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Functional Red Palm Oil as a Fish Oil Alternative on Growth, Feed Utilization, and Coloration in Giant Freshwater Prawn *Macrobrachium rosenbergii*

(Minyak Sawit Merah Berfungsi sebagai Alternatif Minyak Ikan pada Pertumbuhan, Penggunaan Makanan dan Pewarnaan Udang Galah *Macrobrachium rosenbergii*)

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ABSTRACT

Functional red palm oil (FRPO), rich in bioactive compounds, enhances digestion, metabolism, immune function, and coloration in aquatic species. Given Malaysia's robust palm oil industry, investigating FRPO as a sustainable, locally-sourced lipid alternative for aquaculture industry is essential. A 32-day feeding trial was conducted to evaluate the effects of substituting dietary fish oil (FO) with FRPO on growth performance, survival rate, coloration and feed utilization of giant freshwater prawn (GFP), *Macrobrachium rosenbergii*. Three experimental diets were formulated to contain different lipid sources: Diet 1 (100% of FO), Diet 2 (50% FO + 50% FRPO), and Diet 3 (100% of FRPO). A total of 180 prawns with average weight of 0.35 g were assigned into nine tanks and fed twice daily to satiation. Results showed that prawns fed with Diet 2 had significantly ($p < 0.05$) better feed conversion ratio, specific growth rate, percentage weight gain and final weight than other two groups. However, no significant ($p > 0.05$) difference was observed in the survival rate of the experimental prawns. All prawns showed significant differences in lightness (L*), while those fed Diet 3 showing significantly higher redness (a*) compared to the other groups. It is evident that a 50% inclusion of FRPO can enhance pellet palatability, significantly boost growth performance, feed utilization, and coloration in GFP. These findings suggest that FRPO is a viable, sustainable alternative to FO, advancing the development of aquafeeds with local ingredients.

Keywords: Body coloration; fish oil; giant freshwater prawn; palm oil

ABSTRAK

Minyak sawit merah berfungsi (FRPO) yang kaya dengan sebatian bioaktif, meningkatkan pencernaan, metabolik, fungsi imunisasi dan pewarnaan sepsis akuatik. Memandangkan industri minyak sawit Malaysia yang kukuh, penyelidikan FRPO sebagai alternatif lipid yang mampan dan sumber tempatan untuk industri akuakultur adalah penting. Satu uji kaji selama 32 hari telah dijalankan untuk menilai kesan penggantian minyak ikan (FO) dalam diet dengan FRPO terhadap prestasi pertumbuhan, kadar kelangsungan hidup, pewarnaan dan penggunaan makanan udang galah (GFP), *Macrobrachium rosenbergii*. Tiga diet uji kaji telah dirumuskan untuk mengandungi sumber lipid yang berbeza: Diet 1 (100% FO), Diet 2 (50% FO + 50% FRPO) dan Diet 3 (100% FRPO). Sebanyak 180 ekor udang dengan berat badan individu purata 0.35 g telah dibahagikan sama rata ke dalam sembilan tangki. Udang diberi makan sehingga kenyang dua kali sehari. Keputusan menunjukkan bahawa GFP yang diberi makan Diet 2 mempunyai kadar penukaran makanan, kadar pertumbuhan khusus, peratusan kenaikan berat badan dan berat akhir yang lebih baik secara signifikan ($p < 0.05$) berbanding dengan GFP kumpulan lain. Walau bagaimanapun, tiada perbezaan yang signifikan ($p > 0.05$) diperhatikan dalam kadar kelangsungan hidup udang uji kaji. Semua udang menunjukkan perbezaan yang signifikan dalam kecerahan (L*), sementara udang yang diberi Diet 3 menunjukkan kemerahan (a*) yang lebih tinggi dengan signifikan berbanding kumpulan lain. Jelas bahawa penggunaan 50% FRPO dapat meningkatkan kesukaan makanan seterusnya meningkatkan prestasi pertumbuhan, penggunaan makanan dan pewarnaan dalam GFP secara signifikan. Kajian ini mencadangkan bahawa FRPO adalah alternatif yang mampan dan berdaya maju kepada FO, serta dapat memajukan pembangunan makanan akuakultur dengan bahan tempatan.

Kata kunci: Minyak ikan; minyak kelapa sawit; udang galah; warna badan

INTRODUCTION

Since the blue revolution, global aquaculture production has experienced a significant surge, establishing itself as the fastest-growing sector in animal product industries. Aquaculture has become essential in meeting the increasing global demand for aquatic foods. In 2022, for the first time, aquaculture production surpassed capture fisheries, reaching 94.4 million tonnes. This milestone represented 51 percent of the world's total aquatic animal production and marked a record 57 percent of the production destined for human consumption (FAO 2024). This shift highlights aquaculture's growing importance in providing sustainable and reliable sources of aquatic food. The giant freshwater prawn (GFP), *Macrobrachium rosenbergii*, is a prominent contributor to various countries' aquaculture production. Its appeal lies in its favourable taste and nutritional profile, offering essential amino acids, polyunsaturated fatty acids, and protein suitable for human consumption (Muralisankar et al. 2014). Additionally, GFP's popularity in cultivation can be attributed to its robust characteristics, including resilience to fluctuations in salinity, and its compatibility for polyculture with fish such as tilapia (Kim et al. 2013). In Malaysia, the Department of Fisheries has identified GFP as a top-priority species for both export and domestic food production. The annual production figures for 2023 reached 189.05 metric tonnes, with expectations of further growth in the future (DOF 2023). However, significant impediments to the expansion of GFP aquaculture include lack of high-quality GFP broodstock and post larvae, inadequate availability of quality feed, and limitations in cultivation technology and productivity (Chong, Teoh & Wong 2022).

When considering the factors that impact the taste, consumer approval, and market value of prawns, both the natural and cooked colors of the crustacean are commonly used as visual cues, thus higher quality is often linked to a more vibrant red hue. The important determinants influencing prawn coloration include the levels of astaxanthin and carotenoids present in the exoskeleton and hypodermal tissue, as suggested by Parisenti et al. (2011) and Wade et al. (2014). Astaxanthin and carotenoids, essential for prawn coloration, are obtained from the diet, as prawns cannot synthesize these pigments *de novo*. By consuming aquafeeds enriched with carotenoid-rich ingredients, prawns metabolically convert dietary carotenoids into astaxanthin, enhancing their coloration (Rodríguez et al. 2017). In fact, aquafeed plays a crucial role in the aquaculture industry, representing over half of the total input expenditures (Kim et al. 2013). Traditionally, fish oil (FO) served as the primary lipid source in commercial aquafeeds. However, due to the increasing costs of FO and its limited global availability, there is a growing emphasis on exploring alternative lipid resources for the long-term sustainability and scalability of the global aquaculture industry (FAO 2024).

FRPO is a specially formulated type of red palm oil that retains high levels of bioactive compounds, such as carotenoids (primarily α- and β-carotenes), tocopherols, tocotrienols, phytosterols (mainly β-sitosterol), phosphatides, and squalene (Purnama et al. 2020). The bioactive ingredients synergistically enhance nutrient digestion and absorption, support metabolism, improve oxidative and immune status, and boost overall health and production performance in aquatic species (Ng & Gibon 2010). As noted by Ng and Gibon (2010), Soller, Roy and Davis (2019) and Turchini, Torstensen and Ng (2009), this attribute contributes to extending the shelf life of both frozen and fresh products.

Given Malaysia's substantial oil palm sector and successful instances of substituting FO with crude palm oil or palm oil products in the diets of various aquatic species, such as tilapia (Bahurmiz & Ng 2007; Ng, Chong & Wang 2013), catfish (Asdari et al. 2011), rohu (Siddiqua & Khan 2023), hybrid grouper (Gudid et al. 2020), yet limited research has explored potential of FRPO as a locally sustainable lipid source for GFP. As a byproduct of Malaysia's palm oil industry, FRPO is more affordable than imported oils. Its use not only reduces carbon emissions from transportation but also minimizes waste and promotes sustainable resource management, thereby supporting eco-friendly practices in local aquaculture. Hence, this study aims to evaluate FRPO as an alternative lipid source and its impact on growth, feed utilization, survival, and colouration in GFP.

MATERIALS AND METHODS

EXPERIMENTAL DIETS

In the present study, three isonitrogenous and isoenergetic diets were formulated to meet the nutrient requirements of GFP and to contain graded inclusion levels of FRPO as FO replacement: Diet 1, 100% FO; Diet 2, 50% FO and 50% FRPO; and Diet 3, 100% FRPO (Table 1). Fish meal, shrimp meal and soybean meal used in experimental diets contributed to a total protein level of 42% with a ratio fixed at 2:1:2. FRPO (Tomofat® marine functional oil) used in the study was developed and provided by Sunzen Group of Companies (Malaysia). It is formulated with a comprehensive blend of fatty acids, including medium-chain triglycerides, which serve as immediate energy sources that are rapidly absorbed, transported via portal blood, and utilized at the cellular level. Additionally, it contains linoleic acid and α-linolenic acid in an optimal ratio, ensuring balanced nutritional benefits. Carboxymethyl cellulose functioned as a binding agent, while α-cellulose was a filler. All pre-measured dry ingredients were uniformly mixed in a Hobart mixer (LSM20, The Baker). Following this, the oil was thoroughly incorporated into the ingredient mixture, and distilled water was added.

The resulting moist dough underwent extrusion through a 2-mm die using a locally assembled meat mincer. The resultant feed pellets were air-dried at room temperature until reaching approximately 10% moisture content. Subsequently, all diets were kept in airtight polyethylene bags at -20 °C until use (Teoh & Wong 2021).

PROXIMATE ANALYSES

Proximate analysis was conducted on dietary ingredients and experimental diets (Table 1). In summary, the dry matter of the sample was assessed using the oven-drying method, involving drying in the oven at 103 °C until a consistent weight was attained (AOAC 1997). For ash determination, the sample underwent ashing in the furnace at 550 °C for 5 h (AOAC 1997). The Kjeldahl method was applied to determine crude protein content, involving sample digestion with concentrated sulphuric acid (H_2SO_4) and a catalyst composed of potassium sulfate and copper sulfate in a ratio of 7:0.8. The resulting product underwent distillation in the presence of distilled water and 32% sodium hydroxide (NaOH). The distillate was titrated with 0.1 N hydrochloric acid (HCl), and the volume of HCl required for titration was recorded (AOAC 1997). To determine fiber content, the pre-dried defatted sample was sequentially boiled with 0.13 M H_2SO_4 and 0.23 M NaOH. The sample was then washed with distilled water using the Fibrebag system filtration. The dried digested sample was subsequently ashed in the furnace at 550 °C for 4 h and weighed (AOAC 1997). A modified Folch, Lees and Sloane-Stanley (1957) method was adopted to determine lipid content. Samples were soaked overnight with chloroform and methanol (2:1), and a polytron homogenizer was used to homogenize the sample (Teoh & Loo 2023). The homogenized sample was filtered using a Buchner funnel. The filtrate was transferred to a separating funnel, and distilled water was added. The separating funnel was shaken to break the emulsion and left to allow

TABLE 1. Ingredient composition and proximate composition of the experimental diets, except for gross energy content, is presented as mean ± SE (n = 3). No significant difference was recorded among dietary treatments ($p < 0.05$)

	Experimental diets[1]		
	Diet 1	Diet 2	Diet 3
Ingredients (in dry matter basis) (g/ 100 g)			
Fishmeal	29.35	29.35	29.35
Shrimp meal	13.90	13.90	13.90
Soybean meal	39.18	39.18	39.18
Fish oil (FO)	3.52	1.76	0
Functional red palm oil (FRPO)	0	1.76	3.52
Corn starch	4.04	4.04	4.04
Vitamin premix[2]	3.00	3.00	3.00
Mineral premix[3]	4.00	4.00	4.00
Carboxymethyl cellulose	1.00	1.00	1.00
Cholesterol	0.60	0.60	0.60
Choline chloride	1.00	1.00	1.00
Alpha-cellulose	0.41	0.41	0.41
Proximate composition			
Dry matter (%)	84.65 ± 0.10	84.83 ± 0.10	84.47 ± 0.10
Crude protein (%)	42.02 ± 0.59	41.03 ± 0.54	42.05 ± 0.49
Crude lipid (%)	14.15 ± 0.03	14.21 ± 0.11	14.03 ± 0.01
Crude fibre (%)	1.09 ± 0.03	1.02 ± 0.02	1.04 ± 0.04
Ash (%)	18.27 ± 0.07	18.14 ± 0.07	18.04 ± 0.17
Gross energy (kJ/g)	19.71	19.70	19.72

[1]Experimental diets nomenclature: Diet 1 = 100% FO inclusion; Diet 2 = 50% FO and 50% FRPO inclusion; Diet 3 = 100% FRPO inclusion.[2]Vitamin premix (content·kg^{-1}) = Vitamin A, 50 MIU; Vitamin D_3, 10 MIU; Vitamin E, 130 g; Vitamin B_1, 10 g; Vitamin B_2, 25 g; Vitamin B_6, 16 g; Vitamin B_{12}, 100 mg; Biotin, 500 mg; Panthothenic acid, 56 g; Folic acid, 8 g; Niacin, 200 g; Anticake, 20 g; Antioxidant, 0.2 g; Vitamin K_3, 10 g.
[3]Mineral premix (content·kg^{-1}) = Copper, 7.5 g; Iron, 125 g, Manganese, 25 g; Zinc, 125 g; Cobalt, 0.5 g; Iodine, 0.175 g; Selenium, 0.3 g; Anticake, 10 g

the separation of two layers. The lower layer of the extracts was collected, dried at 40 °C until a constant weight was achieved, and then weighed. The nitrogen-free extract of the sample was calculated by subtracting the composition of ash, protein, lipid, and fiber from the composition of dry matter. Gross energy content for each experimental diet was calculated using the formula provided by Bureau, Kaushik and Cho (2002), which is as follow:

Gross energy content (kJ/g) = (% protein × 23.6 kJ/g) + (% lipid × 39.5 kJ/g) + (% NFE × 17.2 kJ/g).

TANK SETUP

The GFP feeding trial was conducted at the Aquaculture Facilities, Universiti Tunku Abdul Rahman (UTAR) in Kampar, Perak. Two circular fiberglass tanks with a capacity of 570 L each served as nursery tanks. These tanks were filled with aerated, dechlorinated water and treated with 12 g of calcium carbonate powder. A batch of 500 GFP post-larvae (PL), each measuring about 1-2 inches, was sourced from Manjung Aquabest Hatchery in Lumut, Perak, and acclimated to the nursery tanks upon arrival. The juveniles were initially fed with Diet 1 (control diet) for 10 days prior to the start of the feeding trial. The experimental setup consisted of nine glass aquaria (30 cm × 46 cm × 61 cm) filled with 55 L of dechlorinated water, each equipped with a top filter system, an aeration stone, and thirteen 12 cm PVC pipes for habitat structures for the GFP. To reduce stress and enhance feeding efficacy, the exteriors of all nine tanks were shielded with dark, black plastic bags.

FEEDING EXPERIMENT

Following a 10-day acclimatization period, each of the nine experimental tanks was stocked with 20 uniformly sized and healthy GFP, each averaging an initial weight of 0.35 ± 0.00 g and the GFP PL were fed three times daily, according to their experimental diet, at 8:30 h, 12:30 h, and 16:30 h to satiation. The daily feed consumption was recorded. Water quality parameters, including pH, temperature, and dissolved oxygen (DO) levels, were monitored daily. The pH values were consistently within a narrow range of 7.54 to 7.57. The water temperature was also uniformly maintained, fluctuating slightly between 26.95 °C and 26.98 °C. Similarly, DO levels were stable, ranging from 7.14 to 7.27 mg/L (Table 2). Prawn body weights were measured biweekly to monitor growth progress.

After the end of the feeding trial, each prawn was individually weighed and their total length recorded. From each replicate tank, three prawns were randomly selected for body color analysis using a Konica Minolta CR-400 chromameter. The body coloration values (L*, a*, b*) were obtained following the methodology outlined by Parisenti et al. (2011). Coloration values are commonly used for objectively measuring color, where L*, a*, and b* measures lightness, red-green, and blue-yellow, respectively, while hue was determined to evaluate the dominant color characteristics of the prawns using the following formula:

$$\text{Hue} = \tan^{-1}(b^*/a^*)$$

The growth performance of the prawns was evaluated based on percentage weight gain and specific growth rate (SGR), calculated as follows:

$$\text{SGR (\%/ day)} = \frac{\ln[\text{Final mean weight (g)}] - \ln[\text{Initial mean weight (g)}]}{\text{Days}} \times 100\%$$

$$\text{Percentage weight gain (\%)} = \frac{\text{Final mean weight (g)} - \text{Initial mean weight (g)}}{\text{Initial mean weight (g)}} \times 100\%$$

Feed conversion ratio (FCR) was calculated to assess feed utilization efficiency, as calculated by the formula herewith:

$$\text{Feed conversion ratio (FCR)} = \frac{\text{Total dry feed consumed (g)}}{\text{Wet weight gain (g)}}$$

Survival rate was calculated to assess prawn productivity using the following formula:

$$\text{Survival rate (\%)} = \frac{\text{Final total number of prawns}}{\text{Initial total number of prawns}} \times 100\%$$

STATISTICAL ANALYSIS

All data were presented as mean ± standard error (SE). Prior to analysis, data normality was assessed using the Shapiro-Wilk test. Subsequently, a one-way analysis of variance (ANOVA) (SPSS 26.0) was conducted to identify any significant differences between the dietary treatments. Post-hoc comparisons of mean values were performed using Duncan's multiple range test at a 5% significance level ($p < 0.05$).

RESULTS

GROWTH PERFORMANCE AND SURVIVAL

In the present study, GFP fed with Diet 2 showed a significantly higher final weight (0.81 ± 0.01 g) compared to those fed with other diets ($p < 0.05$) (Table 3). In contrast, there were no significant differences ($p > 0.05$)

in the final weights of GFP fed with Diet 1 (0.62 ± 0.01 g) and 3 (0.59 ± 0.01 g). Likewise, SGR for GFP on Diet 2 was significantly greater (1.53 ± 0.03%/day) than that of GFP on Diets 1 (0.51 ± 0.01%/day) and 3 (0.37 ± 0.02%/day), with no significant differences between the latter two. Furthermore, GFP fed with Diet 2 also exhibited a significantly higher percentage weight gain (131.14 ± 4.74%) compared to those on Diets 1 (75.23 ± 2.21%) and 3 (64.86 ± 3.15%), which showed no significant variance in weight gain. On the other hand, GFP survival rates across the different diets did not differ significantly, with Diet 1 at 68.33 ± 1.67%, Diet 2 at 66.67 ± 1.67%, and Diet 3 at 68.33 ± 1.67%. Mortality was evident from signs like broken shells, residual body parts, and body whitening which were attributed to the cannibalistic behavior of the prawns (New et al. 2010).

FEED UTILIZATION OF GIANT FRESHWATER PRAWNS

No significant differences were observed in the total feed intake among the experimental GFP across the three dietary treatments, with intakes ranging from 26.38 ± 0.26 to 29.16 ± 0.48 g (Table 2). However, GFP fed Diet 2 showed significantly better FCR (2.98 ± 0.05) after a 32-day feeding trial ($p < 0.05$) compared to those fed Diet 1 (5.61 ± 0.19) and Diet 3 (5.78 ± 0.26).

BODY COLORATION OF GIANT FRESHWATER PRAWNS

The GFP fed on different diets exhibited significant differences in colorimetric results (Table 2). GFP on Diet 2 displayed the significantly highest L* values (35.48 ± 0.06), followed by those on Diet 1 (30.92 ± 0.01) and Diet 3 (27.87 ± 0.01). Regarding redness, GFP on diet 3 appeared redder with the highest a* value (0.68 ± 0.06), significantly outperforming those on Diet 1 (-0.50 ± 0.03) and Diet 2 (-0.46 ± 0.17) GFP on Diet 1 had the highest b* values (4.02 ± 0.05), followed by those on Diet 3 (2.88 ± 0.03) and Diet 2 (1.51 ± 0.06) ($p < 0.05$). GFP on Diet 2 exhibited the highest hue values (106.94 ± 1.25), followed by those on Diet 1 (97.14 ± 0.33) and Diet 3 (76.71 ± 0.11), each significantly different from the others.

TABLE 2. Water conditions of experimental tanks throughout the 32-day feeding trial. Values are presented as mean ± standard error (n = 3). No significant differences were observed among the experimental tank water

Parameters	Dietary treatments[1]		
	Diet 1	Diet 2	Diet 3
pH	7.54 ± 0.04	7.55 ± 0.02	7.57 ± 0.05
Dissolved oxygen (mg/L)	7.27 ± 0.02	7.17 ± 0.03	7.14 ± 0.03
Temperature (°C)	26.98 ± 0.10	26.98 ± 0.07	26.95 ± 0.12

[1]Experimental diets nomenclature: Diet 1 = 100% FO inclusion; Diet 2 = 50% FO and 50% FRPO inclusion; Diet 3 = 100% FRPO inclusion

TABLE 3. Growth performance, survival rate, feed utilization and colorimetric results of GFP fed with different experimental diets for 32 days. Values are presented as mean ± standard error (n = 3). Values in the same row with different superscript letters indicate significant differences by the test of $p < 0.05$ using Duncan's multiple range test

Parameters	Dietary treatments[1]		
	Diet 1	Diet 2	Diet 3
Initial mean weight (g)	0.36 ± 0.02	0.36 ± 0.01	0.36 ± 0.01
Final mean weight (g)	0.62 ± 0.01^{a}	0.81 ± 0.01^{b}	0.59 ± 0.01^{a}
Percentage weight gain (%)	72.53 ± 2.21^{a}	131.14 ± 4.74^{b}	64.86 ± 3.15^{a}
Specific growth rate (SGR, %/ day)	0.51 ± 0.01^{a}	1.53 ± 0.30^{b}	0.37 ± 0.02^{a}
Survival rate (%)	68.33 ± 0.78	66.67 ± 0.79	68.33 ± 0.78
Total feed intake (g)	29.16 ± 0.48	28.53 ± 0.53	26.38 ± 0.26
Feed conversion ratio (FCR)	5.61 ± 0.19^{a}	2.98 ± 0.05^{b}	5.78 ± 0.26^{a}
L* values	30.92 ± 0.01^{a}	35.48 ± 0.06^{b}	27.87 ± 0.01^{a}
a* values	-0.50 ± 0.03^{a}	-0.46 ± 0.17^{a}	0.68 ± 0.06^{b}
b* values	4.02 ± 0.05^{c}	1.51 ± 0.06^{a}	2.88 ± 0.03^{b}
Hue	97.14 ± 0.33^{b}	106.94±1.25^{b}	76.71±0.10^{a}

[1]Experimental diets nomenclature: Diet 1 = 100% FO inclusion; Diet 2 = 50% FO and 50% FRPO inclusion; Diet 3 = 100% FRPO inclusion

DISCUSSION

In the present study, GFP fed with Diet 2 demonstrated significantly higher growth performance compared to those fed with Diets 1 and 3, between which no significant difference was observed, suggesting that partial replacement of FO with FRPO is feasible. Soller, Roy and Davis (2019) similarly showed that partially replacing dietary FO with palm oil is viable, as the growth performance of Pacific white shrimp remained comparable when fed a diet including palm oil. This is due to the inclusion of palm oil in the diet increases the levels of saturated fatty acids, which can then be elongated and desaturated into monounsaturated fatty acids, serving as an energy source for growth (Chen et al. 2017). Furthermore, Bell et al. (2002) indicated that including 50% or more palm oil in the diet resulted in muscle reduction of Atlantic salmon, which explains the relatively inferior growth performance of prawns fed Diet 3 (with 100% FRPO) compared to other groups. This is supported by a study conducted by Kim et al. (2013) which showed that replacing FO entirely with crude palm oil resulted in slightly poorer performance due to the reduced digestibility of saturated fatty acids and lipids. Similarly, Ramesh and Balasubramanian (2005) found lower digestibilities of protein and lipid in black tiger shrimp fed with palm oil inclusion diets. Common prawn feed with 10-12% moisture typically provides prawns with a FCR of around 2-3 (New 2002). In the present study, GFP fed Diet 2 demonstrated significantly better FCR compared to GFP fed Diet 1 and Diet 3, while having a similar total feed intake to GFP fed Diet 1. Previous studies showed that dietary fish oil replacement with palm oil did not affect the total feed intake of GFP (Kim et al. 2013). In light of this, it is suggested that 50% inclusion of FRPO could be beneficial for the pellet palatability and subsequently improve the lipid digestibility of the prawn, ultimately improving the growth performance. Maintaining water parameters is crucial for the optimal growth and performance of GFP. In the present study, there were no significant changes observed in water temperature, DO level, or water pH across all tanks. Replacing dietary FO with FRPO did not significantly affect water quality.

The present study showed significant differences in the coloration values of GFP fed various experimental diets. GFP fed Diet 3 exhibited the darkest color, indicated by the lowest L* value, and the most pronounced red coloration, marked by the highest a* value. Conversely, GFP fed Diet 1 had the highest b* value, and the overall hue was greatest in those fed Diet 2. These findings suggest that the inclusion of 100% FRPO significantly enhances the red coloration of GFP, due to its naturally high carotenoid content (Ng & Gibon 2010). Moreover, Parisenti et al. (2011) noted that prawn darkness is influenced by the amount of astaxanthin. Various factors, including carotenoid availability, stress, temperature, genetics, and photoperiod, affect prawn coloration (Latscha 1989). Rodríguez et al. (2017) explained that crustaceans cannot synthesize carotenoids *de novo* and therefore rely on their diet or metabolic reactions to obtain these pigments. They also discussed that the availability of β-carotene or carotenoids in the diet enables prawns to synthesize astaxanthin. Further supporting this, Kim et al. (2013) observed reddish spots on the exoskeleton of GFP when fed a diet with 100% crude palm oil inclusion. Likewise, Ju, Forster and Dominy (2010) found that prawns fed a diet including palm oil had higher carotenoid content. Reddish coloration is advantageous for prawn aquaculture, as dark red and reddish-orange colors serve as visual indicators of product quality and enhance consumer preference (Wade et al. 2014). However, it is important to note that higher dietary carotenoid content may not promote prawn growth performance. This was suggested by Ju, Forster and Dominy (2010) and corroborated by the current study, where feeding a 100% FRPO diet did not improve GFP growth performance.

In conclusion, the current study found that replacing FO with FRPO is suitable for GFP, as no significant differences were observed in FCR, survival rate, growth performance, and coloration even when 100% FRPO was included. On the other hand, a diet with 100% FRPO improved overall body coloration with significantly higher red-green values and lower lightness values indicating the presence of astaxanthin and carotenoids, which provide a darker and redder body coloration. This suggests that a complete replacement of FO with FRPO as a dietary lipid source for GFP enhances red coloration, potentially increasing market value. However, the best growth performance was observed with a 50% inclusion of FRPO, yielding significantly better results compared to those fed diets with 0% or 100% FRPO. Therefore, future studies should determine the optimal ratio of FRPO to FO for better productivity of GFP farming.

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