

Original Research Articles

Effects of different aquaculture modes on growth performance, size distribution, and muscle nutritional composition of juvenile *Procambarus clarkii*

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This study evaluated the effects of two aquaculture modes on *Procambarus clarkii* growth, size distribution, and muscle quality. Two models were compared: Pond A (high density: 4,428 ind/mu, small size: 3.5 g; control group) and Pond B (low density: 2,261 ind/mu, large size: 9.0 g) over 30 days. Results showed that Pond B significantly enhanced weight gain and the proportion of size 1 and size 2 compared to Pond A ($P < 0.05$), while the control group exhibited a higher hepatosomatic index and proportion of Size 4 crayfish. Although proximate composition (moisture, lipid, ash) and muscle textural properties (hardness, springiness, chewiness, etc.) were unaffected, Pond B crayfish showed significantly lower muscle crude protein content and reduced levels of specific amino acids (glutamate, serine, tyrosine, methionine, lysine; $P < 0.05$). Fatty acid analysis revealed significantly higher saturated (C16:0, C18:0) and monounsaturated (C16:1, C20:1) fatty acids, but lower C18:1n9, linoleic acid (LA), and docosahexaenoic acid (DHA) in Pond B ($P < 0.05$); linolenic acid, arachidonic acid, eicosapentaenoic acid (EPA), and total PUFA remained unchanged. The low-density/large-size model optimizes growth performance and commercial size yield, increasing high-value individuals. However, it compromises specific nutritional aspects (protein, certain amino acids, and key fatty acids). As essential amino acid totals, proximate components (excluding protein), PUFA, and texture were unaffected, this model is recommended for maximizing economic return, though dietary strategies to mitigate nutritional alterations warrant further investigation.

INTRODUCTION

In contemporary intensive and high-density aquaculture practices, while high-density farming yields substantial economic benefits and farmers are often inclined to increase stocking density for higher returns, it frequently leads to deterioration of water quality, frequent disease outbreaks, and inhibited growth of aquatic animals. In severe cases, mass mortality occurs, significantly compromising the health and welfare of aquatic species and reducing farming profitability.^{1,2} Numerous studies have demonstrated that inappropriate stocking densities often result in growth suppression, reduced feed conversion efficiency

and nutrient apparent digestibility, and diminished muscle quality in aquatic animals.^{1,3} High-density farming typically reduces feed intake, thereby limiting growth and leading to a predominance of smaller individuals within the overall cultured population. For instance, Petit et al.⁴ found that *Micropterus salmoides* exhibited the lowest feed intake at the highest stocking density. Concurrently, density stress may also suppress growth performance by downregulating hepatic GH-IGF axis signaling.⁵ Furthermore, with rising living standards, consumer demand for high-quality aquatic products is increasing. However, high-density farming often degrades muscle quality due to deteriorating water conditions, diminishing product value and significantly

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impacting aquaculture profitability.⁶ Therefore, an appropriate stocking density is a crucial factor for ensuring normal growth in aquatic animals.

Beyond stocking density, the individual size of aquatic animals is another key factor influencing farming success, closely intertwined with density. During early growth stages, smaller individuals typically experience minimal impact on growth and feeding behavior even under relatively high stocking densities. However, as aquatic animals grow larger, their increased spatial occupancy subjects them to density stress. Elevated density can trigger changes in water quality characteristics, as a higher biomass per unit volume intensifies dissolved oxygen (O₂) consumption and elevates waste levels (e.g., ammonia (NH₃), carbon dioxide (CO₂), urea, and suspended solids), imposing a range of negative effects on aquatic animals.⁷⁻⁹ Consequently, aquaculture practices must balance both stocking density and animal size. An optimal density-size model can reduce disease outbreaks and mortality while enhancing muscle quality and overall economic returns.

Procambarus clarkii represents a commercially significant aquaculture species in China. By 2023, national production reached 3.16 million tons, ranking fourth among freshwater cultured species nationally.¹⁰ However, industry expansion, frequently characterized by high-density farming practices, results in compromised growth performance and diminished muscle quality in *P. clarkii*,¹¹ imposing significant constraints on profitability and sustainable development. Research further indicates that decreasing stocking density elevates the proportion of larger individuals. While larger crayfish command higher market value, the concomitant yield reduction associated with lower densities adversely impacts overall economic returns. Consequently, minimizing density does not necessarily optimize outcomes from a holistic economic perspective.¹² Although the high-density/small-size model currently predominates in China, a minority of farmers employing low-density/large-size practices report favorable economic returns. The comparative efficacy of these models in maximizing benefits while safeguarding normal growth, health, and welfare of *P. clarkii* remains inadequately characterized. This study therefore investigates the effects of high-density/small-size versus low-density/large-size aquaculture models on growth parameters, size distribution, muscle texture, and nutritional composition of *P. clarkii*. The objective is to evaluate the comparative advantages of these models and provide scientific guidance for healthy crayfish aquaculture practices, thereby facilitating industry development.

MATERIALS AND METHODS

EXPERIMENTAL DESIGN AND FEEDING TRIAL

P. clarkii juveniles used in this feeding trial were procured from Jiangsu Jinfeng Agricultural Technology Co., Ltd. (Yancheng, Jiangsu Province, P.R. China). The experiment was performed in Dinggang Village, Zhongzhuang Development Zone, Jianhu County, Yancheng City, Jiangsu Province. Two ponds with comparable surface areas (ap-

proximately 50 mu) were designated for the trial. Both utilized identical aquaculture water sources and were equipped with equivalent aeration systems. Comprehensive pond preparation and disinfection protocols were completed prior to the experiment, ensuring the absence of wild fish interference and full adherence to aquaculture specifications.

Two distinct culture models were implemented: (1) Pond A: Initial stocking density of 4 428 specimens per mu, with an average individual mass of 3.5 grams (high density, small size; control group). (2) Pond B: Initial stocking density of 2 261 specimens per mu, with an average individual mass of 9.0 grams (low density, large size). The culture period spanned 30 days. Throughout the experimental duration, crayfish-specific formulated feed (developed by the National Technology System for Shrimp and Crab Industries and the Jiangsu Province Crayfish Industry Technology System) was administered. This feed contained approximately 32% crude protein and 5% crude fat.

During the 30-day feeding trial, all groups were fed a daily ration equivalent to 5% of their average body weight according to the method described by Chen et al.¹³ Feed was administered twice daily, with 30% of the total daily ration provided at 06:00 and the remaining 70% at 18:00. Daily patrols and inspections are conducted at both ponds. Any dead crayfish found are promptly removed. Feeding observation platforms are set up to monitor crayfish feeding activity in real time, thus preventing feed waste and water pollution caused by overfeeding. The feeding rate was adjusted biweekly based on body weight measurements. Following the method of Zhang et al., water quality parameters were determined using a water quality instrument (YSI Inc., Yellow Springs, Ohio, U.S.A.). Water quality parameters were maintained within the following ranges: dissolved oxygen > 5.0 mg/L, temperature 26–31 °C, ammonia-N concentration below 0.02 mg/L, and pH 7.5–7.8. A natural photoperiod prevailed throughout the experimental period (May–June).

SAMPLE COLLECTION AND CHEMICAL ANALYSIS

At the end of the trial, the crayfish were fasted for 24 hours before samples were collected from both ponds. Seventy crayfish were randomly selected per pond for morphometric analysis, including body length and weight. Representative specimens from each pond were obtained for size-specific measurements, with sampling quantities exceeding 30 kg per pond. Additionally, muscle tissue samples were collected from each pond for analysis of body composition, muscle texture, amino acids, and fatty acids (with 5 samples per group for muscle texture analysis, while all other indicators are assessed using 3 samples per group).

The muscle composition of crayfish was determined using standardized methods.¹⁴ Moisture content was determined via the constant-weight drying method at 105°C. Crude protein content (N×6.25) was analyzed using the Kjeldahl method (1030-Auto-analyzer, Tecator, Hoganas, Sweden). Crude lipid content was quantified by Soxhlet extraction (Soxtec System, Tecator, Sweden). Crude ash content was quantified via the carbonization method, wherein

samples were combusted in a muffle furnace at 550°C for 6 hours.

The textural properties of crayfish muscles, including hardness, cohesiveness, elasticity, adhesiveness, and chewiness, were analyzed using a texture analyzer (TMS-Touch, FTC, Washington, DC, USA) equipped with an 8 mm diameter flat-end cylinder probe. Parameters were determined via a two-bite compression test. Testing conditions comprised two consecutive compressions at a constant speed of 30 mm/min, achieving a 60% deformation of the original sample height, with an initial trigger force of 0.1 N.¹⁵

Amino acid quantitative determination was performed following the methodology established by Jiang et al.¹² utilizing a high-speed amino acid analyzer (model LA8080, Hitachi, Ltd., Tokyo, Japan). Approximately 0.2 g of the sample was accurately weighed into a 50 mL hydrolysis tube. Subsequently, 20 mL of 1:1 (v/v) HCl was added, and hydrolysis was conducted at 110 °C for 22 h within an electric blast drying oven. Following hydrolysis, the sample was removed, allowed to cool, and quantitatively transferred to a 25 mL volumetric flask. A precisely measured aliquot of 100 µL was then transferred into a 15 mL centrifuge tube. This aliquot was placed in a vacuum drying oven and dried at 60 °C for 2 h to ensure complete solvent removal. After drying, the residue was reconstituted with distilled water to a final volume of 0.5 mL and filtered through a 0.45 µm organic membrane filter prior to instrumental analysis.

Fatty acid analysis was performed using gas chromatography (GC-2010, Shimadzu, Japan) following the methodology described by Jiang et al.¹² Randomly selected 0.2 g samples were combined with 2 mL of a petroleum ether-diethyl ether mixture (v/v, 1:1) and incubated overnight. Subsequently, 1.5 mL of a 2% KOH-methanol solution was added, mixed thoroughly, and the mixture was allowed to stand for 1 h. Following centrifugation at 11,800 ×g for 10 min, the supernatant was discarded. Then, 1.5 mL of 14% (w/w) boron trifluoride-methanol solution (BF₃-CH₃OH) was added. Fatty acid methylation was achieved by incubation in a 55°C water bath for 30 min. After cooling to ambient temperature, 1.5 mL of hexane and 1.5 mL of saturated sodium chloride (NaCl) solution were added for extraction. The mixture was maintained at 4°C to facilitate phase separation. The organic (hexane) supernatant layer was completely transferred, filtered through a 0.22 µm pore size organic phase filter membrane, and subsequently subjected to gas chromatographic analysis.

STATISTICAL ANALYSES

All data were presented as mean SEM (standard error of the mean) values. The data were analysed using the independent samples with the t test in SPSS, version 27.0 (International Business Machines Corporation, Armonk, NY, USA).

RESULTS

GROWTH PERFORMANCE AND SIZE DISTRIBUTION PROPORTIONS

The weight of *P. clarkii* in Pond B, as well as the proportions of Size 1 and Size 2, were significantly higher than those in the control group ($P < 0.05$). The combined proportion of large-sized *P. clarkii* (Size 1 + Size 2) exceeded 35%. Conversely, the hepatosomatic index and the proportion of Size 4 in the control group were significantly higher than those in Pond B ($P < 0.05$). No significant differences were observed in body length, the proportions of Size 3 and Size 5 between the two ponds ($P > 0.05$) (Table 1).

MUSCLE COMPOSITION

The crude protein content in the muscle of *P. clarkii* from pond B was significantly lower than that of the control group ($P < 0.05$), while the moisture, crude lipid, and ash contents in the muscle showed no significant differences between the two ponds ($P > 0.05$) (Table 2).

MUSCLE TEXTURAL PROPERTIES

No significant differences were observed in muscle hardness, springiness, chewiness, gumminess, cohesiveness, resilience, drip loss and cooking loss of *P. clarkii* between the two ponds ($P > 0.05$) (Table 3).

MUSCLE AMINO ACIDS

The muscle contents of glutamate, serine, tyrosine, methionine, and lysine in *P. clarkii* from Pond B were significantly lower than those in the control group ($P < 0.05$). However, no significant differences were observed for other muscle amino acids, essential amino acids, and non-essential amino acids between the two ponds ($P > 0.05$) (Table 4).

MUSCLE FATTY ACIDS

The muscle saturated fatty acids (C16:0 and C18:0) and monounsaturated fatty acids (C16:1 and C20:1) content of *P. clarkii* in Pond B were significantly higher than those in the control group ($P < 0.05$), while the muscle contents of C18:1n9, linoleic acid, and DHA were significantly lower than those in the control group ($P < 0.05$). No significant differences were observed in the muscle contents of linolenic acid, C22:1n9, arachidonic acid, EPA, and PUFA between the two ponds ($P > 0.05$) (Table 5).

DISCUSSION

Our results showed that different aquaculture modes significantly influence the growth performance and size distribution of *P. clarkii*. Compared to the control group, Pond B exhibited significantly higher weight and significantly increased proportions of large-sized crayfish (Size 1 ≥ 50 g and Size 2 35–49g). This provides strong evidence that reduced stocking density enhances individual growth and promotes

Table 1. Effects of different culture modes on growth performance and proportion of different sizes of *P. clarkii*

Item	Pond A	Pond B
Weight (g)	22.57±0.66	29.57±1.37***
Body length (cm)	9.41±0.08	9.63±0.10
HSI (%)	6.85±0.30*	5.98±0.24
Proportion of size 1 (%)	0	13.52±0.62*
Proportion of size 2 (%)	8.46±1.89	21.50±1.34*
Proportion of size 3 (%)	42.92±4.95	32.84±0.23
Proportion of size 4 (%)	33.05±3.31*	15.81±0.49
Proportion of size 5 (%)	15.59±3.77	16.34±2.21

Note: Pond A: high density/small size; Pond B: low density/large size; HSI: Hepatosomatic index = $100 \times (\text{liver weight, g})/(\text{body weight, g})$; Size 1: $\geq 50\text{g}$; Size 2: 35–49g; Size 3: 20–34g; Size 4: 13–19g; Size 5: $\leq 12\text{g}$; Values are means $\pm$ SEM. ***: $P < 0.001$, **: $P < 0.01$, *: $P < 0.05$.

Table 2. Effects of different culture modes on muscle composition of *P. clarkii*

Item (%)	Pond A	Pond B
Moisture	69.45±4.57	72.83±2.86
Crude protein	33.19±0.22*	28.45±1.56
Crude lipid	4.42±0.18	4.54±0.09
Ash	9.40±0.34	9.54±0.54

Note: Pond A: high density/small size; Pond B: low density/large size; Values are means $\pm$ SEM. ***: $P < 0.001$, **: $P < 0.01$, *: $P < 0.05$.

Table 3. Effects of different culture modes on muscle textural properties of *P. clarkii*

Item	Pond A	Pond B
Hardness (N)	442.33±149.79	640.82±182.13
Springiness (mm)	0.74±0.02	0.73±0.01
Chewiness (mJ)	202.62±78.39	292.89±89.82
Gumminess (N)	266.41±95.12	402.85±126.23
Cohesiveness (%)	0.59±0.02	0.60±0.02
Resilience	0.07±0.00	0.08±0.01
Drip loss (%)	4.22±1.06	4.92±0.92
Cooking loss (%)	12.36±1.84	19.10±3.90

Note: Pond A: high density/small size; Pond B: low density/large size; Drip loss (%) = $(W_0 - W_1)/W_0 \times 100$, Cooking loss (%) = $(W_0 - W_2)/W_0 \times 100$, W_0 , initial muscle mass, W_1 , the muscle mass after hanging for 24 h; W_2 , the muscle mass after cooking for 5 min; Values are means $\pm$ SEM. ***: $P < 0.001$, **: $P < 0.01$, *: $P < 0.05$.

the production of larger, commercially valuable sizes. The combined proportion of large-sized *P. clarkii* exceeding 35% in Pond B represents a substantial improvement over yields typical of high-density culture. This finding aligns with the principle that lower densities reduce intra-specific competition for critical resources such as space and food.¹ The alleviation of this competition likely allowed individuals in Pond B greater access to nutrients, directly translating into the observed accelerated somatic growth and higher individual weights. Conversely, the lack of significant differences in body length and in the proportions of Size 3 (20–34g) and Size 5 ($\leq 12\text{g}$) *P. clarkii* suggests that density primarily impacts the extremes of the size spectrum. Specifically, high-density conditions appear to suppress the attainment of the largest sizes while increasing the proportion of moderately small individuals (Size 4), without drastically altering the core mid-size range (Size 3) or the

proportion of the very smallest crayfish (Size 5) observed in this study. However, the underlying mechanisms for this specific size distribution shift are not yet fully understood due to a current paucity of related research, further investigation is warranted.

This study reveal a trade-off between high stocking density and optimal growth/size distribution. High-density culture boosts biomass but reduces individual size, yielding smaller, less valuable crayfish, as shown by controls. Conversely, Pond B's lower density increased marketable sizes, achieving over 35% large-size proportion for economic gain. This optimizes size distribution for profitability, not just density. Thus, moderate or low densities enhance quality and high-value size proportion. Further analyses are necessary to investigate the impacts on end-product quality and nutrition.

Table 4. Effects of different culture modes on muscle amino acids of *P. clarkii*

Item(mg/kg)	Pond A	Pond B
Histidine	3871.49±135.50	3445.12±76.07
Threonine	7076.43±219.98	6363.71±134.89
Arginine	23578.12±560.66	22092.42±295.74
Valine	9201.44±406.47	8304.26±225.78
Methionine	3840.37±128.74**	3178.67±45.44
Phenylalanine	10761.69±884.03	11373.18±1315.43
Isoleucine	10828.32±551.63	11236.98±741.59
Leucine	15514.01±588.90	14326.96±248.34
Lysine	15136.54±458.42*	13791.93±119.93
Aspartic	19978.92±849.56	18868.86±741.51
Glutamic	31344.22±1097.46*	27429.73±557.90
Serine	7362.06±240.64*	6486.76±146.60
Glycine	12015.47±347.42	11531.73±609.63
Alanine	11135.05±313.94	11176.28±350.53
Tyrosine	5905.94±254.31*	4834.97±205.12
Cysteine	135.57±57.26	159.23±81.78
Proline	5773.53±1042.65	4503.21±477.47
EAA	99808.41±3839.88	94113.24±3056.96
NEAA	93650.76±3654.64	84990.77±2898.12

Note: Pond A: high density/small size; Pond B: low density/large size; EAA: essential amino acids, includes Histidine, Threonine, Arginine, Valine, Methionine, Phenylalanine, Isoleucine, Leucine, and Lysine; NEAA: non-essential amino acids, includes Aspartic, Glutamic, Serine, Glycine, Alanine, Tyrosine, Cysteine, and Proline. Values are means ± SEM. ***: $P < 0.001$, **: $P < 0.01$, *: $P < 0.05$.

Table 5. Effects of different culture modes on muscle fatty acids of *P. clarkii* (g/100g)

	Pond A	Pond B
C16:0	0.047±0.001	0.068±0.002***
C16:1	0.008±0.000	0.012±0.000***
C18:0	0.032±0.001	0.040±0.001**
C18:1n9	0.078±0.002*	0.069±0.002
C18:2n6 (LA)	0.032±0.001**	0.026±0.001
C18:3n3 (LNA)	0.007±0.000	0.007±0.000
C20:1	0.004±0.000	0.005±0.000*
C22:1n9	0.008±0.003	0.007±0.003
C20:4n6 (AA)	0.011±0.003	0.009±0.003
C20:5n3 (EPA)	0.036±0.001	0.037±0.001
C22:6n3 (DHA)	0.011±0.000**	0.008±0.000
PUFA	0.097±0.005	0.088±0.004

Note: Pond A: high density/small size; Pond B: low density/large size; LA, linoleic acid; LNA, linolenic acid; AA, arachidonic acid; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid; PUFA, polyunsaturated fatty acid, includes LA, LNA, AA, EPA and DHA; Values are means ± SEM. ***: $P < 0.001$, **: $P < 0.01$, *: $P < 0.05$.

In the present study, the significantly lower crude protein content observed in the muscle of *P. clarkii* reared under Pond B compared to the control group suggests that stocking density and associated size differences may influence protein metabolism or deposition mechanisms in this species. This reduction could be attributed to altered energy allocation strategies under lower competition, where resources might be preferentially directed toward somatic growth or lipid storage rather than protein synthesis, despite the lack of significant differences in crude lipid con-

tent in this study. Alternatively, physiological stress in high-density environments may paradoxically increase protein turnover or mobilization as an adaptive response, as evidenced by Refaey et al.¹⁶'s study on *Ictalurus punctatus*. Their research found that significantly higher muscle crude protein content in the high stocking density group compared to the low stocking density group. However, no significant differences were observed in muscle moisture, crude lipid, and ash contents of crayfish between the two groups, indicating that these biochemical components are

less sensitive to the tested density/size variables. This stability in moisture and ash aligns with findings in *Oreochromis niloticus*, where muscle moisture and ash remained consistent across varying rearing densities when under the same treatment.¹⁷ The unchanged crude lipid content further suggests that lipid metabolism may be regulated independently of density-driven growth dynamics in *P. clarkii*, possibly due to aquatic animal species and rearing environment.¹⁸

Muscle textural properties are crucial for performance and key indicators of muscle quality.¹⁵ Research by Jia et al.¹⁹ demonstrated that density stress significantly altered the textural properties of *Larimichthys crocea* muscle, with the high-density group exhibiting significantly higher values than the low-density group. In contrast, our results indicate that different aquaculture modes had no effect on the textural properties of *P. clarkii* muscle. This may be attributed to consistent environmental conditions or dietary practices between the two aquaculture modes. While size differences are often associated with variations in muscle fiber diameter or connective tissue, the present results suggest that, within the size range studied, these structural differences were insufficient to produce detectable changes in the measured textural or technological properties of *P. clarkii* muscle. This finding contrasts with studies on certain finfish, where size significantly influenced texture,²⁰ highlighting potential species-specific responses. Collectively, these results demonstrate that variations in stocking density and size within this study did not significantly alter the muscle integrity of *P. clarkii*.

In this study, some amino acids (glutamic acid, serine, tyrosine, methionine, and lysine) in Pond B were significantly lower than in the control group. Given that lysine and methionine are crucial for growth and immunity, this reduction may reflect suboptimal nutrient allocation in *P. clarkii* under reduced competition. This phenomenon could be linked to stress responses induced by high-density aquaculture, where crowding might stimulate enhanced energy metabolism and functional protein synthesis, thereby increasing the demand and accumulation of certain specific amino acids.²¹ It also suggests that high density may promote protein synthesis and amino acid retention by increasing metabolic demands and resource competition. This interpretation is supported by the elevated crude protein content observed in the muscle of the control group in this study. Similarly, research on *L. crocea* found that high-density stress likewise led to increased levels of certain specific amino acids.¹⁹

The composition and content of fatty acids in *P. clarkii* are key indicators of their nutritional value.¹² In the present study, compared with the control group, the fatty acid profile shifts in Pond B—characterized by elevated saturated fatty acids (SFAs: C16:0, C18:0) and specific monounsaturated fatty acids (MUFAs: C16:1, C20:1), alongside decreased C18:1n9, linoleic acid (LA), and docosahexaenoic acid (DHA)—highlight altered lipid metabolism pathways. Jia et al.¹⁹ also found that the contents of some essential fatty acids, such as linoleic acid, arachidonic acid, and eicosapentaenoic acid (EPA), were highest in the high-den-

sity group. This may be explained by the preferential utilization of specific energy-related fatty acids, prompting a compensatory accumulation of others to maintain metabolic homeostasis. Conversely, in pond B, the decline in nutritionally critical DHA and LA, despite unchanged total PUFA levels, suggests selective depletion or reduced retention of these long-chain polyunsaturated fatty acids (LC-PUFAs). The preservation of EPA, ARA, and total PUFA content implies that Pond B's conditions did not uniformly impair all LC-PUFAs. Xu et al.¹⁸ also confirmed that different stocking densities did not significantly affect the expression of lipid metabolism-related genes in the liver of tiger puffer (*Takifugu rubripes*).

Notably, the improved growth in Pond B coincided with alterations in muscle nutritional quality. While proximate composition (moisture, lipid, ash) and textural properties (hardness, springiness, etc.) remained unaffected, significant reductions in crude protein and specific amino acids (glutamate, serine, tyrosine, methionine, lysine) were observed. This may reflect a dilution effect associated with accelerated growth or metabolic shifts prioritizing energy allocation towards rapid biomass accumulation over protein deposition. Furthermore, Pond B crayfish displayed a distinct fatty acid profile: elevated saturated (C16:0, C18:0) and monounsaturated (C16:1, C20:1) fatty acids, but reduced levels of nutritionally important C18:1n9, linoleic acid (C18:2n6), and docosahexaenoic acid (DHA). These shifts could stem from differences in dietary utilization, endogenous lipid metabolism, or environmental stressors modulating biosynthetic pathways. The absence of differences in essential amino acid totals, polyunsaturated fatty acids (PUFA), and texture suggests that while specific nutrient components are modulated, the overall essential nutrient profile and eating quality may be largely conserved between models.

CONCLUSION

Overall, this study conclusively demonstrates that adopting a low-density/large-size aquaculture model (initial stocking density: 2,261 ind/mu; avg. size: 9.0 g) optimizes the growth performance and commercial size distribution of *P. clarkii*, significantly increasing the proportion of high-value large-sized individuals compared to a high-density/small-size model. However, this growth advantage comes with trade-offs in specific aspects of muscle nutritional quality, namely reduced crude protein content, lower levels of certain amino acids (glutamate, serine, tyrosine, methionine, lysine), and an altered fatty acid profile (increased SFA/MUFA, decreased C18:1n9, LA, DHA). Critically, proximate composition (excluding protein), essential amino acid totals, PUFA content, and textural properties were unaffected by culture mode. Therefore, the low-density/large-size model is recommended for maximizing production yield and economic return, although strategies to mitigate the observed nutritional alterations, potentially through dietary formulation, warrant further investigation to ensure optimal product quality.

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CONFLICTS OF INTEREST

No competing interests were disclosed.

DATA AVAILABILITY

All are available upon reasonable request.

ETHICAL CONDUCT APPROVAL

The article adheres to the Convention on Biological Diversity and the Convention on Trade in Endangered Species of Wild Fauna and Flora Research

INFORMED CONSENT STATEMENT

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