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Review

# Bioactive compounds of dragon fruit peel: roles of phenolics, flavonoids, tannins, betalains and vitamin C in modulating fish growth, antioxidant defense, and immunity: a sustainable nutraceutical approach for enhancing aquaculture health and disease resistance

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**Abstract**
Dragon fruit peel, an agro-industrial by-product, has gained considerable attention across various sectors, including aquaculture, due to its rich composition of functional compounds beneficial to aquatic animals. This review focuses on the major bioactive phytochemicals present in dragon fruit peel, namely phenolic compounds, flavonoids, tannins, and betalains, along with the essential nutrient vitamin C. It provides a comprehensive overview of these components, including their chemical characteristics and functional roles in fish nutrition when incorporated into diets. In addition, the effects of dragon fruit peel supplementation in aquaculture are discussed based on findings from various studies to enhance current understanding. Collectively, these bioactive constituents have been reported to improve growth performance, enhance feed utilization, strengthen antioxidant defence systems, and promote intestinal health through modulation of gut microbiota and immune-related pathways.

**Keywords:** antioxidant defence; betalains; bioactive compounds; dragon fruit peel; fish nutrition; flavonoids; functional feed additives; gut microbiota; phenolics; tannins; vitamin C

## 1 | INTRODUCTION
The aquaculture sector has experienced rapid expansion and is recognized as one of the fastest-growing food producing industries (FAO 2020), largely driven by the in-

creasing demand for affordable and nutritionally rich sources of animal protein. This rapid growth has led to a greater need for nutritionally balanced aquafeeds, highlighting the importance of identifying sustainable and cost-effective feed ingredients. Conversely, conventional feed ingredients represent a significant portion of production costs, contributing to the rising price of aquafeeds. Ingredients such as fish meal and soybean meal have become increasingly expensive due to their high demand and limited availability (Naylor *et al*. 2021). This has encouraged the exploration of alternative, non-conventional feed resources, particularly plant by-products and agricultural wastes that possess high nutritional value while remaining relatively inexpensive. Many of these plant-derived residues are also rich in bioactive compounds such as phenolics, flavonoids, and carotenoids, which can function as phytogenic feed additives. These phytogenic compounds are known to enhance feed utilization, improve digestive activity, and promote the health status of cultured species, making plant by-products a promising sustainable ingredient in aquafeed formulations (Citrasu 2010). Among these plant by-products, Dragon fruit peel (DFP) has gained increasing attention as a promising functional ingredient in aquafeeds due to its rich nutritional composition and abundance of bioactive compounds. DFP represents the major by-product generated during the consumption and industrial processing of the fruit, constituting approximately 30–35% of the total fruit mass (Li *et al*. 2022). Although commonly discarded as waste, this portion of the fruit contains a wide range of valuable phytonutrients (Arivalagan *et al*. 2021). Studies have reported that dragon fruit peel (DFP) is particularly rich in bioactive compounds such as phenolic compounds, betalains, flavonoids, tannins, and various fatty acids (Jimenez-Garcia *et al*. 2022; Le 2022). Furthermore, it serves as an important source of pectin (Liu *et al*. 2023), a dietary polysaccharide recognized for its potential prebiotic effects (Guo *et al*. 2023). These bioactive components are known to exert several beneficial biological activities, including modulation of lipid metabolism as well as anti-inflammatory, anti-angiogenic, antibacterial, antiproliferative, and cytotoxic effects (Le 2022). Given the presence of these valuable bioactive constituents, dragon fruit peel has attracted increasing research interest as a potential functional ingredient. Therefore, the present review aims to summarize the chemical composition and bioactive constituents of dragon fruit peels, highlight their functional properties, and review the existing research on their application as a potential feed ingredient in aquaculture.

## 2 | METHODOLOGY

The current review sought to deliver a comprehensive overview of the bioactive compounds found in dragon fruit peel (DFP) and explore their possible uses in aquaculture. To achieve this, pertinent literature was gathered from leading scientific databases such as Web of Science, Scopus, Google Scholar, ScienceDirect, and PubMed. The search for literature extended up to the year 2025, employing combinations of keywords including "dragon fruit peel", "pitaya peel", "*Hylocereus*", "bioactive compounds", "phenolics", "flavonoids", "betalains", "tannins", "vitamin C", "aquaculture", "fish nutrition", "growth performance", "antioxidant activity", "immune response", "pigmentation", and "disease resistance".

The search covered studies published between 2000 to 2025, though earlier works were also referenced if they offered essential insights into the chemistry, classification, and biological characteristics of certain compounds. The focus was mainly on peer-reviewed articles written in English. The selection of studies was guided by their pertinence to the composition of DFP and its impact on growth performance, antioxidant status, immune responses, pigmentation, and disease resistance in aquatic species. Additionally, investigations into individual bioactive compounds from sources other than DFP were included to shed light on their potential roles in aquaculture.

## 3 | COMPOSITION OF DRAGON FRUIT PEELS

Dragon fruit (*Hylocereus* spp.) is a climbing cactus belonging to the Cactaceae family, native to the tropical and subtropical forest regions of Mexico and Central and South America (Rodriguez *et al*. 2016; Mercado-Silva 2018). Since its origin, it has been widely distributed to tropical and subtropical regions across America, Asia, Australia, and the Middle East, and is currently cultivated in at least 22 countries within tropical zones (Mizrahi and Nerd 1999; Nobel and De la Barrera 2002). The crop thrives under high temperatures ranging from 30 to 45°C and in areas with prolonged daylight (Hernandez and Salazar 2012). Dragon fruit is primarily categorized into three types based on peel and flesh colour: red flesh with red peel (RP), white flesh with red peel (WP), and white flesh with yellow peel (YP). The most commonly cultivated species are *Hylocereus polyrhizus* (RP), *Hylocereus undatus* (WP), and *Hylocereus megalanthus* (YP) (Le Bellec *et al*. 2006).

Dragon fruit peel (DFP), a major by-product of processing, constitutes approximately 22–44% of the total fruit weight and is commonly discarded, particularly in the beverage industry (Liaotrakoon *et al*. 2012; Li *et al*. 2022). Despite being treated as waste, the peel represents a valuable reservoir of nutrients and bioactive compounds. Both pulp and peel possess high moisture content and are rich in dietary fibre, vitamins, minerals, and antioxidants (Perween *et al*. 2018; Tables 1–3). Notably, dragon fruit peels contain substantial amounts of pectin and dietary fibre (60–80% in dried form), highlighting their potential as an alternative fibre source (Zhuang *et* *al*. 2012; Madane *et al*. 2020; Zaid *et al*. 2020).

The peel is also recognised as a rich source of phytochemicals, including phenolic compounds, flavonoids, fatty acids, polysaccharides, terpenoids, and pigments such as betalains, particularly betacyanins (Jiang *et al*. 2021; Jimenez-Garcia *et al*. 2022; Roriz *et al*. 2022). These compounds contribute to strong antioxidant, antibacterial, anti-inflammatory, and anti-proliferative activities (Wu *et al*. 2006; Manihuruk *et al*. 2017). The presence of natural pigments such as betacyanins and anthocyanins also makes dragon fruit peel a promising source of natural colorants for food applications (Nur *et al*. 2023).

The recovery and utilisation of bioactive compounds from DFP not only offer health benefits but also contribute to waste valorisation and environmental sustainability (Le 2022). Processing methods such as drying can yield approximately 100 g of peel powder from 1 kg of fresh peel, which can be used as a functional ingredient or feed additive for terrestrial and aquatic animals (Matra *et al*. 2021). Therefore, the incorporation of dragon fruit peel into value-added products presents a promising strategy to reduce agro-industrial waste while enhancing nutritional and functional benefits (Chumroenvidhayakul *et al*. 2023; Rifna *et al*. 2023).

**TABLE 1** Proximate compositions of dragon fruit peels.

| Species | Proportion (%) | | | | | Source |
|---|---|---|---|---|---|---|
| | Protein | Fat | Fibre | Ash | Carbohydrate | |
| *Hylocereus polyrhizus* | 6.38 | 0.77 | - | 18.51 | 67.70 | Hotmaida and Sutrisno (2020) |
| *Hylocereus undatus* | 10.36 | 2.34 | 56.91 | 4.48 | 25.91 | Madane *et al.* (2020) |
| *Hylocereus polyrhizus* | 9.44 | 0.81 | 18.91 | 15.59 | - | Anandari *et al.* (2025) |
| *Hylocereus undatus* | 6.37 | 1.06 | 65.2 | 15.91 | 5.68 | Chumroenvidhayakul *et al.* (2025) |
| Red-fleshed | 4.35 | 1.28 | 21.34 | 16.74 | - | Cacatian and Guittap (2018) |
| *Hylocereus undatus* | 8.78 | - | 33.84 | 17.93 | - | Xuan *et al.* (2024) |
| *Hylocereus polyrhizus* | 6.03 | 6.14 | 59.83 | 4.34 | - | Biswas *et al.* (2022) |
| *Hylocereus polyrhizus* | 5.96 | 6.14 | 23.68 | 10.60 | 43.32 | Biswas *et al.* (2025) |
| *Hylocereus undatus* (WW) | 1.28 | 3.26 | 0.98 | 2.22 | 5.16 | Gautam *et al.* (2024) |
| *Hylocereus undatus* (DW) | 9.93 | 25.31 | 7.60 | 17.23 | 40.06 | Gautam *et al.* (2024) |
| *Hylocereus polyrhizus* | 5.5 | <0.0005 | 70.3 | 16.1 | 74.1 | Reterta and Trinidal (2018) |
| *Hylocereous polyrhizus* | 1.23 | 1.02 | 28.95 | 3.96 | 5.87 | Nur *et al.* (2023) |
| *Hylocereus undatus* | 0.29 | 0.51 | 29.33 | 1.96 | 4.99 | Nur *et al.* (2023) |
| *Hylocereous polyrhizus* (fresh peel) | 6.39 | 2.46 | 31.40 | 14.29 | 4 | Chia and Chong (2015) |
| *Hylocereous polyrhizus* (dried peel) | 6 | 6.20 | 23.75 | 10.57 | 47.78 | Chia and Chong (2015) |
| *Hylocereus polyrhizus* | 5.08 | 4.80 | 26.22 | 21.35 | 50.74 | Aprilia and Rakhmawati (2021) |

WW = Wet weight; DW = dry weight

**TABLE 2** Bioactive components present in dragon fruit peels.

| Species | Total phenolic | Total flavonoids | Betalains (betacyanin) | Total tannin | Total carotenoid | Source |
|---|---|---|---|---|---|---|
| *Hylocereus undatus* | 454.79 mg of GAE | - | 335.34 mg of BE $g^{-1}$ powder | - | - | Chumroenvidhayakul *et al.* (2025) |
| *Hylocereus polyrhizus* | 65.71 mg GAE 100 $g^{-1}$ | - | - | - | 1.87 mg $kg^{-1}$ | Biswas *et al.* (2022) |
| *Hylocereus polyrhizus* | 0.34 mg GAE $g^{-1}$ | 53.32 mg QE $g^{-1}$ | - | - | - | Biswas *et al.* (2025) |
| *Hylocereus undatus* (fresh) | 134.3 mg GAE 100 $g^{-1}$ | 90.36 mg QE $100g^{-1}$ | 143.02 µg $100g^{-1}$ | 360.12 mg TAE $100g^{-1}$ | - | Gautam *et al.* (2024) |
| *Hylocereus undatus* (dried) | 64.9 mg GAE 100 $g^{-1}$ | 56.34 mg QE $100g^{-1}$ | 52.34 µg $100g^{-1}$ | - | - | Gautam *et al.* (2024) |
| *Hylocereus polyrhizus* (fresh) | 7.95 mg GAE $g^{-1}$ | - | 41.55 mg $g^{-1}$ | - | - | Chia and Chong (2015) |
| *Hylocereus polyrhizus* (dried) | 7.84 mg GAE $g^{-1}$ | - | 80.21 mg $g^{-1}$ | - | - | Chia and Chong (2015) |

*GAE: Gallic acid equivalent, BE: Betanin equivalent, TAE: Tannic acid equivalent

**TABLE 3** Vitamin c and minerals content in dragon fruit peels.

| Species | Vitamin C (mg 100g$^{-1}$) | Amount (mg kg$^{-1}$) | | | Amount (g kg$^{-1}$) | | | | | Source |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Cu | Zn | P | Ca | Fe | Mg | K | Na | |
| *Hylocereus polyrhizus* | 9.81 | 4.78 | 1.86 | 13.76 | 11.74 | 4.41 | 5.43 | 15.97 | 1.99 | Nur *et al.* (2023) |
| *Hylocereus undatus* | 9.66 | 4.52 | 2.06 | 10.57 | 17.82 | 1.18 | 8.74 | 10.82 | 1.32 | Nur *et al.* (2023) |
| *Hylocereus polyrhizus* | 2.62 | - | - | - | - | - | - | - | - | Biswas *et al.* (2022) |
| *Hylocereus undatus* | 90.34 | - | - | - | - | - | - | - | - | Gautam *et al.* (2024) |

Cu: Copper, Ca: Calcium, Zn: Zinc, Fe: Iron, Mg: Magnesium, P: Phosphorus, K: Potassium, Na: Sodium

## 4 | MAJOR BIOACTIVE COMPOUNDS PRESENT IN DRAGON FRUIT PEELS AND THEIR FUNCTIONAL ROLES IN FISH

### 4.1 Phenolic compounds

Dragon fruit peel (DFP) is a rich source of phenolic compounds, which constitute one of its major bioactive fractions and contribute significantly to its antioxidant properties. The concentration and composition of these compounds vary depending on dragon fruit species, maturity stage, cultivation conditions, and extraction methods (Table 2). Due to their abundance and biological activity, phenolic compounds are considered important contributors to the functional value of DFP and its potential application as a feed additive in aquaculture.

Phenolic compounds (PCs) are a diverse group of phytochemicals characterised by the presence of one or more phenolic groups, structurally consisting of at least one benzene ring bearing one or more hydroxyl functional groups (Naeil *et al*. 2023). These compounds have gained significant attention due to their wide range of biological activities, including antioxidant, immunostimulatory, antibacterial, antiviral, antifungal, and antiprotozoal properties (Prasad *et al*. 2014; Song *et al*. 2015; Magrone *et al*. 2016; Salehi *et al*. 2016; Oniszczuk *et al*. 2019; Hikal *et al*. 2022). Their antioxidant potential is primarily attributed to their ability to interact with various free radicals through mechanisms such as hydrogen atom transfer, single electron transfer, sequential proton loss electron transfer, and transition metal chelation, making them effective and safer alternatives to synthetic antioxidants (Zeb 2020).

Due to the limited number of studies investigating purified phenolic fractions isolated specifically from DFP in aquaculture species, evidence from phenolic-rich plant extracts and polyphenol preparations derived from other botanical sources is discussed below to provide mechanistic insight into the potential roles of DFP-derived phenolics. Although these studies do not directly evaluate DFP, they offer valuable information regarding the biological activities of phenolic compounds that may contribute to the beneficial effects associated with DFP supplementation. For instance, dietary polyphenols have been associated with improved growth performance and feed utilisation in several aquaculture species. Polyphenols derived from chestnut and olive mill wastewater enhanced growth and feed efficiency in common carp (*Cyprinus carpio*), whereas a polyphenol mixture promoted growth in Asian seabass (*Lates calcarifer*) and improved feed conversion and protein efficiency at lower inclusion levels in rainbow trout (*Oncorhynchus mykiss*) (Jahazi *et al*. 2020; Ahmadi *et al*. 2022; Mansoori *et al*. 2024). Likewise, fulvic acid, characterised by a high content of phenolic moieties, improved growth performance and feed utilisation in rainbow trout, suggesting enhanced physiological resilience (Lieke *et al*. 2021).

In addition to their effects on growth, these bioactive constituents contribute to antioxidant defence by reducing lipid peroxidation and modulating antioxidant enzyme activities. For example, mango peel-derived polyphenols reduced muscle malondialdehyde levels in zebrafish (*Danio rerio*), while supplementation with polyphenol-rich preparations enhanced antioxidant capacity and lowered hepatic MDA levels in common carp, Asian seabass, and rainbow trout (Lizárraga-Velázquez *et al*. 2019; Jahazi *et al*. 2020; Ahmadi *et al*. 2022; Mansoori *et al*. 2024). Strong immunomodulatory properties have also been reported. Increased lysozyme activity, immunoglobulin levels, respiratory burst activity, and serum protein concentrations were observed in convict cichlid (*Amatitlania nigrofasciata*), common carp, Asian seabass, and rainbow trout following dietary supplementation. Moreover, the upregulation of immune-related genes, including interleukin-6, tumour necrosis factor-α, and interleukin-1β, further supports their role in enhancing host defence mechanisms (Hoseinifar *et al*. 2020; Jahazi *et al*. 2020; Ahmadi *et al*. 2022; Mansoori *et al*. 2024). In addition to promoting growth and immune function, these compounds have been shown to enhance disease resistance. Notably, chestnut polyphenols increased the post-challenge survival of Nile tilapia (*Oreochromis niloticus*) infected with *Streptococcus agalactiae* (Van Doan *et al.* 2020).

Collectively, available evidence indicates that dietary polyphenols can enhance growth performance, antioxidant status, immune responses, disease resistance, and flesh quality in a variety of aquaculture species. However, most of these findings originate from botanical sources other than DFP. They should therefore be considered mechanistic evidence rather than direct proof of the efficacy of DFP-derived phenolics. Given their abundance in DFP, these constituents are likely to contribute, either individually or synergistically with other bioactive components present in the DFP. Nevertheless, further studies are required to identify the specific phenolic constituents responsible and to clarify their contribution to the overall biological activity of DFP in aquaculture. An overview of representative studies investigating the effects of dietary phenolic compounds in different aquaculture species are compiled in Table 4.

**TABLE 4** Effects of phenolic compounds supplementation in fish species.

| Phenolic compounds | Species | Dose and duration | Effects | Source |
|---|---|---|---|---|
| Polyphenols extracted from chestnut and olive mill wastewater | Common carp (*Cyprinus carpio*). | 0, 0.05, 0.1, and 0.2% (8 weeks) | ↑Growth, ↓FCR, ↑Serum and Mucus (Ig), ↑ Lysozyme, ↑ WBC, ↑ RBC, ↓ MCV, ↑ CAT, ↑Serum peroxidase | Jahazi *et al.* (2020) |
| Fulvic acid | Juvenile rainbow trout (*Oncorhynchus mykiss*) | 50 mg C/L fulvic (28 days) | ↑Growth, ↓FCR, ↑Phagocytosis, Total oxyradical scavenging capacity (TOSC), ↑ Lysozyme activity in the gills | Lieke *et al.* (2021) |
| Phenolic compounds derived from mango peel | Zebrafish (*Danio rerio*) | 50, 100, 150 and 200 mg $kg^{-1}$ | ↑CAT, ↓MDA levels in muscle | Lizárraga-Velázquez *et al.*, 2019 |
| Polyphenol (PMIX), made of chestnut wood extract and olive extract | Asian sea bass (*Lates Calcarifer*) | 0.5, 1.0, 2.5, 5.0 g $kg^{-1}$ | ↑DWG, ↑Mucus lysozyme activity, ↑Immunoglobulin, ↑GR, ↑GST, ↓MDA levels in liver | Ahmadi *et al.* (2022) |
| Polyphenols extracted from chestnut wood (CW) and olive mill waste water | Convict cichlid (*Amatitlania nigrofasciata*) | 0.5, 1.0 and 2.0 g $kg^{-1}$ | ↑Skin mucus total Ig, ↑Lysozyme activity, ↑Serum total protein, ↑Total Ig, ↑Serum respiratory burst, ↑Peroxidase | Hoseinifar *et al.* (2020) |
| Polyphenol-rich extract mixture from chestnut wood and olive (PMIX) | Rainbow trout (*Oncorhynchus mykiss*) | 0.5, 1 and 2 g $kg^{-1}$ diet (8 weeks) | ↑FCR, ↑PER, ↑Growth performance, ↑Serum lysozyme, ↑Respiratory burst activities, ↑SOD, ↑Intestinal interleukin-6 expression, ↑Tumour necrosis factor-alpha, ↑Interleukin-1 beta | Mansoori *et al.* (2024) |
| Chestnut (*Castanea sativa*) polyphenols | Nile tilapia (*Oreochromis niloticus*) | 0, 1, 2, 4, and 8 g $kg^{-1}$ (8-week) | ↑Growth, ↓FCR, ↑Skin mucus, ↑Serum immune parameters ↑Survival rate | Van Doan *et al.* (2020) |
| Olive leaf (polyphenol content of 6–9% in dry weight) | Red sea bream (*Pagrus major*) | 8% | 1.4 times higher myofibril content and 2.2 times higher acid-soluble collagen content | Arsyad *et al.* (2018) |

The symbol '↑' indicates increased or higher values while '↓' indicates decreased or lower values.

### 4.2 Flavonoids

Among the various bioactive compounds present in dragon fruit peel (DFP), flavonoids also constitute a major group and play a significant role in its antioxidant capacity. Their concentrations are influenced by factors including species, maturity stage, cultivation conditions, and extraction methods (Table 2). Due to their diverse biological activities, flavonoids are considered important contributors to the functional properties of DFP and its potential application as a natural feed additive in aquaculture.

Flavonoids are a diverse group of low-molecular-weight phenolic compounds characterised by a C6-C3-C6 carbon skeleton and are classified into several subclasses, including flavones, flavonols, flavanones, flavanols, anthocyanidins, and isoflavones (Ross and Kasum 2002; Middleton *et al*. 2007). Owing to their antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory properties, these compounds have attracted considerable attention as functional ingredients with potential applications in aquaculture nutrition (Cushnie and Lamb 2005; Kumar and Pandey 2013; Alfaridz 2018).

While research specifically examining the impact of individual flavonoids derived from DFP on aquaculture species is still scarce, findings from studies on purified flavonoids and flavonoid-rich extracts from other plants offer significant mechanistic insights into the possible functions of DFP-derived flavonoids. Although these investigations do not focus directly on DFP, they provide crucial information about the biological activities that could play a role in the positive effects linked to DFP supplementation.

Dietary flavonoids have been associated with improved growth performance and metabolic regulation in several aquaculture species. Flavonoids derived from *Allium mongolicum* enhanced growth and immune responses in *Channa argus*, whereas quercetin and epicatechin promoted growth, lipid metabolism, and beneficial gut microbiota in *Totoaba macdonaldi*. Similarly, quercetin and rutin improved growth performance and flesh quality in grass carp (*Ctenopharyngodon idella*) through modulation of metabolic pathways including IGF-1, PI3K, AKT, and FAS (Li *et al*. 2019; Xu *et al*. 2021; Barragán-Longoria *et al.* 2023). In addition to their effects on growth, these phytochemicals exert strong antioxidant and stress-mitigating activities. Rutin supplementation alleviated oxytetracycline-induced hepatic stress in rainbow trout (*Oncorhynchus mykiss*) by restoring liver enzyme activities and enhancing antioxidant defences, while sea buckthorn flavonoids activated the Nrf2-Keap1 pathway and improved antioxidant status in Yellow River carp. Hesperidin also mitigated aflatoxin B1-induced toxicity in African catfish (*Clarias gariepinus*) through restoration of antioxidant balance and reduction of tissue damage (Nazeri *et al*. 2017; Yan *et al*. 2024; Ibrahim *et al*. 2026).

Pronounced immunomodulatory effects have likewise been reported. Supplementation with flavonoid-rich extracts from *Allium mongolicum* and *Taraxacum mongolicum* enhanced immune responses and regulated the expression of inflammatory, apoptotic, and antioxidant-related genes in *Channa argus*. Furthermore, sea buckthorn flavonoids improved resistance against *Aeromonas hydrophila* infection, highlighting their potential role in disease prevention (Li *et al*. 2019; Du *et al*. 2022; Yan *et al*. 2024).

Collectively, available evidence suggests that dietary flavonoids can enhance growth performance, antioxidant capacity, immune responses, metabolic regulation, and resistance to environmental and pathogenic stressors in fish. However, most of these findings are derived from flavonoids obtained from botanical sources other than DFP and should therefore be regarded as mechanistic evidence rather than direct proof of the efficacy of DFP-derived flavonoids. Given their abundance in DFP, these compounds are likely to contribute, either individually or synergistically with phenolic compounds, betalains, and tannins, to the beneficial effects associated with DFP supplementation. Nevertheless, further studies are required to identify the specific flavonoid constituents responsible and to elucidate their contribution to the overall biological activity of DFP in aquaculture. Representative studies investigating the effects of dietary flavonoids in different aquaculture species are summarised in Table 5.

In general, the existing evidence indicates that dietary flavonoids can improve growth performance, antioxidant capacity, immune responses, metabolic regulation, and resistance to environmental and pathogenic stressors in fish. However, most of these results are based on flavonoids sourced from plants other than DFP, and thus should be considered as mechanistic evidence rather than direct proof of the effectiveness of flavonoids derived from DFP. Additional research is necessary to pinpoint the specific flavonoid components responsible and to clarify their role in the overall biological activity of DFP in aquaculture. Table 5 provides a summary of representative studies examining the effects of dietary flavonoids in various aquaculture species.

### 4.3 Betalains

Betalains are water-soluble nitrogen-containing pigments responsible for the characteristic coloration of many flowers and fruits and are mainly synthesized by plants belonging to the order Caryophyllales (Madadi *et al*. 2020). These pigments are broadly classified into red-violet betacyanins and yellow-orange betaxanthins (Gengatharan *et al*. 2015). In dragon fruit peel (DFP), betalains represent one of the major bioactive constituents and contribute significantly to its characteristic coloration (Table 2). Betacyanins are predominantly present in the peels of red-skinned dragon fruits such as *H. polyrhizus* and *H. undatus*. In contrast, betaxanthins are mainly found in the peel of the yellow-skinned *H. megalanthus* (Cejudo-Bastante *et al*. 2016). Moreover, betalain concentrations are generally higher in the peel than in the pulp (Wu *et al*. 2006). Owing to their strong antioxidant properties, betalains have attracted considerable attention as functional pigments with potential applications in food and aquaculture (Khan and Giridhar 2015), and *Hylocereus* species have been recognized as one of the richest natural sources of these compounds after *Beta vulgaris* L. and *Amaranthus* species (Wybraniec and Mizrahi 2002).

There is limited direct evidence on the impact of purified DFP-derived betalains in aquaculture species. However, research involving betalain-rich extracts from dragon fruit and other natural sources has shed light on the physiological functions and mechanisms of these pigments, providing insights into their potential role in the positive effects seen with DFP supplementation. For instance, incorporating a betalain-rich hydroalcoholic extract from pitaya bark into the diet improved growth performance and antioxidant status in *Betta splendens*, as indicated by higher catalase activity and lower hepatic ALT levels, although skin coloration remained unchanged (Gauer *et al*. 2025). In a similar vein, adding betalain-rich beetroot extract to the diet enhanced antioxidant enzyme activities and decreased oxidative stress in *Oreochromis niloticus* (Awad *et al*. 2024). The immunomodulatory effects of betalains in Nile tilapia were further evidenced by increased lysozyme activity, serum protein, globulin concentration, and antioxidant enzymes (Awad *et al*. 2024). Despite their water-soluble nature and limited direct deposition in tissues, these pigments may indirectly support skin colouration by protecting carotenoids from oxidative degradation and preserving pigment stability under stress conditions (Baron *et al*. 2008).

**TABLE 5** Effects of flavonoid supplementation in fish species

| Flavonoids | Species | Dose and duration | Effects | Source |
|---|---|---|---|---|
| Rutin | Rainbow trout (*Oncorhynchus mykiss*) | 500, 1000, and 2000 ppm | Restored liver enzyme levels, ↑Improved antioxidant status, ↓Blood glucose levels | Nazeri *et al.*, 2017 |
| Dietary flavonoids from *Allium mongolicum* | *Channa argus* | 0, 10, 20 or 40 mg kg$^{-1}$ (56 days) | ↑Weight gain, ↑SGR, ↓Serum AKP, ↓Lysozyme activity, ↓C3, ↓IgM concentration, ↓Liver antioxidant enzymes activity (SOD, CAT and GSH-Px), ↓Serum cortisol, ↓MDA, ↓ALT, ↓AST activity, ↑Expression of SOD, IgM, HSP70, HSP90, IκB-α, GR and ↓Expression of NF-κB p65 and inflammatory cytokines (TNF-α, IL-1β and IL-8) transcription in head kidney, ↑Survival rate against *Aeromonas hydrophila* | Li *et al.*, 2019 |
| Sea buckthorn flavonoids | Yellow River carp | 0.1 %, 0.2 %, and 0.4 % (10-week) | ↑Antioxidant status (SOD, CAT, GSH-Px), ↓Oxidative stress markers ($H_2O_2$ and MDA), ↑Immune enzyme activities | Yan *et al.*, 2024 |
| Flavonoid-rich extract of orange (*Citrus sinensis*) juice | Obese zebrafish | 5 mL L$^{-1}$ (Five weeks) | ↓Body weight, ↓Body mass index, ↓Visceral adipose tissue, ↓Adipocyte size and number in overfed fish | Montalbano *et al.* 2019 |
| Quercetin and epicatechin | *Totoaba macdonaldi* | 0.25% and 0.5% | ↑Growth performance, ↓Serum triglycerides, ↓Cholesterol levels, ↑Liver gene expression, promoting metabolic regulation and lipid oxidation, ↑Beneficial bacteria in the intestine and ↓Pathogenic species | Barragán-Longoria *et al.* 2023 |
| Quercetin, rutin, baicalein, and catechin | *Ctenopharyngodon idellus* | - (60 days) | ↑Weight gain, ↑Feed efficiency, ↑Flesh quality, ↑Collagen content, ↑SOD activity and ↓Lipid and protein oxidation, ↑Growth- and metabolism-related genes (IGF-1, PI3K, AKT, and FAS) | Xu *et al.*, 2021 |
| *Taraxacum mongolicum* flavonoids | *Channa argus* | 0, 25, 50 and 100 mg kg$^{-1}$ (56 days) | ↑Growth indices, ↑Digestive enzyme activities, ↓FCR, ↑Immune responses (LY, AKP, ACP, IgM, C3) and antioxidant capacity (SOD, CAT, GSH-Px, GR), ↓Liver damage markers (ALT, AST), ↓Pro-inflammatory (tnf-α, il-1β, il-8) and pro-apoptotic genes (caspase-3, caspase-8, caspase-9, p53, bax, bcl-2), ↑Anti-inflammatory (il-10, tgf-β), antioxidant-related (nrf2, gpx, gst, cat), and heat shock protein genes (hsp70, hsp90) | Du *et al.*, 2022 |
| Hesperidin, a citrus-derived flavonoid | *Clarias gariepinus* | 150 mg kg$^{-1}$ (60 days) | ↑Survival, ↓Tissue damage in liver, kidney, brain, and gills | Ibrahim *et al.*, 2026 |

The symbol '↑' indicates increased or higher values while '↓' indicates decreased or lower values.

Taken together, the current findings indicate that dietary betalains may support antioxidant capacity, immune function, and general physiological health in fish, while also potentially contributing to growth performance and the maintenance of pigmentation. Considering their high abundance in dragon fruit peel, these pigments may act independently or synergistically with other bioactive constituents present in the DFP to mediate the beneficial effects. Nonetheless, additional studies are needed to clarify the specific roles of DFP-derived betalains in fish growth, pigmentation, antioxidant status, and disease resistance.

**4.4 Tannins**

DFP contains tannins within its phenolic composition, which play a role in its antioxidant and antimicrobial characteristics. The levels of tannins differ based on the species of dragon fruit, the stage of ripeness, the conditions under which it is grown, and the methods used for extraction (Table 2). While tannins are typically found in smaller amounts compared to other bioactive components in DFP, they can enhance its functional benefits by influencing antioxidant activity, microbial communities, and physiological reactions. Beyond their ability to neutralize reactive oxygen species, tannins also have the capacity to influence gut microbial communities and enhance intestinal health, positioning them as promising natural substitutes for antibiotic growth promoters (Huang *et al*. 2018; Lu *et al*. 2020; Peng *et al*. 2021; Zhu *et al*. 2021).

While there is a lack of direct research on the impact of tannins derived from DFP on aquaculture species, extensive studies on tannins from various plant sources sheds light on their possible biological roles. For instance, supplementation with 0.1% condensed tannins improved growth performance and glucose metabolism in Japanese seabass (*Lateolabrax japonicus*) through enhanced hepatic enzyme activity (Peng *et al*. 2020). Similarly, low concentrations of hydrolysable tannins improved growth, antioxidant capacity, and muscle quality in *Mastacembelus armatus* (Xue *et al*. 2024), while enhancing health status in *Labeo rohita* without compromising growth (Prusty *et al*. 2007). In juvenile *Micropterus salmoides*, dietary supplementation with 3.75 g $kg^{-1}$ condensed tannin improved growth, feed efficiency, and gut microbiota composition, whereas higher levels resulted in adverse effects (Yang *et al*. 2025).

Beyond their growth-promoting effects, tannins have been reported to enhance antioxidant capacity, support intestinal health, and strengthen host defence. In *Litopenaeus vannamei*, tannin supplementation improved antioxidant enzyme activities under ammonia stress and enhanced resistance to *Vibrio parahaemolyticus* by modulating the gut microbiota and immune responses (Bolívar-Ramírez *et al*. 2022; Zhang *et al*. 2024). Likewise, hydrolysable tannins improved digestive enzyme activity, antioxidant status, and gut microbial composition in shrimp (Zhu *et al*. 2021). These effects are partly attributed to enhanced intestinal barrier integrity through the regulation of tight junction proteins and modulation of gut microbiota, leading to reduced oxidative damage and improved nutrient utilization (Peng *et al*. 2021, 2022). In *Danio rerio*, a combination of hydrolysable and condensed tannins alleviated plant diet-induced intestinal inflammation by suppressing pro-inflammatory cytokine expression and improving intestinal morphology (Imperatore *et al*. 2022).

Despite these beneficial effects, the biological responses to tannins are highly dependent on their type, source, dietary inclusion level, and fish species. While low concentrations are generally advantageous, excessive supplementation may impair growth, feed efficiency, and nutrient utilisation due to reduced feed palatability and interference with digestive processes (Huang *et al*. 2018; Durazzo *et al*. 2019). Species-specific responses further highlight this dose dependency. In juvenile *Micropterus salmoides*, moderate levels of tannic acid enhanced antioxidant capacity and improved hepatic and intestinal health, whereas higher concentrations induced oxidative stress and growth depression (Wang *et al*. 2024). Similarly, excessive condensed tannins impaired intestinal health and immune function in *Ctenopharyngodon idella* through dysregulation of TOR and NF-κB signalling pathways (Li *et al*. 2020). Comparative studies in *C. carpio* further demonstrated that hydrolysable tannins exerted more pronounced adverse effects than condensed tannins, causing growth suppression and feed rejection at elevated levels (Becker and Makkar 1999). Likewise, increasing dietary hydrolysable tannins in *Lateolabrax maculatus* impaired digestion, antioxidant capacity, and tissue integrity, indicating that lower inclusion levels are more beneficial than excessive supplementation (Qiu *et al*. 2023). Representative studies investigating the effects of dietary tannins in aquaculture species are summarized in Table 6 to provide mechanistic insights into their biological functions.

**4.5 Vitamin C**

DFP contains vitamin C (ascorbic acid), a crucial micronutrient that contributes to its antioxidant properties (Table 3). Although vitamin C is not classified as a phytochemical or secondary metabolite, it represents an important bioactive constituent that may contribute to the functional properties of DFP and its potential application in aquaculture nutrition. Since fish are unable to synthesise vitamin C endogenously due to the absence of the enzyme L-gulonolactone oxidase, dietary intake is essential (Drouin *et al*. 2011). Consequently, the vitamin C naturally present in DFP may contribute, at least in part, to the dietary supply of this essential micronutrient when DFP is incorporated into fish feeds.

**TABLE 6** Effects of tannin supplementations in fish species.

| Tannin | Species | Dose and duration | Effect | Source |
|---|---|---|---|---|
| Dietary tannic acid | Largemouth bass (*Micropterus salmoides*) | 200, 400, and 800 mg kg$^{-1}$ (8 weeks) | ↑Survival, ↓Growth performance, ↑Antioxidant capacity, ↑Catalase activity, ↓MDA, ↓Liver glycogen levels | Wang *et al.* (2024) |
| Hydrolysable tannin | Grass carp (*Ctenopharyngodon idellus*) | 0, 0.75, 1.25, and 1.75% (8 weeks) | ↑Trypsin and ↑Amylase activities, ↓Hepatic alanine aminotransferase, ↓Aspartate aminotransferase, ↑mRNA expression of intestinal TOR, ↓Fatty acid synthase expression | Yao *et al.* (2019) |
| Condensed tannins | Juvenile *Lateolabrax japonicus* | 0.1% (56 days) | ↑Growth performance, ↓Serum glucose ↑Gene expression of hepatic glycolysis and gluconeogenesis enzymes | Peng *et al.* (2020) |
| Condensed tannin | Juvenile largemouth bass (*Micropterus salmoides*) | 0, 0.60, 1.50, 3.75, 9.38 g kg$^{-1}$ (56 days) | ↑Growth performance, ↑FCR, ↑ADCs (Protein & Lipid), ↑Intestinal antioxidant capacity, ↑Intestinal immune response, ↑Intestinal villi development | Yang *et al.* (2025) |
| Quebracho tannin (a condensed tannin) | Common carp (*Cyprinus carpio* L.) | 2% (84 days) | No significant impact on feed intake, growth performance, metabolic rate, or carcass composition | Becker and Makkar (1999) |
| Hydrolyzable tannin | Juvenile (*Mastacembelus armatus*) | 0.05%, 0.1%, and 0.2% (60 days) | ↑Growth performance, ↑Hepatopancreatic antioxidant capacity, ↑Muscle quality and ↑Lipase | Xue *et al.* (2024) |
| Tannin | *Litopenaeus vannamei* | 0.1% 0.05%, 0.025% (Eight weeks) | ↑Microbiota diversity | Bolívar-Ramírez *et al.* (2022) |
| Hydrolyzable and condensed tannins | Zebrafish (*Danio rerio*) | 0, 0.9, 1.7, 3.4 g kg$^{-1}$ (12 days) | Restored intestinal morphology and ↓Expression of cytokines | Imperatore *et al.* (2022) |
| Dietary tannin | *Labeo rohita* fingerlings | 2.5, 5, 10, 15 and 20 g kg$^{-1}$ (60 Days) | ↑Hepato somatic index, ↑Muscle cholesterol level ↑Haemoglobin count, ↑Total leucocyte count, ↑Respiratory burst activity | Prusty *et al.* (2007) |
| Hydrolysable tannin | Largemouth bass (*Micropterus salmoides*) | 1g kg$^{-1}$ (56 days) | ↑Growth performance, ↑Hepatic antioxidant capacity, ↑Glycolipid metabolism and ↑Glucose utilization | Yang *et al.* (2024) |
| Condensed tannins (Isolated from grape seed) | Juvenile Japanese seabass (*Lateolabrax japonicus*) | 0, 100, 200 and 400 mg kg$^{-1}$ (56-days) | ↓Serum lipopolysaccharide and ↑Bacterial diversity | Peng *et al.* (2021) |
| Tannin | *Litopenaeus vannamei* | 800 mg kg$^{-1}$ (56 days) | ↑Metabolic regulation and ↑Immune response | Zhang *et al.* (2024) |
| Condensed tannin | Largemouth bass (*Micropterus salmoides*) | 3.75 g kg$^{-1}$ (56 days) | ↑Intestinal barrier integrity, ↑Antioxidant capacity, ↑Beneficial gut microbiota, ↑ATP production, and ↑Mitochondrial enzyme activities | Zhang *et al.* (2025) |
| Condensed tannins (CT), derived from black wattle (*Acacia mearnsii*) tree bark | Nile tilapia (*Oreochromis niloticus*) juveniles | 150, 250, 500, 750, and 1000 mg kg$^{-1}$ (90-day) | ↑Growth performance, ↑Immune responses (lysozyme, complement, and myeloperoxidase activity), and ↑Survival after bacterial challenge | Brutti *et al.* (2024) |

**TABLE 6** Continued.

| Tannin | Species | Dose and duration | Effect | Source |
|---|---|---|---|---|
| Hydrolysable tannin and condensed tannin | Nile tilapia | 0, 5, 15, and 25 g $kg^{-1}$ | ↓Growth performance | Buyukcapar *et al.* (2011) |
| Tannic acid | Nile tilapia (*Oreochromis niloticus*) | 5, 10, 15 and 20 g $kg^{-1}$ (60-day) | ↓Growth performance, Intestinal structural damage, ↓Villus height and width, ↓Catalase activity, ↑Hsp70 and IL-1β | Liu *et al.* (2025) |
| Hydrolyzable tannins | *Litopenaeus vannamei* | 0.05%, 0.1%, 0.15% and 0.2 % (60-day) | ↑Growth performance, ↑Digestive enzyme activities, ↑Antioxidant capacity (SOD, CAT, GPx), ↑Immune responses, ↓Pathogenic bacteria and ↑Disease resistance | Zhu *et al.* (2021) |

The symbol '↑' indicates increased or higher values while '↓' indicates decreased or lower values.

Vitamin C is a water-soluble antioxidant involved in collagen synthesis, metabolism, immune function, and protection against oxidative stress. However, the effectiveness of dietary supplementation varies depending on fish species, developmental stage, and environmental conditions (NRC 2011). Evidence from various aquaculture species indicates that dietary vitamin C can improve growth performance, although optimal inclusion levels differ considerably among species. Positive effects have been reported in Nile tilapia, *L. rohita*, *Barbus sharpeyi*, Japanese seabass, and cobia, whereas growth responses in large yellow croaker appear to be relatively limited (Ai *et al*. 2004, 2006; Tewary and Patra 2008; Yousefi *et al*. 2013; Ibrahim *et al*. 2020). These findings suggest that growth-promoting effects are species dependent.

In addition to growth, vitamin C supplementation has been shown to enhance antioxidant status by increasing the activity of enzymes such as superoxide dismutase, catalase, and glutathione peroxidase, while reducing oxidative stress through activation of protective pathways including Nrf2-Keap1 (Zhou *et al*. 2012; Zhu *et al*. 2023). Improved innate immune responses, characterized by increased lysozyme activity, complement activity, phagocytosis, and immunoglobulin levels, have also been reported, leading to enhanced resistance against bacterial pathogens including *A. hydrophila*, *A. sobria*, *Vibrio harveyi*, and *Edwardsiella tarda* (Ai *et al*. 2006; Misra *et al*. 2007; Ibrahim *et al*. 2020). Furthermore, vitamin C contributes to maintaining tissue integrity and alleviating the adverse effects of environmental stressors by improving haematological parameters, preserving intestinal and hepatic morphology, and reducing stress biomarkers such as cortisol and lipid peroxidation (Nikjoo *et al*. 2023; Devi *et al*. 2024; Xiao *et al*. 2024).

In aquaculture species, the addition of dietary vitamin C has been linked to enhanced growth, improved antioxidant capacity, better immune responses, and increased stress tolerance. Despite this, the majority of research has utilised supplementation levels that far exceed the natural concentrations found in DFP. As a result, the biological effects seen with DFP supplementation are unlikely to be solely due to vitamin C; instead, they are probably the result of the combined effects of various bioactive components. Nonetheless, vitamin C might enhance the antioxidant capabilities of DFP and work in conjunction with phenolic compounds, flavonoids, betalains, and tannins. Table 7 provides a summary of key studies examining the impact of dietary vitamin C supplementation on aquaculture species.

**TABLE 7** Effects of vitamin c supplementation in fish species.

| Vitamin C | Species | Dose and duration | Effect | Source |
|---|---|---|---|---|
| L-ascorbic acid phosphate | Nile tilapia (*Oreochromis niloticus* L.) fingerlings | 0, 200, 300, and 400 mg $kg^{-1}$ | ↑Growth performance, ↑Antioxidant capacity, ↑Immune responses, and ↑Tissue integrity, ↑Serum vitamin C, ↑Interleukin-10, ↑Phagocytic activity, ↑Disease resistance against *Aeromonas sobria*, ↑Liver histoarchitecture and ↑Intestinal morphology (villus height and width) | Ibrahim *et al.* (2020) |
| Dietary vitamin C | Rohu (*Labeo rohita*) | 500, 1000, 1500 mg $kg^{-1}$ (60 days) | ↑Growth performance, ↑Haematological and serological parameters, ↑Non-specific immune responses, ↑Resistance against *Aeromonas hydrophila* infection | Tewary and Patra (2008) |

**TABLE 7** Continued.

| Vitamin C | Species | Dose and duration | Effect | Source |
|---|---|---|---|---|
| Dietary vitamin C | Large yellow croaker (*Pseudosciaena crocea*) | 0.1, 12.2, 23.8, 47.6, 89.7, 188.5 and 489.0 mg ascorbic acid equivalent kg$^{-1}$ diet (8 weeks) | ↑SGR, ↑Survival rate, ↑Serum lysozyme, ↑Phagocytosis, ↑NBT, ↓Cumulative mortality against *Vibrio harveyi* challenge | Ai *et al.* (2006) |
| Dietary vitamin C | Juvenile cobia, *Rachycentron canadum* | 13.6, 27.2, 54.4, 96.6, 193.4 and 386.5 mg ascorbic acid equivalent kg$^{-1}$ diet (8 weeks) | ↑Growth performance, ↑Survival, ↑Hematological parameters, and ↑Innate immune responses, ↑Lysozyme, ↑SOD, ↑AKP, and ↑Total immunoglobulin, ↑Resistance to *Vibrio harveyi* | Zhou *et al.* (2012) |
| L-ascorbyl-2-polyphosphate (LAPP). | Japanese seabass | 0.0, 12.2, 23.8, 47.6, 89.7, 188.5 and 489.0 mg ascorbic acid equivalent kg$^{-1}$ diet (8 weeks) | ↑Growth, tissue ↑Ascorbic acid levels, and ↑Immune responses | Ai *et al.* (2004) |
| Dietary L-ascorbic acid | Fingerlings of *Labeo rohita* | 0, 100, 200 and 500 mg kg$^{-1}$ (8 weeks) | ↑Growth, ↑Survival, and ↑Immune responses, ↑Resistance against *Aeromonas hydrophila* and *Edwardsiella tarda* | Misra *et al.* (2007) |
| Dietary vitamin C | *Barbus sharpeyi* fingerling | 0, 500, 1000, 1500 and 2000 mg kg$^{-1}$ (56 days) | ↑Growth performance, ↑Feed utilization, ↑Body protein and lipid content | Yousefi *et al.* (2013) |
| Dietary vitamin C | *Labeo gonius* fry | 0, 500 and 1000 mg kg$^{-1}$ (90 days) | ↑Hematological parameters, ↑Serum protein levels, ↓Stress indicators (Cortisol, Glucose, and MDA), ↑Survival and feed efficiency | Devi *et al.* (2024) |
| Dietary vitamin C | Caspian roach (*Rutilus rutilus* caspicus) | 0 (control), 500, 1000, and 1500 mg kg$^{-1}$ of vitamin C for 56 days | ↑Lysozyme activity, total immunoglobulin amount, and complement (ACH50), ↑Growth, ↑Digestive enzyme activity, ↑Immunity, and ↑Stress resistance | Nikjoo *et al.* (2023) |
| Dietary vitamin C | Juvenile *Rhynchocypris lagowskii* Dybowski | 200 mg kg$^{-1}$ (8 weeks) | ↑Protease activity, ↑Antioxidant defense (HO-1, CAT, GPx via Nrf2–Keap1 pathway), ↓Pro-inflammatory cytokines (TNF-α, IL-1β) and ↑ Anti-inflammatory cytokines (IL-10, TGF-β) | Zhu *et al.* (2023) |
| Dietary vitamin C | Channel catfish (*Ictalurus punctatus*) | 300 mg L$^{-1}$ | ↑Glycolysis (pk, pfk), antioxidant defenses (SOD, CAT), and ↓Inflammation by downregulating tnf-α, il-1β, and cd68 | Xiao *et al.* (2024) |

The symbol '↑' indicates increased or higher values while '↓' indicates decreased or lower values.

## 5 | EFFECTS OF DRAGON FRUIT PEEL (DFP) SUPPLEMENTATION IN FISH DIET

Dietary inclusion of DFP and its derivatives has been widely reported to enhance growth performance, antioxidant defenses, immune responses, disease resistance, and pigmentation in aquatic species. Available evidence from studies on various cultured species is discussed in the subsequent sections and compiled in Table 8.

### 5.1 Growth performance and feed utilization

Several studies have reported beneficial effects of DFP supplementation on fish growth, although the response appears to be dose-dependent. In Nile tilapia (*Oreochromis niloticus*) reared in a biofloc system, dietary DFP supplementation (20–160 g kg$^{-1}$) generally improved growth compared with the control diet. Fish receiving 40 g kg$^{-1}$ DFP showed the highest improvement, achieving approximately 1.5-fold higher weight gain and an improved specific growth rate after eight weeks of feeding. However, no additional benefits were observed at the highest inclusion level (160 g kg$^{-1}$), indicating that excessive supplementation may reduce efficacy (Xuan *et al.*

2024). In comet goldfish (*Carassius auratus*), DFP supplementation (5–15%) also promoted growth, with the most pronounced response observed at 10% inclusion, followed by a decline at 15% (Andriani *et al.* 2025). A comparable dose-dependent pattern was reported in snakehead (*Channa striata*), where inclusion levels of 1.5–2.0% significantly enhanced growth, whereas lower levels (0.5–1.0%) produced no significant effects. The best performance was recorded at 2.0% supplementation (Rakhmawati *et al*. 2021). Likewise, moderate dietary inclusion of red pitaya peel flour improved growth and feed utilization in Sangkuriang catfish (*Clarias gariepinus*), with 5% supplementation identified as the most effective level (Putri and Sukarti 2024).

**TABLE 8** Effects of dragon fruit supplementation in fish species.

| Dragon fruit peels | Species | Dose and duration | Effects | Source |
|---|---|---|---|---|
| Dragon fruit peel (DFP) powder | Nile tilapia (*Oreochromis niloticus*) | 0, 20, 40, 80, and 160 g kg$^{-1}$ (8 weeks) | ↑Growth, ↑Immune response indicators in skin mucus and blood serum, ↑IL-1, IL-8, LBP, GPx, GST-α, and GSR expression | Xuan *et al.* (2024) |
| Dragon fruit peel meal | Freshwater crayfish (*Cherax quadricarinatus*) | 5%, 10%, 15% and 20% (2 months) | ↑Color brightness (86.01 in claws and 87.59 teslon). ↑Color quality of from brown to bluish color | Rakhmawati *et al.* (2023) |
| Red dragon fruit peel flour | Tilapia (*Oreochromis niloticus*) fingerlings | 0%, 5%, 10% and 15% kg$^{-1}$ (30 days) | ↑Growth, ↑SGR, ↑Lactic acid bacteria | Fadillah *et al.* (2024) |
| Red pitaya peel flour | Sangkuriang catfish | 0%, 5%, 10%, and 20% (25 days) | ↑Weight gain, ↓FCR | Putri and Sukarti (2024) |
| Dragon fruit skin meal | Comet fish (*Carassius auratus*) | 0%, 5% 10%, and 15% | ↓FCR, ↑SGR, ↑Body coloration | Andriani *et al.* (2025) |
| Red dragon fruit peel meal | Koi carp fish (*Cyprinus carpio*). | 5%, 10%, and 15% (42 days) | ↑Skin coloration | Kurnia *et al.* (2019) |
| Red dragon fruit (*Hylocereus polyrhizus*) peel | Goldfish (*Carassius auratus*), | 0, 50, 100, 150, and 200 mL kg$^{-1}$ | ↑Color brightness | Mega (2025) |
| Red dragon fruit peel extract | Guppy fish | 0%, 10%, 15%, and 20% | ↑Color brightness | Maulida *et al.* (2025) |
| Red dragon fruit peel (*Hylocereus undatus*) flour | Clownfish (*Amphiprion percula*) | 0%, 10%, 15% and 20% | Influenced Hue, Saturation, and Brightness (HSB) values | Yesepus and Felix (2024) |
| Red dragon fruit (*Hylocereus polyrhizus*) juice by-products (RJB) | Juvenile red seabream (*Pagrus major*) | 0, 0.2, 0.4, 0.8, and 1% (56 days) | ↑Catalase and Glutathione levels, ↑Lysozyme activity, ↑Survival following *Edwardsiella tarda* infection | Oh *et al.* (2025) |
| Dragon fruit peel flour | Snakehead (*Channa striata*) | 0, 0.5, 1.0, 1.5 and 2.0% of feed (60 days) | ↑SGR, ↑Feed efficiency | Rakhmawati *et al.* (2021) |

The symbol '↑' indicates increased or higher values while '↓' indicates decreased or lower values.

In contrast, several studies have reported no significant growth-promoting effects of DFP or its derivatives. Dietary inclusion of red dragon fruit by-product meal (5-15%) did not affect the growth of ornamental koi carp (*C. carpio*) (Kurnia *et al*. 2019). Similarly, supplementation with red dragon fruit peel extract (50–200 mL kg$^{-1}$ feed) did not influence growth in goldfish (Mega 2025), while dietary inclusion of dragon fruit peel extract (10–20%) had no significant effect on weight gain, length increment, or survival in guppy (*Poecilia reticulata*) (Maulida *et al*. 2025). Similarly, incorporation of red dragon fruit (*H. polyrhizus*) juice by-products (0.2–1.0%) did not significantly alter growth, feed utilization, or biometric indices in juvenile red seabream (*Pagrus major*) (Oh *et al*. 2025).

Therefore, the available evidence indicates that DFP can enhance growth in certain fish species when incorporated at appropriate dietary levels. However, these effects are not consistently observed across species, and several studies have reported negligible responses. Such discrepancies are likely attributable to differences in fish species, culture conditions, dietary formulation, the form of DFP used (powder, extract, or by-product meal), and inclusion level. Overall, the growth-promoting effects of DFP appear to be both species- and dose-dependent, emphasizing the importance of determining optimal supplementation levels for individual aquaculture species.

**5.2 Immune and antioxidant responses**

In Nile tilapia (*Oreochromis niloticus*) reared in a biofloc system, dietary supplementation with DFP (20–160 g $kg^{-1}$) improved both innate immune responses and antioxidant status. Fish receiving DFP exhibited significantly higher lysozyme and peroxidase activities in the skin mucus and blood serum than the control group, with the most pronounced responses generally observed at 40 g $kg^{-1}$. In addition, DFP supplementation upregulated the expression of several immune- and antioxidant-related genes, including IL-1, IL-8, LBP, GST-α, GPx, and GSR in both liver and intestinal tissues, indicating activation of immune and oxidative defense mechanisms. Overall, these findings suggest that moderate dietary inclusion of DFP can strengthen both mucosal and systemic immunity while improving antioxidant defenses in Nile tilapia (Xuan *et al*. 2024). Comparable responses have been reported in juvenile red seabream (*P. major*) fed diets containing red dragon fruit (*H. polyrhizus*) juice by-products (0–1%). Although superoxide dismutase activity was unaffected, fish receiving 1% supplementation exhibited higher catalase activity and glutathione levels. Moreover, lysozyme activity was significantly elevated relative to the control group, indicating improved antioxidant status and innate immune function (Oh *et al*. 2025).

Collectively, the available evidence suggests that DFP and its derivatives can enhance antioxidant defenses and stimulate innate immune responses in fish. However, the magnitude of these effects appears to depend on species, dietary inclusion level, and the form of supplementation employed.

**5.3 Colour enhancement**

In freshwater crayfish (*Cherax quadricarinatus*), dietary supplementation with red dragon fruit peel meal (5–20%) significantly improved color quality, with the most pronounced effect observed at 10% inclusion. Supplemented crayfish exhibited a shift from brown to bluish hues, highlighting the potential of DFP as a natural pigment source for ornamental aquaculture (Rakhmawati *et al*. 2023). In comet goldfish (*Carassius auratus*), inclusion of dragon fruit peel meal (5–15%) increased color vibrancy across the head, body, and tail regions, with the greatest response observed at 15% supplementation (Andriani *et al*. 2025). A dose-dependent increase in pigmentation was also reported in ornamental koi carp (*C. carpio*), where diets containing 15% red dragon fruit by-product meal (RDFM) produced the highest black and orange skin coloration (Kurnia *et al*. 2019). Likewise, supplementation with red dragon fruit peel extract improved body coloration in guppy (*Poecilia reticulata*), with the highest pigmentation score recorded at 20% inclusion (Maulida *et al*. 2025). In clownfish (*Amphiprion percula*), dietary incorporation of red dragon fruit rind (*H. undatus*) flour (10–20%) helped maintain the natural coloration during culture, as reflected by changes in hue, saturation, and brightness values (Yesespus *et al.* 2024).

**5.4 Disease resistance**

Enhanced disease resistance following supplementation with dragon fruit derivatives has also been reported in juvenile red seabream (*P. major*). Fish fed diets containing 0-1% red dragon fruit (*H. polyrhizus*) juice by-products exhibited increased resistance to *Edwardsiella tarda* infection. Following bacterial challenge, fish receiving 1% supplementation showed the highest cumulative survival rate, and Kaplan–Meier analysis confirmed significantly greater resistance compared with the other dietary groups (Oh *et al*. 2025). These findings suggest that dragon fruit-derived products can enhance host defense mechanisms and improve resistance to bacterial pathogens.

**5.5 Mechanisms and factors influencing the efficacy of DFP supplementation**

Although numerous studies have demonstrated beneficial effects of dietary dragon fruit peel (DFP) supplementation on growth, antioxidant status, immunity, pigmentation, and disease resistance in aquatic species, the responses are not always consistent. These variations indicate that the efficacy of DFP is influenced by multiple factors, including dietary inclusion level, fish species, culture conditions, and the form of DFP used.

One of the most important factors affecting the response to DFP supplementation is dosage. Several studies have demonstrated dose-dependent effects, where moderate inclusion levels produced the most favorable outcomes. For example, growth performance was enhanced at intermediate levels of DFP supplementation in Nile tilapia, comet goldfish, snakehead, and Sangkuriang catfish, whereas higher inclusion levels failed to provide additional benefits or even resulted in reduced responses (Rakhmawati *et al*. 2021; Putri and Sukarti 2024; Xuan *et al*. 2024; Andriani *et al*. 2025). Similar dose-dependent trends have also been observed for pigmentation and immune parameters. These findings suggest that the biological effects of DFP are dependent on achieving an optimal dietary inclusion level, and excessive supplementation may reduce nutrient utilization or alter feed palatability.

Species-specific differences also contribute to the variability in responses. Positive effects on growth have been reported in some species, whereas little or no improvement was observed in others, including koi carp, guppy, goldfish, and red seabream (Kurnia *et al*. 2019; Maulida *et al*. 2025; Mega 2025; Oh *et al*. 2025). Such discrepancies may be attributed to differences in digestive physiology, metabolic requirements, feeding habits, and the ability of different species to utilize the bioactive compounds present in DFP. In addition, variations in culture conditions, experimental duration, and dietary composition may further influence the effectiveness of supplementation.

The form in which DFP is incorporated into diets may also affect its biological activity. Previous studies have employed DFP in the form of powder, extracts, flour, juice by-products, and by-product meals, which may differ considerably in their concentrations and bioavailability of bioactive constituents. Consequently, differences in processing methods and formulation could partly explain the inconsistencies observed among studies. Most available studies have evaluated whole DFP or its derivatives rather than purified compounds, making it difficult to identify the specific components responsible for the observed biological effects. Therefore, future studies should focus on elucidating the mechanisms of action of individual bioactive compounds, determining optimal inclusion levels for different species, and establishing standardized processing methods to maximize the functional value of DFP in aquaculture nutrition.

## 6 | CONCLUSIONS

Dragon fruit peel represents a promising and sustainable functional ingredient for aquaculture, owing to its rich composition of bioactive compounds such as phenolics, flavonoids, tannins, betalains, and essential nutrient vitamin C. These compounds collectively contribute to improved growth performance, enhanced antioxidant capacity, strengthened immune responses, and better intestinal health in fish. Additionally, their ability to modulate gut microbiota and mitigate environmental and dietary stress highlights their potential as natural alternatives to conventional feed additives and antibiotics. However, the effects of these bioactive compounds are highly dependent on inclusion levels, chemical composition, and species-specific responses. In particular, compounds such as tannins may exert anti-nutritional effects at higher concentrations, emphasizing the need for careful dose optimization. Furthermore, variations in extraction methods and feed formulation can influence their efficacy. Future research should focus on elucidating the molecular mechanisms underlying their biological effects, standardizing inclusion levels, and evaluating long-term impacts under commercial farming conditions. Overall, the incorporation of dragon fruit peel in aquafeeds offers a viable strategy for improving fish health and promoting sustainable aquaculture practices.

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**ETHICAL APPROVAL**

All applicable international, national and/or institutional guidelines for the care and use of animals were followed in this study.

**CONFLICT OF INTEREST**

The author declares no conflict of interest.

**AUTHORS' CONTRIBUTION**

Ng Chinglembi Devi: Literature search, Data curation, Formal analysis, Writing – original draft; Cheryl Antony: Conceptualization, Writing – review and editing, Supervision; Elangovan Prabu: Writing – review and editing, Supervision; S. Selvaraj: Supervision. A. Uma: Supervision; S. Kumar: Review and editing; S. Malla: Review and editing; Kumaresan M: Supervision.

**AI USE DECLARATION**

In the preparation of this manuscript, generative AI tools (such as ChatGPT developed by OpenAI) were used only to assist in language editing, grammar correction, and improving the clarity of expression. The use of AI was limited to linguistic refinement and did not involve any data generation, data interpretation, or content creation that would affect the scientific integrity of the work. The authors take full responsibility for the content, accuracy, and originality of the manuscript.

**DATA AVAILABILITY STATEMENT**

No new datasets were generated or analysed during the current study. All information discussed in this review was obtained from previously published sources cited in the manuscript.

**REFERENCES**

Ahmadi A, Bagheri D, Hoseinifar SH, Morshedi V, Paolucci M (2022) Beneficial role of polyphenols as feed additives on growth performances, immune response and antioxidant status of *Lates calcarifer* (Bloch, 1790) juveniles. Aquaculture 552: 737955.

Ai Q, Mai K, Tan B, Xu W, Zhang W, … Liufu Z (2006) Effects of dietary vitamin C on survival, growth, and immunity of large yellow croaker, *Pseudosciaena crocea*. Aquaculture 261(1): 327–336.

Ai Q, Mai K, Zhang C, Xu W, Duan Q, … Liufu Z (2004) Effects of dietary vitamin C on growth and immune response of Japanese seabass, *Lateolabrax japonicus*. Aquaculture 242(1–4): 489–500.

Alfaridz F (2018) Review jurnal: klasifikasi dan aktivitas farmakologi dari senyawa aktif flavonoid. Farmaka, 16(3).

Anandari A, Susilawati I, Tanuwiria UH (2025) Supplementation of dragon fruit peel waste (*Hylocereus polyrhizus*) in goat ration on digestibility and fermentability *in vitro*. International Journal of Research 11: 783–790.

Andriani Y, Nabila SR, Pratama RI, Pratiwy FM, Hanidah II (2025) The effectiveness of dragon fruit peel *Hylocereus polyrhizus* in feed on color quality and growth performance of comet fish *Carassius auratus*. Jurnal Akuakultur Indonesia 24(2): 172–184.

Aprilia T, Rakhmawati R (2021) Quality improvement of feed chemical composition with the addition of dragon fruit skin flour (*Hylocereus polyrhizus*). e-Jurnal Rekayasa dan Teknologi Budidaya Perairan 9(2): 1101–1108.

Arivalagan M, Karunakaran G, Roy TK, Dinsha M, Sindhu BC, ... Shivashankara KS (2021) Biochemical and nutritional characterization of dragon fruit (*Hylocereus* species). Food chemistry 353: 129426.

Arsyad MA, Akazawa T, Nozaki C, Yoshida M, Oyama K, ... Ogawa M (2018) Effects of olive leaf powder supplemented to fish feed on muscle protein of red sea bream. Fish Physiology and Biochemistry 44(5): 1299–1308.

Awad ES, Abdelzaher MF, Abbas WT, Darwish DA, Abdel-Monsef M, … Gaafar AY (2024) Effect of beetroot (*Beta vulgaris* L.) extract on enhancing the immune status and antioxidant enzymes of the Nile tilapia (*Oreochromis niloticus*) exposed to lead. Egyptian Journal of Aquatic Biology and Fisheries 28(3): 439–459.

Baron M, Davies S, Alexander L, Snellgrove D, Sloman KA (2008) The effect of dietary pigments on the coloration and behaviour of flame-red dwarf gourami, *Colisa lalia*. Animal Behaviour 75(3): 1041–1051.

Barragán-Longoria MF, Hinojosa-Alvarez S, Hernandez-Perez J, Gonzalez-Cobian LN, Fabian-Ortiz E, … Chavez-Santoscoy RA (2023) Supplementation of flavonoids and inulin in *Totoaba macdonaldi*: microbiota, liver gene expression and growth performance responses. Aquaculture Reports 31: 101654.

Becker K, Makkar HPS (1999) Effects of dietary tannic acid and quebracho tannin on growth performance and metabolic rates of common carp (*Cyprinus carpio* L.). Aquaculture 175(3–4): 327–335.

Biswas M, Alam M, Ahmed S, Uddin MS, Talukder AR, ... Biswas B (2025) Valorization of red dragon fruit peel (*Hylocereus polyrhizus*) as a dunctional ingredient for fortified biscuits: physicochemical, nutritional, and sensory implications. Future Foods 12: 100768.

Biswas O, Kandasamy P, Das SK (2022) Effect of dragon fruit peel powder on quality and acceptability of fish nuggets stored in a solar cooler (5±1 °C). Journal of Food Science and Technology 59(9): 3647–3658.

Bolívar-Ramírez NC, Mallmann AS, Schleder DD, Machado C, Seiffert WQ, do Nascimento Vieira F (2022) Tannins as a food additive in pacific white shrimp diet. Aquaculture 556(4): 738232.

Brutti DD, Uez DE, Maysonnave GS, Konrath RA, da Silva VM, ... Sutili FJ (2024) Condensed tannins from black wattle as a promising nutritional additive for Nile tilapia: Growth, immune and antioxidant responses, and gut morphology. Animal Feed Science and Technology 318: 116152.

Buyukcapar HM, Atalay AI, Kamalak A (2011) Growth performance of Nile tilapia (*Oreochromis niloticus*) fed with diets containing different levels of hydrolysable and condensed tannin. Journal of Agricultural Science and Technology 13(7): 1045–1051.

Cacatian SB, Guittap LJV (2018) Production, proximate analysis and functional properties of dragon fruit peel powder. IAMURE International Journal of Ecology and Conservation 25(1): 1–1.

Cejudo-Bastante MJ, Hurtado N, Delgado A, Heredia FJ (2016) Impact of pH and temperature on the colour and betalain content of Colombian yellow pitaya peel (*Selenicereus megalanthus*). Journal of Food Science and Technology 53(5): 2405–2413.

Chia SL, Chong GH (2015) Effect of drum drying on physico-chemical characteristics of dragon fruit peel (*Hylocereus polyrhizus*). International Journal of Food Engineering 11(2): 285–293.

Chumroenvidhayakul S, Thilavech T, Abeywardena M, Adisakwattana S (2023) Dragon fruit peel waste (*Hylocereus undatus*) as a potential ingredient for reducing lipid peroxidation, dietary advanced glycation end products, and starch digestibility in cookies. Antioxidants 12(5): 1002.

Chumroenvidhayakul S, Thilavech T, Abeywardena MY, Conlon M, Dallimore J, ... Adisakwattana S (2025) Dragon fruit peel (*Hylocereus undatus*) modulates hepatic lipid metabolism and inflammation in a rat model of high-fat, high-fructose-induced metabolic dysfunction. Antioxidants 14(3): 319.

Citarasu T (2010) Herbal biomedicines: a new opportunity for aquaculture industry. Aquaculture International 18(3): 403–414.

Cushnie TT, Lamb AJ (2005) Antimicrobial activity of flavonoids. International Journal of Antimicrobial Agents 26(5): 343–356.

Devi NC, Waikhom G, Singh SK, Das P, Debbarma S, ...

Irungbam S (2024) Effects of vitamin C on growth and non-specific immune response of *Labeo gonius* fry in density-dependent biofloc rearing. Aquaculture Nutrition 2024(1): 9930544.

Drouin G, Godin JR, Pagé B (2011) The genetics of vitamin C loss in vertebrates. Current genomics 12(5): 371–378.

Du JH, Xu MY, Wang Y, Lei Z, Yu Z, Li MY (2022) Evaluation of *Taraxacum mongolicum* flavonoids in diets for *Channa argus* based on growth performance, immune responses, apoptosis and antioxidant defense system under lipopolysaccharide stress. Fish and shellfish immunology 131: 1224–1233.

Durazzo A, Lucarini M, Souto EB, Cicala C, Caiazzo E, ... Santini A (2019) Polyphenols: a concise overview on the chemistry, occurrence, and human health. Phytotherapy Research 33(9): 2221–2243.

Fadillah R, Pagoray H, Saptiani G, Reynalta R (2024) Supplementation of red dragon fruit (*Hylocereus polyrhizus*) peels flour as a prebiotic in tilapia (*Oreochromis niloticus*). Acta Aquatica: Aquatic Sciences Journal 11: 191–197.

FAO (2020) The state of world fisheries and aquaculture. Sustainability in action. Rome.

Gauer PC, Ferreira AC, Siqueira MS, Gimênes-Junior H, Abe HA, ... Honorato CA (2025) Hydroalcoholic extract of pitaya (*Hylocereus guatemalensis*) supplied in the diet for blue *Betta splendens* and its effects on fish pigmentation. Anais Da Academia Brasileira de Ciencias 97(2): e20240212.

Gautam N, Basyal B, Bhattarai K (2024) Effects of drying temperature on bioactive compounds retention in dragon fruit (*Hylocereus undatus*) peel powder. Himalayan Journal of Science and Technology 8(1): 62–70.

Gengatharan A, Dykes GA, Choo WS (2015) Betalains: natural plant pigments with potential application in functional foods. LWT-Food Science and Technology 64(2): 645–649.

Guo X, Zhang X, Ying X, Ma A, Li Z, ... Guo Q (2023) Fermentation properties and prebiotic potential of different pectins and their corresponding enzymatic hydrolysates. Food Hydrocolloids 143(2): 108878.

Hernández YDO, Salazar JAC (2012) Pitahaya (*Hylocereus* spp.): a short review. Comunicata Scientiae 3(4): 220–237.

Hikal WM, Said-Al Ahl HAH, Tkachenko KG, Mahmoud AA, Bratovcic A, ... Atanassova M (2022) An overview of pomegranate peel: a waste treasure for antiviral activity. Tropical Journal of Natural Product Research 6(1): 15–19.

Hoseinifar SH, Jahazi MA, Nikdehghan N, Van Doan H, Volpe MG, Paolucci M (2020) Effects of dietary polyphenols from agricultural by-products on mucosal and humoral immune and antioxidant responses of convict cichlid (*Amatitlania nigrofasciata*). Aquaculture 517: 734790.

Hoseinifar SH, Yousefi S, Van Doan H, Ashouri G, Gioacchini G, … Carnevali O (2020) Oxidative stress and antioxidant defense in fish: the implications of probiotic, prebiotic, and synbiotics. Reviews in fisheries science & aquaculture 29(2): 198–217.

Hotmaida Y, Sutrisno (2020) Non-destructive determination of the main chemical components of red dragon fruit peel flour by using Near-Infrared Reflectance Spectroscopy (NIRS). IOP Conference Series: Earth and Environmental Science 542(1): 012007.

Huang Q, Liu X, Zhao G, Hu T, Wang Y (2018) Potential and challenges of tannins as an alternative to in-feed antibiotics for farm animal production. Animal nutrition 4(2): 137–150.

Ibrahim RE, Ahmed SA, Amer SA, Al-Gabri NA, Ahmed AI, ... Metwally AE (2020) Influence of vitamin C feed supplementation on the growth, antioxidant activity, immune status, tissue histomorphology, and disease resistance in Nile tilapia, *Oreochromis niloticus*. Aquaculture Reports 18: 100545.

Ibrahim RE, Elshopakey GE, AlSaqufi AS, Mansour AT, Alkhamis Y, ... Mansour MF (2026) Hesperidin flavonoid protects African catfish from aflatoxin B1-induced oxidative stress, hepato-renal dysfunction, neurotransmitter disorders, and histological changes. Fish Physiology and Biochemistry 52(2): 47.

Imperatore R, Fronte B, Scicchitano D, Orso G, Marchese M, ... Paolucci M (2022) Dietary supplementation with a blend of hydrolyzable and condensed tannins ameliorates diet-induced intestinal inflammation in zebrafish (*Danio rerio*). Animals 13(1): 167.

Jahazi MA, Hoseinifar SH, Jafari V, Hajimoradloo A, Van Doan H, Paolucci M (2020) Dietary supplementation of polyphenols positively affects the innate immune response, oxidative status, and growth performance of common carp, *Cyprinus carpio* L. Aquaculture 517(1): 734709.

Jiang H, Zhang W, Li X, Shu C, Jiang W, Cao J (2021) Nutrition, phytochemical profile, bioactivities and applications in food industry of pitaya (*Hylocereus* spp.) peels: a comprehensive review. Trends in Food Science & Technology 116: 199–217.

Jimenez-Garcia SN, Garcia-Mier L, Ramirez-Gomez XS, Aguirre-Becerra H, Escobar-Ortiz A, ... Feregrino-Perez AA (2022) Pitahaya peel: a by-product with great phytochemical potential, biological activity, and functional application. Molecules 27(16): 5339.

Khan MI, Giridhar P (2015) Plant betalains: chemistry and biochemistry. Phytochemistry 117: 267–295.

Kumar S, Pandey AK (2013) Chemistry and biological activities of flavonoids: an overview. The Scientific World Journal 2013(1): 162750.

Kurnia A, Nur I, Muskita WH, Hamzah M, Iba W, … Kalidupa N (2019) Improving skin coloration of koi carp (*Cyprinus carpio*) fed with red dragon fruit peel meal. Aquaculture, Aquarium, Conservation and Legislation 12(4): 1045–1053.

Le Bellec F, Vaillant F, Imbert E (2006) Pitahaya (*Hylocereus* spp.): a new fruit crop, a market with a future. Fruits 61(4): 237–250.

Le NL (2022) Functional compounds in dragon fruit peels and their potential health benefits: a review. International Journal of Food Science and Technology 57(5): 2571–2580.

Li M, Feng L, Jiang WD, Wu P, Liu Y, … Zhou XQ (2020) Condensed tannins decreased the growth performance and impaired intestinal immune function in on-growing grass carp (*Ctenopharyngodon idella*). British Journal of Nutrition 123(7): 737–755.

Li M, Zhu X, Tian J, Liu M, Wang G (2019) Dietary flavonoids from *Allium mongolicum* Regel promotes growth, improves immune, antioxidant status, immune-related signaling molecules and disease resistance in juvenile northern snakehead fish (*Channa argus*). Aquaculture 501: 473–481.

Li X, Zhang ZH, Qiao J, Qu W, Wang MS, ... Qi X (2022) Improvement of betalains stability extracted from red dragon fruit peel by ultrasound-assisted microencapsulation with maltodextrin. Ultrasonics Sonochemistry 82: 105897.

Liaotrakoon W, De Clercq N, Lewille B, Dewettinck K (2012) Physicochemical properties, glass transition state diagram and colour stability of pulp and peel of two dragon fruit varieties (*Hylocereus* spp.) as affected by freeze-drying. International Food Research Journal 19(2): 743–750.

Lieke T, Steinberg CE, Pan B, Perminova IV, Meinelt T, … Kloas W (2021) Phenol-rich fulvic acid as a water additive enhances growth, reduces stress, and stimulates the immune system of fish in aquaculture. Scientific Reports 11(1): 174.

Liu J, Zhang X, Lu Q, Zhang H, Lin L, Li Q (2025) Tannic acid reduced the growth performance, antioxidant, and immune functions of the Nile tilapia (*Oreochromis niloticus*). Aquaculture 596: 741872.

Liu Y, Chen H, Chen S, Zhang Y, Zhang J, ... Li D (2023) Pectin-rich dragon fruit peel extracts: an environmentally friendly emulsifier of natural origin. Food Chemistry 429: 136955.

Lizárraga-Velázquez CE, Hernández C, González-Aguilar GA, Heredia JB (2019) Effect of dietary intake of phenolic compounds from mango peel extract on growth, lipid peroxidation and antioxidant enzyme activities in zebrafish (*Danio rerio*). Latin American Journal of Aquatic Research 47(4): 602–611.

Lu RH, Qin CB, Yang F, Zhang WY, Zhang YR, ... Nie GX (2020) Grape seed proanthocyanidin extract ameliorates hepatic lipid accumulation and inflammation in grass carp (*Ctenopharyngodon idella*). Fish Physiology and Biochemistry 46(5): 1665–1677.

Madadi E, Mazloum-Ravasan S, Yu JS, Ha JW, Hamishehkar H, Kim KH (2020) Therapeutic application of betalains: a review. Plants 9(9): 1219.

Madane P, Das AK, Nanda PK, Bandyopadhyay S, Jagtap P, … Maity B (2020) Dragon fruit (*Hylocereus undatus*) peel as antioxidant dietary fibre on quality and lipid oxidation of chicken nuggets. Journal of Food Science and Technology 57(4): 1449–1461.

Magrone T, Fontana S, Laforgia F, Dragone T, Jirillo E, Passantino L (2016) Administration of a polyphenol-enriched feed to farmed sea bass (*Dicentrarchus labrax* L.) modulates intestinal and spleen immune responses. Oxidative Medicine and Cellular Longevity 2016(1): 2827567.

Manihuruk FM, Suryati T, Arief II (2017) Effectiveness of the red dragon fruit (*Hylocereus polyrhizus*) peel extract as the colorant, antioxidant, and antimicrobial on beef sausage. Tropical Animal Science Journal 40(1): 47–54.

Mansoori A, Allaf Noveirian H, Hoseinifar SH, Sajjadi M, Ashouri G, … Paolucci M (2024) Polyphenol-rich extracts enhance growth, immune function, and antioxidant defense in juvenile rainbow trout (*Oncorhynchus mykiss*). Frontiers in Nutrition 11: 1487209.

Matra M, Totakul P, Viennasay B, Phesatcha B, Wanapat M (2021) Dragon fruit (*Hylocereus undatus*) peel pellet as a rumen enhancer in Holstein crossbred bulls. Animal Bioscience 34(4): 594.

Maulida S, Harahap NR, Handayani LS (2025) The effect of adding red dragon fruit peel extract (*Hylocereus polyrhizus*) in feed to increase color brightness in guppy fish (*Poecilia reticulata*). BIO Web of Conferences 156: 03016.

Mega DAU (2025) Red dragon fruit peel as a natural pigment enhancer in goldfish (*Carassius auratus*). Asian Journal of Agriculture 9(2): 777–786.

Mercado-Silva EM (2018) Pitaya—*Hylocereus undatus* (haw). Exotic fruits 339–349.

Middleton ET, Steel SA, Doherty SM (2007) The effect of prior bisphosphonate exposure on the treatment response to teriparatide in clinical practice. Calcified Tissue International 81(5): 335–340.

Misra CK, Das BK, Mukherjee SC, Pradhan J (2007) Effects of dietary vitamin C on immunity, growth and survival of Indian major carp *Labeo rohita*, fingerlings. Aquaculture Nutrition 13(1): 35–44.

Mizrahi Y, Nerd A (1999) Climbing and columnar cacti: new arid land fruit crops. Perspectives on new crops and new uses 1: 358–366.

Naiel MA, El-Kholy AI, Negm SS, Ghazanfar S, Shukry M, … Abdel-Latif HM (2023) A mini-review on plant-derived phenolic compounds with particular emphasis on their possible applications and beneficial uses in aquaculture. Annals of Animal Science 23(4): 971–977.

National Research Council, Division on Earth, Life Studies, & Institute for Laboratory Animal Research (2011) Guidance for the description of animal research in scientific publications. National Academic Press.

Naylor RL, Hardy RW, Buschmann AH, Bush SR, Cao L, … Troell M (2021) A 20-year retrospective review of global aquaculture. Nature 591(7851): 551–563.

Nazeri S, Farhangi M, Modarres S (2017) The effect of different dietary inclusion levels of rutin (a flavonoid) on some liver enzyme activities and oxidative stress indices in rainbow trout, *Oncorhynchus mykiss* (Walbaum) exposed to oxytetracycline. Aquaculture Research 48(8): 4356–4362.

Nikjoo M, Farhangi M, Patimar R, Adineh H, Alizadeh M (2023) The protective effect of vitamin C on growth, digestive enzymes, immune response, and gill histology in Caspian roach (*Rutilus rutilus caspicus*) under diazinon stress. Aquaculture Reports 32: 101698.

Nobel PS, De la Barrera E (2002) Stem water relations and net CO2 uptake for a hemiepiphytic cactus during short-term drought. Environmental and experimental botany 48(2): 129–137.

Nur MA, Uddin MR, Uddin MJ, Satter MA, Amin MZ (2023) Physiochemical and nutritional analysis of the two species of dragon fruits (*Hylocereus* sp.) cultivated in Bangladesh. South African Journal of Botany 155: 103–109.

Oh HY, Kim KT, Lee TH, Kang DY, Kwon DH, … Kim HS (2025) Functional potential of red dragon fruit (*Hylocereus polyrhizus*) juice by-products as a natural feed additive for juvenile red seabream (*Pagrus major*): implications for antibiotic-free aquaculture. Antibiotics 14(11): 1096.

Oniszczuk T, Oniszczuk A, Gondek E, Guz L, Puk K, … Wójtowicz A (2019) Active polyphenolic compounds, nutrient contents and antioxidant capacity of extruded fish feed containing purple coneflower (*Echinacea purpurea* (L.) Moench.). Saudi journal of biological sciences 26(1): 24–30.

Peng K, Huang W, Zhao H, Sun Y, Chen B (2021) Dietary condensed tannins improved growth performance and antioxidant function but impaired intestinal morphology of *Litopenaeus vannamei*. Aquaculture Reports 21: 100853.

Peng K, Wang G, Zhao H, Wang Y, Mo W, … Huang Y (2020) Effect of high level of carbohydrate and supplementation of condensed tannins on growth performance, serum metabolites, antioxidant and immune response, and hepatic glycometabolism gene expression of *Lateolabrax japonicus*. Aquaculture reports 18: 100515.

Peng X, Ed-Dra A, Song Y, Elbediwi M, Nambiar RB, ... Yue M (2022) *Lacticaseibacillus rhamnosus* alleviates intestinal inflammation and promotes microbiota-mediated protection against *Salmonella* fatal infections. Frontiers in Immunology 13: 973224.

Perween T, Mandal KK, Hasan MA (2018) Dragon fruit: an exotic super future fruit of India. Journal of Pharmacognosy and Phytochemistry 7(2): 1022–1026.

Prasad VGNV, Swamy PL, Rao TS, Rao GS (2014) Antibacterial synergy between quercetin and polyphenolic acids against bacterial pathogens of fish. Asian Pacific Journal of Tropical Disease 4: S326–S329.

Prusty AK, Sahu NP, Pal AK, Reddy AK, Kumar S (2007) Effect of dietary tannin on growth and haemato-immunological parameters of *Labeo rohita* (Hamilton) fingerlings. Animal Feed Science and Technology 136(1–2): 96–108.

Putri FI, Sukarti K (2024) Evaluation of red pitaya (*Hylocereus polyrhizus*) peel as a feed additive in Sangkuriang catfish (*Clarias gariepinus*). Jurnal Agroqua: Media Informasi Agronomi dan Budidaya Perairan 22(2): 164–174.

Qiu J, Huang W, Cao J, Zhao H, Chen B, … Peng K (2023) Dietary hydrolyzable tannins reduce growth performance and induce histological damage of Chinese seabass (*Lateolabrax maculatus*). Frontiers in Marine Science 10: 1183438.

Rakhmawati R, Aprilia T, Indariyanti N, Saputra A, Eulis M (2023) Color quality improvement of *Cherax quadricarinatus* with dragon fruit peel meal utilization. Jurnal Ilmu-Ilmu Perairan, Pesisir dan Perikanan 12(3): 314–319.

Rakhmawati R, Aprilia T, Kurniawan A (2021) Enhancement the growth of snakehead (*Channa striata*) with addition of dragon fruit peel flour to the diet. Sriwijaya Journal of Environment 6(2): 53–58.

Reterta AJE, Trinidad TP (2018) Nutritional content and utilization of dragon fruit (*Hylocereus polyrhizus*) peels. NRCP Research Journal 16(Special issue No. 1): 41–52.

Rifna EJ, Misra NN, Dwivedi M (2023) Recent advances in extraction technologies for recovery of bioactive compounds derived from fruit and vegetable waste peels: a review. Critical Reviews in Food Science and Nutrition 63(6): 719–752.

Rodriguez EB, Vidallon MLP, Mendoza DJR, Reyes CT (2016) Health-promoting bioactivities of betalains from red dragon fruit (*Hylocereus polyrhizus* (Weber) Britton and Rose) peels as affected by carbohydrate encapsulation. Journal of the Science of Food and Agriculture 96(14): 4679–4689.

Roriz CL, Heleno SA, Alves MJ, Oliveira MBP, Pinela J, Dias MI, … Barros L (2022) Red pitaya (*Hylocereus costaricensis*) peel as a source of valuable molecules: extraction optimization to recover natural colouring agents. Food Chemistry 372: 131344.

Ross JA, Kasum CM (2002) Dietary flavonoids: bioavailability, metabolic effects, and safety. Annual review of Nutrition 22(1): 19–34.

Salehi M, Soltani M, Hosseini-Shekarabi SP (2016) Effects of antifungal activity of Daenensis thyme (*Thymus daenensis*) and Mentha (*Mentha longifolia*) essential oils on rainbow trout (*Oncorhynchus mykiss*) eggs hatchability. Iranian Journal of Aquatic Animal Health 2(2): 97–107.

Song K, Ling F, Huang A, Dong W, Liu G, ... Wang G (2015) In vitro and in vivo assessment of the effect of antiprotozoal compounds isolated from *Psoralea corylifolia* against *Ichthyophthirius multifiliis* in fish. International Journal for Parasitology: Drugs and Drug Resistance 5(2): 58–64.

Tewary A, Patra BC (2008) Use of vitamin C as an immunostimulant. Effect on growth, nutritional quality, and immune response of *Labeo rohita* (Ham.). Fish Physiology and Biochemistry 34(3): 251–259.

Van Doan H, Hoseinifar SH, Hung TQ, Lumsangkul C, Jaturasitha S, ... Paolucci M (2020) Dietary inclusion of chestnut (*Castanea sativa*) polyphenols to Nile tilapia reared in biofloc technology: impacts on growth, immunity, and disease resistance against *Streptococcus agalactiae*. Fish and Shellfish Immunology 105: 319–326.

Wang Y, Wu J, Li L, Yao Y, Chen C, ... Liu W (2024) Effects of tannic acid supplementation of a high-carbohydrate diet on the growth, serum biochemical parameters, antioxidant capacity, digestive enzyme activity, and liver and intestinal health of largemouth bass, *Micropterus salmoides*. Aquaculture Nutrition 2024(1): 6682798.

Wu LC, Hsu HW, Chen YC, Chiu CC, Lin YI, Ho JAA (2006) Antioxidant and antiproliferative activities of red pitaya. Food chemistry 95(2): 319–327.

Wybraniec S, Mizrahi Y (2002) Fruit flesh betacyanin pigments in *Hylocereus cacti*. Journal of Agricultural and Food Chemistry 50(21): 6086–6089.

Xiao K, Wang X, Wang MM, Guo HX, Liu WB, Jiang, G. Z. (2024) Metabolism, antioxidant and immunity in acute and chronic hypoxic stress and the improving effect of vitamin C in the channel catfish (*Ictalurus punctatus*). Fish Physiology and Biochemistry 50(1): 183–196.

Xu Z, Yang H, Poolsawat L, Rahman MM, Xu X, ... Leng X (2021) Flavonoid-enriched diets improved the growth and flesh quality of grass carp (*Ctenopharyngodon idellus*) based on metabolomics. Aquaculture Nutrition 27(6): 2514–2528.

Xuan CL, Nguyen VL, Wannavijit S, Outama P, Khongdee N, ... Van Doan H (2024) Modulation of growth, immunity, and immune-antioxidant gene expression in Nile tilapia, *Oreochromis niloticus*, culture under biofloc system by dragon fruit, *Hylocereus undatus*, peel powder. Journal of the World Aquaculture Society 55(5): e13088.

Xue X, Chen Y, Yu Z, Feng Y, Zhang L, ... Shu H (2024) Effects of diet supplemented with hydrolyzable tannin on the growth performance, antioxidant capacity, and muscle nutritional quality of juvenile *Mastacembelus armatus*. Aquaculture Nutrition 2024(1): 8266189.

Yan X, Pang P, Qin C, Mi J, Yang L, ... Nie G (2024) Improvement of sea buckthorn (*Hippophae rhamnoides* L.) flavonoids on the antioxidant and immune performance of Yellow River carp (*Cyprinus carpio* L.) fed high-carbohydrate diet. Fish and Shellfish Immunology 144: 109289.

Yang M, Jiang D, Lai W, Chen K, Zhang L, ... Jiang J (2024) Hydrolysable tannin improves growth performance and liver health of largemouth bass (*Micropterus salmoides*) fed high soybean meal diets. International Journal of Biological Macromolecules 276: 133773.

Yang M, Jiang D, Zhang L, Lu L, Xu Y, ... Jiang J (2025) Dietary condensed tannin supplementation improves growth performance and feed utilization of juvenile largemouth bass (*Micropterus salmoides*) through positively regulating serum lipids and intestinal health. Aquaculture 595: 741607.

Yao J, Chen P, Ringø E, Zhang G, Huang Z, Hua X (2019) Effect of diet supplemented with rapeseed meal or hydrolysable tannins on the growth, nutrition, and intestinal microbiota in grass carp (*Ctenopharyngodon idellus*). Frontiers in Nutrition 6: 154.

Yesepus AO, Felix R, Pasaribu W (2024) Effects of adding red dragon fruit peel (*Hylocereus polyrhizus*) at different dosages in feed on the color change of clownfish (*Amphiprion percula*). Grouper: Jurnal Ilmiah Perikanan 15(1): 51–60.

Yousefi P, Yavari V, Zakeri M, Salati AP, Keyvanshokooh S (2013) Effect of dietary supplementation of vitamin C on growth performance, feed utilization and carcass composition of *Barbus sharpeyi* fingerlings. Journal of the Persian Gulf 4(14): 23–31.

Zaid RM, Mishra P, Noredyani AS, Tabassum S, Ab Wahid Z, Sakinah AM (2020) Proximate characteristics and statistical optimization of ultrasound-assisted extraction of high-methoxyl-pectin from *Hylocereus polyrhizus* peels. Food and Bioproducts Processing 123: 134–149.

Zeb A (2020) Concept, mechanism, and applications of phenolic antioxidants in foods. Journal of Food Biochemistry 44(9): e13394.

Zhang L, Yang M, Jiang D, Xiao Z, He Y, ... Jiang J (2025) Condensed tannin ameliorates intestinal damage and mitochondrial dysfunction induced by high-fat diets in largemouth bass (*Micropterus salmoides*).

International Journal of Biological Macromolecules 311: 143642.

Zhang X, Gong H, Chen P, Wang J, Chen Z, … Li J (2024) Effects of tannin supplementation in diet on the resistance to ammonia stress of Pacific white shrimp *Litopenaeus vannamei*. Aquaculture Nutrition++ 2024(1): 5539701.

Zhou Q, Wang L, Wang H, Xie F, Wang T (2012) Effect of dietary vitamin C on the growth performance and innate immunity of juvenile cobia (*Rachycentron canadum*). Fish and Shellfish Immunology 32(6): 969–975.

Zhu R, Liu Z, Lu M, Wu X, Zhao X, … Wu LF (2023) The protective role of vitamin C on intestinal damage induced by high-dose glycinin in juvenile *Rhynchocypris lagowskii* Dybowski. Fish and Shellfish Immunology 134: 108589.

Zhu XF, Guo H, Li GL, Zhu CH (2021) Effects of dietary hydrolyzable tannins on growth performance, antioxidant capacity, intestinal microflora and resistance against *Vibrio parahaemolyticus* of juvenile Pacific white shrimp, *Litopenaeus vannamei* (Boone, 1931). Aquaculture Reports 19: 100601.

Zhuang Y, Zhang Y, Sun L (2012) Characteristics of fibre-rich powder and antioxidant activity of pitaya (*Hylocereus undatus*) peels. International Journal of Food Science and Technology 47(6): 1279–1285.