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Quality Improvement of Hybrid Catfish Flesh: Physicochemical and Sensory Responses to Functional Additive-Enriched Plant-Based Diets

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ABSTRACT

This research investigated the effects of high-protein plant-based diets supplemented with functional additives on the physicochemical and sensory qualities of hybrid Asian-African catfish (*Clarias macrocephalus* × *Clarias gariepinus*). Dried Papaya Leaves (DPL) with 2% incorporation were added to a commercial diet, and two methods of incorporation were applied: coating on the outer part (2% DPL-coated) and incorporation well into the feed (2% DPL-incorporated). A commercial diet without DPL served as the control. Catfish were reared under controlled conditions and fed experimental diets (4 weeks). The similar values obtained for moisture, protein, and ash contents indicated that the addition of DPL in the commercial diet, regardless of the method of incorporation, did not affect these properties. The lowest values of chewiness, cohesiveness, hardness, and springiness were reported for fish flesh with 2% DPL-incorporated treatments compared to 2% DPL-coated and control treatments, with no significant difference. This sample also revealed significant differences in L*, b*, and ΔE* values compared to the other two samples, resulting in a noticeable flesh colour change magnitude. A similar pattern was observed in both the Hedonic Scale and Qualitative Descriptive Analysis (QDA), suggesting that the sensory attributes evaluated may not have influenced the panellists' scores. In conclusion, the inclusion of 2% DPL as a functional additive in high-protein plant-based diets does not compromise the physicochemical quality or sensory acceptability of hybrid catfish. These findings suggest that DPL has strong potential as a sustainable and natural feed additive for aquaculture applications. Thus, a longer feeding trial (12 weeks) is recommended for future work to better determine the long-term effects of DPL supplementation on the physicochemical and sensory quality of fish flesh.

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1. Introduction

The aquaculture industry in Malaysia is highly diversified, encompassing inland and marine fish farming, diadromous fishes, crustaceans, mollusks, and aquatic plants. By 2015, the total production reached 506,465.25 tonnes, valued at 3.3 billion Malaysian Ringgit. Over the past five years, the sector has grown at an annual average of 10% [1]. Over 30 finfish species are farmed, with African catfish, red tilapia, sea bass, river catfish (*Pangasius* sp.), and red snapper being prominent. The hybrid Asian-African catfish, the species used in this study, is an important farmed fish in Malaysia's aquaculture sector. The Asian catfish (*Clarias macrocephalus*) and the African catfish (*Clarias gariepinus*) were crossbred to create the hybrid catfish. This hybridisation aims to increase growth rate, disease resistance, and adaptability by combining desirable traits from both parents.

Aquaculture industries worldwide face similar challenges, such as rising prices and demand for fish meal, a primary protein source in aquafeeds. Aquafeed is a nutritionally formulated diet designed to meet the requirements of aquatic animals. These issues have created an opportunity to explore other protein sources, such as plant-based or animal-based ingredients [2]. According to the author, substituting fishmeal with plant proteins in species such as Nile tilapia and rainbow trout did not halt fish growth. Aquafeed also acts as an alternative feed source for catfish, replacing animal waste products that may raise *toyibban* (wholesomeness) concerns. Aquafeed is a diet formulated to meet the nutritional requirements of aquatic animals. Notably, the main component of aquafeed is fish meal, which provides most of the protein fish need. However, fish meal is more expensive than animal waste, making aquafeed much pricier [3].

This research examines the effects of a high-protein, plant-based diet on the physicochemical properties and sensory qualities of hybrid catfish species. This study aligns with major concerns regarding the effects of a high-protein plant-based diet on the physicochemical properties and sensory qualities of fish fillets in aquaculture. In addition, incorporating plant proteins such as soybean meal and corn gluten into catfish diets may change the moisture content, crude protein, fat composition, ash levels, and pH of fish muscle, even though these plant proteins are cost-effective and accessible alternatives to fish meal [2]. The nutritional value, shelf life, texture, and quality of the fish fillets are all mainly determined by these physicochemical characteristics. For example, fat and protein levels affect flavour and nutritional value, whereas moisture content influences freshness and shelf life. On the other hand, changes in muscle structure resulting from the addition of plant-based protein may affect the water-holding capacity, firmness, and cooking attributes of the fillets [4,5].

One of the primary concerns is the limited ability of catfish to digest plant-based ingredients, ultimately influencing customer preference, especially in supporting growth performance, flesh quality, and consumer acceptability of the sensory qualities of the catfish. Given the rising interest in sustainable aquaculture and the shift toward high-protein plant-based aquafeed, it is essential to understand how these formulations affect catfish quality attributes. Thus, this study aimed to investigate the physicochemical properties and sensory attributes of hybrid Asian-African catfish fed a high-protein plant-based diet supplemented with functional additives. This study also seeks to determine its viability as a sustainable and consumer-friendly fish meal substitute.

2. Materials and Methods

Materials

The hybrid Asian-African catfish used in this study were farmed at the Aquatic Research Complex, Universiti Sains Malaysia (USM), under a controlled aquaculture environment for a month. All

experimental fish were reared in large tanks with a capacity of 300 gallons (≈1135.62 L), with approximately 15-25 catfish per tank. Three feed formulations (Table 1) were used as experimental diets: control, 2% Dried Papaya Leaves (DPL) coated, and 2% DPL-incorporated. According to [6], 2% DPL incorporation in fish meal contributed to a significant improvement in weight gain for red hybrid tilapia (*Oreochromis mossambicus* x *Oreochromis niloticus*). The control diet was a commercial plant-based diet purchased from the market. The 2% DPL-coated diet was subsequently formulated by adding DPL powder as a surface coating to the control feed. Lastly, for the 2% DPL-incorporated diet, DPL powder was mixed directly into the feed formulation. The fish were farmed for a 4-week feeding trial to produce a marketable size of approximately 150 to 250 g per fish. This feeding trial period was selected based on [7], which reported that 3 to 4 weeks of feeding resulted in a significant increase in body weight. They were then harvested and transported to Universiti Sains Islam Malaysia (USIM) for further analysis. All chemicals and reagents used in this study were analytical grade and purchased from trusted and reputable suppliers such as Sigma-Aldrich and Merck.

Experimental diets

Table 1
Feed composition of the experimental diets

No.	Composition	Control (%)	2% DPL-coated (%)	2% DPL-incorporated (%)
1	Crude Protein	32	32	32
2	Crude Fat	3	3	3
3	Moisture	12	12	12
4	Dried papaya leaf powder	-	2	2

Methods

Catfish preparation

The dead fish were thoroughly washed under clean running water to remove dirt, mucus, blood, and any surface contaminants. Following this, the fish were gutted by making an incision along the belly to remove the internal organs. After gutting, the fish were rinsed again to ensure cleanliness. Each fish was then measured for length and weighed to record its biometric data. Once cleaned and prepared, the fish were carefully filleted using a clean, sharp stainless-steel knife. An incision was made behind the gills, and the knife was guided along the backbone to separate the flesh from the bones. The filleting process ensured that only the edible muscle portions were retained, whereas the bones, skin, head, and remaining internal organs were discarded. The resulting flesh was then placed in clean, food-grade containers and stored in a freezer at -20°C to preserve its freshness, safety, and overall quality for further analysis.

Physical analysis

Moisture

The moisture content of the sample was measured using an oven-drying method, in accordance with [8]. The fish flesh was ground into smaller particles. An analytical balance was used to weigh approximately 3 g of the minced fish sample, which was then placed in a crucible. Following this, the sample was dried in a forced-draft oven for 16 to 18 hours at 105°C until a constant weight was obtained. It was dried, allowed to cool to room temperature in a desiccator, and then weighed again.

The moisture content percentage was determined by dividing the weight difference between the wet and dry samples by the weight of the wet sample. The formula used is as follows:

$$\text{Moisture content } (\%) = \frac{\text{w1} - \text{w2}}{\text{w1}} \times 100,$$

Where, w1 = weight of sample before drying (g),
w2 = weight of sample after drying (g).

Colour

The fish flesh was first washed with clean water and gently patted dry using paper towels to remove surface moisture. The flesh was then ground to obtain a homogeneous sample. Colour analysis of the fish sample was conducted using the CIE L*a*b* colour space system with a colorimeter (LabScan® XE Spectrophotometer, HunterLab). In this system, L* represents lightness, a* indicates redness (+) or greenness (−), and b* denotes yellowness (+) or blueness (−). Prior to measurement, approximately 20 g of each sample was weighed and placed on a designated sample plate. Concurrently, colour values were measured automatically and recorded by the accompanying software according to the manufacturer's instructions.

Texture

Texture analysis of grilled fish flesh samples was performed using a Texture Analyser (Stable Micro Systems, Surrey, UK). The fillets were cut into uniform blocks measuring 2 cm × 2 cm × 0.5 cm and cooked in an oven at 180°C for 20 minutes until a core temperature of 72°C was achieved, without the addition of oil or butter. Furthermore, Texture Profile Analysis (TPA) was conducted to evaluate textural parameters, including chewiness, cohesiveness, hardness, and springiness. A flat-ended cylindrical probe with an 8 mm diameter compressed the samples twice to 60% deformation. The pre-test speed was set at 5 mm/s, the post-test speed at 2 mm/s, with a trigger force of 5 g and a holding time of 5 s. All measurements were performed according to the manufacturer's instructions.

3. Results and Discussion

Physical analysis

Moisture content

Table 2 summarises the moisture content of catfish samples fed different experimental diets. Based on statistical analysis, the results displayed no significant difference ($p > 0.05$) in moisture content among the control, 2% DPL-coated, and 2% DPL-incorporated diets. Moisture content ranged from 5.88 ± 0.15 to 6.24 ± 0.09, suggesting relatively uniform water levels across diets. Although the results were not significant, catfish fed with the 2% DPL-incorporated feed (6.24 ± 0.09) demonstrated a slightly higher mean moisture content compared to the control (6.02 ± 0.28) and 2% DPL-coated sample (5.88 ± 0.15).

Table 2
Moisture content of catfish samples (%) under different experimental diets

Experimental diet	Moisture content (%)
Control	6.02 ± 0.28[a]
2% DPL-coated	5.88 ± 0.15[a]
2% DPL-incorporated	6.24 ± 0.09[a]

These findings suggest that the inclusion of DPL powder, whether it was applied as a coating or incorporated into the diet, did not greatly affect water retention in catfish flesh. Moisture content in fish is largely dependent on intrinsic muscle structure, protein composition, and post-harvest handling rather than minor dietary alterations [9]. Moreover, all catfish samples were obtained from the same species, age group, and rearing environment, and underwent similar processing and storage conditions. Thus, the observed similarity in moisture content is expected. Additionally, these results indicate that adding 2% DPL powder did not negatively affect muscle integrity or cause excessive water loss, which is essential for maintaining textural quality and yield.

Next, although the results were not significant, the slightly higher moisture content may be associated with enhanced protein digestibility due to the presence of papain, a proteolytic enzyme naturally found in papaya leaves. Notably, papain has been reported to enhance protein hydrolysis and nutrient absorption [10], which may influence muscle composition and water retention capacity indirectly. Nonetheless, at the addition level applied in this study (2%), this effect was insufficient to yield a statistically significant change in moisture content.

Remarkably, the catfish fed a 2% DPL-coated diet presented the lowest moisture value. This may be due to applying papaya leaf powder to the feed surface, which could lead to partial enzyme loss during feeding or reduced enzyme interaction during digestion. On the other hand, in comparison to 2% DPL-incorporated feed, where DPL powder is more uniformly distributed throughout the feed matrix.

Colour

The colour parameters (L*, a*, b*, ΔE*) of catfish subjected to different experimental diets are presented in Fig. 1. The L* value (lightness) presented a significant difference ($p < 0.05$), with catfish fed with a 2% DPL-incorporated diet exhibiting the highest L* value (54.53 ± 1.64). This indicates a lighter flesh colour than the control (51.54 ± 0.56) and 2% DPL-coated (49.56 ± 0.85) groups.

The significant increase in L* value for the 2% DPL-incorporated group suggests that adding DPL powder to the diet formulation improved flesh lightness. This increase in lightness may be closely related to the higher moisture content that results from the same treatment. Higher moisture content in fish flesh improves light scattering within the flesh matrix, increasing reflectance and creating a lighter appearance. In addition, flesh lightness is commonly associated with improved flesh quality, water-holding capacity, and greater protein organisation within muscle tissue. Previous studies have presented similar findings, where diet supplementation increases nutrient absorption and muscle hydration, resulting in significant changes in colour parameters, particularly L* values [11]. The uniform integration of DPL into the feed matrix likely ensured a consistent intake of bioactive components, particularly papain. In this sense, it may have improved protein hydration and muscle structure, hence contributing to greater moisture retention and higher flesh lightness.

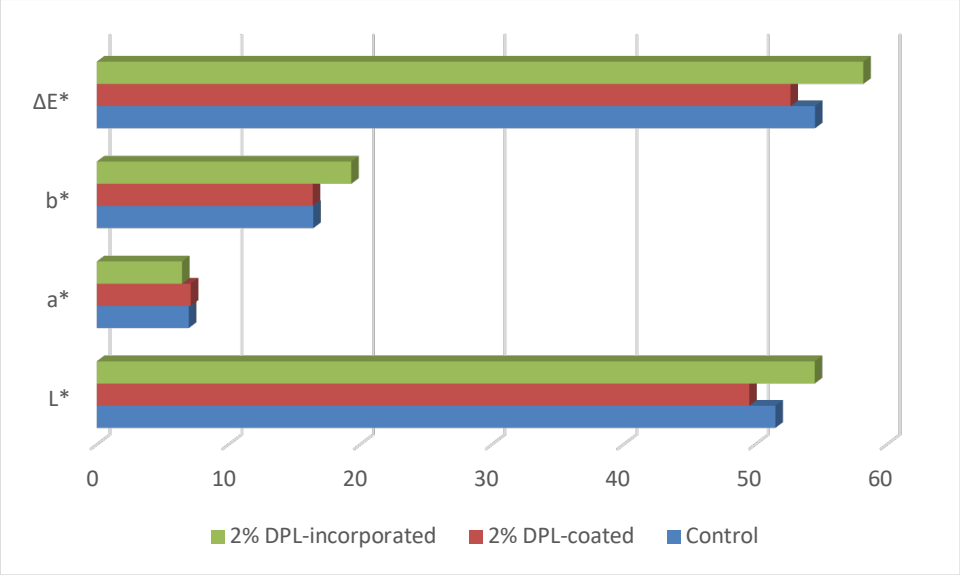


Fig. 1. Colour parameters (L*, a*, b*, ΔE*) of catfish samples under different experimental diets

Additionally, no significant difference ($p > 0.05$) was observed among all treatments in the a* value, indicating that the inclusion of DPL powder did not significantly affect the redness of catfish flesh. Redness in fish flesh is primarily related to myoglobin content and the oxidative state of flesh pigments [12]. The consistent a* values in this study imply that the experimental diet did not cause oxidative stress or modify flesh pigment composition. This aligns with results reported in studies assessing dietary functional additives in fish [13]. This outcome is preferable, as excessive changes in redness may negatively affect consumer preference.

Conversely, significant differences ($p < 0.05$) were observed in the b* value across all groups. The 2% DPL-incorporated treatment recorded the highest b* value (19.33 ± 0.43), indicating increased yellowness. Moreover, the same treatment had the highest overall colour difference (ΔE*), indicating a more noticeable colour change, compared to the control and 2% DPL-coated groups. This may be linked to natural pigments such as chlorophyll derivatives and carotenoid-like substances in papaya leaves. When incorporated into the diet, these compounds are absorbed and deposited more efficiently, leading to visible colour changes.

Texture

The TPA of catfish subjected to different experimental diets (Fig. 2) exhibited no significant differences ($p > 0.05$) in chewiness, cohesiveness, hardness, and springiness. Although minor numerical variations were observed, particularly in hardness and chewiness, these differences were not statistically significant.

Chewiness exhibited a decreasing trend from the control to the 2% DPL-incorporated group, while cohesiveness and springiness remained relatively consistent throughout all the catfish samples under different experimental diets. In comparison, hardness values ranged from 4.76 ± 1.85 to 6.31 ± 0.76, with the control group demonstrating the highest mean, followed by the 2% DPL-coated and 2% DPL-incorporated groups.

These results suggest that the textural properties of catfish were not affected by the inclusion of 2% DPL powder, whether applied as a coating or incorporated into the diet. The additive supplementation level was insufficient to cause major structural modifications in muscle fibre function or connective tissue composition.

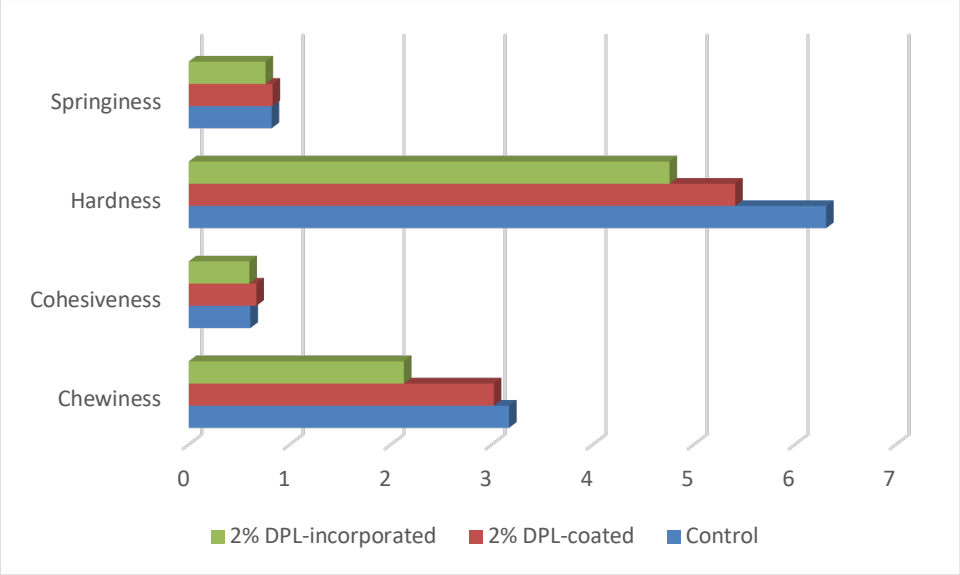


Fig. 2. TPA of catfish samples under different experimental diets

Following this, the uniformly firm texture across all catfish samples may be strongly influenced by rearing conditions rather than feed formulation alone. All experimental fish were raised in large tanks with a capacity of 500 gallons (approximately 2,270 L), with approximately 15 to 25 catfish per tank. The comparatively low number of fish in a large water volume likely encouraged greater swimming activity. Similarly, increased physical activity correlates with improved muscle development, higher muscle fibre density, and enhanced firmness due to muscle contraction during continuous movement. At the same time, fish that swim more actively tend to develop firmer muscle texture, which explains the consistent values observed among catfish samples.

Furthermore, the minimal significant variations in cohesiveness and springiness suggest that the myofibrillar protein network remained structurally stable across all samples. This observation is consistent with the protein content results, where no significant differences were recorded between samples. On a similar note, the correlation between textural qualities, including cohesiveness and hardness, and protein content organisation suggests that similar protein levels support comparable TPA outcomes.

Moisture content may also have influenced textural similarity. High, consistent moisture content across all samples may have masked minor dietary effects on texture by preserving flesh softness and elasticity. In this regard, the comparatively low-fat content reported in this study could explain the lack of excess softness or greasiness, as lipid formation is often linked with reduced hardness and chewiness in fish flesh.

Chemical analysis

Ash

The ash content ranged from 1.25 ± 0.04% to 1.30 ± 0.04% (Fig. 3) and presented no significant difference ($p > 0.05$) among catfish samples fed with different experimental diets. The highest ash value was observed in the catfish fed the 2% DPL-coated diet, while the control group exhibited the lowest ash value. Nevertheless, these differences were minimal and statistically insignificant, indicating similar mineral content across all experimental diet treatments.

Fat content

The fat content of catfish samples fed different experimental diets is displayed in Fig. 3. The study revealed a significant difference ($p < 0.05$) in fat content among the samples. The 2% DPL-incorporated sample exhibited the highest fat content (13.89 ± 0.56%), followed by the control (8.08 ± 0.25%) and 2% DPL-coated samples (7.57 ± 0.22%). According to Tukey's post hoc analysis, the 2% DPL-incorporated group differed significantly ($p < 0.05$) from both the control and 2% DPL-coated groups. In comparison, no significant differences were observed between the control and 2% DPL-coated treatments.

The fat contents recorded in this study fall within the typical lipid range reported for catfish species, indicating that the flesh composition remains nutritionally acceptable and not excessively low. Catfish are generally classified as moderately fatty fish, with lipid content influenced by diet composition, energy balance, and growth performance. Accordingly, the fat content observed in the control and 2% DPL-coated groups reflects normal lipid deposition under plant-based dietary conditions, suggesting that replacing fish meal with plant protein did not affect energy reserves or muscle lipid quality.

The significantly higher lipid content in the 2% DPL-incorporated group may be associated with improved nutrient utilisation efficiency. When DPL powder is incorporated directly into the feed matrix, the bioactive compounds, particularly papain, are likely more stable and uniformly distributed compared to surface coating. Building on this, improved protein digestibility may increase overall metabolic efficiency by allowing extra feed energy to be stored as fat in muscle tissue rather than used solely for maintenance [14]. Thus, enhanced digestive enzyme activity has been reported to improve feed conversion and energy retention in fish.

In contrast, the 2% DPL-coated group exhibited slightly lower fat content compared to the control, although the difference was not statistically significant. This may be due to nutrient leaching during feed immersion in water before ingestion. Surface-coated feeds are generally more susceptible to nutrient loss, potentially reducing lipid availability for absorption [15]. Consequently, the incorporation method appears more effective in preserving additive stability and enhancing nutrient retention.

From a product quality perspective, the observed lipid levels are desirable. Lipid content contributes significantly to flavour, juiciness, and overall palatability of fish flesh [16]. Despite the higher lipid deposition in the 2% DPL-incorporated group, sensory evaluation demonstrated no negative impact on taste or overall acceptability. This implies that the increased fat content remained within a favourable range for consumer preference. Furthermore, lipid distribution within muscle tissue can influence light reflectance [17]. In essence, this may partly explain the higher L* value observed in the incorporated treatment.

Hence, the results indicate that incorporation of 2% DPL powder into high-protein plant-based diets enhances lipid deposition without compromising flesh quality. The fat content remained within a nutritionally acceptable range for catfish, supporting both physiological performance and consumer acceptability.

Protein content

Figure 3 displays the protein content of catfish fed with different experimental diets. According to the statistical analysis used, Analysis of Variance (ANOVA), there was no significant difference ($p > 0.05$) in protein content among the control, 2% DPL-coated, and 2% DPL-incorporated groups. Among the experimental diets, the 2% DPL-incorporated feed recorded the highest mean protein content (18.55 ± 0.26). This was followed by the control feed (17.75 ± 1.04) and the 2% DPL-coated feed (17.53 ± 0.40). Although numerical differences were presented, these variations were not statistically

significant. Such a finding implies that the protein composition of catfish flesh was not significantly affected by the 2% addition of DPL powder (coated or incorporated).

Protein content in fish is mostly determined by the diet protein level, amino acid balance, digestibility, and overall growth performance [18]. Therefore, the similar protein values observed among the treatments were expected, as all experimental diets were formulated to meet basic protein requirements.

In addition, the slightly higher protein content in the 2% DPL-incorporated group may be linked to improved nutrient utilisation, although it was not statistically significant. According to [19], papaya leaves contain bioactive compounds, including papain, alkaloids, flavonoids, and phenolic compounds, which have been confirmed to enhance digestive enzyme activity and protein digestibility in fish. Against this background, papain, a proteolytic enzyme, may facilitate protein breakdown and amino acid absorption, leading to a slight improvement in muscle protein synthesis [18].

In contrast, the lower protein content observed in the 2% DPL-coated group could be associated with decreased bioavailability of these compounds. Feed coating methods may cause partial loss of water-soluble components through leaching when the feed is immersed in water, reducing their physiological effects [15]. This may explain why the coated diet did not exhibit the same nutritional enhancement as the incorporated diet.

Overall, these results indicate that a 2% supplementation of DPL does not adversely affect protein content, hence maintaining the nutritional quality of catfish flesh. Previous studies have reported similar findings, where herbal feed additives enhanced health or digestibility without impacting proximate protein composition. From a product-quality perspective, maintaining consistent protein levels is crucial, as protein content strongly determines fish nutritional value and consumer acceptance.

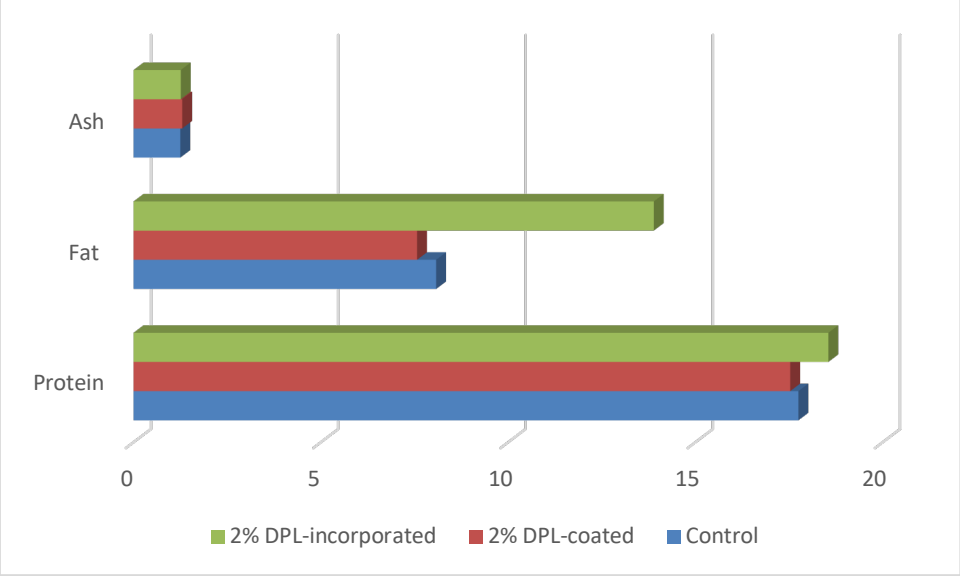


Fig. 3. Chemical analysis of catfish samples under different experimental diets

The results suggest that the lack of significant differences in ash content among treatments indicates that adding 2% DPL powder did not markedly affect mineral formation in catfish flesh. This may be due to the relatively low inclusion rate of DPL, which was insufficient to cause changes in mineral intake or retention compared to the commercial diet. Agbanimu and Adeparusi [21] reported similar findings, where no significant changes in the ash content of African catfish diets added with

plant-based additives at low inclusion levels were observed. This indicates minimal mineral transfer into muscle tissue.

Furthermore, fish muscle mineral content is tightly regulated, with dietary minerals mostly used for metabolic processes or skeletal development rather than stored in edible tissues. Consequently, minor dietary modifications may not be reflected in muscle ash content. The present findings are supported by [22], which reported that plant-derived feed additives typically create functional or physiological effects without significantly altering proximate mineral composition, unless applied at higher concentrations or over extended feeding duration.

The similar ash content across the catfish samples also aligns with trends in other proximate parameters, such as protein and fat content, which demonstrated minimal changes. This indicates that DPL inclusion did not significantly modify the overall nutritional value of the fish flesh. Additionally, the relatively uniform moisture content among the samples may have influenced the similar ash values, since moisture changes can affect ash concentration through dilution effects within the flesh matrix.

Sensory evaluation
9-Point hedonic test

Figure 4 displays the mean hedonic scores for appearance, colour, texture, taste, and overall acceptability of catfish samples fed with different experimental diets. Based on the results, all samples achieved mean scores above the midpoint of the 9-point hedonic scale, signifying general consumer acceptability.

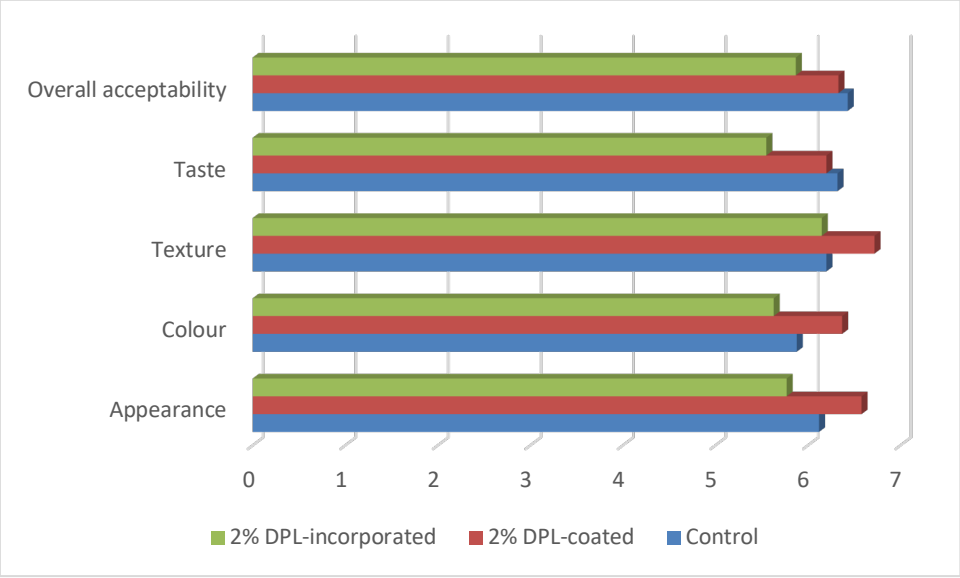


Fig. 4. Mean hedonic scores (Sensory evaluation) of catfish samples under different experimental diets

For appearance and colour parameters, the 2% DPL-coated group scored significantly higher than the 2% DPL-incorporated group ($p < 0.05$), whereas the control group yielded intermediate values. Despite this, texture, taste, and overall acceptability attributes demonstrated no significant difference ($p > 0.05$), suggesting that the inclusion of the functional additive of 2% DPL did not cause a significant change in these sensory qualities.

The relatively higher sensory scores recorded in the 2% DPL-coated group may be attributed to differences in the dietary inclusion method of DPL powder. Feed coating may facilitate more uniform

exposure of catfish to bioactive compounds, potentially affecting flesh characteristics and post-cooking appearance. Nonetheless, further studies are required to verify the underlying mechanism.

On the contrary, catfish fed with a 2% DPL-incorporated diet presented lower sensory mean scores across most attributes, particularly appearance, colour, and overall acceptability. Nevertheless, these differences were not statistically significant. These lower scores are likely affected by processing-related factors rather than the diet formulation itself. During sample preparation, all fish fillets were grilled under standardised temperature and time conditions. However, the incorporated catfish appeared less thoroughly cooked compared to the control and coated groups. This observation can be linked to variation in fish size, as the incorporated catfish were larger (approximately 200-300 g) than those in the control (150-250 g) and coated groups (100-200 g), despite being reared for the same period (one month). In essence, larger fish typically require longer cooking time to ensure uniform heat distribution, and inadequate cooking may adversely affect appearance, colour development, and texture perception.

At the same time, no significant differences were observed in texture, taste, or overall acceptability among the groups, suggesting that the 2% dietary inclusion of DPL did not negatively affect palatability. Furthermore, from a textural perspective, the sensory texture scores align with the instrumental TPA results, which detected no significant differences in firmness or chewiness among catfish samples. This agreement between instrumental and sensory analyses strengthens the conclusion that dietary DPL addition did not compromise consumer acceptance of textural quality. Together, these findings are also consistent with previous research that moderate amounts of plant-based additives do not adversely influence the sensory qualities of fish flesh.

Overall, the results indicate that dietary addition of 2% DPL, particularly when applied through feed coating, is acceptable. Meanwhile, the slightly lower mean scores in the incorporated group are more likely related to fish size and cooking consistency rather than the intrinsic effects of the diet formulation.

Qualitative Descriptive Analysis (QDA)

Figure 5 illustrates the radar plot profiles of sensory qualities for catfish samples fed control, 2% DPL-coated, and 2% DPL-incorporated diets. The sensory profiles of all samples displayed a similar shape, implying comparable sensory attributes in aroma, taste, mouthfeel, and colour. In particular, the control and 2% DPL-coated samples exhibited slightly larger polygon regions, particularly for texture intensity. This indicates firmer and more structured flesh. In contrast, the 2% DPL-incorporated sample revealed a visibly reduced radius along the texture axis, confirming lower texture intensity evaluated by trained panellists. The smaller sensory polygon likely reflects differences in perceived doneness during oven grilling rather than an intrinsic diet effect, as the 2% DPL-incorporated sample appeared less fully cooked under similar grilling conditions. In this sense, the significant overlap across the remaining sensory axes suggests that DPL addition did not disrupt the overall sensory balance of catfish.

Aroma

Aroma intensity, classified in this study as the perceived freshness aroma of the grilled catfish samples ranging from none to strong, was generally low among catfish samples fed the control, 2% DPL-coated, and 2% DPL-incorporated diets. Despite this, no significant difference ($p > 0.05$) was observed among the groups. This indicates that including 2% DPL powder did not adversely affect the perceived freshness of catfish flesh.

The overall lower aroma intensity can be associated with the post-harvest handling and storage conditions of the samples. The catfish were first stored at -20°C and then transported in ice-filled containers prior to sensory evaluation. Freezing and thawing can reduce freshness-related aroma intensity by inhibiting volatile compound production and altering muscle structure. Thus, it reduces the perception of fresh fish aroma after cooking. Likewise, freeze-thaw cycles may accelerate subtle oxidative changes that mask the clean, fresh aroma without necessarily producing strong off-odours.

In addition, although the intensity of freshness aroma was decreased, trained panellists did not detect significant off-odours such as sour, rancid, or ammonia-like treatment. This indicates that although freezing reduced aroma intensity, it did not impair overall sensory quality or introduce spoilage symptoms. Importantly, the similar aroma scores across treatments suggest that adding DPL powder did not worsen aroma perception.

Moreover, oven grilling regulates aroma development by encouraging thermal reactions that primarily influence aroma formation, reducing treatment variability. The consistency between the Qualitative Descriptive Analysis (QDA) aroma results and the 9-point hedonic test presented no significant differences in overall acceptability. It further supports the conclusion that DPL supplementation does not negatively impact freshness aroma, even under frozen storage conditions.

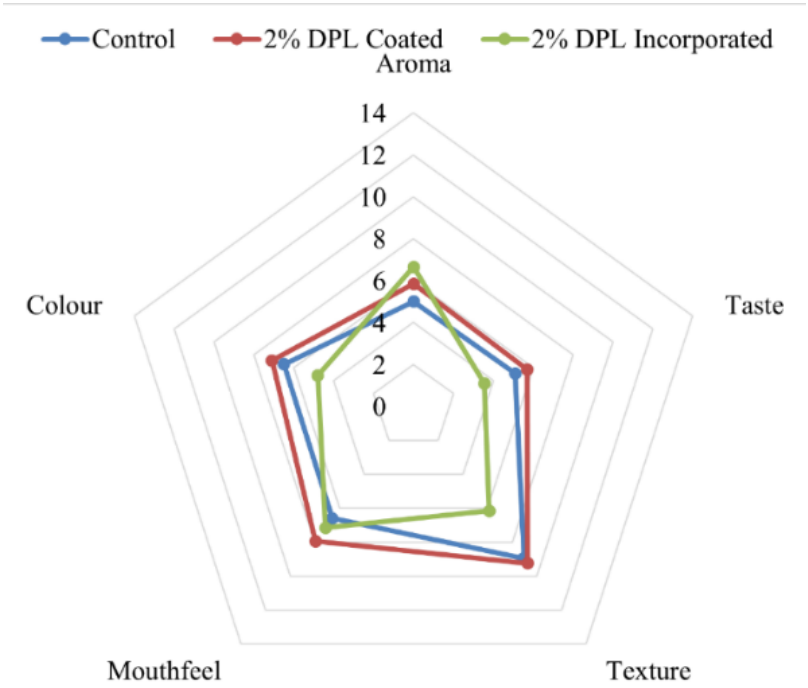


Fig. 5. QDA of catfish samples under different experimental diets

Taste

The taste intensity did not exhibit significant differences ($p > 0.05$) between the control, 2% DPL-coated, and 2% DPL-incorporated samples. Significantly, trained panellists did not observe a noticeable increase in bitterness in either of the DPL treatments. Such an observation indicates that the inherent bitterness associated with papaya leaves did not appear in the sensory characteristics of catfish flesh.

DPL are known to possess a bitter taste due to the presence of alkaloids, phenolic compounds, and other secondary metabolites [21]. However, these compounds are predominantly metabolised during digestion and are unlikely to be directly deposited in muscle tissue. In fish, flavour perception is primarily influenced by water-soluble taste-active molecules such as free amino acids, small peptides, and nucleotides, rather than the dietary plant formulation [24]. Given that the proximate

analysis presented no significant difference in protein content among treatments, the taste-active compounds that contribute to umami and overall flavour are expected to be comparable across treatments.

In addition, the absence of bitterness perception among trained panellists aligns with the 9-point hedonic taste scores, which resulted in no significant differences between treatments. This agreement between descriptive and hedonic evaluations indicates that DPL inclusion at 2% does not affect taste quality or introduce undesirable bitterness in catfish flesh.

Texture

The texture intensity ranged from soft to firm, and the 2% DPL-incorporated sample exhibited the lowest value. During sample preparation, the sample appeared less thoroughly cooked despite being cooked at the same temperature and duration as the other treatments. This may be associated with a combination of factors. First, the catfish fed the 2% DPL-incorporated diet were originally larger (approximately 200-300 g) compared to the control (150-250 g) and 2% DPL-coated group (100-200 g). This may have caused subtle variations in muscle density or thickness despite being cut to the same size. Second, the slightly higher moisture content of the 2% DPL-incorporated sample may have encouraged greater moisture release during cooking, creating a more concentrated steaming effect that reduced surface temperature and slowed protein denaturation. These factors can yield a lower perceived firmness and softer bite, without regard to dietary influences.

Furthermore, the instrumental TPA revealed no significant differences in chewiness, cohesiveness, hardness, and springiness among the samples. This implies that the lower texture intensity reported by trained panellists in QDA may suggest differences in cooking thoroughness rather than intrinsic changes in muscle structure caused by the diet formulation. Consequently, the QDA texture outcome likely signifies a processing-related factor rather than a genuine negative impact of DPL inclusion on flesh texture.

Mouthfeel

Mouthfeel intensity exhibited no significant difference ($p > 0.05$) among the control, 2% DPL-coated, and 2% DPL-incorporated samples. In the context of this study, mouthfeel generally reflected the residual aftertaste experienced after swallowing, rather than textural characteristics such as juiciness or lubrication. The results suggest that the addition of DPL powder did not result in unpleasant aftertaste or lingering sensations in the catfish flesh.

Residual aftertaste in fish products is often linked to persistent bitterness, astringency, and metallic flavours, which may originate from lipid oxidation products or secondary metabolites from plants. Although DPLs are known to taste bitter, trained panellists did not detect lasting bitterness or a herbal aftertaste in either 2% DPL-coated or 2% DPL-incorporated products. This indicates that bitter compounds from papaya leaves were either metabolised during digestion, present at concentrations below sensory thresholds, or effectively masked during thermal processing.

In addition, the cooking procedure may have reduced residual aftertaste by promoting flavour development through heat-induced mechanisms. This may minimise the persistence of any plant-related flavour profiles. Moreover, the absence of significant differences in mouthfeel supports the taste results, as no bitterness was detected, and aligns with the 9-point hedonic evaluations, which yielded similar taste value and overall acceptability among all samples. In general, these findings indicate that 2% DPL supplementation does not negatively affect the residual aftertaste of hybrid catfish flesh.

Colour

Although instrumental colour analysis revealed significant differences in L* and b* values, QDA colour intensity did not differ significantly ($p > 0.05$) among treatment groups. This emphasises the difference between instrumental sensitivity and human visual perception.

Human colour perception combines surface reflectance, transparency, and contextual information rather than relying on absolute colour coordinates [25]. Hence, the numerical differences observed using instruments were likely below the sensory detection threshold of trained panellists. Similar inconsistencies between instrumental colour measurements and sensory perception have been widely reported in fish and meat products [26].

4. Conclusions

Overall, the results demonstrated that the inclusion of 2% DPL, regardless of application technique, did not adversely affect the physicochemical characteristics of catfish flesh. Moisture, protein, and ash contents exhibited no significant differences among treatments, indicating that the nutritional quality and mineral composition of the fish were well maintained. Although fat content differed significantly, the values remained relatively low across all samples, reflecting a generally lean flesh profile. Meanwhile, the slightly higher fat content observed in the 2% DPL-incorporated group suggests improved nutrient stability and utilisation when the additive is uniformly integrated into the feed matrix.

Instrumental colour analysis revealed significant differences in lightness (L*) and yellowness (b*), with the 2% DPL-incorporated group exhibiting lighter and more yellow flesh colour. These changes were likely associated with higher fat content in these fish. However, these instrumental differences were not perceived as significant by trained panellists during QDA, highlighting that numerical colour variations remained within acceptable sensory thresholds.

TPA presented no significant differences in chewiness, cohesiveness, hardness, or springiness among treatments, suggesting that adding DPL at 2% did not change muscle structure or integrity. Sensory evaluation using a 9-point hedonic test further supported these findings, as all samples achieved acceptable scores for appearance, texture, taste, and overall acceptability. Notably, the slightly lower sensory scores observed in the 2% DPL-incorporated group were attributed to processing-related factors. This is particularly true for cooking uniformity associated with larger fish size and higher moisture content, rather than intrinsic effects of the diet formulation.

Concurrently, QDA supported the conclusion that dietary DPL supplementation did not negatively influence aroma, taste, mouthfeel, or colour perception. Minor differences in texture intensity were again linked to cooking conditions rather than feed composition. Collectively, these findings indicate that DPL can be safely incorporated into high-protein plant-based diets for hybrid catfish without compromising flesh quality or consumer acceptability.

In conclusion, incorporating 2% DPL as a functional additive in aquafeed represents a promising and sustainable alternative to conventional feed additives. The results support its potential application in aquaculture while maintaining the physicochemical stability and sensory quality of catfish flesh. Fig. 6 summarises the research and related results.

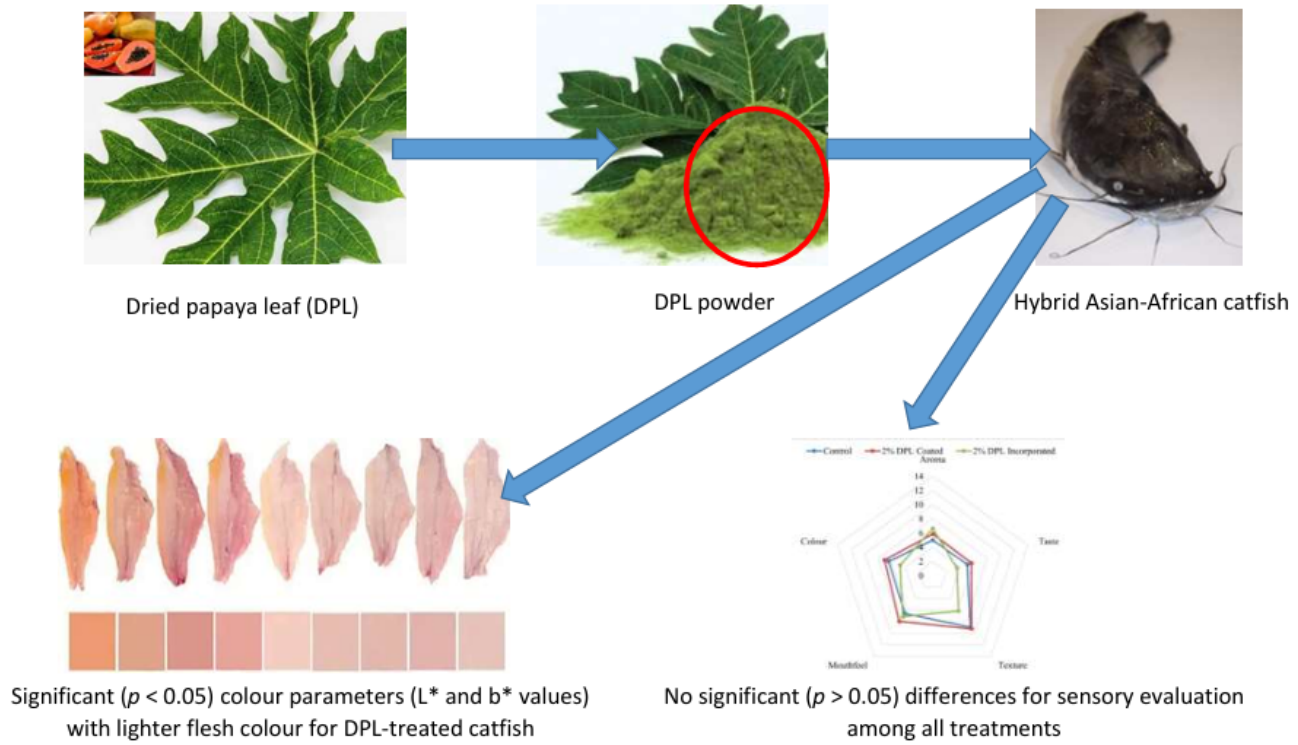


Fig. 6. Graphical summary of research done

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References

[1] FAO 2021. AQUASTAT [WWW Document]. AQUASTAT. URL http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en (accessed 9.4.20)

[2] Dani, D. 2018. "A Review on Replacing Fish Meal in Aqua Feeds using Plant Protein Sources". *International Journal of Fisheries and Aquatic Studies* 6 (2): 164–179.

[3] Ghamkhar, R. and Hicks, A., 2020. "Comparative Environmental Impact Assessment of Aquafeed Production: Sustainability Implications of Forage Fish Meal and Oil Free Diets". *Resources, Conservation and Recycling*, *161*, p.104849. https://doi.org/10.1016/j.resconrec.2020.104849

[4] Ng, W. K. and Chen, M. L., 2002. "Replacement of Soybean Meal with Palm Kernel Meal in Practical Diets for Hybrid Asian-African Catfish, Clarias macrocephalus × C. gariepinus". *Journal of Applied Aquaculture*, *12*(4), pp.67-76. https://doi.org/10.1300/J028v12n04_06

[5] Dauda A. B., Natrah I., Karim M., Kamarudin M. S. and Bichi A. H. 2018. "African Catfish Aquaculture in Malaysia and Nigeria: Status, Trends and Prospects". *Fish Aqua Journal* 9 (1). https://doi.org/10.4172/2150-3508.1000237

[6] Hamid, N.K.A., Somdare, P.O., Harashid, K.A.M., Othman, N.A., Karim, Z.A., Lee, S.W. and Dawood, M.A.O. (2022) Effect of papaya (Carica papaya) leaf extract as a dietary growth promoter supplement in red hybrid tilapia (Oreochromis mossambicus x Oreochromis niloticus) diet. *Saudi Journal of Biological Science*, 29, pp 3911–3917. https://doi.org/10.1016/j.sjbs.2022.03.004

[7] Lee, S., Zhai, S., Deng, D-F., Li, Y., Blaufuss, P.C., Eggold, B.T. and Binkowski, F. (2022) Feeding Strategies for Adapting Lake Sturgeon (Acipenser fulvescens) Larvae to Formulated Diets at Early Life Stages. *Animals*, 12, 3128. https://doi.org/10.3390/ani12223128

[8] AOAC 2005. Official Method Analysis. 18th Edition, Association of Official Analytical Chemists, Washington DC.

[9] Parvej, A. M., Rahman, M., Abdullah, M., Siddique, A. and Joardder, M. U. H. 2024. "Evaluation of Mechanical Properties of Dried Fish from Convective and Pulsed Microwave Convective Drying: A Comparison Study". *Measurement: Food*, 14, 100172. https://doi.org/10.1016/j.meafoo.2024.100172

[10] Rachmawati, D. and Prihartono, A. A., 2019. "Effect of Papain Enzyme Supplementation on Growth Performance and Nutrient Utilization of Catfish (Pangasius hypopthalmus)". *Malaysian Applied Biology*, 48 (5), pp.1-10. https://jms.mabjournal.com/index.php/mab/article/view/1581/173

[11] Hien, T. T. T., Loc, T. V., Tu, T. L. C., Phu, T. M., Duc, P. M., Nhan, H. T. and Liem, P. T. 2022. "Dietary Effects of Carotenoid on Growth Performance and Pigmentation in Bighead Catfish (Clarias macrocephalus günther, 1864). *Fishes* 7 (1): 37. https://doi.org/10.3390/fishes7010037

[12] Pujol, A., Ospina-E, J. C., Alvarez, H. and Muñoz, D. A. 2023. "Myoglobin Content and Oxidative Status to Understand Meat Products' Color: Phenomenological Based Model". *Journal of Food Engineering,* 348*,* 111439. https://doi.org/10.1016/j.jfoodeng.2023.111439

[13] Li, D., Chen, W., Yin, Y., Yang, L., Chen, M., Sun, Y. and Ye, J. 2024. "Effects of Carnosine Addition in Low-Fishmeal Feed on the Growth Performance, Muscle Antioxidant Capacity and Flesh Quality of Orange-Spotted Grouper (Epinephelus coioides)". *Fishes* 9 (11): 467–467. https://doi.org/10.3390/fishes9110467

[14] Jobling, M., 1994. "Fish bioenergetics". *Fish and fisheries series*, *13*.

[15] Ighwela, K. A., Ahmad, A. B. and Abol-Munafi, A. B., 2014. "Water Stability and Nutrient Leaching of Different Levels of Maltose Formulated Fish Pellets". *arXiv preprint arXiv:1409.5062*. https://doi.org/10.48550/arXiv.1409.5062

[16] Yildirim-Aksoy, M., Shelby, R., Lim, C. and Klesius, P. H. 2007. "Growth Performance and Proximate and Fatty Acid Compositions of Channel Catfish, *Ictalurus Punctatus*, Fed for Different Duration with a Commercial Diet Supplemented with Various Levels of Menhaden Fish Oil". *Journal of the World Aquaculture Society* 38: 461-474.

[17] Nielsen, S.S., 2017. "Introduction to food analysis". In *Food analysis* (pp. 3-16). Cham: Springer International Publishing.

[18] Radhakrishnan, G., Shivkumar, V. S. M., Yashwanth, B. S., Pinto, N., Pradeep, A. and Prathik, M. R., 2020. "Dietary protein requirement for maintenance, growth, and reproduction in fish: A review". *Journal of Entomology and Zoology Studies*, 8 (4), pp.208-215.

[19] Tadese, D. A., Song, C., Sun, C., Liu, B., Liu, B., Zhou, Q., Xu, P., Ge, X., Liu, M., Xu, X., Tamiru, M., Zhou, Z., Lakew, A. and Kevin, N. T. 2021. "The Role of Currently used Medicinal Plants in Aquaculture and Their Action Mechanisms: A Review". *Reviews in Aquaculture 14* (2): 816–847. https://doi.org/10.1111/raq.12626

[20] Somdare, P., Badaki, J., Faokunla, O. and Ogbe, K. 2025. "Effect of Papaya Leaf Powder as a Feed Additive on Growth Performance and Haematological Parameters of African Catfish (Clarias gariepinus)". *Scientia Africana* 24 (1): 191–204. https://doi.org/10.4314/sa.v24i1.18

[21] Agbanimu, A. B. and Adeparusi, E. O. 2020. "Growth Performance and Nutrient Utilization of African Catfish (Clarias gariepinus) Juveniles Fed Varying Inclusions of Defatted African Palm Weevils (Rhynchophorus phoenicis) Meal". *Aquaculture Studies*, 73–79. https://doi.org/10.4194/2618-6381-v20_2_01

[22] Gatlin, D. M., Barrows, F. T., Brown, P., Dabrowski, K., Gaylord, T. G., Hardy, R. W., Herman, E., Hu, G., Krogdahl, Å., Nelson, R., Overturf, K., Rust, M., Sealey, W., Skonberg, D. J., Souza, E., Stone, D., Wilson, R. and Wurtele, E. 2007. "Expanding the Utilization of Sustainable Plant Products in Aquafeeds: A Review. *Aquaculture Research* 38 (6): 551–579. https://doi.org/10.1111/j.1365-2109.2007.01704.x

[23] Kam, N., Setiadi, J. F., Hardoko, H. and Rosa, D. 2022. "Correlation between Bitterness Removal and Functional Properties of Papaya (Carica papaya L.) Leaves". *Indonesian Food Science & Technology Journal* 5 (2): 71–75. https://doi.org/10.22437/ifstj.v5i2.14800

[24] Hu, Y., Xiao, N., Ye, Y. and Shi, W. 2022. "Fish Proteins as Potential Precursors of Taste-Active Compounds: An *In Silico* Study". *Journal of the Science of Food and Agriculture* 102 (14): 6404–6413. https://doi.org/10.1002/jsfa.12006

[25] Foster, D. H. 2011. "Color Constancy". *Vision Research* 51 (7): 674–700. https://doi.org/10.1016/j.visres.2010.09.006

[26] Bland, J. M., Bett-Garber, K. L., Li, C. H., Brashear, S. S., Lea, J. M. and Bechtel, P. J. 2018. "Comparison of Sensory and Instrumental Methods for the Analysis of Texture of Cooked Individually Quick Frozen and Fresh-Frozen Catfish Fillets. *Food Science & Nutrition* 6 (6): 1692–1705. https://doi.org/10.1002/fsn3.737