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Optimizing Fermented Water Hyacinth Supplementation with *Neurospora crassa* in Ducks: Implications for Performance and Small Intestine Morphology

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ABSTRACT

Water hyacinth is a potential alternative feed ingredient for ducks, but its utilization is limited by high fiber content and low digestibility. The present study aimed to evaluate the effects diets containing water hyacinth fermented with *Neurospora crassa* on feed intake, nutrient intake, growth performance, carcass traits, and intestinal morphology in Pekin ducks. A total of 100 ducks with an average initial body weight of 116 g were used in a completely randomized design with five treatments and four replications. Each replicate consisted of five ducks, and the experiment was conducted from 7 to 35 days of age. The treatments consisted of 0% water hyacinth (P1), 5% non-fermented water hyacinth (P2), 5% fermented water hyacinth (P3), 10% fermented water hyacinth (P4), and 15% fermented water hyacinth (P5). The feeding trial was conducted for four weeks. The analyzed parameters included feed intake, crude protein intake, crude fiber intake, metabolizable energy, feed conversion ratio, final body weight, weight gain, carcass percentage, and intestinal morphology. The results revealed that fermented water hyacinth inclusion had no significant effect on feed intake, metabolizable energy, feed conversion ratio, final body weight, weight gain, carcass percentage, breast percentage, thigh percentage, back percentage, and wing percentage among all treatment groups. No significant differences were observed in intestinal morphology parameters, including duodenal length, jejunal length, ileal length, and intestinal villus length among groups P1 to P5. However, ducks fed 15% fermented water hyacinth (P5) demonstrated significantly higher crude protein and crude fiber intakes compared to other groups. Water hyacinth fermented with *Neurospora crassa* can be included in Pekin duck diets at up to 15% without negatively affecting feed intake, growth performance, carcass traits, or intestinal morphology, while increasing crude protein and crude fiber intakes.

Keywords: Carcass trait, Duck, Fermentation, Intestinal morphology, *Neurospora crassa*, Water hyacinth

INTRODUCTION

Duck farming plays a vital role in supporting food security and the local economy (Adzitey and Adzitey, 2011). Small-scale duck farming contributes to food security and rural economic development by improving household access to animal-source foods, increasing duck consumption and sales, and providing an important source of income for smallholder farmers (Hossain et al., 2021; Herlina et al., 2023; Priyanto et al., 2025). In addition to producing eggs and meat, ducks also possess significant economic value, as duck farming provides income for farmers, supports household livelihoods, and contributes to the economic sustainability of smallholder farming systems (Ali et al., 2025). In 2020, the global duck population was estimated at 1.15 billion, of which approximately 1.0 billion, or 89%, were located in Asia, with the highest population concentrations found in China, Vietnam, Bangladesh, and Indonesia (FAO, 2025). According to Statistics Indonesia (2026), the duck population in Indonesia was recorded at 45,330,236. The large duck population may partly reflect ducks' resilience to environmental conditions and their capacity to adapt to locally available feed (Rosario and Secondez, 2025). The relatively large duck population may be linked to their tolerance of local environmental conditions and their capacity to convert available local and alternative feed resources into productive outputs (Rosario and Secondez, 2025). However, duck productivity is often constrained by the quality and availability of feed. Poor feed quality negatively affects growth performance, feed efficiency, and overall production performance in duck farming systems (Linh et al., 2022). Feed quality remains an important constraint in duck production, as inadequate or nutritionally imbalanced diets may reduce production performance and overall productivity in duck farming systems (Susanti et al., 2025).

The high cost of feed ingredients may limit farmers' ability to provide high-quality diets for Pekin ducks, leading to the use of lower-cost alternative feed ingredients with variable nutritional quality (Ding et al., 2022). Rising feed costs often force producers to compromise on ingredient quality and nutritional balance in feed formulation (Mottet et al., 2017). Constraints in feed availability and high feed costs may result in the formulation of nutritionally inadequate diets,

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thereby reducing production performance and farm efficiency (Gunawan et al., 2024). Feed costs represent the most substantial component of duck production expenses. Because feed cost represents a major proportion of poultry production expenses, the use of locally available alternative feed ingredients is needed to reduce dependence on commercial feed (Thirumalaisamy et al., 2016; Alhotan, 2021).

Water hyacinth is a promising low-cost feed resource because it grows abundantly in freshwater ecosystems, is widely available in tropical areas, and can be processed into poultry feed ingredients, with its rapid growth under favorable environmental conditions enabling the production of substantial biomass and strengthening its potential as an alternative feed ingredient (Chala et al., 2026). Water hyacinth (*Eichhornia crassipes*), an invasive aquatic weed with rapid growth and high biomass production, has potential as an alternative feed ingredient for ducks due to its abundant availability and low utilization cost. However, its high fiber content limits its direct application in poultry diets, requiring appropriate processing methods such as fermentation to improve its nutritional value and utilization efficiency (Harun et al., 2021; Antonio et al., 2025). The high biomass production, extensive distribution, and relatively low economic value of water hyacinth provide opportunities for its utilization as a feed ingredient, particularly after appropriate processing to enhance nutrient availability and utilization (Harun et al., 2021; Nandiyanto et al., 2024). Different studies have reported that water hyacinth (*Eichhornia crassipes*) has potential as an alternative feed ingredient for livestock and poultry due to its availability, low cost, and nutritional composition (Gunnarsson and Petersen, 2007; Hamiyanti et al., 2025). Although water hyacinth is commonly classified as an invasive aquatic weed, its high availability in freshwater environments provides an opportunity for its utilization as an inexpensive alternative feed ingredient in duck production systems (Rajan et al., 2023; Hamiyanti et al., 2025). Muazzasari et al. (2023) reported that water hyacinth infestation in the Batujai Reservoir, Lombok Island, covers approximately 267 hectares. Despite its abundance, water hyacinth cannot be optimally used as a poultry feed ingredient without prior processing. However, its application in poultry diets should be considered carefully, as its relatively high fiber content and potential antinutritional compounds may reduce nutrient digestibility and utilization in poultry (Ayoola et al., 2024; Nhara et al., 2026). Fermentation was therefore applied to improve its feeding value by modifying the fiber structure and increasing the availability of nutrients. *Neurospora crassa* was selected as the fermenting agent in the present study based on previous evidence showing that this fungus can produce fiber-degrading enzymes that break down complex plant materials, thereby improving the suitability of water hyacinth for inclusion in duck diets (Ciptaan et al., 2022). However, the high crude fiber content of water hyacinth, which is difficult for livestock to digest, poses a significant challenge to its utilization as feed. High levels of fiber and antinutritional factors in this feed ingredient may reduce digestibility and nutrient utilization, thereby posing a significant challenge to its use as a feed ingredient (Hossain et al., 2015). Water hyacinth contains 28.10% crude fiber, 8.7% crude protein, and 3.32% crude fat (Saud et al., 2023).

One microorganism that has been used for feed fermentation is *Neurospora crassa*, recognized for its ability to produce hydrolytic enzymes, such as cellulase, that facilitate the degradation of complex organic substrates (Yu et al., 2023). Previous studies have demonstrated that fermentation using *Neurospora crassa* can reduce the crude fiber content of water hyacinth and enhance its nutritional value as a potential feed ingredient (Nuraini et al., 2009; Maslami et al., 2024). *Neurospora crassa* is a filamentous fungus commonly used as a fermenting microorganism due to its ability to produce hydrolytic enzymes that degrade complex organic materials, including fiber components, which supports its application in feed fermentation by reducing crude fiber content and improving the nutritional quality of fibrous plant materials such as water hyacinth (Chen et al., 2025). *Neurospora crassa* produces cellulase enzymes and has an advantage over other molds because it also produces β-carotene (Bayram et al., 2019; Toma et al., 2023). The utilization of water hyacinth fermented with *Neurospora crassa* has the potential to enhance feed digestibility and nutritional value in local ducks, as previous findings have demonstrated that *Neurospora crassa* fermentation can reduce the crude fiber content of water hyacinth, improve its value as a feed ingredient, and support growth performance when included in duck diets (Maslami et al., 2024).

The incorporation of *Neurospora crassa*-fermented feed ingredients has been reported as a promising strategy to improve feed utilization and maintain productive performance, as previous studies demonstrated that *Neurospora crassa*-fermented ingredients can be included in broiler diets without negatively affecting production performance and carcass weight, while also contributing to improved carcass characteristics through the utilization of fermented plant-based feed materials (Mirnawati et al., 2018; Fenita et al., 2024). Mirnawati et al. (2018) and Fenita et al. (2024) are among the previous studies reporting that Neurospora crassa-fermented plant-based feed ingredients can be included in broiler diets, with no negative effects on productive performance or carcass quality. Furthermore, Nuraini et al. (2009) reported that the inclusion of *Neurospora crassa*-fermented feed ingredients in poultry diets improved nutrient utilization and supported growth performance, indicating the potential of fermented feed products as alternative feed sources for poultry. A previous study by Maslami et al. (2024) demonstrated that fermentation of water hyacinth using *Neurospora crassa* improved its nutritional characteristics as an alternative feed ingredient by reducing crude fiber content and enhancing its potential utilization as an energy source. In addition, fermented water hyacinth with *Neurospora crassa* has been evaluated in poultry diets and was reported to be usable at appropriate inclusion levels without negative effects on digestive organ development (Al-Aboudi and Hamodi, 2023; Maslami et al., 2025). The present study aimed to assess the effects of dietary inclusion of water hyacinth fermented with *Neurospora crassa* on growth performance, carcass traits, and small intestinal morphology in ducks.

MATERIALS AND METHODS

Ethical approval

The present study was conducted in accordance with the approved ethical procedures of the Ethics Committee of the University of Mataram, Mataram, Indonesia. All procedures involving Pekin ducks were carried out in accordance with the institutional guidelines for animal care and use, and ethical approval was obtained prior to the commencement of the experiment.

Study time and location

The present study was conducted from February to July 2025. Duck rearing was conducted at the Teaching Farm Laboratory, Faculty of Animal Husbandry, University of Mataram, Indonesia.

Study design

The experiment was conducted using a completely randomized design with five treatment groups and four replications, yielding a total of 20 experimental pens. Allocation of treatments to pens was carried out using a randomization process to minimize potential allocation bias. The treatment groups included 0% water hyacinth (P1), 5% water hyacinth (P2), 5% fermented water hyacinth (P3), 10% fermented water hyacinth (P4), and 15% fermented water hyacinth (P5). Each replicate within each treatment consisted of five ducks serving as experimental units. All pens were maintained under uniform management practices and comparable environmental conditions throughout the study period. A total of 100 local commercial Pekin ducks were used in the present study. The ducks were purchased from a local market in West Lombok, Indonesia, and consisted of mixed-sex, one-day-old ducklings with an average initial body weight of 50 g. After an adaptation period, the experimental treatments were started in the second week when the ducks reached an average initial body weight of 116 g.

The ducks were housed in pens measuring 1 × 1 × 0.7 m with a stocking density of 5 ducks/m². Each pen was equipped with a tube feeder and a manual drinker, and the floor was covered with rice husk bedding, which was replaced or maintained regularly to ensure hygiene. During the experimental period, the house temperature was maintained at approximately 22-30˚C, with relative humidity ranging from 72%-89%. A continuous lighting program of 24 h light and 0 h dark was applied throughout the experimental period based on previously reported lighting management protocols for broiler chickens (Bayram and Özkan, 2010). Before the dietary treatments began at 7 days of age, the ducks were reared from day 1 to day 7 in the same treatment pens and were provided with commercial starter feed. During the initial period, all ducks were managed under uniform housing conditions, with free access to feed and drinking water. The experimental diets were introduced after the ducks reached 7 days of age. The experimental diets were formulated using corn, rice bran, soybean meal, commercial feed, mineral premix containing calcium and phosphorus, and fermented water hyacinth as feed ingredients. The dietary formulation was adjusted according to the inclusion levels of fermented water hyacinth in each treatment while meeting the nutrient requirements of ducks according to the Indonesian National Standardization Agency (BSN, 2015). The composition and nutrient content of the experimental diets are presented in Table 1, while the calculated nutrient composition and metabolizable energy values (kcal/kg) of the experimental diets are presented in Table 2.

Water hyacinth fermentation

Fresh water hyacinth used in this study was obtained from Batu Jai Dam, West Lombok, Indonesia. The material was cleaned and dried under sunlight before being processed for fermentation. The dried water hyacinth was then ground using a hammer mill equipped with a 2 mm sieve to produce uniformly ground material. The ground water hyacinth material obtained after drying and grinding was used as the substrate for fermentation with *Neurospora crassa*. Water hyacinth fermentation was conducted using *Neurospora crassa* for five days at a temperature of 30˚C. Before fermentation, the substrate moisture content was adjusted to approximately 50%, and the initial pH of the water hyacinth substrate was 7.0, which provided suitable conditions for the growth of *Neurospora crassa*. The fermentation process was performed under aerobic conditions with adequate air exchange. After incubation, the fermented water hyacinth was dried and used as an ingredient in the experimental diets. Following grinding, the water hyacinth was subjected to fermentation, which was initiated by adding groundwater to achieve a moisture content of 50%. Before fermentation, the water hyacinth substrate was sterilized in an autoclave using hot steam at 121˚C for 15 minutes. After sterilization, the substrate was allowed to cool to 40˚C before being inoculated with *Neurospora crassa*. The sterilized water hyacinth substrate was inoculated with 2% *Neurospora crassa* starter based on the substrate weight and mixed thoroughly until the starter was evenly distributed. The inoculated substrate was then placed in clean fermentation containers and incubated for five days at room temperature under aerobic conditions. Following this step, the water hyacinth was dried and prepared for the subsequent fermentation process (Maslami et al., 2024).

Table 1. Nutrient content of feed ingredients and metabolizable energy for Pekin ducks during a 28-day rearing period

Feed ingredients	Crude protein	Crude fat	Crude fiber	ME (kcal/kg)	Ca	P
Corn	8.04	4.52	3.64	2730.68	0.01	0.3
Rice bran	11.3	8.56	14.19	2794.67	0.03	1.07
Commercial feed*	20.5	2	8	2900	3.5	0.5
Soybean meal	36.5	9	3	2760	0.2	0.6
Mineral (Ca and P)**	0	0	0	0	32.5	1
Fermented water hyacinth	14.06	0.09	22.17	3332.38	1.3	0.3
Water hyacinth	11	0.023	28	3000	1.3	0.3

ME: Energy metabolism, Ca: Calcium, P: Phosphorus. *Commercial feed: CP511 PT, Japfa Cemfeed, Indonesia. ** Minerals (Ca and P), Japfa Cemfeed, Indonesia

Table 2. Composition of experimental diets fed to Pekin ducks for 28 days (from 7 to 35 days of age)

Feed ingredients	P1	P2	P3	P4	P5
Corn	30.00	35.00	32.00	25.00	22.00
Rice bran	7.50	4.50	4.50	4.50	4.50
Commercial feed	36.00	34.00	35.00	35.00	35.00
Soybean meal	25.00	20.00	22.00	24.00	22.00
Mineral (Ca and P)	1.50	1.50	1.50	1.50	1.50
Fermented water hyacinth	0.00	0.00	5.00	10.00	15.00
Water hyacinth	0.00	5.00	0.00	0.00	0.00
Total (%)	100.00	100.00	100.00	100.00	100.00
Corn	19.76	18.14	18.99	19.86	21.09
Crude fat	6.05	5.47	5.57	5.43	5.12
Crude fiber	4.71	5.61	5.32	6.24	7.17
Ca (%)	0.94	0.97	0.99	1.05	1.12
P (%)	0.52	0.64	0.82	0.49	0.48
Metabolizable energy (Kcal /kg)	2870.80	2871.50	2893.40	2924.07	2953.57

P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth, Ca: Calcium, P: Phosphorus

Preparation of the cage

The ducks were housed in partitioned floor pens during the experimental period. Each pen was covered with rice husk bedding and contained five ducks, representing one experimental unit. The rice husk bedding was maintained regularly to keep the pen clean and reduce moisture accumulation. Each pen was equipped with a feeder and drinker, and all pens were managed under similar housing and environmental conditions throughout the study. Before the arrival of the one-day-old Pekin ducklings, the housing area and partitioned floor pens were cleaned and whitewashed as part of the cage preparation procedure. Upon arrival, the ducklings were weighed to determine their average initial body weight, which was 50 g. The ducklings were then placed in the prepared pens and managed under uniform housing conditions before the dietary treatments began. Following a three-day whitewashing process, the cages were treated with a disinfectant solution (Rodalon). Prior to the arrival of the one-day-old Pekin ducklings, each pen was equipped with a 100-watt lamp, drinking and feeding facilities, a black plastic tray for fecal collection, and a weighing scale to support the management and data collection procedures. Each partitioned floor pen was assigned a serial number and served as one experimental unit. At 7 days of age, the ducklings were allocated to their respective pens, with five ducks housed in each pen. Thus, the stocking density was five ducks per pen, equivalent to 5 ducks/m² based on the pen area. Before being placed in their respective enclosures, the ducklings were weighed.

Management and housing

As a disease prevention measure, the ducks were vaccinated against Newcastle disease (ND) on day 1 and day 14. The cages were numbered 1-20, and the treatments were randomly assigned to the cages. At 7 days of age, all ducks were weighed individually to determine their baseline body weight before being allocated to their respective treatment groups. Ducks with body weights below or above the reference value were then selected and distributed evenly across the treatment groups, so that each experimental unit had a relatively similar initial body weight. The ducks were subsequently distributed into the numbered cage units. Each cage unit measured 100 × 80 × 75 cm (length × width × height) and accommodated 5 ducks.

Experimental diet

The experimental diets were formulated and balanced based on the Indonesian National Standard for meat-type duck grower-finisher feed (BSN, 2018). The diets were prepared according to the predetermined feed composition for each treatment and were provided *ad libitum* throughout the experimental period. The remaining feed was weighed on a daily basis. Water was provided *ad libitum* and replaced every morning and evening. Body weight was recorded weekly after the ducks had been fasted for 8 hours. The treatment was concluded in the 35 day.

Measurement of parameters

Feed and nutrient intake

The total treatment period is from 7 days to 35 days, with weekly measurements of feed intake. The intake of crude protein and crude fat was determined by calculating the product of crude protein and crude fat content of the feed and the feed intake. The intake of crude protein and crude fiber was determined by multiplying the crude protein and crude fiber contents of the diet by feed intake (Mirza et al., 2016). The crude protein and crude fiber contents of the experimental diets were calculated from the feed formulation using the nutrient composition of each feed ingredient, which had previously been analyzed in the laboratory. Metabolizable energy was calculated by multiplying the amount of feed consumed by the metabolizable energy content of each experimental diet.

Performance and carcass traits

Weekly body weight gain was calculated from the difference between body weights recorded at the beginning and end of each observation week. Feed conversion ratio (FCR) was determined by dividing feed intake by body weight gain, following Gous (2010), who described FCR as feed intake per unit of weight gain. Before slaughter, live body weight was recorded. Carcass percentage was calculated as the ratio of carcass weight to live body weight multiplied by 100%, following Soeparno (2015).

Morphology of the small intestine

The small intestine was first cleared of digesta and then weighed. Histological evaluation was performed using one duck from each replicate, resulting in four ducks per treatment. For each duck, four jejunal sections per treatment were examined. Intact and well-oriented villi were selected from each section, and their morphological characteristics were measured. Segment lengths were determined anatomically, with the duodenum measured from the ampulla to the bile duct, the jejunum from the bile duct to Meckel's diverticulum, and the ileum from Meckel's diverticulum to the ileocecal junction (Han et al., 2016; Kimiaeitalab et al., 2017). Intestinal villus length was measured using a 1.5-cm jejunal sample carefully obtained from the region midway between the bile duct opening and Meckel's diverticulum. The jejunal sample was thoroughly rinsed with 0.9% NaCl physiological saline solution to maintain its integrity and prepare it for subsequent fixation (Sadeghi et al., 2015). The fixation process involved the use of a 100 g/L buffered formalin solution at pH 7.0, which served as a stabilizing agent during the procedure. After fixation, the intestinal samples were prepared for histological analysis by embedding them in paraffin, slicing them into 5-µm-thick sections, and applying hematoxylin and eosin staining (Sadeghi et al., 2015). Intestinal villus height was measured using a light microscope (Olympus, Japan) following hematoxylin and eosin (H&E) staining. Intact and well-oriented villi were selected from each jejunal section, and villus height was measured using image analysis software. The mean value of villus measurements from each duck was used for statistical analysis to ensure consistency and reproducibility of the histological data.

Statistical analysis

The data were analyzed using Analysis of Variance (ANOVA), followed by Duncan's Multiple Range Test (DMRT) when significant differences among treatments were detected. The level of significance was set at p less than 0.05. All statistical analyses were performed using SAS software (Statistical Analysis System) version 9.4.

RESULTS AND DISCUSSION

Feed and nutrient intake

The results indicated that dietary inclusion levels of fermented water hyacinth had no significant effect ($p > 0.05$) on feed intake, metabolizable energy, or FCR. The metabolizable energy values of the experimental diets were estimated based on their proximate nutrient composition. In contrast, dietary supplementation with fermented water hyacinth significantly affected ($p < 0.05$) crude protein and crude fiber intake. Crude fiber intake was quantified by first determining the fiber content of each experimental diet through proximate analysis. The effects of dietary treatments containing fermented water hyacinth with *Neurospora crassa* on feed intake, nutrient intake, metabolizable energy, and FCR of Pekin ducks during the 35-day feeding trial are presented in Table 3.

Table 3. Effects of diets containing fermented water hyacinth with *Neurospora crassa* on feed and nutrient intake, metabolizable energy, and feed conversion ratio in Pekin ducks over a 35-day feeding trial

Parameters	Treatment groups					P-value
	P1	P2	P3	P4	P5	
Feed intake (g)	2328.40 ± 26.53	2446.90 ± 146.61	2406.50 ± 46.53	2353.90 ± 20.27	2425.30 ± 23.85	0.20
Crude protein intake (g)	450.23 ± 11.551^{b}	438.43 ± 26.59^{b}	444.65 ± 16.35^{b}	453.38 ± 9.54^{b}	516.77 ± 28.45^{a}	< 0.05
Crude fiber intake (g)	107.35 ± 2.75^{d}	135.59 ± 8.22^{bc}	124.57 ± 4.58^{c}	142.45 ± 3.00^{b}	175.69 ± 9.67^{a}	< 0.05
Metabolizable energy (kcal/kg)	6541.12 ± 193.82	6940.13 ± 486.11	6774.36 ± 287.58	6675.35 ± 162.18	7237.13 ± 460.11	0.07
Feed conversion ratio (%)	2.49 ± 0.04	2.42 ± 0.03	2.44 ± 0.05	2.45 ± 0.07	2.43 ± 0.05	0.44

$^{a, b, c}$ Mean different superscript letters in the row indicate significant differences across the treatments ($p < 0.05$). P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth.

Feed intake

The inclusion of fermented water hyacinth up to 15% did not affect feed intake in meat ducks during the experimental period, indicating that the fermented ingredient was well accepted by the ducks without adverse effects on feed consumption. The comparable feed intake among treatments suggested that fermentation with *Neurospora crassa* improved the suitability of water hyacinth as a feed ingredient by enhancing its nutritional characteristics and reducing the limitations associated with its high fiber content. Similar responses have been reported in ducks fed fermented water hyacinth-based diets, where appropriate inclusion levels maintained feed acceptance and production performance (Rompas et al., 2016; Pangeran et al., 2021; Hamiyanti et al., 2025). Furthermore, the similar metabolizable energy content among dietary treatments may have contributed to the consistent feed intake observed in this study, as dietary energy density plays an important role in regulating voluntary feed consumption in poultry (Hong et al., 2022; Lim et al., 2024; Wu et al., 2026).

In the present study, the crude fiber content of the experimental diets ranged from 4.71% to 7.17%. Although this range should not necessarily be interpreted as optimal, it can be regarded as acceptable because it does not exceed the maximum crude fiber limit of 5% specified for grower meat duck feed in SNI 8508:2018 (BSN, 2018). The crude fiber values observed in the present study were therefore unlikely to cause a marked reduction in feed intake, particularly because the metabolizable energy content of the diets remained relatively adequate and comparable among treatments**.** A recent study by Hao et al. (2021) revealed that dietary fiber can contribute to gastrointestinal development and gut microbial balance in ducks when supplied at an appropriate level. In a broader poultry context, moderate fiber inclusion may support gut function and nutrient utilization, although its effect depends on the fiber source, diet composition, and bird species (Jha and Mishra, 2021; Zhang et al., 2023a). Thus, the crude fiber level in the present diets was more appropriately interpreted as being within an acceptable range for duck feed, rather than as a universal optimal level.

As illustrated in Figure 1, the weekly feed intake of ducks increased with age. The increase may be associated with the greater nutrient and energy requirements required to support body growth and development during the growing period, as previously reported in growing White Pekin ducks (Hong et al., 2022). Based on the results of the present study, feed intake tended to increase after the first week of rearing. The increase in feed intake may be associated with the increasing nutrient and energy requirements required to support body weight gain and growth during the growing period, as dietary metabolizable energy plays an important role in determining growth performance and nutrient utilization in ducks (Wu et al., 2019; Guo et al., 2023). The higher energy requirements associated with increasing body weight may support muscle development, bone formation, and other metabolic processes during the growth period. Consequently, ducks tend to increase feed consumption to meet their nutritional requirements for growth and development (Hong et al., 2022). According to the findings of Wang et al. (2024), the amount of feed consumed by poultry increases in direct proportion to their body weight and the stage of their physiological development. Moreover, the increase in feed intake observed as ducks grew older may be related to their higher energy requirements for maintenance and body tissue development. In duck diets, dietary energy level is an important factor influencing growth performance and feed utilization, as reported in studies evaluating different metabolizable energy levels in White Pekin ducks and BAU Black and White ducks (Barman et al., 2025). The average feed intake recorded in the present study was within a range similar to the values reported by Rusfidra et al. (2025), who observed feed intake in meat ducks ranging from 81.21 to 84.07 g/bird.

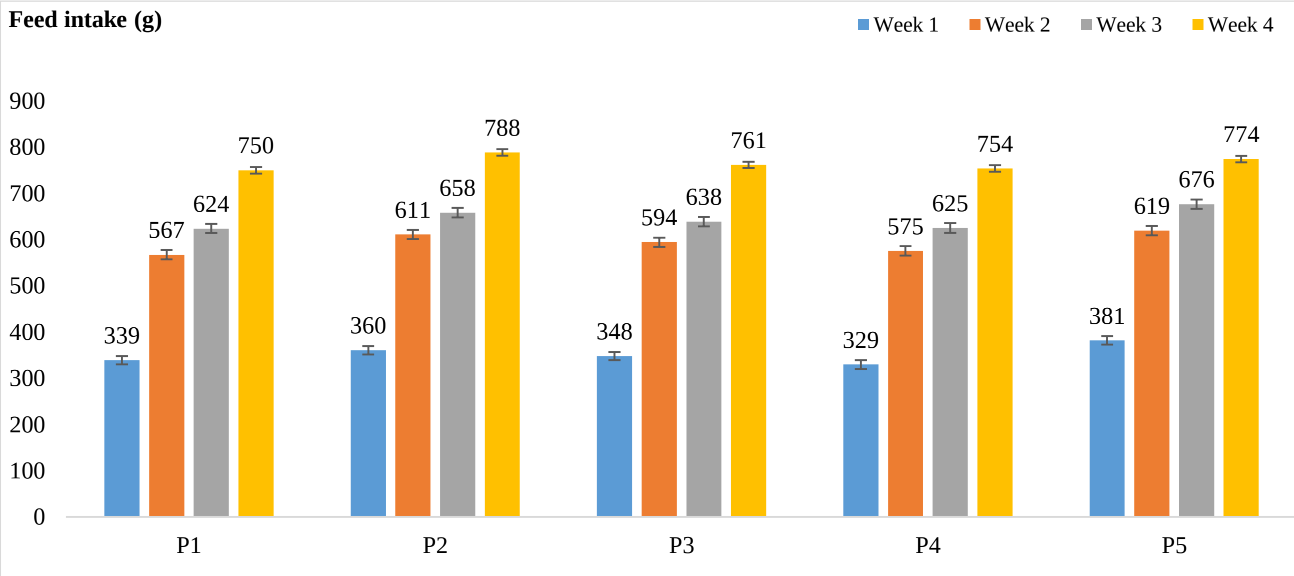

Figure 1. Weekly feed intake of mixed-sex Pekin ducks aged 7 days fed diets containing fermented water hyacinth with *Neurospora crassa* over 28 days. P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth

Crude protein intake

The differences in crude protein intake among treatment groups can be explained by the variation in feed intake and the crude protein content of each experimental diet. In the present study, crude protein intake was not measured as a separate nutrient consumed directly, but was calculated from the amount of feed consumed by the ducks and the crude protein concentration of the corresponding diet. Therefore, treatment groups with higher feed intake and higher dietary crude protein content tended to display greater crude protein intake. Crude protein intake was influenced by both the quantity of feed consumed and the nutrient composition of the diet.

Fermented water hyacinth inclusion significantly affected crude protein intake among treatment groups, with the highest intake observed in ducks fed the 15% fermented water hyacinth diet. The higher crude protein intake observed in Pekin ducks fed this diet was likely associated with the increased crude protein concentration of the fermented water hyacinth-based ration, as dietary protein content directly influences nutrient intake and protein supply for growth performance in poultry (Musigwa et al., 2023). Differences in dietary composition, particularly crude protein concentration, may contribute to variations in protein intake among Pekin ducks, as dietary protein levels influence nutrient intake and growth performance in growing ducks (Shen et al., 2026). Similar observations were reported by Wu et al. (2024), who demonstrated that diets with higher protein content increased protein consumption in Pekin ducks. Variations in crude protein intake compared with those in previous studies may be related to differences in duck strain, age, body weight, feed intake, dietary composition, and experimental conditions (Zeng et al., 2015; Xie et al., 2017). Therefore, comparisons with previous reports should be interpreted within the context of different experimental designs. The relationship between dietary crude protein concentration, feed intake, and crude protein intake is presented in Figure 2.

Adequate crude protein intake is essential for supporting growth and physiological functions in ducks because dietary protein provides amino acids required for tissue deposition, protein synthesis, and efficient nutrient utilization (Wu et al., 2026). In Pekin ducks, crude protein level has been shown to influence growth performance and feed efficiency, indicating the importance of sufficient protein supply during the growing period (Cho et al., 2020). A recent study by Wu et al. (2024) reported that dietary crude protein level and amino acid balance are closely related to growth performance, carcass traits, nutrient digestibility, and nitrogen utilization in growing Pekin ducks.

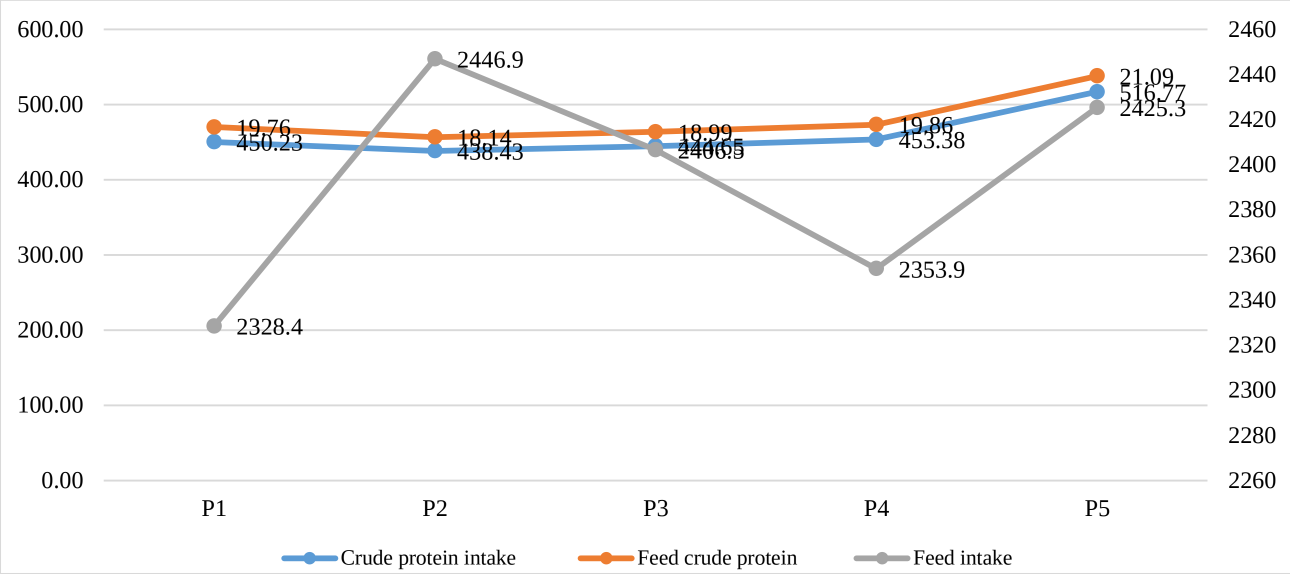

Figure 2. Interaction between feed intake, dietary crude protein content, and crude protein consumption in mixed-sex Pekin ducks fed diets containing fermented water hyacinth with *Neurospora crassa* from day 7 to 35 days of age. P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth

Crude fiber intake

The differences in crude fiber intake among treatment groups can be attributed to variations in feed intake and the crude fiber content of each experimental diet. In the present study, crude fiber intake was not measured as a separate component consumed directly, but was calculated based on the amount of feed consumed and the crude fiber concentration of the corresponding diet. Therefore, treatment groups with higher feed intake or higher dietary crude fiber content tended to indicate greater crude fiber intake. Crude fiber intake was influenced by both the inclusion level of fermented water hyacinth in the diet and the total amount of feed consumed by the ducks.

The results of the present study indicated a significant difference in crude fiber intake among the treatment groups ($p < 0.05$). Crude fiber intake was higher in P5 compared with the other groups, whereas P1 indicated the lowest crude fiber intake, indicating that dietary treatments influenced the amount of crude fiber consumed by the ducks. The highest crude fiber intake was observed in treatment P5, reaching 175.69 g per bird (6.27 g per bird per day). The greater crude fiber intake in treatment group P5 was related to the higher crude fiber concentration of the diet, which reached 7.17%. The crude fiber level observed in the treatment diet required careful interpretation because it exceeded the maximum crude fiber level of 5% recommended for meat duck grower feed according to SNI 8508:2018 (BSN, 2018). The response of ducks to dietary fiber may also differ according to the fiber source and feed formulation. In the present study, fermented water hyacinth was used as the main fiber source, whereas El-Katcha et al. (2021) used soybean hulls and reported that higher dietary fiber did not significantly reduce body weight, although it affected feed efficiency and intestinal morphology. Therefore, the increased crude fiber intake in P5 mainly reflected the higher fiber content of the diet and feed consumption, rather than indicating that the diet remained within the recommended limit. The increase in crude fiber intake corresponding to feed fiber content is illustrated in Figure 3.

In the present study, crude fiber intake differed significantly among treatment groups compared to the control group ($p < 0.05$). The variation in crude fiber intake among treatments was mainly associated with differences in dietary crude fiber concentration and feed consumption. Although digestive function was not directly measured in the present study, dietary fiber has been reported to influence gastrointestinal function, nutrient utilization, and intestinal morphology in poultry, depending on the fiber source, inclusion level, and diet formulation (Singh et al., 2021; Zhang et al., 2023b). Therefore, the digestive responses discussed in the present study should be considered as supportive interpretations based on previous literature rather than direct experimental observations, as dietary crude fiber has been reported to influence gastrointestinal function by enhancing intestinal motility (peristalsis), which may facilitate digestive processes and gastric emptying (Singh and Kim, 2021). The promotion of peristalsis by crude fiber facilitates feed processing, reduces the risk of constipation, and supports gastric emptying, as dietary fiber has been reported to modulate gastrointestinal activity, digestive organ development, nutrient utilization, and gut health in poultry, with its effects depending on the type, source, and inclusion level of fiber (Tejeda and Kim, 2021). Furthermore, the increased crude fiber content may contribute to improvements in intestinal morphology, as reflected by the morphological changes observed in the present study. Short-chain fatty acids (SCFAs) act as an energy source for intestinal cells, thereby contributing to overall digestive health (Zhang et al., 2023b).

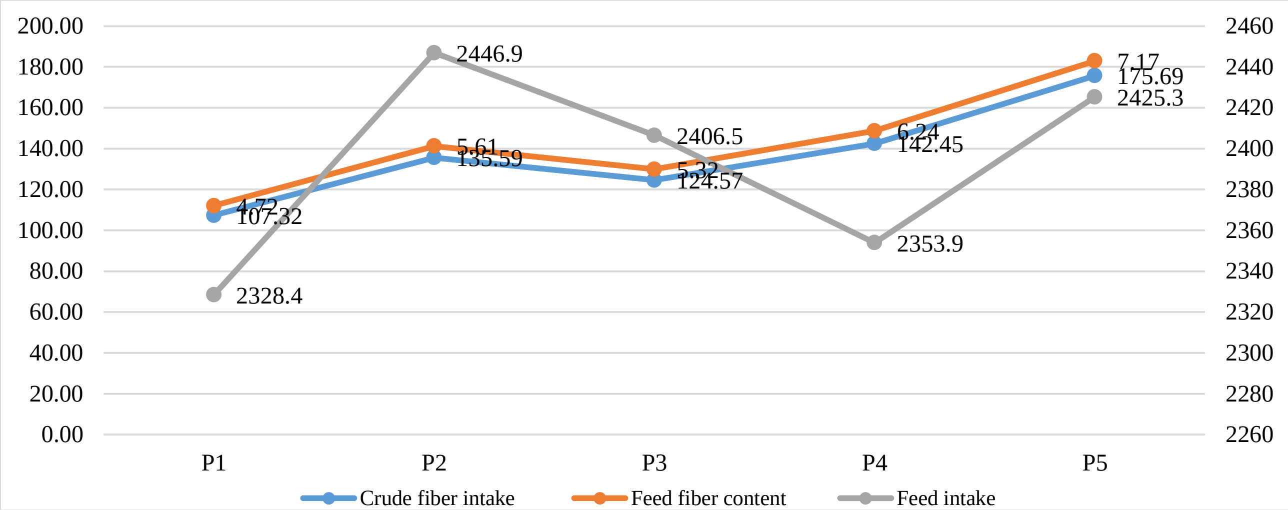

Figure 3. Interaction between feed intake, crude fiber content of feed, and crude fiber consumption in mixed-sex Pekin ducks fed diets containing fermented water hyacinth with *Neurospora crassa* from day 7 to 35 days of age. P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth

Metabolizable energy

The results of the present study revealed that there was no significant difference in metabolizable energy among the treatment groups, namely P1, P2, P3, P4, and P5, which were fed diets containing different levels of fermented water hyacinth ($p > 0.05$). The absence of a significant difference in energy intake can be attributed to the similar energy content of the diets across the various treatments, which did not influence the amount of energy consumed by the ducks ($P > 0.05$). The pattern of metabolizable energy among treatments is presented in Figure 4. The metabolizable energy content of the rations ranged from 2870.80 to 2953.57 kcal/kg, with P5 slightly exceeding the recommended upper limit of 2900 kcal/kg. The metabolizable energy range of the experimental diets was generally consistent with the levels recommended by BSN (2019) and NRC (1994), which specify 2700-2900 kcal/kg for poultry diets. During the 28-day treatment period, daily metabolizable energy ranged from 233.60 kcal/kg per bird per day in P1 to 258.47 kcal/kg per bird per day in P5. In contrast, El-Katcha et al. (2021) reported lower daily metabolizable energy in Pekin ducks, ranging from 163.23 to 167.03 kcal/duck/day; however, differences in experimental design, feed ingredients, and ration composition should be considered when comparing these results with the present study. Differences in daily metabolizable energy may be related to feed type, ration composition, duck breed, and age, as these factors influence nutrient density, palatability, metabolic requirements, and feed consumption capacity (Yang et al., 2025). It is important to recognize the pivotal role of metabolizable energy in supporting duck growth. The energy consumed by ducks is utilized for different metabolic processes, including body growth, thermoregulation, and physical activity (Fouad et al., 2018). When ducks consume sufficient energy, it is directed toward supporting the formation of body tissues, such as muscles and bones, which are essential for optimal growth (Zeng et al., 2015).

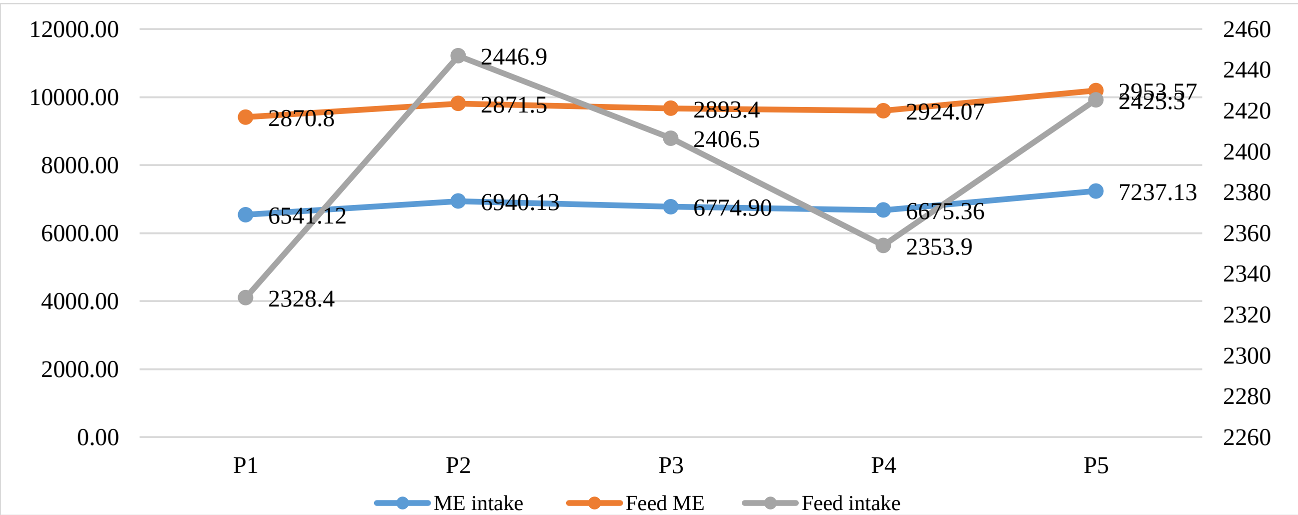

Figure 4. Relationship between feed intake, metabolizable energy content of feed, and energy consumption in mixed-sex Pekin ducks fed diets containing fermented water hyacinth with *Neurospora crassa* from day 7 to 35 days of age. P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth

Feed conversion ratio

The results indicated that dietary supplementation with different levels of water hyacinth had no significant effect on the FCR of ducks ($p > 0.05$). The absence of a significant difference in FCR may be related to the relatively comparable nutrient intake among treatments, allowing ducks to utilize the diets with similar efficiency. In the present study, the crude protein content of the experimental diets ranged from 18.14% to 21.09%, while the metabolizable energy was formulated at 2,900 kcal/kg. As described by Hong et al. (2022), the balance between protein and energy in the diet exerts a significant influence on body weight, which, in turn, modulates FCR. The FCR values obtained in the present study ranged from 2.42 to 2.49, which were lower than those reported in previous studies, including 5.48 in Muscovy ducks fed commercial diets (Sabrina et al., 2025) and 3.04 in Magelang meat ducks (Listyowati et al., 2020). The lower FCR recorded in the present study suggests that the ducks were able to convert feed into body weight more efficiently. Differences in breed, feed formulation, nutrient composition, management practices, and experimental conditions may explain the variation in FCR values among studies. The absence of significant variations in FCR can be ascribed to the comparable feed intake observed among the treatment groups. Despite the variation in the quantity of water hyacinth present in the diets, the ducks exhibited no significant difference in their feed consumption, resulting in comparable body weight gains ($p > 0.05$). The relationship among feed intake, body weight gain, and FCR is presented in Figure 5. The figure revealed that changes in feed intake and body weight gain are closely associated with the resulting FCR values. In Pekin ducks, Li et al. (2020) found that sufficient overall feed consumption and daily weight gain were important factors contributing to efficient feed conversion. Although a direct relationship between higher feed intake and improved FCR has not been consistently demonstrated, the amount of feed consumed plays an important role in determining the efficiency of feed conversion into body weight gain. In this context, ducks that consume adequate feed to support their growth tend to have lower FCR values, indicating better feed efficiency (Zhao et al., 202

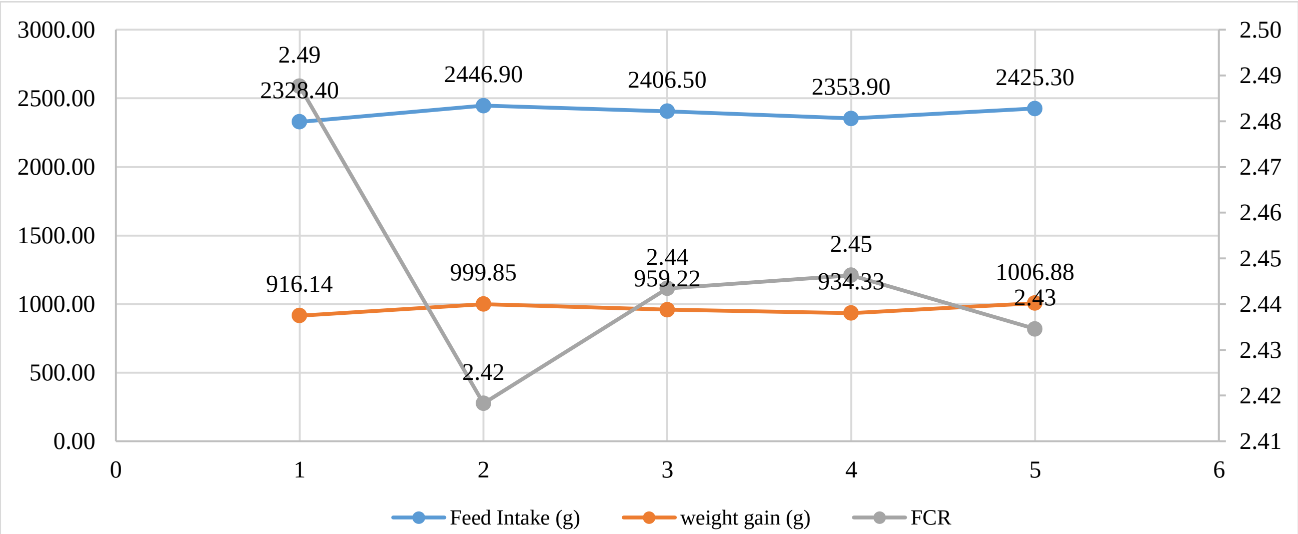

Figure 5. Relationship between feed intake, body weight gain, and feed conversion ratio in mixed-sex Pekin ducks fed diets containing fermented water hyacinth with *Neurospora crassa* from day 7 to 35 days of age. P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth

Performance and carcass traits

The results of the present study indicated that supplementation with fermented water hyacinth at different levels did not significantly affect final body weight, body weight gain, carcass percentage, breast percentage, thigh percentage, back percentage, or wing percentage ($p > 0.05$). The average values of growth performance and carcass characteristics are shown in Table 4.

Table 4. Mean growth performance and carcass traits of Pekin ducks fed diets containing fermented water hyacinth with *Neurospora crassa* reared for 28 days

Parameters	Treatment groups					P-value
	P1	P2	P3	P4	P5	
Final body weight (g)	1029.69 ± 27.02	1122.50 ± 70.84	1080.27 ± 52.69	1049.83 ± 45.68	1114.58 ± 55.94	0.43
Weight gain (g)	916.14 ± 26.62	999.85 ± 65.39	959.22 ± 50.83	934.33 ± 43.17	1006.88 ± 59.99	0.338
Carcass percentage	61.20 ± 1.91	58.91 ± 0.82	61.36 ± 1.51	60.97 ± 1.31	60.11 ± 1.29	0.55
Breast percentage	33.25 ± 0.62	32.86 ± 1.05	33.09 ± 0.86	33.16 ± 0.81	32.76 ± 0.62	0.97
Thigh percentage	31.70 ± 0.41	31.12 ± 1.25	31.68 ± 0.96	31.00 ± 0.54	31.80 ± 1.45	0.95
Back percentage	20.98 ± 0.77	21.47 ± 0.85	21.40 ± 1.49	21.75 ± 0.85	22.16 ± 1.03	0.82
Wing percentage	14.51 ± 0.47	14.54 ± 0.61	13.83 ± 0.64	14.09 ± 0.51	13.32 ± 0.78	0.06

P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth.

Final body weight

The results of the present study revealed that different levels of water hyacinth inclusion in the diet did not significantly affect the final body weight of ducks among the treatment groups (P1-P5; $p > 0.05$), as presented in Table 4. The final body weight of ducks at 35 days of age ranged from 1,029.69 g in P1 to 1,122.50 g in P2, with values of 1,080.27 g in P3, 1,049.83 g in P4, and 1,114.58 g in P5. The absence of a significant difference among treatments may be related to the adequacy of dietary nutrients and the relatively comparable feed intake across treatment groups. Although the level of water hyacinth included in the diets varied, the available nutrients appeared sufficient to support duck growth during the experimental period. The comparable final body weight among treatments is consistent with previous reports showing that adequate dietary protein and metabolizable energy are key factors in maintaining duck growth performance, even when feed ingredients or diet composition differ among treatments (Li et al., 2020). The protein content of the feed plays a crucial role, and maintaining a balance between protein and energy is essential to optimize growth. Excessive protein and imbalanced energy in the diet may lead to fat accumulation, which hinders the development of muscle mass in ducks (Starčević et al., 2021).

The absence of a significant difference in final body weight can be ascribed to the comparable feed intake observed across treatment groups. Feed intake is a pivotal factor influencing growth and final body weight in Pekin ducks. The amount of feed consumed is directly related to the energy and nutrients required to support body development. Shu et al. (2025) indicated that discrepancies in final body weight are predominantly dictated by feed intake. The final body weight of ducks in the present study ranged from 1,029.69 to 1,122.50 g at 35 days of age. The final body weight observed in the present study was lower than that reported by Gunawan et al. (2023), who recorded a body weight of 1,500 g in Pekin ducks at 42 days of age fed diets containing 22% crude protein. The difference may be related to the older age of ducks and the higher dietary crude protein level used in their study. The final body weight observed in the present study was higher than the 769.84 g reported by Wen et al. (2015) for Pekin ducks at 35 days of age.

Weight gain

As demonstrated in Table 4, the results indicate that there is no statistically significant difference ($p > 0.05$) in body weight gain among ducks fed diets with varying levels of water hyacinth. Body weight gain of Pekin ducks across the treatments was recorded at 916.14 g-1006.88 g. The body weight gain observed in the present study was greater than that reported for Kamang ducks aged 3-7 weeks (616.75 g), male Bayang ducks aged 3-8 weeks (521.86 g), and male Tegal ducks raised from 2-8 weeks (480.83 g; Rafian et al., 2023; Triani et al., 2024).

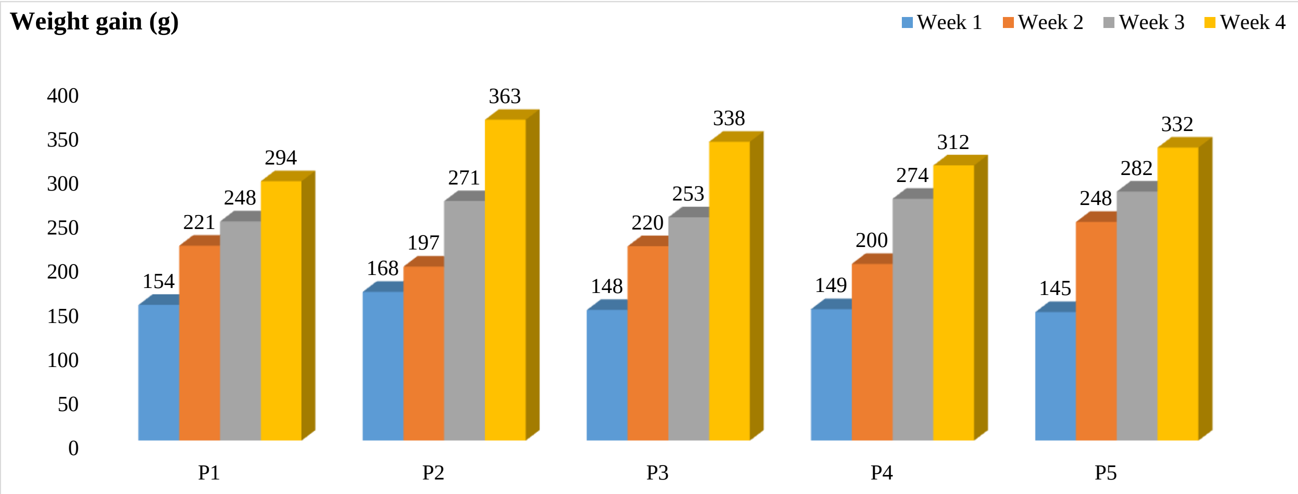

Figure 6. Weight gain of mixed-sex Pekin ducks fed diets containing fermented water hyacinth with *Neurospora crassa* from day 7 to 35 days of age. P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth

The absence of a significant difference in body weight gain can be attributed to the similarity in final body weight, feed intake, and nutrient content across treatments. The comparable body weight gain among treatments may be associated with similar feed intake and adequate nutrient availability in the experimental diets, which allowed ducks to maintain relatively similar growth responses (Shu et al., 2025). In addition, the study by Downing et al. (2022) indicated that the primary factors influencing duck growth are the consumption, quality, and quantity of feed provided.

The weekly body weight gain increased with the age of the Pekin ducks, as illustrated in Figure 6. Observations of Pekin duck weight gain revealed a consistent weekly increase as the ducks aged. The body weight gain recorded in the present study, which reached 916.14 g, indicates that Pekin ducks continued to grow during the experimental period. The progressive body weight gain observed in the present study is consistent with Zhou et al. (2024), who reported that Pekin ducks gain body weight progressively as they mature. Progressive growth in ducks is influenced by physiological factors, including metabolism, nutritional requirements, and environmental conditions (Inayat et al., 2024).

Carcass percentage

A thorough examination of the data revealed that the carcass percentage of Pekin ducks did not differ significantly ($p > 0.05$), with values ranging from 58.91% to 61.36%, as illustrated in Table 4. The carcass percentages recorded in the present study among the treatment groups (P1-P5) were comparable to the reported eviscerated carcass yield of Pekin ducks, which ranges from 58.9% to 62% after the removal of feathers, head, feet, and internal organs (Kokoszyński et al., 2019). The inclusion of fermented water hyacinth at different dietary levels did not significantly influence carcass yield or carcass part proportions among treatments (P1-P5; $p > 0.05$). Based on Table 4, carcass percentage varied from 58.91% in P2 to 61.36% in P3. The breast proportion ranged from 32.76% in P5 to 33.16% in P4, thigh proportion from 31.00% in P4 to 31.80% in P5, back proportion from 20.98% in P1 to 22.16% in P5, and wing proportion from 13.32% in P5 to 14.54% in P2. In the present study, the crude protein content of the experimental diets ranged from 18.14% to 21.09%, indicating that the diets still provided sufficient protein to support carcass development. Therefore, the absence of significant differences in carcass percentages among treatments may be related to the relatively adequate crude protein content across the experimental diets. The relationship between dietary nutrient levels, production performance, and carcass yield is supported by Sritiawthai et al. (2013), who reported that dietary protein and energy levels influence production performance and carcass yield in meat ducks. Crude protein constitutes a substantial component of Pekin duck feed and plays a pivotal role in promoting muscle growth and carcass development. Dietary protein concentration has been reported to improve growth performance in Pekin ducklings, while adequate amino acid supply, particularly methionine, contributes to better carcass and breast meat yield in growing Pekin ducks (Chen et al., 2016; Wu et al., 2019).

Intestinal morphology characteristics

The findings of the present study indicated that supplementation with fermented water hyacinth at different levels did not significantly influence the length of the duodenum, jejunum, ileum, or intestinal villi in Pekin ducks ($p > 0.05$). The average values of intestinal morphology parameters are shown in Table 5.

Table 5. Effects of diets containing fermented water hyacinth with *Neurospora crassa* on intestinal morphology of Pekin ducks reared for 28 days

Treatment groups \ Parameter	Duodenum (cm)	Jejunum (cm)	Ileum (cm)	Intestinal villi (μm)
P1	40.5 ± 2.18	57.5 ± 1.12	27 ± 1.41	288.16 ± 24.47
P2	40.25 ± 1.48	60.75 ± 2.95	26.75 ± 1.30	244.18 ± 14.29
P3	40.25 ± 1.09	60.5 ± 5.77	27.25 ± 1.79	308.19 ± 39.14
P4	41.75 ± 1.30	63.25 ± 5.40	27 ± 1.58	263.91 ± 31.76
P5	40.5 ± 1.12	63.25 ± 2.86	27 ± 2.23	258.29 ± 29.28
P-value	0.67	0.50	0.94	0.10

P1: 0% water hyacinth, P2: 5% water hyacinth, P3: 5% fermented water hyacinth, P4: 10% fermented water hyacinth, P5: 15% fermented water hyacinth.

Preliminary analysis of the results in Table 5 indicated that there was no statistically significant difference ($p > 0.05$) in the lengths of the duodenum, jejunum, ileum, or intestinal villi. The non-significant differences among all treatment groups (P1, P2, P3, P4, and P5) in duodenal length, jejunal length, ileal length, and intestinal villus length indicated that fermented water hyacinth supplementation did not markedly affect small intestinal morphology in Pekin ducks. Based on Table 5, duodenal length ranged from 40.25 cm in P2 and P3 to 41.75 cm in P4, while jejunal length ranged from 57.50 cm in P1 to 63.25 cm in P4 and P5. Ileal length ranged from 26.75 cm in P2 to 27.25 cm in P3, and intestinal villus length ranged from 244.18 μm in P2 to 308.19 μm in P3. The uniformity in measurements is likely attributable to the comparable feed intake across treatments, which ensured a consistent supply of nutrients for intestinal growth. The relatively similar intestinal morphology observed among the treatment groups in the present study may be related to comparable feed intake and adequate nutrient availability across the experimental diets. Nutrient intake is important for maintaining intestinal epithelial development and villus structure because intestinal villi are associated with nutrient absorption capacity. Similar to the present study, Sritiawthai et al. (2013) reported that variation in dietary energy did not significantly alter villus height or crypt depth in the duodenum, jejunum, and ileum of meat ducks, although dietary protein affected jejunal villus height. In addition, Jiang et al. (2012) reported that dietary fiber sources such as alfalfa meal could influence gastrointestinal development and villus morphology in growing ducks, indicating that feed composition may affect intestinal structure depending on nutrient balance and ingredient characteristics.

The treatments did not significantly affect the small-intestinal morphology of Pekin ducks ($p > 0.05$). In the present study, the crude fiber content of the experimental diets ranged from 4.71% to 7.17%. Therefore, the absence of significant differences in intestinal morphology among all treatment groups (P1, P2, P3, P4, and P5) may be associated with the crude fiber levels provided by the diets, which remained within a range that could still be tolerated by Pekin ducks. According to Hao et al. (2021), the range of crude fiber to which ducks can adapt is relatively wide, ranging from 3.09% to 7.52%. Physiologically, crude fiber contributes to increased intestinal motility and overall digestive health. However, at low to moderate crude fiber levels, dietary fiber may have a limited effect on intestinal villus morphology when the diets still provide adequate nutrients. In the present study, the crude fiber content ranged from 4.71% to 7.17%, which was close to the adaptable fiber range reported by Han et al. (2017) in meat ducks. The absence of significant changes in intestinal morphology in the present study may indicate that the crude fiber level in the diet remained within a tolerable range for ducks. Previous studies have shown that ducks can adapt to a relatively wide range of dietary fiber levels, although intestinal responses may vary depending on fiber level, fiber source, and dietary supplementation strategy (El-Katcha et al., 2021). A similar response was reported by Kim et al. (2019), who found that different dietary energy levels in Pekin ducks did not significantly change jejunal villus height or crypt depth. Consequently, even with differences in fiber composition among treatments, adequate nutrient availability and metabolizable energy support normal intestinal morphology development.

CONCLUSION

Water hyacinth fermented with *Neurospora crassa* can be included in Pekin duck diets at up to 15% without negatively affecting feed intake, growth performance, carcass traits, or intestinal morphology under the conditions of the present study, while increasing crude protein and crude fiber intakes. The present study had limitations, including the relatively short experimental period and the use of only one duck breed, which may limit the broader application of the findings. Further studies are suggested to investigate the long-term effects of fermented water hyacinth utilization, evaluate different fermentation methods, and examine its application in different duck breeds and production conditions

DECLARATIONS

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Authors' contributions

Vebera Maslami was responsible for conceptualizing the study, experimental implementation, data collection, and initial manuscript drafting. I Ketut Gede Wiryawan contributed to data processing, statistical analysis, interpretation of the results, and manuscript revision. Azhary Noersidiq contributed to study supervision, methodological guidance, interpretation of findings, and manuscript editing. All authors read and approved the final edition of the manuscript.

Availability of data and materials

The data generated in this study are relevant and presented in this published article. Supporting data related to the findings are available from the corresponding author upon reasonable request.

Competing interests

The authors declared no conflict of interest.

Ethical considerations

The authors confirmed that the manuscript is original, has not been published elsewhere, and represents the final edition approved prior to publication. The authors stated that no AI-based tools were utilized in conducting the study or preparation of the article. All authors confirmed the originality and authenticity of the data presented in this study before submitting and after accepting the manuscript.

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