

Original Research Articles

Effect of dietary garlic (*Allium sativum*) powder dosage on growth and hematological indices of swamp eel (*Monopterus albus* Zuiew, 1793) fry

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The swamp eel (*Monopterus albus*) is a commercially significant freshwater species that is widely cultivated in Asia. Garlic (*Allium sativum*) is known to contain bioactive compounds that possess antimicrobial, antioxidant, and immunostimulatory properties, and it has increasingly been used as a natural feed additive in aquaculture. This study examined the effects of dietary garlic powder levels (0, 5, 10, 15, and 20 g kg⁻¹) on the growth performance and hematological indices of *M. albus* fry over two consecutive 45-day rearing phases. The experiments were conducted using a completely randomized design with three replicates in 16.4-liter plastic trays containing 4 cm in Experiment 1 and 7 cm in Experiment 2. In Experiment 1, fry were used at the onset of exogenous feeding (0.026 ± 0.003 g). The 10 g kg⁻¹ dosage significantly improved weight gain, daily weight gain, specific growth rate in weight, and feed conversion ratio (FCR) compared to higher dosages (15–20 g kg⁻¹) ($P \leq 0.05$). Survival was significantly higher at 10–15 g kg⁻¹ than for those at other levels ($P \leq 0.05$). Erythrocyte, leukocyte, lymphocyte, and monocyte counts peaked at 5 g kg⁻¹ and significantly declined at 15–20 g kg⁻¹ ($P \leq 0.05$). Experiment 2 used larger fry that had been pre-reared for 45 days (0.84 ± 0.24 g). No significant differences in growth or length parameters ($P \geq 0.05$) and survival reached 100% across all groups, while fry fed a 10 g kg⁻¹ dosage exhibited a significantly lower FCR ($P \leq 0.05$). Erythrocyte counts remained stable at 0–10 g kg⁻¹ and gradually decreased at higher dosages. Leukocyte, lymphocyte, and monocyte counts increased significantly at 5 g kg⁻¹ compared with the control ($P \leq 0.05$) and remained stable across the 5–20 g kg⁻¹ range, while neutrophil counts were significantly elevated at 5–10 g kg⁻¹ ($P \leq 0.05$). Overall, dietary garlic powder at 5–10 g kg⁻¹ appears optimal for balancing growth, feed efficiency, survival, and hematological stability, whereas higher levels may inhibit growth performance and physiological status in *M. albus* fry.

INTRODUCTION

The swamp eel (*M. albus* Zuiew, 1793) is an air-breathing freshwater species widely distributed throughout East and Southeast Asia. It commonly inhabits muddy ponds, swamps, canals, and rice fields, where it can burrow into moist soil and survive for extended periods during the dry season, including estivation in mud for more than 40 days.¹⁻⁴ In addition to its air-breathing ability, which confers tolerance to low dissolved oxygen levels, salinity fluctuations, and suboptimal water conditions, the swamp eel is highly adaptable to aquaculture systems, particularly in regions with limited water availability or infrastructure.^{5,}

⁶ Nutritionally, swamp eel flesh is characterized by a high protein content (approximately 66.7%), a low lipid proportion (around 10.74%), and the presence of various bioactive compounds with recognized health-promoting properties.^{7,} ⁸ Beyond its nutritional value, *M. albus* is also prized for its distinctive flavor and its longstanding use in traditional medicine.^{4,9}

In Vietnam's Mekong Delta, *M. albus* has gained increasing attention as an economically viable and environmentally sustainable species for aquaculture diversification.^{10,} ¹¹ However, commercial production remains constrained by slow growth under captive conditions, high sensitivity to handling and stocking stress, and heightened suscep-

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tibility to diseases, particularly in intensive systems.^{12,13} Moreover, wild populations are increasingly threatened by overexploitation, habitat degradation, and pollution from agricultural and industrial sources,^{14,15} while disease outbreaks linked to poor water quality and high stocking densities cause substantial mortality in cultured stocks.¹⁶ These challenges emphasize the need to implement improved health and nutritional strategies to enhance growth and disease resistance in farmed swamp eels.

In aquaculture, the use of herbal feed additives is increasingly promoted as an alternative to antibiotics and synthetic growth enhancers, owing to their natural bioactive compounds that are safe for both the environment and consumers.^{17,18} Among these, garlic (*A. sativum*) has received considerable attention due to its rich bioactive compound profile, including allicin, ajoene, diallyl sulfides, saponins, and flavonoids, which exhibit antioxidant, immunostimulatory, and broad-spectrum antimicrobial activities. Furthermore, garlic is widely available and cost-effective.¹⁹⁻²²

Garlic supplementation via dietary inclusion or immersion can improve the performance of farmed aquatic animals, and the improvements depend on garlic form, dosage, species, life stage, and application duration.²² A review by Valenzuela-Gutiérrez et al.²³ indicated that dietary garlic powder levels were evaluated in aquaculture over a wide range from 0.05 to 40 g kg⁻¹. In general, supplementation at 5–20 g kg⁻¹ promoted growth, enhanced antioxidant status, and improved physiological responses. improvement in growth, hematological parameters, immune responses, digestive capacity, and antioxidant status.²⁴⁻²⁷ While dietary garlic (*A. sativum*) powder at a level of 40 g kg⁻¹ was reported to enhance performance, feed utilization, hemato-biochemical parameters, and body composition in *Lates calcarifer* juveniles,²⁸ another study indicated that a level of 25 g kg⁻¹ could reduce overall performance in *Lateolabrax japonicus*.²⁵ Furthermore, research on juvenile *Dicentrarchus labrax* suggested that garlic powder supplementation should not exceed 2% (20 g kg⁻¹) to avoid potential negative effects on red blood cell counts and hematocrit.²⁹

Hematological indices are key indicators of fish health, stress, and welfare.³⁰⁻³² These indices are especially important for *M. albus*, which is an air-breathing species that lives in muddy, stagnant water systems and highly volatile habitats.¹ Their relevance is heightened during early developmental stages of *M. albus*, when respiratory and circulatory functions are still developing³³ and eels are especially susceptible to sublethal stressors.³⁴ Numerous studies on dietary herbal supplements in various fish species have shown improvements in hematological, serum biochemical, and immunological parameters, as well as overall performance.^{17,29,35-37} However, data on garlic supplementation in eels, particularly during the fry stage, remains limited. A recent study using a commercial garlic-based additive containing enzymes and yeast improved growth and feed utilization in European eel (*Anguilla anguilla*) fry, but pure garlic powder was not evaluated.³⁸ This study evaluated graded dietary garlic powder levels (0–20 g kg⁻¹) to determine their effects on growth, survival, and hematological

indices of *M. albus* fry, aiming to identify practical and safe supplementation levels for sustainable eel aquaculture.

MATERIALS AND METHODS

EXPERIMENTAL MATERIALS

Swamp eel (*M. albus*) fry at the onset of exogenous feeding (mean weight of 0.026 g; mean length of 2.96 cm) were obtained from a local hatchery for Experiment 1. The fry were then transported to the Experimental Wet Lab in slightly oxygenated Styrofoam boxes containing freshwater from the reproduction facility for 30 minutes. The hatchlings were acclimated to the experimental conditions for five days before the trial began. The eels in Experiment 2 (mean size of 0.84 g and 9.01 cm) resulted from the 45-day rearing period of Experiment 1. Prior to stocking for both experiments, the eels were screened for pathogens and checked for morphological abnormalities to ensure that only healthy individuals were selected. Additionally, they were bathed in 3% saltwater for 15 minutes to remove external parasites. Freshwater used in the study was obtained from tap water and vigorously aerated for 24 hours to remove residual chlorine. The 16.4-liter plastic trays (31 × 22 × 24 cm) were used in both experiments, maintained at a water depth of 4 cm in Experiment 1 and 7 cm in Experiment 2. The trays were equipped with a nylon mesh substrate covering approximately one-fifth of the bottom area and were lightly aerated during the experimental periods. A shrimp commercial pellet feed (45% protein) with particle sizes ranging from 0.8 – 1.0 mm (Thang Long Company, Vietnam) was used as the base feed (Table 1). Garlic (*A. sativum*) cloves with the skin removed were purchased from a local market and dried at 70°C for 13 hours. Dried garlic and base feed were ground separately into fine powders using a locally available grinder. The garlic powder was then mixed with the basal feed powder using a mixer to formulate experimental diets with dosages of 0, 5, 10, 15, and 20 g kg⁻¹. The prepared diets were sealed in polyethylene bags and stored at 20°C until use. Before feeding, the diets were sufficiently weighed to the required ration of each treatment and made into a paste with 0.5–1 mL of water. The resulting slurry was formed into flat cakes (~2 cm in diameter) and placed on the rearing trays.

EXPERIMENTAL DESIGN

This study was conducted at the aquaculture wet lab of Tra Vinh University, located in southern Vietnam, from 03 May to 05 May 2025. Two consecutive 45-day experiments were conducted using a completely randomized design with three replicates per treatment. It aimed to investigate the effects of various dietary garlic powder dosages (0, 5, 10, 15, and 20 g kg⁻¹) on the growth performance and some selected hematological indices of *M. albus* fry. The detailed experimental procedures are presented as follows:

Experiment 1 investigates how varying dosages of dietary garlic powder affect the rearing performance and hematological indices of *M. albus* fry during their first 45

Table 1. Proximate nutritional components of basal feed used in experiments.

Protein (%)	45
Lipid (%)	6
Fiber (%)	4
Moisture content (%)	10
Phosphorus (%)	0.8
Lysine (%)	2.1
Ethoxyquin (ppm)	150

days of growth. After the adaptation period, a total of 1500 healthy eel fry at the onset of exogenous feeding were randomly distributed among 15 plastic trays, with 100 individuals per tray. Three trays were assigned to each experimental diet. The fry in each treatment were fed their respective diets until they appeared satiated, as indicated by their ceasing to bait. Feeding was done twice daily at 07:00 and 16:00, amounting to approximately 5–7% of body weight on a dry-matter basis each day. During each feeding session, both baiting behaviors and the amount of uneaten feed remaining in each tray were monitored to adjust the feed rations for subsequent feedings. A complete (100%) water exchange was conducted daily in all rearing trays to maintain water quality,¹¹ as *M. albus* requires a high-protein diet (42–45%),^{39,40} resulting in substantial organic waste and nitrogenous excretion.⁴¹ Water quality parameters were monitored daily, including temperature, which ranged from $27.92 \pm 0.94^\circ\text{C}$ in the morning to $29.34 \pm 1.31^\circ\text{C}$ in the afternoon, and pH values varied from 8.11 ± 0.21 to 8.21 ± 0.19 , as measured with a HANNA meter (Model HI98103, Romania). Since the water was renewed daily, the concentrations of inorganic nitrogen compounds (TAN and NO_2^-), measured using Sera test kits (Germany), remained very low and within the optimal range for *M. albus* growth.^{5, 42,43}

Experiment 2 investigates how different dosages of dietary garlic powder affect the rearing performance and hematological indices of *M. albus* fry over the final 45 days of their rearing period: Seven hundred and fifty eel fry collected at the end of Experiment 1 were randomly arranged into 15 plastic trays at a density of 50 individuals each. The fry were fed the five trial diets for 45 days, with all management and care methods following those outlined in Experiment 1.

COLLECTING SAMPLES AND CALCULATING DATA

In both experiments, fry were measured before stocking and then every 15 days throughout the rearing period. At each sampling time, five eels were randomly collected from each tray (15 individuals per trial diet) to assess growth performance. Individual body weights were determined using a digital scale with a precision of 0.01 g after blotting with blotting paper, while total lengths were measured with a graduated ruler to the nearest millimeter. At the end of each experiment, the survival rate and feed conversion ratio were recorded. The performance parameters were calculated using the following formulas:

Mean weight (MW, g) = total weight of 15 eels / 15
 Mean length (ML, cm) = total length of 15 eels / 15
 Weight gain (WG, g) = final weight – initial weight
 Length gain (LG, cm) = final length – initial length
 Daily weight gain (DWG, g day⁻¹) = (final weight – initial weight) / number of rearing days
 Daily length gain (DLG, cm day⁻¹) = (final length – initial length) / number of rearing days
 Specific growth rate in weight (SGR_w, % day⁻¹) = ((ln (final weight) – ln (initial weight)) / number of rearing days) × 100
 Specific growth rate in length (SGR_L, % day⁻¹) = ((ln (final length) – ln (initial length)) / number of rearing days) × 100
 Survival rate (%) = (final eel number / initial eel number) × 100
 Feed conversion ratio (FCR) = total dry feed fed (g)/total wet weight gain (g)

Moreover, at the end of each 45-day experiment, 9 eels were randomly selected from each diet (3 eels per tray) for hematological examination. The eels were anesthetized using ice. Approximately 0.4 mL of blood was taken from each eel's caudal vein using a syringe and placed in EDTA containers (BD Microtainer, UK) as an anticoagulant. The blood samples were then hematologically analyzed. The hematological parameters analyzed included erythrocyte count, leukocyte count, and differential leukocyte count (lymphocytes, monocytes, and neutrophils). Erythrocyte quantification was performed according to the method of Natt and Herrick,⁴⁴ while leukocyte quantification and differential classification were performed according to the procedure described by Hrubec et al.⁴⁵

DATA ANALYSIS

Prior to analysis, data were tested for normality using the Shapiro–Wilk test and for homogeneity of variances using Levene's test. Differences among treatment groups were analyzed using one-way analysis of variance (ANOVA). Significant differences among means were subsequently identified using Tukey's post hoc test, with statistical significance set at $P = 0.05$. All statistical analyses were performed using SPSS software (version 20.0).

Table 2. Initial mean weight (IMW), mean weight (MW), weight gain (WG), daily weight gain (DWG), and specific growth rate in weight (SGR_w) of *Monopterus albus* fry during the first 45 days of rearing under various dietary garlic powder dosages (n = 15).

Parameters	Dietary garlic powder dosages (g kg ⁻¹)				
	0	5	10	15	20
IMW (g ind ⁻¹)	0.026±0.003	0.026±0.003	0.026±0.003	0.026±0.003	0.026±0.003
MW ₁₅ (g ind ⁻¹)	0.06±0.02 ^a	0.06±0.02 ^a	0.05±0.02 ^a	0.05±0.02 ^a	0.05±0.02 ^a
MW ₃₀ (g ind ⁻¹)	0.33±0.08 ^a	0.31±0.06 ^a	0.30±0.06 ^a	0.29±0.06 ^a	0.29±0.05 ^a
MW ₄₅ (g ind ⁻¹)	0.78±0.24 ^a	0.85±0.28 ^a	0.83±0.28 ^a	0.72±0.16 ^a	0.71±0.09 ^a
WG (g ind ⁻¹)	0.75±0.24 ^{ab}	0.83±0.28 ^{ab}	0.88±0.25 ^b	0.70±0.16 ^a	0.68±0.09 ^a
DWG (g day ⁻¹)	0.02±0.01 ^{ab}	0.02±0.01 ^{ab}	0.02±0.01 ^b	0.02±0.00 ^a	0.02±0.00 ^a
SGR _w (% day ⁻¹)	0.07±0.01 ^{ab}	0.08±0.01 ^{ab}	0.08±0.01 ^b	0.07±0.01 ^a	0.07±0.00 ^a

Values are presented as mean±SD. Values with different letters (a, b) in the same row show a significant difference ($P \leq 0.05$).

RESULTS

THE PERFORMANCE OF *M. ALBUS* FRY DURING THE FIRST 45 DAYS OF REARING

The fry fed a diet containing 10 g kg⁻¹ garlic powder achieved the highest WG, DWG, and SGR_w, which were significantly greater than those observed at 15 and 20 g kg⁻¹ ($P \leq 0.05$, Table 2), but did not show significant differences from those at 0 and 5 g kg⁻¹ ($P \geq 0.05$, Table 2). Most growth performance parameters for length did not exhibit significant variation across the tested garlic powder dosage range (0–20 g kg⁻¹) ($P \geq 0.05$, Table 3), except for ML₁₅ at 0 and 5 g kg⁻¹. The lowest FCR was observed at the 10 g kg⁻¹ dosage, and there was no significant difference from that at the 0, 5, and 15 g kg⁻¹ ($P \geq 0.05$, Table 4). In contrast, the FCR at 20 g kg⁻¹ was significantly higher than that at the other levels ($P \leq 0.05$, Table 4). The fry that were fed 10 and 15 g kg⁻¹ dosages exhibited the highest survival rates, which were significantly greater than those at other dietary garlic levels ($P \leq 0.05$, Table 4).

The highest erythrocyte count was recorded at the dietary garlic powder level of 5 g kg⁻¹, which was significantly higher than those observed at 15 and 20 g kg⁻¹ ($P \leq 0.05$, Table 5), while no significant differences were observed among dosages within the 0–10 g kg⁻¹ range ($P \geq 0.05$, Table 5). The highest leukocyte, lymphocyte, and monocyte counts were also observed at the 5 g kg⁻¹ dosage, significantly exceeding those in the 15 and 20 g kg⁻¹ dosages ($P \leq 0.05$, Table 5); however, there was no significant difference between the dosages of 5 and 10 g kg⁻¹ ($P \geq 0.05$, Table 5). Neutrophil counts did not show significant differences among treatments ($P \geq 0.05$, Table 5).

THE PERFORMANCE OF *M. ALBUS* FRY DURING THE SECOND 45 DAYS OF REARING

No significant differences in length or weight growth parameters among tested dietary garlic powder levels ($P \geq 0.05$, Tables 6 & 7). Survival remained at 100% across all dietary garlic powder dosages (0–20 g kg⁻¹) (Table 8). However, fish

fed a 10 g kg⁻¹ level showed a significantly lower FCR compared to those at other dosages ($P \leq 0.05$, Table 8).

The erythrocyte count was consistently maintained within the range of 0–10 g kg⁻¹ ($P \geq 0.05$, Table 9), but it showed a gradual decrease at higher dosages of 15–20 g kg⁻¹ ($P \geq 0.05$, Table 9). Leukocyte, lymphocyte, and monocyte count significantly increased at the 5 g kg⁻¹ dosage compared to those of the control group (0 g kg⁻¹) ($P \leq 0.05$, Table 9) and remained relatively stable within the 5–20 g kg⁻¹ range (except for leukocyte count at the 20 g kg⁻¹ dosage) ($P \geq 0.05$, Table 9). Neutrophil counts were significantly higher at the 5–10 g kg⁻¹ dosages compared to the other levels ($P \leq 0.05$, Table 9).

DISCUSSION

GROWTH PERFORMANCE

During the first rearing phase, a dietary garlic powder dosage of 10 g kg⁻¹ optimally enhanced the growth performance and survival of *M. albus* fry, as evidenced by the highest values of WG, DWG, SGR_w, and SR. Studies indicated that early fry stages of swamp eels have high metabolic demands but still-developing digestive capacity and stress tolerance.^{2,13} In these circumstances, dietary supplementation with appropriate levels of garlic powder may promote gut microbiota balance, improve digestive efficiency, and enhance nutrient absorption.^{17,26,46,47} These effects are attributed to organosulfur compounds present in garlic, such as allicin, diallyl disulfide, and ajoene, which stimulate bile secretion, thereby enhancing feed palatability and nutrient utilization in fish.^{36,48} Consistently, the lowest FCR values at the end of the first rearing phase were recorded in diets containing 10–15 g kg⁻¹ garlic powder. Additionally, garlic contains bioactive compounds with antioxidant, immunomodulatory, anti-inflammatory, and antibacterial properties.^{19–21,49} These protective components of garlic likely contributed to the highest growth performance observed at a 10 g kg⁻¹ dosage and significantly improved survival and feed efficiency at levels of 10–15 g kg⁻¹. While research on eel species is still limited, dietary garlic powder levels of approximately 10–20 g kg⁻¹ were re-

Table 3. Initial mean length (IML), mean length (ML), length gain (LG), daily length gain (DLG), and specific growth rate in length (SGR_L) of *Monopterus albus* fry during the first 45 days of rearing under various dietary garlic powder dosages (n = 15).

Parameters	Dietary garlic powder dosages (g kg ⁻¹)				
	0	5	10	15	20
IML (cm ind ⁻¹)	2.96±0.10	2.96±0.10	2.96±0.10	2.96±0.10	2.96±0.10
ML ₁₅ (cm ind ⁻¹)	4.50±0.89 ^b	4.37±0.75 ^b	3.75±0.56 ^a	4.08±0.59 ^{ab}	3.62±0.73 ^a
ML ₃₀ (cm ind ⁻¹)	7.08±0.96 ^a	6.93±0.92 ^a	6.57±0.60 ^a	7.01±0.80 ^a	7.10±0.84 ^a
ML ₄₅ (cm ind ⁻¹)	9.62±1.21 ^a	9.60±1.13 ^a	9.91±1.22 ^a	9.89±1.00 ^a	9.80±0.86 ^a
DL (cm ind ⁻¹)	6.66±1.21 ^a	6.64±1.13 ^a	6.95±1.22 ^a	6.93±1.00 ^a	6.84±0.86 ^a
DLG (cm day ⁻¹)	0.15±0.03 ^a	0.15±0.03 ^a	0.15±0.03 ^a	0.15±0.02 ^a	0.15±0.02 ^a
SGR _L (% day ⁻¹)	0.03±0.00 ^a	0.03±0.00 ^a	0.03±0.00 ^a	0.03±0.00 ^a	0.03±0.00 ^a

Values are presented as mean±SD. Values with different letters (a, b) in the same row show a significant difference ($P < 0.05$).

Table 4. Survival rate and feed conversion ratio (FCR) of *Monopterus albus* fry after the first 45 days of rearing under various dietary garlic powder dosages (n = 15).

Parameters	Dietary garlic powder dosages (g kg ⁻¹)				
	0	5	10	15	20
Survival rate (%)	81.33±7.51 ^a	82.33±4.16 ^a	92.00±0.00 ^b	92.00±0.00 ^b	83.00±6.08 ^a
FCR	2.87±0.16 ^a	3.23±0.39 ^{ab}	2.73±0.17 ^a	2.80±0.15 ^a	3.54±0.46 ^b

Values are presented as mean±SD. Values with different letters (a, b) in the same row show a significant difference ($P < 0.05$).

Table 5. The counts of erythrocytes, leukocytes, lymphocytes, monocytes, and neutrophils (million cells mm⁻³) in the blood of *Monopterus albus* fry after the first 45 days of rearing under various dietary garlic powder dosages (n = 15).

Parameters	Dietary garlic powder dosages (g kg ⁻¹)				
	0	5	10	15	20
Erythrocytes	3.191±0.11 ^{bc}	3.393±0.53 ^c	3.245±0.50 ^{bc}	2.502±0.41 ^a	2.752±0.20 ^{ab}
Leukocytes	0.09±0.01 ^a	0.15±0.03 ^b	0.12±0.02 ^{ab}	0.09±0.02 ^a	0.11±0.02 ^a
Lymphocytes	0.06±0.00 ^{ab}	0.07±0.02 ^b	0.06±0.02 ^{ab}	0.05±0.00 ^a	0.06±0.03 ^{ab}
Monocytes	0.02±0.00 ^a	0.05±0.02 ^c	0.05±0.02 ^{bc}	0.03±0.02 ^{ab}	0.04±0.00 ^{bc}
Neutrophils	0.02±0.01 ^a	0.02±0.01 ^a	0.01±0.00 ^a	0.01±0.00 ^a	0.02±0.00 ^a

Values are presented as mean±SD. Values with different letters (a, b, c) in the same row show a significant difference ($P < 0.05$).

Table 6. Initial mean weight (IMW), mean weight (MW), weight gain (WG), daily weight gain (DWG), and specific growth rate in weight (SGR_W) of *Monopterus albus* fry during the second 45 days of rearing under various dietary garlic powder dosages (n = 15).

Parameters	Dietary garlic powder dosages (g kg ⁻¹)				
	0	5	10	15	20
IMW (g ind ⁻¹)	0.84±0.24	0.84±0.24	0.84±0.24	0.84±0.24	0.84±0.24
MW ₁₅ (g ind ⁻¹)	1.29±0.34 ^a	1.08±0.25 ^a	1.06±0.36 ^a	1.36±0.53 ^a	1.21±0.38 ^a
MW ₃₀ (g ind ⁻¹)	1.99±0.90 ^a	2.08±0.79 ^a	2.56±0.71 ^a	1.94±0.84 ^a	2.39±0.87 ^a
MW ₄₅ (g ind ⁻¹)	4.54±1.34 ^a	4.11±1.21 ^a	4.92±1.82 ^a	4.69±1.63 ^a	4.66±1.43 ^a
WG (g ind ⁻¹)	3.69±1.34 ^a	3.27±1.21 ^a	4.08±1.82 ^a	3.85±1.63 ^a	3.81±1.43 ^a
DWG (g day ⁻¹)	0.08±0.03 ^a	0.07±0.03 ^a	0.09±0.04 ^a	0.09±0.04 ^a	0.08±0.03 ^a
SGR _W (% day ⁻¹)	3.65±0.71 ^a	3.45±0.61 ^a	3.77±0.89 ^a	3.69±0.79 ^a	3.7±0.72 ^a

Values are presented as mean±SD. Values with different letters (a, b) in the same row show a significant difference ($P < 0.05$).

Table 7. Initial mean length (IML), mean length (ML), length gain (LG), daily length gain (DLG), and specific growth rate in length (SGR_L) of *Monopterus albus* fry during the second 45 days of rearing under various dietary garlic powder dosages (n = 15).

Parameters	Dietary garlic powder dosages (g kg ⁻¹)				
	0	5	10	15	20
IML (cm ind ⁻¹)	9.01±2.37	9.01±2.37	9.01±2.37	9.01±2.37	9.01±2.37
ML ₁₅ (cm ind ⁻¹)	11.35±1.46 ^a	10.68±1.19 ^a	10.64±1.08 ^a	11.74±1.39 ^a	11.31±1.02 ^a
ML ₃₀ (cm ind ⁻¹)	13.16±1.95 ^a	13.73±2.31 ^a	14.6±1.79 ^a	12.82±1.96 ^a	13.67±2.09 ^a
ML ₄₅ (cm ind ⁻¹)	16.75±1.46 ^a	16.14±1.07 ^a	17.15±2.18 ^a	16.94±2.09 ^a	16.71±1.95 ^a
DL (cm ind ⁻¹)	7.74±14 ^a	7.13±1.07 ^a	8.14±2.18 ^a	7.93±2.09 ^a	7.70±1.95 ^a
DLG (cm day ⁻¹)	0.17±0.03 ^a	0.16±0.02 ^a	0.18±0.05 ^a	0.18±0.05 ^a	0.17±0.04 ^a
SGR _L (% day ⁻¹)	1.37±0.19 ^a	1.29±0.14 ^a	1.41±0.29 ^a	1.39±0.27 ^a	1.36±0.26 ^a

Values are presented as mean±SD. Values with different letters (a, b) in the same row show a significant difference ($P < 0.05$).

Table 8. Survival rate and feed conversion ratio (FCR) of *Monopterus albus* fry after the second 45 days of rearing under various dietary garlic powder dosages (n = 15).

Parameters	Dietary garlic powder dosages (g kg ⁻¹)				
	0	5	10	15	20
Survival rate (%)	100	100	100	100	100
FCR	2.29±0.09 ^b	2.15±0.07 ^b	1.99±0.03 ^a	2.15±0.14 ^b	2.20±0.04 ^b

Values are presented as mean±SD. Values with different letters (a, b) in the same row show a significant difference ($P < 0.05$).

Table 9. The counts of erythrocytes, leukocytes, lymphocytes, monocytes, and neutrophils (million cells mm⁻³) in the blood of *Monopterus albus* fry after the second 45 days of rearing under various dietary garlic powder dosages (n = 15).

Parameters	Dietary garlic powder dosages (g kg ⁻¹)				
	0	5	10	15	20
Erythrocytes	3.885±0.049 ^b	3.933±0.025 ^b	3.781±0.122 ^b	3.557±0.496 ^{ab}	3.230±0.243 ^a
Leukocytes	0.09±0.13 ^a	0.16±0.01 ^c	0.15±0.01 ^{bc}	0.14±0.03 ^{bc}	0.13±0.03 ^b
Lymphocytes	0.06±0.002 ^a	0.10±0.005 ^b	0.10±0.009 ^b	0.11±0.02 ^b	0.09±0.01 ^b
Monocytes	0.021±0.004 ^a	0.030±0.007 ^b	0.030±0.004 ^{ab}	0.023±0.007 ^{ab}	0.022±0.008 ^{ab}
Neutrophils	0.01±0.003 ^a	0.02±0.003 ^b	0.02±0.003 ^b	0.01±0.003 ^a	0.01±0.003 ^a

Values are presented as mean±SD. Values with different letters (a, b, c) in the same row show a significant difference ($P < 0.05$).

ported to promote growth performance, feed efficiency, and survival in various fish and crustacean species.^{17,25,26,28,50-52} However, the present study also indicated a significant reduction in growth performance at 15–20 g kg⁻¹, along with a significant decrease in SR and an increase in FCR at 20 g kg⁻¹. These observations may be attributed to the negative effects of excessive garlic consumption, which can result in intestinal mucosal damage, disruption of gut microbiota equilibrium, reduced feed intake, gastrointestinal irritation, and metabolic stress, as documented in *Oreochromis niloticus*,^{53,54} *Cyprinus carpio*,⁵⁵ and *Perca fluviatilis*.²⁶ Furthermore, potential overexposure to allicin may cause pro-oxidative or cytotoxic effects, as demonstrated in *Tilapia zillii*,⁵⁰ *Perca fluviatilis*,²⁶ and *Oreochromis niloticus*.⁵²

During the second rearing phase, growth performance showed no significant differences, and survival rates re-

mained at 100% across all treatments (0–20 g kg⁻¹). Additionally, the lowest FCR was at 10 g kg⁻¹. These findings may be attributed to size- and stage-dependent shifts in metabolic patterns and energy accumulation in the fry. In fish and other animals, such as eels, growth rates typically slow as they grow larger and older. This slowdown occurs because more energy is allocated to maintenance and basic metabolism rather than to the production of new body tissue.^{56,57} This distribution of energy may allow garlic supplementation to improve feed efficiency without causing additional biomass growth. Similar trends have been reported in various fish and eel species, where appropriate levels of garlic supplementation improved feed efficiency without impacting final body sizes.^{26,38,47,50,58,59} Furthermore, survival rates reached 100% across all treatments in the second phase. These outcomes may be due to the fry gradually acclimating to the added garlic in their diet,

which likely enhanced their immunity and contributed to a more physiologically stable state. Similar duration-dependent responses have been observed in European eel juveniles³⁸ and tilapia,⁶⁰ indicating that dietary garlic powder dosages are most beneficial during the early rearing stages, when physiological plasticity and vulnerability to stress are at their peak. However, the growth-promoting effects of garlic appear to diminish in larger individuals. The garlic level of 10 g kg⁻¹ during the second phase resulted in the lowest FCR and an SR of 100%, which is significant for reducing feed costs and enhancing productivity in aquaculture.

HEMATOLOGICAL RESPONSES

The monitored hematological indices generally remained within ranges reported for *M. albus*.^{3,42,61,62} This indicates that garlic supplementation modulated rather than disrupted the normal physiological status of the fry.

During the first phase, erythrocyte counts were highest at 5 g kg⁻¹ and stayed about the same for treatments between 0 and 10 g kg⁻¹. However, they dropped sharply at 15–20 g kg⁻¹. Leukocyte, lymphocyte, and monocyte counts followed a similar pattern, peaking at 5 g kg⁻¹, staying stable between 5 and 10 g kg⁻¹, and dropping at higher doses. Erythrocyte counts increased at a dietary garlic powder level of 5 g kg⁻¹, consistent with evidence that garlic-derived bioactive compounds and antioxidants can enhance hematopoietic function and support erythrocyte production at appropriate dosages.^{26,48} The observed variations in erythrocyte counts indicate that a dietary garlic powder level of 5–10 g kg⁻¹ optimally supports erythrocyte production in early-stage swamp eel fry. However, excessive supplementation may inhibit these processes. Swamp eels with gills are considerably reduced, providing limited gas-exchange capacity. Instead, oxygen uptake primarily occurs across the highly vascularized epitheliums of the buccopharyngeal cavity and esophagus, supported by a very high blood–oxygen affinity.^{33,63–66} Consequently, *M. albus* relies on hemoglobin with a strong oxygen-binding capacity and efficient erythrocyte function to thrive in hypoxic and highly variable environmental conditions.^{2,33} Thus, the maintenance of high and stable erythrocyte counts at a dietary garlic powder level of 0–10 g kg⁻¹ possibly supported adequate oxygen transport during rapid early growth, whereas reductions in erythrocyte abundance in higher (15–20 g kg⁻¹) levels can impair oxygen transport efficiency and aerobic capacity, thereby limiting energy availability for growth.^{33,66} In addition, dose-dependent adverse effects of excessive garlic supplementation have been reported in *Tilapia zillii*, *Cyprinus carpio*, and *Perca fluviatilis*, where high garlic intake was associated with oxidative stress or cytotoxic responses linked to allicin overexposure.^{36,50,54,55} On the other hand, leukocyte and differential leukocyte counts are key indicators of fish immune status.⁶⁷ In swamp eels, which are frequently exposed to fluctuating water quality, hypoxia, and pathogen-rich muddy habitats, maintaining high and stable leukocyte levels within physiological ranges is particularly advantageous for sustaining immune and antibacterial capacity.^{2,13,16,33}

Dietary garlic powder dosages of 5–10 g kg⁻¹ may optimally support immune function by providing higher and more stable counts of leukocyte types during the early developmental stage of swamp eel fry.

During the second rearing phase, a distinct pattern of hematological responses emerged compared to the first. Erythrocyte counts were stable within the range of 0–10 g kg⁻¹ with garlic powder dosages and gradually decreased at higher dosages (15–20 g kg⁻¹). Total leukocyte, lymphocyte, and monocyte counts showed a significant increase at a dosage of 5 g kg⁻¹ compared to the control group (0 g kg⁻¹) and remained relatively stable throughout the 5–20 g kg⁻¹ range. The relatively stable hematological responses further supported the finding that there were no significant differences in growth performance, with survival rates consistently maintained at 100% across all treatments during the second rearing phase. Additionally, neutrophil counts increased significantly at dosages of 5–10 g kg⁻¹, indicating enhanced rapid response to stress and opportunistic infections.⁶⁷

In conclusion, this study indicates that a dietary garlic powder level of 10 g kg⁻¹ is optimal for *M. albus* fry during both rearing phases, promoting growth rate, survival rate, and feed efficiency while preserving hematological balance. Lower levels (5 g kg⁻¹) may be sufficient when the primary goal is hematological balances rather than growth performance. Higher levels (≥15 g kg⁻¹) may impair the physiological and growth efficiency. However, the assessments are limited by the use of basic hematological indices, controlled experimental conditions, and the lack of long-term evaluations, which should be expanded in future studies.

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AUTHORS' CONTRIBUTION

Conceptualization: Huong K. Huynh (Equal), Diep X. Doan (Equal). Methodology: Huong K. Huynh (Equal), Diep X. Doan (Equal), Nhi T.H. Nguyen (Equal). Formal Analysis: Huong K. Huynh (Equal), Nhi T.H. Nguyen (Equal). Investigation: Nhi T.H. Nguyen (Equal), Diep X. Doan (Equal), Huong K. Huynh (Equal), Minh T.T. Vo (Equal). Writing—Original Draft: Huong K. Huynh (Equal), Diep X. Doan (Equal). Writing—Review & Editing: Diep X. Doan. Supervision: Huong K. Huynh (Lead), Diep X. Doan (Equal).

COMPETING OF INTEREST – COPE

No competing interests were disclosed

ETHICAL CONDUCT APPROVAL – IACUC

The animal experiments adhered to relevant national and international guidelines. Only the fry swamp eel (*M. albus*)

underwent weighing and measuring and was anesthetized using ice for blood sampling, ensuring no harm was caused. After the experiments, the eels were returned to the storage tanks for further research.

INFORMED CONSENT STATEMENT

All authors and institutions have confirmed this manuscript for publication.

DATA AVAILABILITY STATEMENT

All are available upon reasonable request.

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