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Effects of Palm Kernel Meal Inclusion on Growth Performance, Nutritional Utilization, and Economic Viability in *Pangsianodon hypophthalmus* Diets

(Kesan Penambahan Makanan Biji Sawit terhadap Prestasi Pertumbuhan, Penggunaan Pemakanan dan Daya Tahan Ekonomi dalam Diet *Pangsianodon hypophthalmus*)

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ABSTRACT

This study evaluated graded inclusion levels of palm kernel meal (PKM) in practical diets for fingerling *Pangasianodon hypophthalmus*. Five isonitrogenous and isoenergetic diets containing 0%, 10%, 20%, 30%, and 40% PKM were fed for 84 days to assess growth performance, feed utilization, and economic viability. The results showed that inclusion levels above 20% significantly reduced growth rate, feed efficiency, and protein utilization ($P < 0.05$), whereas survival remained unaffected. Feed cost decreased progressively with increasing PKM inclusion, resulting in a 14.5% reduction in production cost. However, economic profitability declined beyond the 20% level, indicating a trade-off between feed cost reduction and biological performance of the fish. Overall, practical diets for *P. hypophthalmus* can incorporate up to 20% PKM without compromising productivity or economic return.

Keywords: Economic viability; feed cost efficiency; growth performance; palm kernel meal; *Pangasianodon hypophthalmus*

ABSTRAK

Penyelidikan ini menilai tahap penambahan berperingkat bagi makanan biji sawit (PKM) dalam diet praktikal untuk anak ikan *Pangasianodon hypophthalmus*. Lima diet isonitrogenous dan isoenergetik yang mengandungi 0%, 10%, 20%, 30% dan 40% PKM telah diberi makan selama 70 hari untuk menilai prestasi tumbesaran, penggunaan makanan dan kebolehlaksanaan ekonomi. Keputusan menunjukkan bahawa tahap penyertaan melebihi 20% secara signifikan mengurangkan kadar pertumbuhan, kecekapan makanan dan penggunaan protein ($P < 0.05$), manakala kadar kemandirian tetap tidak terjejas. Kos makanan berkurangan secara progresif dengan peningkatan penglibatan PKM, menghasilkan pengurangan kos pengeluaran sebanyak 14.5%. Namun, keuntungan ekonomi menurun melebihi tahap 20%, menunjukkan adanya pertukaran antara pengurangan kos makanan dan prestasi biologi ikan. Secara keseluruhan, diet praktikal untuk *P. hypophthalmus* boleh mengandungi sehingga 20% PKM tanpa menjejaskan produktiviti atau pulangan ekonomi.

Kata kunci: Kebolehlaksanaan ekonomi; kecekapan kos makanan; kek biji sawit; *Pangasianodon hypophthalmus*; prestasi pertumbuhan

INTRODUCTION

Aquaculture nutrition increasingly seeks sustainable and cost-effective alternatives to fish meal and soybean meal amid escalating feed ingredient prices. Palm kernel meal (PKM), a by-product of the palm oil industry, is widely available in tropical regions and offers potential as a partial replacement for conventional protein sources. Its utilization converts agro-industrial residues into functional feed ingredients (Hanum 2023), thereby supporting circular bioeconomy objectives.

PKM is characterised by moderate protein levels and residual oil content; however, its relatively high fiber concentration and limited digestibility may constrain nutrient utilization in fish (Abdollahi et al. 2016; Olaniyi 2014; Roberts et al. 2024; Tadjong et al. 2020). Previous studies have demonstrated that growth and feed efficiency responses in tilapia and catfish vary depending on inclusion level and dietary processing strategies (Lim, Dominy & Klesius 2001; Ng et al. 2002; Syahrizal et al. 2022; Wattanakul et al. 2021).

Despite these insights, information regarding its application in *P. hypophthalmus*, an economically important freshwater species in Southeast Asian, remains limited. While PKM incorporation has been investigated nutritionally, its economic implications in aquafeed formulation remain insufficiently quantified. Although several studies have reported potential reductions in feed cost (Mugwanya et al. 2022; Tadjong et al. 2020), few have evaluated impacts on profitability indicators such as benefit–cost ratio or net return. An integrated biological and economic assessment is therefore necessary to inform production-level decision-making (Turchini, Trushenski & Glencross 2018).

Processing innovations such as enzymatic treatment and fermentation have been explored to enhance PKM digestibility and nutritional value (Devi & Marlida 2023; Leong et al. 2023; Ogunji et al. 2021). Continued exploration of alternative feed ingredients aims to replace conventional resources while maintaining growth performance and animal health (Altop, Güngör & Erener 2019; Hakimi et al. 2019; Leong et al. 2023). Nevertheless, species-specific evidence for Pangasius remains scarce.

Despite increasing interest in PKM as an alternative feed ingredient, existing research has primarily focused on growth responses or nutritional characterisation, with limited attention to integrated economic performance and sparse evidence specific to *P. hypophthalmus*. To address this gap, the present study applies a dual biological–economic evaluation framework to examine graded PKM inclusion in practical diets. By simultaneously assessing growth performance, feed utilization efficiency, cost structure, and profitability indices, this work provides species-specific evidence linking nutritional outcomes with economic feasibility in tropical aquaculture systems.

MATERIALS AND METHODS

DIET FORMULATION AND PREPARATION

The ingredient composition of the feed is shown in Table 1. Five isonitrogenous and isoenergetic diets containing 0%, 10%, 20%, 30%, and 40% PKM were formulated (designated as PKM0, PKM10, PKM20, PKM30, and PKM40). The experimental diets were derived from ingredients readily available in the public market of Jambi and through online markets in Indonesia. All ingredients were finely ground, thoroughly mixed, pelleted at 2 mm, and air-dried. The diets were subsequently stored in air-tight container until used.

FISH AND EXPERIMENTAL DESIGN

Fingerling of *P. hypophthalmus*, sourced from the Center of Freshwater Aquaculture Development, Sungai Gelam, Jambi, Indonesia, underwent a two-week acclimation period in the conditioning hapa nets (5 m × 5 m × 1.5 m) before being transferred to 15 experimental hapa nets (2 × 2 × 1.5 m) that were set up in a 500 m^2 fishpond. Experimental fish were provided with commercial feed *ad libitum* two times daily before the commencement of the experiment. A total of sixty fish with initial weight of approximately 12.6 g were randomly distributed into each experimental hapa net (15 hapa net for three replicates per treatment). Fish were feed twice daily at 5% of body weight and cultivate for 84 days. The measurement of water parameters occurred throughout the conditioning phase as well as during the feeding experiment. Dissolved oxygen, pH, and water temperature varied from 0.39 to 2,77 mg L^{-1}, 6.16 to 7.50, and 26.1 to 29.0 °C, respectively.

GROWTH PERFORMANCE

Multiple growth indicators, such as weight gain (WG), average daily rate (ADGR), feed efficiency ratio (FER), protein efficiency ratio (PER), and specific growth rate (SGR), were computed utilizing the equations provided by Perera et al. (2025):

$$\text{Weight gain (WG)} = \text{Final weight} - \text{Initial weight}$$

$$\text{Average daily growth rate (ADGR)} = \text{Weight gain/Culture period}$$

$$\text{Feed efficiency ratio (FER)} = \text{Weight gain/Feed intake}$$

$$\text{Specific growth rate (SGR \%)} = [\ln(\text{final body weight}) - \ln(\text{initial body weight}))/(\text{Culture period})] \times 100$$

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

ECONOMIC VIABILITY

The economic analyses were conducted by the methodologies outlined by Jimoh et al. (2015), Kiamfu et al. (2020), Pallaya-Baleta et al. (2021), and Wachira et al. (2021). The evaluations encompass the incidence cost, profit index, profit per kilogram, total cost, total variable cost, total fixes cost, total revenue, gross margin, net return, and benefit-cost ratio. The calculations were performed utilizing the following formulas:

$$\text{Incidence cost} = \text{cost of feed/weight of fish} \times 100$$

TABLE 1. Ingredient composition and proximate analysis of experimental PKM inclusion diets for *P. hypophthalmus* feeding trial

Ingredient (%)	Experimental diets				
	PKM0	PKM10	PKM20	PKM30	PKM40
Fish meal	20	20	20	20	20
Shrimp head meal	5	5	5	5	5
Soybean meal	15.3	13.8	12	10.4	9
Polished bran	13	10.2	10	9.7	6
Fine bran	12.47	11.97	7.87	4.87	4.87
Coconut meal	30.2	25	21.1	16	11.1
Palm kernel meal	0	10	20	30	40
Tapioca	2.5	2.5	2.5	2.5	2.5
Fish oil	0.5	0.5	0.5	0.5	0.5
Fish premix*	0.5	0.5	0.5	0.5	0.5
Phytase enzyme	0.03	0.03	0.03	0.03	0.03
Molasses	0.5	0.5	0.5	0.5	0.5
Total	100	100	100	100	100
Proximate chemical composition (% as dry matter)					
Crude protein	28.25	28.25	28.25	28.25	28.25
Crude fat	9.99	9.50	9.89	9.93	9.90
Fiber	6.62	7.22	7.89	8.44	9.12
Ash	10.51	10.25	9.95	9.68	9.45
NFE**	44.63	44.77	44.03	43.70	43.27
Digestible energy (kcal g-1)***	435.07	431.09	431.64	430.68	428.73

*Fish premix (per kg): Vitamin A 170,000.00 IU, Vitamin D3 50,000.00 IU, Vitamin E 3,000.00 IU, Vitamin K3 135.00 mg, Vitamin B1 200.00 mg, Vitamin B2 330.00 mg, Vitamin B6 335.00 mg, Vitamin B12 0.45 mg, Biotin 4.00 mg, Folic Acid 65.00 mg, Calpan 1,000.00 mg, Nicovinic Acid 2,000.00 mg, Iron 1,335.00 mg, Copper 100.00 mg, Zinc 3,350.00 mg; **NFE: nitrogen free extract; ***Calculated based on digestible energy according to Watanabe (1988); 1 g of protein contains 5.6 kcal g^{-1}, 1 g of nitrogen free extract contains 4.1 kcal g^{-1}, and 1 g of lipid contains 9.4 kcal g^{-1}

Profit index = value of fish/cost of feed

Profit/kg = value of 1 kg fish – incidence cost

Total variable cost (TVC) = cost of fingerlings + cost of feeding

Total fixed cost (TFC) = cost of hapa nets + pond rent

Total cost (TC) = TVC + TFC

Total Revenue (TR) = Price of fish x Biomass output (kg)

Gross margin (GM) = TR - TVC

Net Return (NR) = TR - TC

Expense structure ratio (ESR) = TFC/TC

Benefit cost ratio (BCR) = TR/TC

Gross ratio (GR) = TC/TR

Rate of return (ROR) = NR/TC

STATISTICAL ANALYSIS

Data were analyzed using a one-way analysis of variance (ANOVA) follows by Duncan's post hoc test using the JASP 0.19.3.0 statistical software package. Differences were considered at $P < 0.05\%$.

ETHICAL APPROVAL

All experimental procedures were conducted in accordance with applicable ethical and professional standards governing animal research and complied with Regulation No. 6/PERMEN-KP/2020 of the Ministry of Marine Affairs and Fisheries, Indonesia. Formal approval for the study was granted by the Center of Freshwater Aquaculture Development, Sungai Gelam, Jambi.

RESULTS

GROWTH PERFORMANCE, FEED UTILIZATION AND SURVIVAL

The growth performance of *P. hypophthalmus* fed diets with palm kernel meal inclusion is presented in Table 2, while the monitoring of growth trend is shown in Figure 1. The initial weights of fish across different treatment groups showed no statistical difference ($P > 0.05$), confirming successful random allocation. However, a significant decline in final body weight and weight gain was observed with PKM inclusion level exceeding 20% ($P < 0.05$). The highest final weight recorded was 33.67 ± 0.25 g for the control group (PKM0), with the lowest was 28.21 ± 0.31 g in the PKM40 group. Further, weight gain mirrored these results, peaking at 21.09 ± 0.07 g in the PKM0 group and declining to 15.68 ± 0.43 g in PKM40. The average daily growth rate and specific growth rate also exhibited a downward trend, correlating with higher PKM levels.

As for feed utilization metrics, the feed conversion ratio (FCR) worsened as PKM levels increased, from 3.01 in PKM0 to 3.80 in PKM40, indicating reduced feed efficiency. The feed efficiency ratio (FER) and protein efficiency ratio (PER) demonstrated similar declines, further confirming the adverse impact of high PKM inclusion on feed utilization efficiency. Interestingly, despite declines in growth performance and feed conversion ratio, survival rates remained high across all treatments, ranging from 97% to 99%, with no significant variation due to PKM inclusion ($P > 0.05$). This suggests that while PKM may adversely affect growth performance, it does not pose health risks to the fish.

FEED INGREDIENT COST AND PRODUCTION COST

Table 3 details the cost composition of the experimental diets. The cost of feed ingredients per kilogram decreased progressively with increasing PKM inclusion, from IDR 4,933.06 in PKM0 to IDR 4,220.76 in PKM40, representing a 14.5% cost saving at the highest PKM level. This reduction was primarily due to the substituting of expensive ingredients (fish meal, soybean meal) with the more economical PKM. The total feed production cost, which included fixed costs for electricity, fuel, packaging, and manpower (Table 4), followed a similar trend, decreasing from IDR 5,533.06 (PKM0) to IDR 4,820.76 (PKM40).

GROSS PROFIT AND ECONOMIC INDICES

Gross profit analysis (Table 5) showed that, despite a reduction in feed costs, weight gain decreased significantly with higher PKM inclusion ($P < 0.05$). The incidence cost (feed cost per kilogram of weight gain) was lowest in PKM20, suggesting optimal feed cost efficiency at moderate PKM levels. The profit index improved with increasing PKM, from 3.25 (PKM0) to 3.73 (PKM40), reflecting the lower feed cost per unit value of fish produced. However, profit per kilogram remained relatively stable across treatments, with slight increases in PKM20-PKM40.

COST OF PRODUCTION AND REVENUE

Table 6 presents the cost of production and revenue parameters. Biomass production and feed fed both declined significantly with increasing PKM inclusion ($P < 0.05$). While total variable and total production costs decreased

TABLE 2. Growth performance and survival of *P. hypophthalmus* fed diets with increasing PKM inclusion level diet for 84 days

Parameters	Experimental diet				
	PKM0	PKM10	PKM20	PKM30	PKM40
Growth Metrics					
Weight (Initial) g	12.58 ± 0.27[a]	12.63 ± 0.32[a]	12.64 ± 0.015[a]	12.57 ± 0.27[a]	12.53 ± 0.02[a]
Weight (Final) g	33.67 ± 0.25[e]	31.39 ± 0.35[c]	32.35 ± 0.12[d]	30.07 ± 0.09[b]	28.21 ± 0.31[a]
Weight gain (g)	21.09 ± 0.07[e]	18.76 ± 0.35[c]	19.71 ± 0.09[d]	17.50 ± 0.29[b]	15.677 ± 0.434[a]
Average daily growth rate	0.25 ± 0,00[d]	0.22 ± 0.01[c]	0.24 ± 0.01[d]	0.207 ±0 .006[b]	0.187 ± 0.006[a]
Specific growth rate (%)	3.43 ± 0.05[c]	3.33 ± 0.11[bc]	3.41 ± 0.06[c]	3.29 ± 0.03[ab]	3.18 ± 0.03[a]
Feed Utilization					
Feed conversion ratio	3.01 ± 0.01[a]	3.35 ± 0.13[bc]	3.24 ± 0.06[b]	3.80 ± 0.04[c]	3.80 ± 0.04[d]
Feed efficiency ratio	33.30 ± 0.17[d]	29.89 ± 1.12[bc]	30.91 ± 0.54[c]	29.00 ± 0.77[b]	26.31 ± 0.30[a]
Protein efficiency ratio	1.09 ± 0.010[b]	0.97 ± 0.037[a]	0.99 ± 0.026[a]	0.91 ± 0.03[a]	1.50 ± 0.10[c]
Survival	3.43 ± 0.05[c]	3.33 ± 0.11[bc]	3.41 ± 0.06[c]	3.29 ± 0.03[ab]	3.18 ± 0.03[a]
Survival rate (%)	99.00 ± 1.00[b]	98.33 ± 0.58[ab]	98.67 ± 0.58[b]	97.67 ± 0.58[ab]	97.00 ± 1.00[a]

PKM0 - Palm Kernel Meal inclusion 0%; PKM10 - Palm Kernel Meal inclusion 10%; PKM20 - Palm Kernel Meal inclusion 20%; PKM30 - Palm Kernel Meal inclusion 30%; PKM40 - Palm Kernel Meal inclusion 40%. Values are mean ± SD (n = 3). Different superscript letters within rows indicate significant differences ($P < 0.05$)

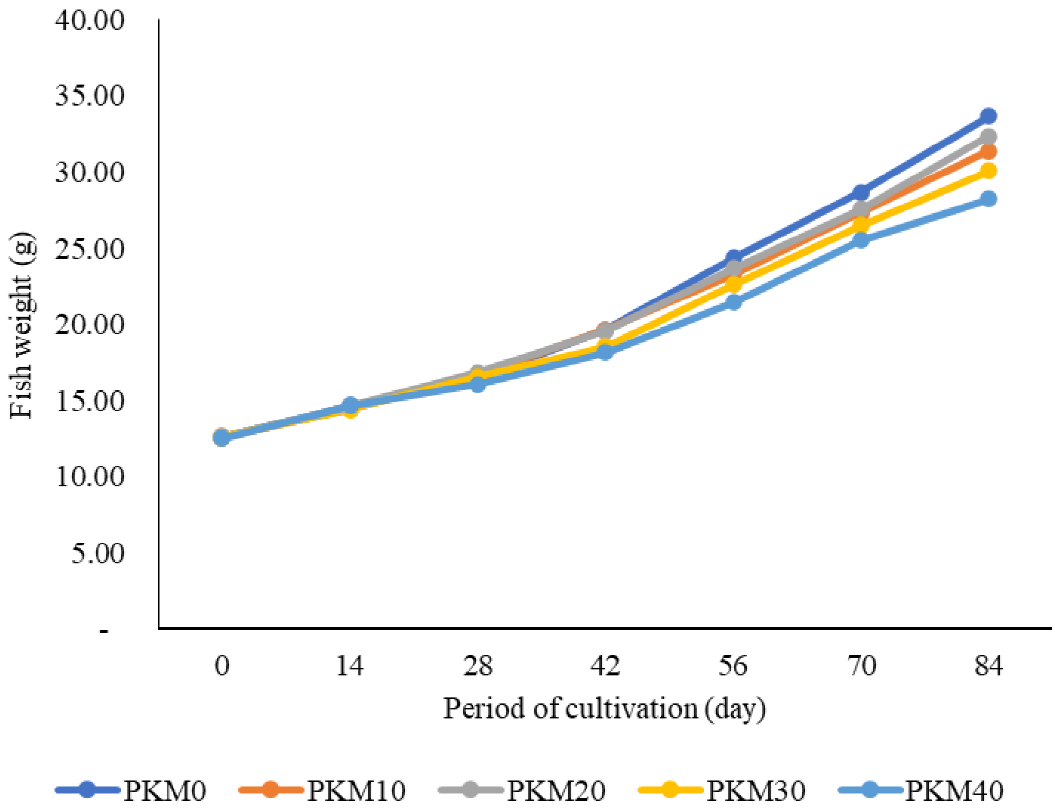

FIGURE 1. Growth trend of *Pangasianodon hypophthalmus* fed diets with graded palm kernel meal inclusion levels

TABLE 3. Ingredient price and formulation cost per kilogram of experimental PKM inclusion diets for *P. hypophthalmus* feeding trial

Feed ingredient	Price per kg (IDR)	Experimental diet				
		PKM0	PKM10	PKM20	PKM30	PKM40
Fish meal	7,850	1,570.00	1,570.00	1,570.00	1,570.00	1,570.00
Shrimp head meal	4,500	225.00	225.00	225.00	225.00	225.00
Soybean meal	7,500	1,147.50	1,035.00	900.00	780.00	675.00
Polished bran	3,000	390.00	306.00	300.00	291.00	180.00
Fine bran	1,800	224.46	215.46	141.66	87.66	87.66
Coconut meal	3,000	906.00	750.00	633.00	480.00	333.00
Palm kernel meal	1,700	0	170.00	340.00	510.00	680.00
Tapioca	8,000	200.00	200.00	200.00	200.00	200.00
Fish oil Boster	25,000	125.00	125.00	125.00	125.00	125.00
Fish premix*	20,000	100.00	100.00	100.00	100.00	100.00
Phytase enzyme	67,000	20.10	20.10	20.10	20.10	20.10
Molasses	5,000	25.00	25.00	25.00	25.00	25.00
Total		4,933.06	4,741.56	4,579.76	4,413.76	4,220.76

PKM0 - Palm Kernel Meal inclusion 0%; PKM10 - Palm Kernel Meal inclusion 10%; PKM20 - Palm Kernel Meal inclusion 20%; PKM30 - Palm Kernel Meal inclusion 30%; PKM40 - Palm Kernel Meal inclusion 40%. All prices expressed in Indonesian Rupiah (IDR)

TABLE 4. Feed production costs for different PKM inclusion level

Parameters	Experimental diet				
	PKM0	PKM10	PKM20	PKM30	PKM40
Feed ingredient	4,933.06	4,741.56	4,579.76	4,413.76	4,220.76
Electricity	150.00	150.00	150.00	150.00	150.00
Fuel	100.00	100.00	100.00	100.00	100.00
Plastic bag	100.00	100.00	100.00	100.00	100.00
Manpower	250.00	250.00	250.00	250.00	250.00
Total	5,533.06	5,344.56	5,179.76	5,013.76	4,820.76

PKM0 - Palm Kernel Meal inclusion 0%; PKM10 - Palm Kernel Meal inclusion 10%; PKM20 - Palm Kernel Meal inclusion 20%; PKM30 - Palm Kernel Meal inclusion 30%; PKM40 - Palm Kernel Meal inclusion 40%. All prices expressed in Indonesian Rupiah (IDR)

TABLE 5. Gross profit analysis of experimental diets

Parameters	Experimental diet				
	PKM0	PKM10	PKM20	PKM30	PKM40
Weight gain (g)	21.09 ± 0.07e	18.76 ± 0.35c	19.71 ± 0.09d	17.50 ± 0.29b	15.68 ± 0.43a
Cost of feed (IDR)	5,533.06	5,344.56	5,179.76	5,013.76	4,820.76
Incidence cost (IDR per kg)	10,526.14 ± 114.08c	10,706.47 ± 72.11b	10,157.89 ± 39.49a	10,224.02 ± 50.16a	10,246.02 ± 39.97a
Value of fish (IDR)	18,000	18,000	18,000	18,000	18,000
Profit index	3.25	3.37	3.48	3.59	3.73
Profit per kg (IDR)	1.71 ± 0.02b	1.68 ± 0.01a	1.77 ± 0.01c	1.76 ± 0.01c	1.76 ± 0.01c

PKM0 - Palm Kernel Meal inclusion 0%; PKM10 - Palm Kernel Meal inclusion 10%; PKM20 - Palm Kernel Meal inclusion 20%; PKM30 - Palm Kernel Meal inclusion 30%; PKM40 - Palm Kernel Meal inclusion 40%. Some values are mean ± SD (n = 3). Different superscript letters within rows indicate significant differences (P < 0.05)

TABLE 6. Cost of production and revenue analysis

Parameters	Experimental diet				
	PKM0	PKM10	PKM20	PKM30	PKM40
Biomass (g)	2,009.07 ± 33.80^{c}	1,831.88 ± 108.80^{b}	1,876.64 ± 71.19^{b}	1,763.87 ± 31.55^{b}	1,607.43 ± 57.72^{a}
Feed fed (g)	3,821.66 ± 35.63^{b}	3,668.87 ± 197.63^{b}	3,679.87 ± 125.34^{b}	3,597.03 ± 59.30^{a}	3,416.69 ± 133.90^{a}
Total variable cost (IDR)	17,533.06	17,344.56	17,179.76	17,013.76	16,820.76
Total cost (IDR)	23,533.06	23,344.56	23,179.76	23,013.76	22,820.76
Total revenue (IDR)	36,163.20 ± 608.35^{c}	32,973.90 ± 1,958.46^{b}	33,779.52 ± 1,281.52^{b}	31,789.60 ± 567.98^{b}	28,933.74 ± 1,038.89^{a}
Gross margin (IDR)	18,630.14 ± 608.35^{c}	15,629.34 ± 1,958.46^{b}	16,599.76 ± 1,281.51^{bc}	14,735.84 ± 567,98^{b}	12,112.98 ± 1,038.89^{a}

PKM0 - Palm Kernel Meal inclusion 0%; PKM10 - Palm Kernel Meal inclusion 10%; PKM20 - Palm Kernel Meal inclusion 20%; PKM30 - Palm Kernel Meal inclusion 30%; PKM40 - Palm Kernel Meal inclusion 40%. Values are mean ± SD (n = 3). Different superscript letters within rows indicate significant differences (P < 0.05) with higher PKM inclusion, total revenue and gross margin also declined, from IDR 36,163.20 and IDR 18,630.14 in PKM0 to IDR 28,933.74 and IDR 12,112.98 in PKM40, respectively. This demonstrates that the cost savings from PKM inclusion did not fully compensate for the reduced biological output, resulting in lower profitability at higher PKM levels.

PROFITABAILITY ANALYSIS

The profitability indicators are summarized in Table 7. The benefit-cost ratio (BCR), rate of return, and net return all decreased significantly with increasing PKM inclusion ($P < 0.05$), with the highest values observed in PKM0 and the lowest in PKM40. The gross ratio increased with PKM inclusion, indicating reduced efficiency in converting costs to revenue. The expense structure ratio remained stable across treatment, suggesting that the proportion of variable to total costs was unaffected by PKM level.

DISCUSSION

The inclusion of palm kernel meal (PKM) in aquafeed demonstrated measurable effects on growth performance and feed utilization parameters in *P. hypohpthalmus*. Fish fed diet containing up to 20% PKM exhibited performance comparable to the control treatment, whereas higher inclusion levels resulted in reduced growth efficiency. This response aligns with previous observations in finfish and crustacean where increased dietary fiber, non-starch polysaccharides and the presence of anti-nutritional limit nutrient digestibility and energy availability (Abdollahi et al. 2016; Hasan et al. 2023; Lim et al. 2001; Ng, Lim & Boey 2002; Swar & Mohamed 2018; Wattanakul et al. 2021). Similar reductions in feed utilization efficiency have been reported when plant-based protein ingredients with elevated structural carbohydrates replace conventional protein sources (Brezas & Hardy 2020; Iheanacho et al. 2025; Liu et al. 2019). By confirming these physiological constraints in Pangasius culture, the present study extends existing nutritional knowledge to a species for which integrated evaluations remain limited.

At moderate inclusion levels (10-20%), growth responses remained stable, suggesting that partial substitution of fish meal and soybean meal with PKM can be implemented without compromising metabolic efficiency, as it optimizes energy intake alongside the amino acid composition essential for growth (Jahan et al. 2023; Sitindaon et al. 2021). Comparable tolerance thresholds have been observed in tilapia and catfish systems, particularly when diets are carefully balanced or supplemented with enzymes to improve digestibility (Syahrizal et al. 2022; Wattanakul et al. 2021). These cross-species comparisons highlight the roles of formulation strategy and digestive plasticity in mediating alternative utilization of ingredient. The present findings therefore provide species-specific empirical support for moderate PKM incorporation as a viable feeding strategy in tropical freshwater aquaculture production systems.

Despite the observed decline in growth performance at higher inclusion levels, survival rates remained consistently high across treatments. This indicates that PKM inclusion primarily affects production efficiency rather than fish health or physiological viability. Previous studies have similarly reported stable survival following dietary substitution with plant-derived by-products, reinforcing the interpretation that performance limitations arise from digestibility and nutrient availability rather than pathological stress responses (Ayisi, Alhassan & Sarfo 2021; Daim & Mamat 2021). Distinguishing between growth suppression and health impairment is essential when evaluating alternative feed ingredients, particularly in applied aquaculture (Turchini, Trushenski & Glencross 2018).

From an economic standpoint, the progressive reduction in feed formulation and production costs observed with increasing PKM inclusion confirms the financial attractiveness of utilizing agro-industrial by-products. Feed costs constitute the dominant operational expenditure in aquaculture systems (Tacon & Metian 2008), and cost savings through ingredient substitution have been widely documented to ensure that the reduction in feed cost not disproportionately impact (Mugwanya et

TABLE 7. Profitabilitiy indicator from biological output and production costs across of *P. hypophthalmus* dietary PKM-based

Parameters	Experimental diet				
	PKM0	PKM10	PKM20	PKM30	PKM40
Benefit cost ratio	1.54 ± 0.03[c]	1.40 ± 0.08[b]	1.45 ± 0.05[bc]	1.38 ± 0.03[b]	1.27 ± 0.04[a]
Gross ratio	0.65 ± 0.01[a]	0.71 ± 0.04[b]	0.69 ± 0.02[ab]	0.72 ± 0.01[b]	0.79 ± 0.03[c]
Expense structure ratio	0.25	0.26	0.26	0.26	0.26
Rate of return	0.54 ± 0.03[c]	0.42 ± 0.08[b]	0.45 ± 0.05[bc]	0.38 ± 0.03[b]	0.27 ± 0.04[a]
Net return (IDR)	12,630.14 ± 608.35[c]	9,629.34 ± 1,958.46[b]	10,599.76 ± 1,281.52[bc]	8,735.84 ± 567.98[b]	6,112.98 ± 1,038.89[a]

PKM0 - Palm Kernel Meal inclusion 0%; PKM10 - Palm Kernel Meal inclusion 10%; PKM20 - Palm Kernel Meal inclusion 20%; PKM30 - Palm Kernel Meal inclusion 30%; PKM40 - Palm Kernel Meal inclusion 40%. Values are mean ± SD (n = 3). Different superscript letters within rows indicate significant differences ($P < 0.05$)

al. 2022; Shapawi, Ng & Mustafa 2007). However, the concurrent decline in biomass output and profitability metrics demonstrates a clear biological–economic trade-off. While ingredient substitution reduces input costs, excessive inclusion compromises production output and revenue generation (Güroy et al. 2022).

This integrated evaluation represents a key contribution of the study. Many previous investigations assess growth or economic performance independently, whereas the present approach demonstrates that optimization of feed formulation requires balancing biological productivity with financial outcomes. Similar trade-off dynamics have been reported in carp and tilapia production systems where excessive substitution reduced net returns despite lower feed costs (Pangesti, Hermana & Setiyono 2023). Assessing the economic effects of incorporating PKM into these diets is crucial, given the absence of thorough analyses that consider diverse aquaculture environments and practices (Adrizal et al. 2011; Bélanger et al. 2021; Obirikorang et al. 2015). By explicitly linking nutritional responses to profitability indices, the study provides decision-relevant evidence to support feed formulation strategies that align with farm-level operational realities.

Beyond production efficiency, the utilization of PKM reflects broader sustainability considerations in aquaculture nutrition. Incorporating locally available agricultural by-products contributes to circular bioeconomy principles by reducing reliance on imported protein ingredients and valorising waste streams (Aragao et al. 2022, 2019; Azizi et al. 2021; Hariati et al. 2022; Onomu & Okuthe 2024; Qian et al. 2024; Wilkinson & Young 2020). Nevertheless, sustainability gains must be evaluated alongside productivity impacts. The present findings suggest that inclusion levels exceeding physiological tolerance thresholds undermine both biological performance and economic viability, reinforcing the importance of balanced formulation approaches.

Overall, the results indicate that PKM can be incorporated into Pangasius diets at moderate levels without compromising biological performance or profitability, whereas excessive inclusion reduces efficiency across production metrics. Future research should explore technological and nutritional strategies-including enzyme supplementation, fermentation processing, and amino acid balancing-to enhance digestibility and expand utilization thresholds. Such advances would further strengthen the role of PKM within sustainable aquafeed innovation frameworks.

CONCLUSION

Palm kernel meal can be utilised as a partial substitute in diets for *Pangasianodon hypophthalmus*, with optimal performance observed at moderate inclusion levels and reduced productivity at higher levels of substitution, despite lower feed costs. The principal contribution of this study lies in integrating nutritional efficiency, biological performance, and economic evaluation within a single framework. These findings provide species-specific evidence supporting balanced feed formulation strategies and highlight the importance of linking nutritional experimentation with production-level decision metrics. Further research should explore technological and nutritional optimisation approaches to expand utilization thresholds and strengthen the role of PKM in sustainable aquafeed systems.

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