

## Research Article

# Phytase supplementation enhances mineral digestibility and blood indices in *Catla catla* fed plant-based diets

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## Abstract

In the fish feed industry, fishmeal (FM) is highly valuable for its excellent combination of essential amino acids and fatty acids. However, due to its high cost and low availability, researchers are focusing on alternative sustainable plant-based protein sources. However, phytate, a major phosphorus-rich compound in plants, has a chelating effect that significantly reduces the absorption and bioavailability of essential nutrients, leading to nutritional imbalances. Adding phytase enzyme (PHY) in aqua feed improves the digestibility of minerals and reduces their excretion. Therefore, this study assessed the impact of PHY supplementation on hematological indices and mineral digestibility in *Catla catla* when fed different plant protein-based diets for FM replacement such as *Moringa oleifera* leaf meal (MOLM), sunflower meal (SFM), canola meal (CM), guar meal (GM). Nine test diets were formulated: a control diet without PHY, and eight experimental diets with PHY added at 250 or 500 FTU/kg. The results revealed that the addition of 500 FTU/kg of PHY to a 50% MOLM significantly enhances the digestibility of minerals like P, Mg, Al, Na, K, Cu, and Zn, when compared to control and other test levels. In terms of blood indices, this supplementation increased the values of RBCs ( $3.18 \times 10^6 \text{mm}^{-3}$ ), Hb (8.68 g/100 ml), PCV (30.07 %) and WBCs ( $8.20 \times 10^3 \text{mm}^{-3}$ ) count as well as serum liver enzymes alanine aminotransferase (0.93 U/L) and aspartate aminotransferase (3.11 U/L). The results indicated that the most effective combination was a diet (T<sub>3</sub>) containing 50% MOLM and 500 FTU kg<sup>-1</sup> PHY, which yielded optimal hematological and mineral profiles. Conclusively, this study shows that PHY-supplemented plant-based fish diets reduce the need for mineral supplements, lowering feed costs and environmental impact.

## Article info

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## Introduction

Indian major carps (IMCs; *Catla catla*, *Cirrhinus mrigala*, and *Labeo rohita*) dominate the freshwater aquaculture sector, making up around 87% of total production (FAO, 2017; Ghosh *et al.*, 2021). They are extensively farmed in India and the surrounding countries. They are native to South Asia and belong to the Cyprinidae family. Due to their high demand, these species hold significant economic value (Hossain *et al.*, 2022). *C. catla* is a surface feeder, commonly known as Thaila, and is farmed alongside other fish species in a polyculture system (Aslam *et al.*, 2016). As the sole member of the monotypic genus *Catla*, it is widely recognized as a fast-growing fish species in southern Asia. As a eurythermal species, *C. catla* grows best in water temperatures between 25 and 32°C (Shakir *et al.*, 2013). Notably, the global *C. catla* output increased by 2.8 million tons in the first decade of the twenty-first century, with continued growth reported in 2012 (FAO, 2015).

In Pakistan, inland and coastal water resources play a vital role in the nutrition and economic growth of cultivable fish species. There is a growing need in the global aquaculture industry to maximize production efficiency while reducing environmental impact. As aquaculture has become more intensive, several challenges have arisen, including the production of affordable, high-quality fish feed and techniques for removing anti-nutrients from feed (Sardar *et al.*, 2007). Aquaculture has emerged as the fastest-growing sector in animal protein production, accounting for almost half of the world's total fish consumption (FAO, 2010, 2022). Feed

costs account for approximately 60% of the overall expense of fish farming (Shahzad *et al.*, 2018). Fishmeal (FM) is considered one of the best protein sources for aqua feeds due to its well-balanced amino acid profile (Luthada-Raswiswi *et al.*, 2021). However, FM is relatively expensive and poses sustainability concerns due to overfishing and limited sources (Siddiqui *et al.*, 2022). To address these issues, researchers have explored alternative protein sources, including plant proteins (PPs), which offer a cost-effective and sustainable solution (Chakraborty *et al.*, 2019). Agricultural by-products such as rapeseed meal (Luo *et al.*, 2012), soybean meal (Ye *et al.*, 2011), sunflower meal (SFM) (Iqbal *et al.*, 2022), and cottonseed meal (Hassan *et al.*, 2019) have been identified as potential substitutes for FM.

To achieve sustainable and profitable commercial production, scientists are now exploring unconventional plant-based sources, including seeds, leaves, and other nutrient-rich alternative by-products (Abo-State *et al.*, 2014). *Moringa oleifera*, a member of the Moringaceae family, has emerged as a viable source of protein for fish feed. This fast-growing plant has numerous commercial applications, including food additives and medicinal uses. Moringa leaves have a crude protein content ranging from 25% to 32%, making them a valuable ingredient for sustainable aqua feed production (Shahzad *et al.*, 2017). Moreover, SFM is an affordable and valuable alternative source of essential nutrients, particularly in animal feed and aquaculture. Following soybean meal, cottonseed meal, and rapeseed meal, SFM meal is considered the world's fourth-

largest protein source (Anjum *et al.*, 2014). Canola meal (CM) is another excellent protein source for animal feed. Research has explored the nutritional benefits of CM for various animal species (Enami and Safafar, 2010). CM is used as a feed supplement for numerous fish species, including sea bass, perch, bream, trout, salmon, catfish, carp, and turbot (Enami, 2011). Legume seeds are a valuable ingredient in fish feed due to their high content of protein, carbohydrates, and lipids. One promising leguminous plant is guar (*Cyamopsis tetragonoloba*), which belongs to the Fabaceae family. Guar meal (GM) is commonly used as a nutritious feed supplement for dairy animals in countries like India and Pakistan, and its potential as a fish feed ingredient is worth exploring (Barlaya *et al.*, 2021).

The utilization of plant by-products in fish feed is limited due to their high level of indigestible carbohydrates and the existence of anti-nutritional components such as phytate (Laining *et al.*, 2011). Phytate can hinder mineral uptake in fish, but supplementing their diet with phytase (PHY), an enzyme that breaks down phytate, alleviates this issue. The best way to lessen the effects of phytate is to use the enzyme PHY incorporated into the fish diet in various forms, such as microbial PHY (Hussain *et al.*, 2016a,b). By releasing phosphorus and minerals from phytate, microbial PHY reduces inositol phosphate levels. Since agastric and monogastric animals, including fish, lack the bacteria that produce PHY, adding exogenous microbial PHY to plant-based fish diets enhances mineral digestibility and bioavailability. This reduces nutrient loss,

especially phosphorus, through fish feces, thereby minimizing aquatic pollution (Priya *et al.*, 2023). PHY deficiency can lead to three main issues: (1) water pollution due to nutrient release from fish, (2) the need for dietary phosphorus supplements, and (3) depletion of phosphorus deposits. Supplementing fish feed with PHY can address nutritional issues by improving phosphorus bioavailability (Hussain *et al.*, 2016a,b). However, this study evaluated the effects of PHY supplementation on hematological profiles and mineral digestibility in *C. catla* fingerlings fed plant-based diets (MOLM, SFM, CM, and GM), aiming to minimize mineral supplement requirements, reduce feed costs, and mitigate environmental impacts.

## Materials and methods

### *Fish and experimental conditions*

*C. catla* (average weight:  $6.10 \pm 0.02$  g) were obtained from the Rahim Yar Khan Fish seed hatchery and were taken to the Fish Nutrition lab, where they were kept in specially designed glass aquaria to collect fish waste. For two weeks, they were remained in these aquaria to acclimatize to the experimental environment. The fingerlings were fed the basal diet twice a day until satiation during the acclimatization phase (Allan and Rowland, 1992). Water quality parameters were monitored constantly using a pH meter (Jenway 3510), a dissolved oxygen (DO) meter (Jenway 970), and an electrical conductivity meter (HANNA: HI. 8633) throughout the trial. A capillary system was used to continuously ventilate each aquarium to keep the water fresh and well-oxygenated.

### Experimental diets and their formulation

Before test diet preparation, feed ingredients were purchased from a commercial feed mill and ground and sieved to a 2 mm particle size (Table 1). Standard procedures were used to examine the chemical composition of test diets and feed ingredients (AOAC, 1995). After mixing the dry components in an electric mixer for ten to twenty minutes, fish oil was added gradually while the mixture was stirred continuously. To examine the mineral digestibility, chromium oxide (1%) was used as an inert marker. Water, constituting approximately 10–15% of the total amount, was added to prepare the dough for each test diet. The dough was then processed via a lab extruder to form floating pellets (Lovell, 1989; Faisal *et al.*,

2024). Four plant-based protein sources (MOLM, SFM, CM, and GM) were used as a substitution (15% and 50%) of FM in the test diets. PHY was added to these diets at levels of 250 and 500 FTU/kg, with the exception of the control diet. Nine test diets were formulated, including a control diet (without PHY) and eight experimental diets. Eight test diets (T2-T9) were formulated by spraying varying PHY levels, including 250 and 500 FTU/kg. Plant by-products with a 15% replacement level were supplemented with 250 FTU/kg, while plant meals with a 50% substitution level received 500 FTU/kg supplementation. This study consisted of a 70-day feeding experiment.

**Table 1: Ingredients composition (%) of diets.**

Ingredients	Test Diet (TD; control)	<i>Moringa oleifera</i> leaf meal			Sunflower meal		Canola meal		Guar meal	
	TD-1	TD-2	TD-3	TD-4	TD-5	TD-6	TD-7	TD-8	TD-9	
Plant by-products	-	35	50	35	50	35	50	35	50	
Fishmeal	50	15	-	15	-	15	-	15	-	
Soybean meal	15	15	15	15	15	15	15	15	15	
Rice polish	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	
Wheat flour	17	17	17	17	17	17	17	17	17	
Fish oil	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	
Vitamin Premix	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Ascorbic acid	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Mineral Premix	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Chromic oxide	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Phytase level	0 FTU kg <sup>-1</sup>	250 FTU kg <sup>-1</sup>	500 FTU kg <sup>-1</sup>	250 FTU kg <sup>-1</sup>	500 FTU kg <sup>-1</sup>	250 FTU kg <sup>-1</sup>	500 FTU kg <sup>-1</sup>	250 FTU kg <sup>-1</sup>	500 FTU kg <sup>-1</sup>	

### Feeding regimen and sampling procedure

*C. catla* were fed the recommended diets at 4% of their live wet weight. For each test diet, three replicates were allocated and

fifteen fish were randomly assigned to each tank (70 litre water capacity). Following the two-hour feeding session, uneaten feed was manually siphoned from each tank. The

tanks were then thoroughly cleaned, and the water was refreshed with fresh tap water. Fecal samples were collected from each tank using the specialized feces collection tube. To minimize nutrient leaching, the fecal threads were handled carefully to prevent breakage. The collected feces from each treatment were then dried and preserved for subsequent chemical analysis (Hussain *et al.*, 2024).

#### *Blood collection and hematological analysis*

Tricaine methanesulfonate (MS-222; 150 mg/L solution; 15 minutes) and sodium bicarbonate (as buffer) (Wagner *et al.*, 1997) was used to anesthetize the fish for blood sampling. These blood samples were sent for hematological testing. The packed cell volume (PCV) was determined using a 25 mm capillary tube and centrifuged in a hematocrit microcentrifuge following the Wintrobe and Westergreen technique as explained by Blaxhall and Daisley (1973). A hemocytometer with an improved Neubauer counting chamber, as indicated by Blaxhall and Daisley (1973), was used to calculate white blood cells and red blood cell counts. The hemoglobin (Hb) concentration was estimated using the method explained by Wedemeyer and Yastuke (1977). Blood serum samples were analyzed using a veterinary biochemistry analyzer (Beckman Coulter AU680, USA). This analyzer was used to measure the activities of two key liver enzymes: alanine aminotransferase (ALT) and aspartate aminotransferase (AST) (Ahmed *et al.*, 2023). The other indices *i.e.* mean corpuscular haemoglobin

concentration (MCHC), mean corpuscular haemoglobin (MCH), and mean cell volume (MCV) were calculated as determined by Hussain *et al.* (2024).

#### *Minerals assessment*

A conical flask was filled with a 1-g sample to calculate mineral content, and 20 mL of nitric acid (HNO<sub>3</sub>) was added. Then, the flask was set on a heated plate. When the liquid started to boil, 10 mL of perchloric acid were added and the mixture was heated until 1 mL mixture remained. Then the flask was removed and distilled water was added to attain the final volume of 50 mL making it crystal clear. Before mineral testing, the solution was filtered through filter paper to remove all solid particles from the digesting solution. The mineral compositions were calculated by using an atomic absorption spectrophotometer (Hitachi, Z-8200, Japan) after appropriate dilution (AOAC, 1995). A flame photometer (Jenway PFP-7, UK) was used to estimate the amount of sodium and potassium. Phosphorus was analyzed calorimetrically by using a UV/VIS 2001 Spectrophotometer at 350 nm.

#### *Apparent digestibility coefficient calculation*

Chromium oxide (Cr<sub>2</sub>O<sub>3</sub>) is an inert marker used to determine digestibility. Its concentration is determined using an acid digestion method, which involves oxidizing ash samples of feed and feces with perchloric acid (HClO<sub>4</sub>), followed by Divakaran (2002). The ADCs for diets were measured by using the formula described in NRC (1993) and Hussain *et al.* (2024).

### Statistical analysis

One-way analysis of variance (ANOVA) was applied to the resulting data (Steel *et al.*, 1996). Tukey's Honest Significant Difference test (HSD) was used to compare the mean differences, and a p-value less than 0.05 was considered significant (Snedecor and Cochran, 1991). For data analysis, the CoStat computer software (Version 6.4, 93940 USA) was used.

## Results

### Hematological studies

The hematological indices of *C. catla* fed diets with varied levels of FM replacement with four different plant-based protein sources are shown in Table 2. The fish fed on test diet T<sub>3</sub>, which was replaced with 50% of MOLM supplemented with 500 FTU kg<sup>-1</sup> PHY, showed the highest values of PCV (30.07%), MCHC (33.60%), RBCs (3.18×10<sup>6</sup>mm<sup>-3</sup>), and WBCs (8.20×10<sup>3</sup>mm<sup>-3</sup>). Conversely, fish fed on test diet T<sub>7</sub> with 50% CM supplemented with 500 FTU kg<sup>-1</sup> PHY showed the second-highest values of RBCs

(3.11×10<sup>6</sup>mm<sup>-3</sup>), MCHC (30.27%), WBCs (8.13×10<sup>3</sup>mm<sup>-3</sup>), and PCV (29.77%) than the fish fed with the control diet. The fish fed with the control diet with 0% plant by-products with no supplementation had the lowest values of RBCs (2.37×10<sup>6</sup>mm<sup>-3</sup>), WBCs (6.95×10<sup>3</sup>mm<sup>-3</sup>), PCV (19.93%), and MCHC (21.73%). Similarly, fish fed test diet T<sub>5</sub> (50% SFM supplemented with 500 FTU kg<sup>-1</sup>) had the maximum values of MCH (70.8 pg) and MCV (210.1 fl), while fish fed the control test diet had the lowest values of MCH (24.47 pg) and T8 had the lowest value of MCV (85.12 fl). The best results were observed when the plant-based diets were replaced by up to 50%. PHY supplementation with plant-based diets played a significant role, both individually and jointly. The highest values of RBCs, WBCs, PCV, and MCHC were observed in MOLM-based diets supplemented with 500 FTU kg<sup>-1</sup> level of PHY enzyme; whereas 50% CM supplemented with PHY (500 FTU kg<sup>-1</sup> level) also played a potential role.

**Table 2: Blood parameters of *Catla catla* fed PHY supplemented with four different plant-based protein sources.**

Test diets	Fishmeal Protein Replacement Levels	Plant by-products Replacement Levels	PHY (FTU/kg <sup>1</sup> )	RBCs (10 <sup>6</sup> mm <sup>-3</sup> )	WBCs (10 <sup>3</sup> mm <sup>-3</sup> )	Hb (g/100ml)	PCV (%)	Alanine aminotransferase (U/L)	MCHC (%)	Aspartate aminotransferase (U/L)	MCH (pg)	MCV (fl)
T <sub>1</sub>	50	0	0	2.37±0.18 <sup>i</sup>	6.95±0.05 <sup>i</sup>	4.53±0.58 <sup>e</sup>	19.93±0.58 <sup>e</sup>	0.86±0.02 <sup>d</sup>	21.73±0.02 <sup>i</sup>	2.43±0.09 <sup>e</sup>	24.47±0.01 <sup>a</sup>	93.73±1.53 <sup>e</sup>
T <sub>2</sub>	35	MOLM	15	3.06±0.03 <sup>c</sup>	8.13±0.02 <sup>c</sup>	7.46±0.06 <sup>e</sup>	26±0.58 <sup>e</sup>	0.89±0.03 <sup>bc</sup>	29.73±0.02 <sup>f</sup>	2.96±0.12 <sup>c</sup>	27.81±0.48 <sup>c</sup>	99.49±0.02 <sup>e</sup>
T <sub>3</sub>	0	50	500	3.18±0.16 <sup>a</sup>	8.20±0.17 <sup>a</sup>	8.68±0.10 <sup>e</sup>	30.07±0.10 <sup>e</sup>	0.93±0.01 <sup>a</sup>	33.60±0.02 <sup>f</sup>	3.11±0.18 <sup>a</sup>	27.06±0.59 <sup>c</sup>	87.06±0.59 <sup>b</sup>
T <sub>4</sub>	35	SFM	15	2.93±0.04 <sup>f</sup>	7.96±0.03 <sup>f</sup>	6.68±0.19 <sup>f</sup>	22.01±0.02 <sup>f</sup>	0.89±0.02 <sup>bc</sup>	26.44±0.04 <sup>b</sup>	2.85±0.11 <sup>d</sup>	54.30±0.92 <sup>b</sup>	141.1±0.02 <sup>e</sup>
T <sub>5</sub>	0	50	500	2.97±0.02 <sup>c</sup>	8.08±0.07 <sup>c</sup>	6.99±0.02 <sup>e</sup>	24.01±1.01 <sup>e</sup>	0.87±0.05 <sup>c</sup>	28.01±0.02 <sup>e</sup>	2.83±0.08 <sup>d</sup>	70.8±1.56 <sup>i</sup>	210.1±0.99 <sup>e</sup>
T <sub>6</sub>	35	CM	15	3.02±0.01 <sup>d</sup>	8.09±0.02 <sup>d</sup>	7.20±0.26 <sup>d</sup>	25.34±0.56 <sup>d</sup>	0.89±0.08 <sup>bc</sup>	27.01±0.01 <sup>f</sup>	2.94±0.17 <sup>c</sup>	28.0±0.99 <sup>f</sup>	103.18±1.04 <sup>f</sup>
T <sub>7</sub>	0	50	500	3.11±0.10 <sup>b</sup>	8.13±0.02 <sup>b</sup>	7.90±0.01 <sup>b</sup>	29.77±0.02 <sup>b</sup>	0.92±0.04 <sup>ab</sup>	30.27±0.78 <sup>e</sup>	3.06±0.15 <sup>b</sup>	27.61±0.50 <sup>d</sup>	97.43±1.00 <sup>d</sup>
T <sub>8</sub>	35	GM	15	2.86±0.11 <sup>b</sup>	7.81±0.09 <sup>b</sup>	5.97±0.07 <sup>b</sup>	23.34±0.57 <sup>b</sup>	0.90±0.07 <sup>b</sup>	31.31±0.34 <sup>b</sup>	2.67±0.13 <sup>f</sup>	26.6±0.02 <sup>b</sup>	85.12±1.54 <sup>e</sup>
T <sub>9</sub>	0	50	500	2.90±0.66 <sup>g</sup>	7.92±0.04 <sup>f</sup>	6.16±0.01 <sup>f</sup>	23.67±1.14 <sup>f</sup>	0.88±0.03 <sup>c</sup>	27.98±0.08 <sup>f</sup>	2.72±0.17 <sup>e</sup>	49.53±0.55 <sup>g</sup>	141.8±11.26 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p<0.05$ ). The results are presented as mean  $\pm$  SD of three replicates.

### Mineral digestibility

Tables 3-13 present the impacts of PHY on the mineral digestibility of *C. catla*. Supplementing *C. catla* fingerlings with PHY enzyme resulted in improved mineral digestibility. The maximum mineral digestibility values were 63.12% for Ca, 70.78% for P, 60.56% for Na, 70.76% for K, 52.69% for Cr, 68.08% for Mg,

73.14% for Fe, 73.18% for Cu, 59.84% for Al, 67.20% for Mn, and 63.3% for Zn were observed when fish were fed the T<sub>3</sub> test diet, which included 50% MOLM supplemented with 500 FTU kg<sup>-1</sup> PHY. When the feed mentioned above was given to *C. catla* fingerlings, the lowest amount of minerals was also observed in their feces.

**Table 3: Mineral content analysis (%) of Ca in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50	0	0	3.21±0.02	2.58±0.02 <sup>a</sup>	23.56±4.84 <sup>i</sup>
T <sub>2</sub>	35	MOLM	15	3.21±0.03	1.46±0.04 <sup>g</sup>	57.95±3.58 <sup>e</sup>
T <sub>3</sub>	0	50	500	3.21±0.02	1.22±0.03 <sup>i</sup>	63.12±1.48 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	3.16±0.04	1.86±0.03 <sup>d</sup>	49.88±1.42 <sup>f</sup>
T <sub>5</sub>	0	50	500	3.15±0.02	1.75±0.04 <sup>e</sup>	50.17±1.57 <sup>e</sup>

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>6</sub>	35	CM	15	250	3.11±0.02	1.65±0.03 <sup>f</sup>	51.50±0.82 <sup>d</sup>
T <sub>7</sub>	0		50	500	3.12±0.03	1.23±0.05 <sup>h</sup>	58.79±2.05 <sup>b</sup>
T <sub>8</sub>	35	GM	15	250	3.16±0.02	2.08±0.02 <sup>b</sup>	40.23±1.05 <sup>h</sup>
T <sub>9</sub>	0		50	500	3.16±0.03	1.95±0.02 <sup>c</sup>	45.56±1.56 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean ± SD of three replicates.

**Table 4: Mineral content analysis (%) of Na in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50	MOLM	0	0	0.22±0.02	0.236±0.003 <sup>a</sup>	33.17±1.37 <sup>i</sup>
T <sub>2</sub>	35		15	250	0.21±0.03	0.117±0.002 <sup>h</sup>	55.23±0.14 <sup>c</sup>
T <sub>3</sub>	0		50	500	0.23±0.03	0.103±0.025 <sup>i</sup>	60.56±1.40 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.24±0.03	0.146±0.003 <sup>d</sup>	48.33±0.49 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.25±0.02	0.139±0.007 <sup>e</sup>	50.56±0.44 <sup>e</sup>
T <sub>6</sub>	35		15	250	0.27±0.02	0.126±0.003 <sup>g</sup>	52.23±0.14 <sup>d</sup>
T <sub>7</sub>	0	CM	50	500	0.26±0.02	0.134±0.045 <sup>f</sup>	58.51±0.30 <sup>b</sup>
T <sub>8</sub>	35		15	250	0.24±0.03	0.175±0.001 <sup>b</sup>	44.33±1.60 <sup>h</sup>
T <sub>9</sub>	0	GM	50	500	0.24±0.05	0.161±0.005 <sup>c</sup>	46.88±2.32 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean ± SD of three replicates.

**Table 5: Mineral content analysis (%) of K in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50	MOLM	0	0	0.26±0.02	0.246±0.004 <sup>a</sup>	36.62±0.12 <sup>i</sup>
T <sub>2</sub>	35		15	250	0.26±0.03	0.136±0.004 <sup>g</sup>	63.09±0.91 <sup>c</sup>
T <sub>3</sub>	0		50	500	0.27±0.03	0.086±0.012 <sup>i</sup>	70.76±1.41 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.27±0.03	0.173±0.002 <sup>d</sup>	51.45±0.14 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.25±0.03	0.167±0.005 <sup>e</sup>	55.46±0.17 <sup>e</sup>
T <sub>6</sub>	35		15	250	0.26±0.01	0.150±0.002 <sup>c</sup>	59.62±0.12 <sup>d</sup>
T <sub>7</sub>	0	CM	50	500	0.25±0.02	0.122±0.002 <sup>h</sup>	65.46±0.29 <sup>b</sup>
T <sub>8</sub>	35		15	250	0.25±0.02	0.197±0.002 <sup>b</sup>	47.46±0.29 <sup>h</sup>
T <sub>9</sub>	0	GM	50	500	0.24±0.02	0.183±0.002 <sup>c</sup>	50.45±0.14 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean±SD of three replicates.

**Table 6: Mineral content analysis (%) of P in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50	MOLM	0	0	0.515±0.003	0.535±0.002 <sup>a</sup>	34.65±0.81 <sup>i</sup>
T <sub>2</sub>	35		15	250	0.515±0.004	0.356±0.020 <sup>f</sup>	54.32±1.15 <sup>c</sup>
T <sub>3</sub>	0		50	500	0.515±0.002	0.284±0.003 <sup>i</sup>	70.78±1.36 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.516±0.003	0.432±0.011 <sup>d</sup>	44.99±3.94 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.513±0.002	0.414±0.003 <sup>e</sup>	45.68±3.66 <sup>c</sup>
T <sub>6</sub>	35		15	250	0.514±0.003	0.319±0.007 <sup>g</sup>	48.45±2.14 <sup>d</sup>
T <sub>7</sub>	0	CM	50	500	0.514±0.003	0.313±0.002 <sup>h</sup>	59.60±1.00 <sup>b</sup>
T <sub>8</sub>	35		15	250	0.515±0.003	0.495±0.004 <sup>b</sup>	40.74±3.47 <sup>h</sup>
T <sub>9</sub>	0	GM	50	500	0.514±0.004	0.464±0.003 <sup>c</sup>	43.08±2.43 <sup>g</sup>

Results are presented as mean±SD (N=3). Values with distinct superscripts in the same column indicate significant variations ( $p < 0.05$ ).

**Table 7: Mineral content analysis (%) of Fe in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50		0	0	0.019±0.010	0.249±0.013 <sup>a</sup>	33.42±0.09 <sup>i</sup>
T <sub>2</sub>	35	MOLM	15	250	0.014±0.00	0.101±0.002 <sup>g</sup>	52.14±0.93 <sup>e</sup>
T <sub>3</sub>	0		50	500	0.013±0.00	0.009±0.002 <sup>i</sup>	73.14±0.96 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.013±0.001	0.153±0.001 <sup>d</sup>	45.37±2.85 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.013±0.00	0.140±0.003 <sup>e</sup>	46.85±1.91 <sup>e</sup>
T <sub>6</sub>	35	CM	15	250	0.013±0.00	0.131±0.004 <sup>f</sup>	49.52±1.46 <sup>d</sup>
T <sub>7</sub>	0		50	500	0.013±0.00	0.009±0.003 <sup>h</sup>	53.86±4.87 <sup>b</sup>
T <sub>8</sub>	35	GM	15	250	0.013±0.00	0.172±0.001 <sup>b</sup>	42.70±3.16 <sup>h</sup>
T <sub>9</sub>	0		50	500	0.012±0.001	0.161±0.003 <sup>c</sup>	43.37±3.41 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean  $\pm$  SD of three replicates.

**Table 8: Mineral content analysis (%) of Cu in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50		0	0	0.0113±0.0004	0.01598±0.00002 <sup>a</sup>	33.79±5.76 <sup>i</sup>
T <sub>2</sub>	35	MOLM	15	250	0.0115±0.0006	0.01006±0.00003 <sup>g</sup>	49.85±0.29 <sup>c</sup>
T <sub>3</sub>	0		50	500	0.0121±0.0002	0.00766±0.00028 <sup>a</sup>	73.18±3.53 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.0124±0.0005	0.01195±0.00002 <sup>d</sup>	45.38±3.59 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.0122±0.0002	0.01116±0.00003 <sup>e</sup>	46.05±5.64 <sup>e</sup>
T <sub>6</sub>	35	CM	15	250	0.0122±0.0001	0.01086±0.00003 <sup>f</sup>	47.18±1.71 <sup>d</sup>
T <sub>7</sub>	0		50	500	0.0125±0.0001	0.00929±0.00012 <sup>h</sup>	60.39±1.05 <sup>b</sup>
T <sub>8</sub>	35	GM	15	250	0.0117±0.0002	0.01298±0.00002 <sup>b</sup>	41.14±0.93 <sup>h</sup>
T <sub>9</sub>	0		50	500	0.0118±0.0002	0.01235±0.00002 <sup>c</sup>	43.15±0.92 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean  $\pm$  SD of three replicates.

**Table 9: Mineral content analysis (%) of Zn in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50		0	0	0.0288±0.0004	0.0185±0.0002 <sup>g</sup>	60.3±1.11 <sup>c</sup>
T <sub>2</sub>	35	MOLM	15	250	0.0291±0.0003	0.0123±0.0002 <sup>i</sup>	63.3±1.82 <sup>a</sup>
T <sub>3</sub>	0		50	500	0.0290±0.0001	0.0274±0.0003 <sup>d</sup>	55.47±4.05 <sup>f</sup>
T <sub>4</sub>	35	SFM	15	250	0.0293±0.0004	0.0215±0.0004 <sup>e</sup>	58.3±1.94 <sup>e</sup>
T <sub>5</sub>	0		50	500	0.0290±0.0004	0.0197±0.0002 <sup>f</sup>	59.3±0.75 <sup>d</sup>
T <sub>6</sub>	35	CM	15	250	0.0286±0.0004	0.0154±0.0002 <sup>h</sup>	62.63±1.06 <sup>b</sup>
T <sub>7</sub>	0		50	500	0.0292±0.0009	0.0306±0.0003 <sup>b</sup>	51.47±1.19 <sup>h</sup>
T <sub>8</sub>	35	GM	15	250	0.0294±0.0004	0.0296±0.0003 <sup>c</sup>	52.75±6.07 <sup>g</sup>
T <sub>9</sub>	0		50	500	0.0288±0.0004	0.0185±0.0002 <sup>g</sup>	60.3±1.11 <sup>c</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean  $\pm$  SD of three replicates.

**Table 10: Mineral content analysis (%) of Mn in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50		0	0	0.0113±0.0001	0.0184±0.0002 <sup>a</sup>	31.40±0.78 <sup>i</sup>
T <sub>2</sub>	35	MOLM	15	250	0.0117±0.0001	0.0100±0.0004 <sup>g</sup>	54.07±5.65 <sup>c</sup>
T <sub>3</sub>	0		50	500	0.0119±0.0002	0.0077±0.0002 <sup>i</sup>	67.20±1.26 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.0117±0.0003	0.0130±0.0005 <sup>d</sup>	48.92±3.26 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.0121±0.0002	0.0120±0.0002 <sup>e</sup>	50.40±1.33 <sup>e</sup>
T <sub>6</sub>	35	CM	15	250	0.0114±0.0004	0.0111±0.0003 <sup>f</sup>	52.64±1.05 <sup>d</sup>
T <sub>7</sub>	0		50	500	0.0120±0.0004	0.0099±0.0002 <sup>h</sup>	56.97±3.10 <sup>b</sup>
T <sub>8</sub>	35	GM	15	250	0.0118±0.0005	0.0154±0.0002 <sup>b</sup>	44.92±2.82 <sup>h</sup>
T <sub>9</sub>	0		50	500	0.0119±0.0006	0.0149±0.0003 <sup>c</sup>	47.87±3.97 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean ± SD of three replicates.

**Table 11: Mineral content analysis (%) of Mg in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50		0	0	0.0055±0.0004	0.2487±0.012 <sup>a</sup>	33.70±0.16 <sup>i</sup>
T <sub>2</sub>	35	MOLM	15	250	0.0054±0.0004	0.1013±0.0003 <sup>g</sup>	50.23±7.47 <sup>c</sup>
T <sub>3</sub>	0		50	500	0.0051±0.0001	0.0089±0.0002 <sup>i</sup>	68.08±5.90 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.0055±0.0004	0.1534±0.0003 <sup>d</sup>	41.21±0.90 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.0221±0.0291	0.1403±0.0003 <sup>e</sup>	44.63±0.34 <sup>e</sup>
T <sub>6</sub>	35	CM	15	250	0.0055±0.0003	0.1313±0.0003 <sup>f</sup>	45.62±3.53 <sup>d</sup>
T <sub>7</sub>	0		50	500	0.0051±0.0001	0.0091±0.0002 <sup>h</sup>	54.58±0.45 <sup>b</sup>
T <sub>8</sub>	35	GM	15	250	0.0058±0.0002	0.1721±0.0011 <sup>b</sup>	38.18±4.19 <sup>h</sup>
T <sub>9</sub>	0		50	500	0.0055±0.0002	0.1614±0.0003 <sup>c</sup>	39.26±3.48 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean ± SD of three replicates.

**Table 12: Mineral content analysis (%) of Cr in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50		0	0	0.032±0.004	0.535±0.002 <sup>a</sup>	25.48±0.37 <sup>i</sup>
T <sub>2</sub>	35	MOLM	15	250	0.031±0.004	0.356±0.020 <sup>g</sup>	43.89±3.64 <sup>c</sup>
T <sub>3</sub>	0		50	500	0.031±0.003	0.284±0.003 <sup>i</sup>	52.69±1.64 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.033±0.003	0.432±0.011 <sup>d</sup>	38.81±2.62 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.028±0.008	0.414±0.003 <sup>e</sup>	40.07±5.17 <sup>e</sup>
T <sub>6</sub>	35	CM	15	250	0.029±0.003	0.391±0.007 <sup>f</sup>	42.72±0.87 <sup>d</sup>
T <sub>7</sub>	0		50	500	0.025±0.003	0.313±0.002 <sup>h</sup>	45.55±0.57 <sup>b</sup>
T <sub>8</sub>	35	GM	15	250	0.024±0.003	0.495±0.004 <sup>b</sup>	35.89±0.96 <sup>h</sup>
T <sub>9</sub>	0		50	500	0.029±0.003	0.464±0.003 <sup>c</sup>	37.55±0.57 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean ± SD of three replicates.

**Table 13: Mineral content analysis (%) of Al in diets, feces and nutrient absorption assessment of *Catla catla* fed on PHY supplemented four plant-based protein sources.**

Test diets	Fishmeal Protein Substitution Levels (%)	Plant by-products	Plant by-products Replacement Levels (%)	PHY (FTU/kg <sup>1</sup> )	Diets	Feces	Digestibility
T <sub>1</sub>	50		0	0	0.00018±0.00001	0.01840±0.00019 <sup>a</sup>	26.64±5.77 <sup>i</sup>
T <sub>2</sub>	35	MOLM	15	250	0.00018±0.00001	0.01004±0.00002 <sup>g</sup>	46.51±1.23 <sup>e</sup>
T <sub>3</sub>	0		50	500	0.00018±0.00001	0.00767±0.00019 <sup>i</sup>	59.84±5.50 <sup>a</sup>
T <sub>4</sub>	35	SFM	15	250	0.00018±0.00001	0.01303±0.00002 <sup>d</sup>	38.38±3.85 <sup>f</sup>
T <sub>5</sub>	0		50	500	0.00018±0.00001	0.01204±0.00002 <sup>e</sup>	39.75±5.86 <sup>e</sup>
T <sub>6</sub>	35	CM	15	250	0.00042±0.00042	0.01114±0.00002 <sup>f</sup>	42.51±0.65 <sup>d</sup>
T <sub>7</sub>	0		50	500	0.00018±0.00001	0.00994±0.00002 <sup>h</sup>	48.42±0.99 <sup>b</sup>
T <sub>8</sub>	35	GM	15	250	0.00018±0.00001	0.01540±0.00019 <sup>b</sup>	35.05±2.11 <sup>h</sup>
T <sub>9</sub>	0		50	500	0.00018±0.00001	0.01493±0.00002 <sup>c</sup>	36.64±0.82 <sup>g</sup>

Means with distinct superscript letters within a column denote substantial variations ( $p < 0.05$ ). The results are presented as mean  $\pm$  SD of three replicates.

The table below explains how these values differ significantly from the other test diets. These findings revealed that for fish to perform at their best in mineral digestibility, 500 FTU kg<sup>-1</sup> of PHY supplementation is required. When comparing the digestibility values obtained at diet T<sub>3</sub> to the control diet and the other replacement levels ( $p < 0.05$ ). The second highest level, T<sub>7</sub>, which released the least amount of minerals through waste, was likewise supplemented with 500 FTU kg<sup>-1</sup> of PHY along with 50% of CM in place of FM. Second highest mineral digestibility values of Ca (58.79%), P (59.60), Na (58.51%), K (65.46%), Cr (45.55%), Mg (54.58%), Fe (53.86%), Cu (60.39%), Al (48.42%), Mn (56.97%), and Zn (62.63%) were recorded. The lowest mineral digestibility values were observed in T<sub>1</sub> diet. The mineral digestibility of *C. catla* fish was positively affected by PHY. In conclusion, this study showed that MOLM and CM-based diets supplemented with PHY had the potential to improve the

mineral digestibility of *C. catla* fingerlings both individually and collectively.

### Discussion

This study investigated the impact of PHY supplementation on the hematological and mineral digestibility profiles of *C. catla* fingerlings fed plant-based diets (MOLM, SFM, CM, and GM), with the goal of reducing the need for mineral supplements, lowering production costs, and minimizing environmental impact.

Hematological indices are valuable markers for assessing fish stress, nutritional status, and overall health (Khalafalla *et al.*, 2020), and also reflect physiological alterations in fish (Ranjan *et al.*, 2021). Moreover, these are crucial for assessing the quality of feed and its impact on fish health (Shahzad *et al.*, 2017). Analysis of ALT and AST levels in blood serum provides valuable insights into the liver health of fish, enabling researchers to detect potential liver damage or disease (Ahmed *et al.*, 2023). The current study revealed that fish fed with diet T<sub>3</sub>, which

replaced 50% of MOLM with 500 FTU kg<sup>-1</sup> PHY, exhibited the highest values for PCV (30.07 %), MCHC (33.60 %), RBCs (3.18×10<sup>6</sup>mm<sup>-3</sup>), ALT (0.93 U/L) and AST (3.11 U/L) and WBCs (8.20×10<sup>3</sup>mm<sup>-3</sup>). Notably, 50 % CM supplemented with PHY (500 FTU kg<sup>-1</sup>) also showed significant benefits. Overall, supplementing plant-based meal diets with PHY had a substantial impact, both individually and in combination. Nasr *et al.* (2021) suggested that replacing plant by-products such as SFM and soybean meal has beneficial outcomes in response to hemato-biochemical parameters. Notably, replacing fishmeal with plant-based protein sources stimulated an increase in goblet cells, which secrete mucus, and thickened the muscularis layer. This enhancement is likely due to boost mucus secretion and expand absorptive surfaces, ultimately supporting improved gut health and nutrient uptake (Nasr *et al.*, 2021).

Supporting findings showed that Atlantic cod (*Gadus morhua*) found that PHY supplementation increased WBC count compared to a control diet (Lazado *et al.*, 2010). Another study reported a slight increase in Hb levels in fish fed a PHY-supplemented diet, although the difference was not statistically significant (Yoo and Bai, 2014). PHY supplementation at 500 FTU kg<sup>-1</sup> has also been shown to improve hematocrit and Hb levels in fish (Sardar *et al.*, 2007). Furthermore, a study on *Oreochromis niloticus* found that a soybean meal-based diet supplemented with PHY at 500 FTU kg<sup>-1</sup> resulted in better hematological responses, including higher RBC and WBC counts, compared to a

Jatropha meal-based diet (Kumar *et al.*, 2010). Existing research on the impact of PHY on fish hematology is scarce, highlighting a significant knowledge gap in this area.

Phytate, a storage form of phosphorus in plants, strongly binds to minerals, making them less available for digestion and absorption in fish (Nwanna *et al.*, 2007; Soetan and Oyewole, 2009). The release and absorption of vital minerals are improved when the PHY enzyme action breaks down the chelated structure of phytate. Many studies have suggested that phytate binds minerals, such as Mg Mn, Ni, Cr, Fe, P, and K, forming insoluble complexes that are less bioavailable (Hussain *et al.*, 2016a,b). This study found that adding PHY to diets based on MOLM and CM enhanced mineral absorption in *C. catla* fingerlings by breaking down phytate-mineral complexes. The maximum mineral digestibility values for P- 70.78%, Ca- 63.12%, Na- 60.56%, Cr- 52.69%, Mg- 68.08%, Cu- 73.18%, K- 70.76%, Fe- 73.14%, Al- 59.84%, Mn- 67.20%, and Zn- 63.3% were observed when fingerlings were fed T<sub>3</sub> diet, 50% MOLM supplemented with 500 FTU kg<sup>-1</sup> of PHY. Similarly, when *C. catla* were fed the same T<sub>3</sub> diet, their feces also showed the lowest mineral content. In conclusion, this study demonstrates that supplementing MOLM and CM diets with PHY can improve mineral digestibility in *C. catla* fingerlings, individually and collectively.

Shahzad *et al.* (2018) found that PHY inclusion enhanced mineral absorption in *C. catla* fed MOSM-based diets. Similarly, Cheng and Hardy (2002) reported increased mineral utilization when PHY was added to

plant meal-based diets, as it released minerals bound to phytate in plant feed ingredients. Zhu *et al.* (2014) also noted a significant reduction in fecal mineral content after PHY supplementation. Furthermore, Liu *et al.* (2013) noted a substantial increase in Ca and P absorption in Grass carp fed PHY-supplemented diets. The optimal level of PHY supplementation depends on the type of plant ingredients in the diet and the specific fish species being researched (Baruah *et al.*, 2007). According to Marjan *et al.* (2014) stated that PHY inclusion enhances mineral absorption. Specifically, the optimal PHY level for achieving maximum mineral absorption (ADC%) in *Labeo rohita* was found to be 750 FTU kg<sup>-1</sup>. This level resulted in significantly higher absorption of essential minerals (Fe, Zn, Na, Ca, Cu, Mn, P, and K) when compared to a control diet, particularly when a dry bread meal-based diet was used as a supplement.

In line with our research, Hussain *et al.* (2016a) recorded maximum mineral utilization in *L. rohita* fed a diet consisting of corn soybean meal (CSM), 400 FTU kg<sup>-1</sup> PHY, and 4% citric acid. However, it's essential to note that various factors can significantly impact the effectiveness of PHY supplementation, including phytate levels, digestive system pH, fish species, experimental conditions, feed processing, PHY quality, and feed preparation methods (Dersjant-Li *et al.*, 2015). The present study's outcomes suggest that increased mineral uptake and utilization, facilitated by PHY supplementation, can lead to reduced water pollution and improved health in *C. catla* fingerlings.

## Conclusion

The study revealed that PHY supplementation with plant by-products significantly improved the hematological and mineral profiles of *C. catla*. It was noted that the highest hematological parameters and mineral digestibility rates were achieved with the T<sub>3</sub> diet, which consisted of 50% MOLM and 500 FTU kg<sup>-1</sup> of PHY. Optimal results were achieved with a diet consisting of 50% MOLM and 500 FTU kg<sup>-1</sup> PHY, in contrast with other diets and control. In conclusion, the present study reveals that PHY-supplemented plant-based fish diets can decrease the need for additional mineral supplements, resulting in lower feed costs and reduced environmental impact through minimized waste discharge into aquatic ecosystems. Future research should prioritize the development of more economical and eco-friendly aquafeed solutions.

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## Conflicts of interest

The Authors declare that there is no conflict of interest.

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