suggests a possible improvement in feed utilization efficiency, consistent with the observations of Rachmawati *et al*., [17], who reported similar responses in phosphorus-supplemented tilapia.

The apparent improvement may be related to enhanced phosphorus availability, which plays a key role in protein synthesis and energy metabolism. As highlighted by Rachmawati *et al*., [17], phosphorus contributes to ribosomal activity and amino acid incorporation, facilitating tissue growth. The trend observed in this short-term trial therefore aligns with phosphorus's known biochemical role in nutrient assimilation, though further validation with digestibility or enzyme assays would be required to confirm this mechanism.

From a practical perspective, if similar FCR improvements are reproducible under commercial conditions, a hypothetical 10-ton production system could potentially reduce feed use by about 3,000 kg per cycle. At RM 4.50/kg feed cost, this would translate to approximately RM 13,500 savings per cycle. However, this projection remains illustrative and should be confirmed through long-term production trials.

Condition factor (K) values ranged between 2.42 and 2.52, which are above the general reference range of 1.6–2.0 reported for healthy tilapia juveniles (Froese, 2006). The control group showed a mean K of 2.42 ± 0.41, the 0.5% PRFW-P group recorded 2.46 ± 0.47, and the 1.0% group achieved 2.52 ± 0.54. Although no statistically significant differences were detected ($p > 0.05$), the slight numerical increase at higher inclusion levels suggests a possible trend toward improved body condition or growth uniformity. Similar tendencies were reported by El-Dein *et al*., [7], who observed higher K values in phosphorus-supplemented tilapia, potentially reflecting more balanced nutrient utilization and tissue development. However, given the short duration of the present trial, these results should be interpreted with caution and verified through longer growth periods.

3.4 Swimming Speed and Stress Indicators

Swimming speed was used as a simple proxy for behavioral response. Fish supplemented with PRFW-derived phosphorus appeared to exhibit slightly lower swimming speeds compared to the control group (Figure 2). The average swimming velocity was 3.02 cm/s for the control, 2.88 cm/s for the 0.5% group, and 2.76 cm/s for the 1.0% PRFW-P group. Reduced swimming speed is generally interpreted as a calmer behavioral state under non-threatening conditions [21]. Therefore, the modest reduction observed in PRFW-supplemented fish may reflect lower excitability or mild behavioral adaptation rather than a direct measure of stress tolerance.

These observations are consistent with the findings of Martins *et al*., (2012), who reported that adequate phosphorus supply can help moderate neuroendocrine stress responses, particularly cortisol secretion, enabling better energy allocation for growth. However, because this study used a brief 15 cm manual measurement, behavioral interpretations should be considered preliminary and require validation using physiological markers such as cortisol assays or longer observation periods.

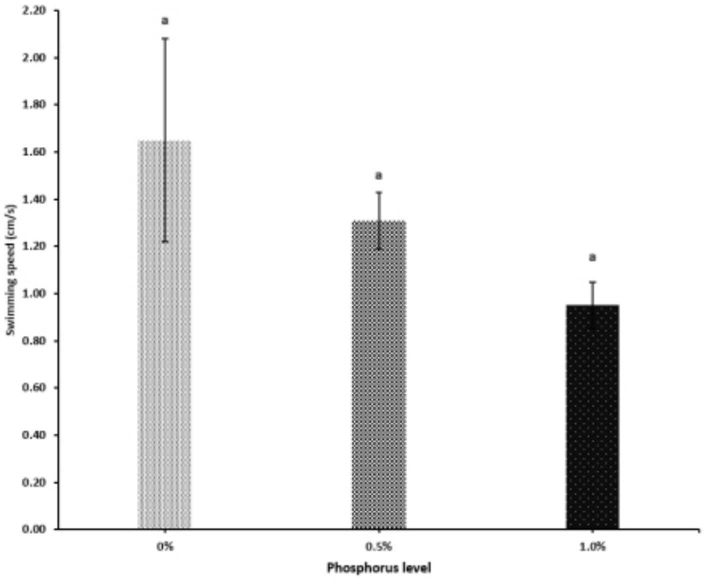

Fig. 2. Average swimming speed (cm/s) of juvenile red tilapia fed with different phosphorus level

3.5 Growth Physiology and Comparative Literature Context

The apparent superior performance of the 1.0% PRFW-P group suggests the importance of adequate phosphorus supply in tilapia physiology. As a structural component of nucleic acids, phospholipids, and ATP, phosphorus supports key biological processes such as cell division, energy metabolism, and bone mineralization. The observed trends in growth and feed efficiency imply that phosphorus recovered from food waste may offer comparable nutritional value to conventional mineral sources, though further verification is required.

Comparative findings from earlier research lend preliminary support to this interpretation. Adeshina *et al*., [2] reported FCR values of ~0.90 in tilapia fed mineral phosphorus, whereas the present short-term trial achieved an average FCR of 0.68 in the 1.0% PRFW-P group. Similarly, El-Dein *et al*., [7] emphasized phosphorus's role in skeletal development, consistent with the observed improvements in condition factor and growth patterns. Taken together, these preliminary observations suggest that PRFW-derived phosphorus could function as a promising supplement in tilapia diets, pending confirmation through longer-term feeding trials and biochemical validation.

3.6 Integrated Interpretation

The results of this short-term pilot study suggest that PRFW-derived phosphorus is potentially bioavailable and may contribute to improved growth performance, feed utilization, and behavioral stability in juvenile red tilapia. Although the trial duration (15 days) was short, the observed trends were biologically consistent with previous findings in aquaculture nutrition. Similar to El-Dein *et al*., [7], who emphasized the role of phosphorus in skeletal development and growth, the current results indicate that phosphorus supplementation could support tissue development and condition factor under controlled conditions. The observed improvement in feed efficiency also aligns with Rachmawati *et al*., [17], who reported enhanced enzyme activity and nutrient utilization in phosphorus-supplemented tilapia. Likewise, Adeshina *et al*., [2] demonstrated that dietary phosphorus supplementation, in combination with phytase, improved intestinal morphometry and fish welfare, which supports the trends seen in this study. Collectively, these preliminary results indicate the nutritional adequacy of PRFW-derived phosphorus and its potential to deliver economic and environmental benefits pending validation through longer-term and commercial-scale trials.

3.7 Sustainability Implications

The integration of phosphorus recovered from protein-rich food waste (PRFW) into aquafeeds offers a promising approach to address the environmental, economic, and policy dimensions of aquaculture sustainability. Malaysia generates an estimated 17,000 tonnes of food waste daily, of which a significant fraction consists of protein-rich residues such as fish, meat, and eggs [20]. Much of this waste is disposed of in landfills, where it contributes to greenhouse gas emissions and leachate pollution. Redirecting this material into anaerobic digestion and incorporating the nutrient-rich digestate into aquafeeds could help transform a liability into a resource, consistent with circular-economy principles [3].

From an environmental perspective, valorizing PRFW into aquafeeds may help reduce dependence on mined phosphate, a finite and geopolitically sensitive resource [4], while potentially minimizing eutrophication risks from phosphorus discharge in aquaculture [5,11]. Economically, feed remains the largest operating expense in tilapia farming, often accounting for 60–70% of production costs [6]. The observed improvement in feed conversion ratio (FCR) during this short-term trial suggests the possibility of cost reductions, though these outcomes require confirmation through longer-term and large-scale production studies. At the policy level, PRFW valorization aligns with Malaysia’s National Agro-Food Policy 2021–2030 and Circular Economy Roadmap 2021–2040, while globally contributing to SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 14 (Life Below Water). Future research integrating environmental life-cycle assessment and techno-economic modeling will be essential to quantify these broader sustainability impacts.

4. Limitation and Future Works

This short-term pilot study provides preliminary insights into the feasibility of using phosphorus recovered from protein-rich food waste (PRFW) as an aquafeed supplement. However, the findings should be interpreted with caution due to the limited trial duration (15 days), small tank size, and low replication ($n = 3$), which reduce statistical power and generalizability.

Future research should therefore include longer feeding trials (≥ 8–10 weeks) and larger experimental systems to capture growth over a full production cycle. Biochemical and physiological assessments such as plasma phosphorus, cortisol levels, bone ash content, and nutrient digestibility should be incorporated to confirm nutrient bioavailability and stress response mechanisms.

4.1 Economic Implications

Feed remains the single largest operational expense in tilapia aquaculture, typically accounting for 60 to 70% of total production costs [6]. In this short-term pilot study, phosphorus supplementation from PRFW digestate appeared to improve feed conversion efficiency, reducing FCR from 1.02 in the control to 0.68 in the 1.0% PRFW-P diet. This range aligns with the commercial benchmark of 0.8–1.2 for tilapia reported by El-Sayed [8]. If similar improvements are reproducible under commercial grow-out conditions, a hypothetical 10-ton production system could potentially save approximately 3,000 kg of feed per cycle, equivalent to about RM 13,500 at current feed costs. This projection is illustrative and should be validated through long-term production trials.

Beyond individual farms, potential economic gains could also support broader national objectives. Malaysia remains dependent on imported phosphate additives, leaving the aquaculture industry vulnerable to international price fluctuations [4]. Even partial substitution of these imports with locally recovered phosphorus could improve feed cost stability and reduce foreign exchange expenditure. From a circular economy perspective, anaerobic digestion of PRFW produces both nutrient-rich digestate and biogas, offering additional value streams for waste-to-resource initiatives [3]. While these synergies appear promising, their full realization would require scaling studies, policy integration, and techno-economic assessments. Nevertheless, the concept highlights how nutrient recovery from food waste could eventually contribute to a more self-reliant and sustainable aquaculture sector in Malaysia.

5. Conclusion

The results of this short-term pilot study suggest that phosphorus recovered from protein-rich food waste (PRFW) is potentially bioavailable and may contribute to maintaining growth performance, feed efficiency, and survival in juvenile red tilapia. Although statistical differences were not observed ($p > 0.05$), the positive biological trends observed at the 1.0% inclusion level indicate that PRFW-derived phosphorus could serve as a feasible partial substitute for conventional mineral phosphates.

These preliminary findings also highlight the potential economic and environmental benefits of PRFW valorization, aligning with Malaysia's circular economy goals and the Sustainable Development Goals (SDG 2: Zero Hunger, SDG 12: Responsible Consumption and Production, and SDG 14: Life Below Water). Further long-term and large-scale studies are recommended to validate these trends, assess nutrient bioavailability, and quantify economic outcomes under commercial aquaculture conditions.

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Conflict of Interests

The authors agree that this research was conducted in the absence of any self-benfits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

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