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REVIEW

Astaxanthin supplementation in shellfish aquaculture: comparative impacts on growth, immunity and bioavailability solutions

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Abstract Astaxanthin, a keto-carotenoid with significant antioxidative and immunomodulatory effects, has surfaced as a prospective functional feed supplement in shellfish farming. Dietary supplementation has been demonstrated to markedly augment antioxidant enzyme activities (SOD, CAT, GPx) and regulate critical inflammatory mediators (IL-2, IFN-γ), consequently enhancing survival rates and growth performance in species such as *Litopenaeus vannamei*, *Babylonia areolata*, and *Haliotis discus* under environmental and pathogenic stress. Nonetheless, its extensive utilization is constrained by inadequate bioavailability and elevated production expenses. Furthermore, evidence supporting its efficacy in bivalves is weak, lacking standardized dose–response trials, which impedes its practical use. Recent breakthroughs in nano-encapsulation, protein-lipid complexation, and microbial fermentation are increasingly improving delivery efficiency and economic viability. This study consolidates existing knowledge on the mechanisms of astaxanthin action, species-specific physiological effects, and sustainable delivery methods, advocating for its strategic incorporation into non-finfish aquaculture systems.

Keywords Astaxanthin . Antioxidant . Bivalves . Crustaceans . Delivery strategies . Immunomodulatory . Optimal dosages

Introduction

Astaxanthin, a potent antioxidant xanthophyll, surpasses β-carotene and vitamin E in activity and is widely used in aquafeeds. It enhances product quality through its well-established role in pigmentation of aquatic animal flesh, skin and fillets. (Li et al. 2025)

Prior study has demonstrated that astaxanthin dietary supplements can promote growth performance and increase stress tolerance in both post-larval and adult shrimp. The elevated cost of synthetic astaxanthin restricted its use in practical feed applications (Xie et al. 2018). Crustaceans, particularly penaeid shrimp such as *Litopenaeus vannamei*, represent one of the primary aquaculture species for which astaxanthin has been studied. Its application in this group has shown consistent improvements in Growth and metabolism (Wang et al. 2020)

The low aqueous solubility of astaxanthin significantly impairs its intestinal absorption and overall bioavailability in aquatic organisms. Its efficacy is further hindered by chemical instability due to heat, light, oxidation, acidic pH, and processing. Strategies like microencapsulation and liposome delivery have shown promise in enhancing its stability and improving gastrointestinal uptake in aquaculture applications. Astaxanthin production remains constrained by high costs, limited raw materials, (Hwang et al. 2024; Sun et al.

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2021), and inefficient extraction processes (Qi et al. 2020; Simat et al. 2022). Solutions such as alternative biological sources (Zhao et al. 2024; Zhang et al. 2024) optimized culture conditions (Ahmadkelayeh et al. 2020), nanotechnology, microencapsulation (Lee et al. 2022; Denga et al. 2024), and green extraction using waste-based media (Dang et al. 2024) offer promising improvements. However, further research is needed to address scalability, economic feasibility, and long-term impacts. Bridging these knowledge gaps is essential to ensure cost-effective, sustainable production and support the broader application of astaxanthin in aquaculture and industry.

Aquaculture feeds include a broad range of nutraceuticals designed to meet nutritional requirements and support physiological functions such as immune defense, reproduction, and growth. A growing variety of feed additives is used to ensure proper feed intake, digestion, absorption, and tissue conversion (Mustafa and Al-Faragi 2021).

The incorporation of feed additives has become a standard approach in modern aquaculture practices. (Boyd et al. 2020). A feed additive is a trace or minimal amount of material that is put in during the feed processing, production, and utilization. Feed additives are advantageous to aquatic animals because they can stimulate growth, immunity, lipid metabolism, and gastrointestinal health (Rohani et al. 2022). Their impacts are, however, different depending on the type, structure, and characteristics (Ahmadifar et al. 2021). One of the most important nutrient sources in aquaculture is microalgae, which is also the most abundant natural source of astaxanthin (*Haematococcus pluvialis*) (Riccio and Lauritano 2019; Ruiz-Dominguez et al. 2019). They are also used as sources of pigments, biofuels, and pharmaceuticals (Ravishankar and Ambati 2019).

Aquatic animals are among the most traded food commodities, with over 450 farmed species across diverse environments (FAO 2022). Global aquaculture has expanded since 1950 (FAO 2023), now surpassing wild fisheries (Ritchie and Roser 2021), growing rapidly across ecosystems (Desbois et al. 2025; FAO 2022) and requiring innovation, skilled labor (Subasinghe et al. 2023), and governance (Partelow et al. 2023).

This review uniquely considers the use of astaxanthin as a feed additive in aquaculture, its biological action, species-specific dosage, and delivery methods to enhance bioavailability. The focus has been made on species-specific performance characteristics, sustainable production approaches, and future perspectives of incorporating astaxanthin into commercial aquafeeds.

Astaxanthin and its perspectives

The carotenoids comprise a group of over 600 lipophilic pigments predominantly found in plants, which form the foundation of the coloration of several organisms in nature. Some of the common carotenoids are beta carotene, lycopene, lutein, astaxanthin, and zeaxanthin (Mularczyk et al. 2020).

Sources and extraction techniques of astaxanthin

Astaxanthin (3,3′-dihydroxy-β,β-carotene-4,4′-dione) is a red carotenoid pigment that is lipophilic, insoluble in water, and soluble in many chemical solvents. The primary natural sources include the microalga *Haematococcus pluvialis*, the red yeast *Phaffia rhodozyma,* and by-products from crustaceans (Mularczyk et al. 2020). Natural sources are extensively employed in nutraceuticals, aquafeeds, and cosmetics owing to the powerful antioxidant effects of astaxanthin.

Various extraction techniques have been utilized to obtain astaxanthin, encompassing traditional methods such as solvent, acid, enzymatic, and oil-based extraction, as well as more sophisticated approaches including microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), ionic liquids, and deep eutectic solvents (Roy et al. 2021). Oil-based extraction utilizing olive oil has exhibited superior recovery efficiency (~93%) in comparison to acid-based approaches such as hydrochloric acid (~80%) (Hu et al. 2025). However, conventional solvent-based methods pose challenges such as residual solvent contamination, reduced and environmental concerns (Martins et al. 2023).

Astaxanthin appears in many stereoisomeric forms, which significantly affect its bioavailability and antioxidant activity. Natural enantiomers (3S,3′S and 3R,3′R) are commonly found in *H. pluvialis* and *P. rhodozyma,* exhibit superior bioactivity compared to the synthetic meso-form (3R,3′S) (Mularczyk et al.

2020). The chemical formula of the enantiomers is shown in Figure 1.

The microbial production of astaxanthin has drawn interest as a sustainable alternative. Genetically modified bacteria, yeasts, and fungi are utilized to manufacture pigments such astaxanthin, β-carotene, lycopene, and canthaxanthin. For example, the manufacture of astaxanthin in *Escherichia coli* was augmented through the successive insertion of the crtZ gene (Gong et al. 2020). *Saccharomyces cerevisiae*, a prevalent model organism, is utilized for carotenoid synthesis owing to its genetic manipulability, safety, and industrial scalability (Varghese et al. 2023; Shi et al. 2019).

Astaxanthin mechanisms and functions

The unique molecular structure of astaxanthin is characterized by conjugated double bonds, hydroxyl groups, and keto groups underpins its potent antioxidant activity. These structural characteristics allow it to donate electrons, quench free radicals, and stop chain reactions by changing the reactive species into more stable species. Its lipophilic nature allows integration into cell membranes, facilitating direct radical scavenging, modulation of cellular signaling, upregulation of antioxidant enzymes, and immune enhancement (Chae et al. 2022).

Astaxanthin, as a molecule, also interacts with a number of signaling pathways that are associated with oxidative stress response. The nuclear factor erythroid 2-related factor 2 (Nrf2) is one of such pathways. Under oxidative stress, astaxanthin promotes the release of Nrf2, which dissociates from its inhibitor Keap1, translocates to the nucleus, and binds to antioxidant response elements (ARE) to activate genes involved in cellular defense. This leads to upregulation of antioxidant enzymes such as SOD, CAT, and GPx, thereby enhancing cellular defense and mitigating oxidative damage (Davinelli et al. 2022). The antioxidative mechanisms of astaxanthin are summarized in Figure 2.

In addition to its antioxidant properties, astaxanthin exhibits significant immunomodulatory effects in crustaceans and bivalves. It enhances macrophage phagocytic activity, improving pathogen clearance and

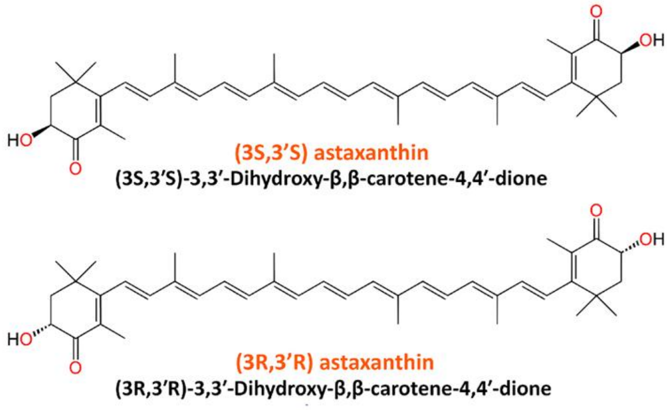

Fig. 1 Two naturally occurring astaxanthin enantiomers and their chemical structures (Bjørklund et al. 2022)

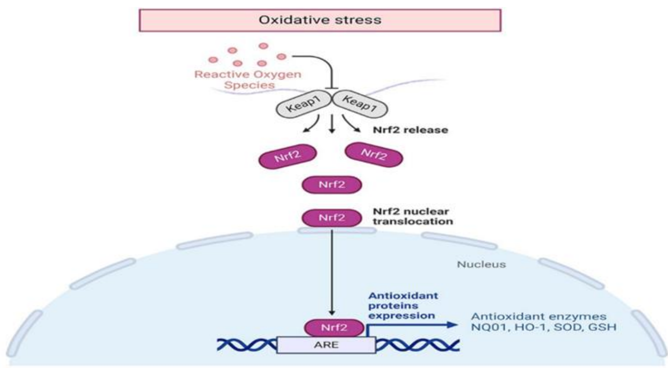

Fig. 2 The chemical processes underlying astaxanthin antioxidative actions (Wang et al. 2024)

promoting cytokine release such as interleukin-2 (IL-2) and interferon-gamma (IFN-γ), which play key roles in immune signaling and lymphocyte function (Alkhattabi et al. 2022). Astaxanthin also improves the activity of natural killer (NK) cells, which are a key element of the intrinsic immune patrols as they attack cells infected with viruses and malignant cells. At the molecular scale, astaxanthin affects certain important immune-related pathways, including the JAK/STAT and NF-κB pathways. The use of astaxanthin reduces the release of pro-inflammatory cytokines and suppresses the possibility of excessive inflammation and oxidative damage through the inhibition of the NF- κB (Khan 2025). These effects not only strengthen host defense but also help maintain immune homeostasis under stress conditions.

Comparative bioactivity in shellfish

Crustaceans

Crustaceans obtain astaxanthin either by the metabolic conversion of ingested carotenoids such as β-carotene, lutein, and zeaxanthin, or by absorbing it from prey species that have already experienced bioconversion (Šimat et al. 2022). Astaxanthin is present in their bodies in both free and bound forms, complexed with fatty acids like palmitic, oleic, stearic, or linoleic acids, dispersed throughout tissue membranes, blood, and eggs. Deng et al. (2024) presented robust experimental evidence demonstrating the consistent benefits of astaxanthin on antioxidant enzyme activity (e.g., SOD, CAT, GPx), non-specific immune parameters (e.g., hemocyte counts, phenoloxidase), and pathogen resistance (e.g., against Vibrio spp.) in species such as *Litopenaeus vannamei* and swimming crabs. Optimal dietary levels range from 24 to 200 mg/kg, with stronger responses often observed under bacterial challenge conditions, where groups receiving astaxanthin exhibited markedly improved survival rates (Deng et al. 2024). The dose–response relationship of astaxanthin in crustaceans is extensively researched but remains inconsistent owing to variations in source type, delivery matrix, and exposure time, hence limiting the ability to perform cross-study meta-analyses. Despite this diversity, astaxanthin regularly supports innate immunity and antioxidant capacity. Šimat et al. (2022) observed that growth responses (SGR/WGR) are inconsistent: certain studies indicate enhancements, whereas others reveal no notable growth impact but improved survival or egg quality. The disparities are significantly affected by the source (natural versus synthetic) and formulation (e.g., microalgal powder versus pure extract), which influence both deposition and physiological results. Cholesterol supplementation has been demonstrated to enhance stress resistance and hypoxia adaption in shrimp, as indicated by reduced Hsp70 and increased HIF-1α expression (Niu et al. 2014).

Gastropods (abalone, ivory shell)

In gastropods like *Haliotis spp.* and *Babylonia*, dietary astaxanthin is linked to higher antioxidant defenses, increased heat and disease tolerance, and improved muscle quality (Li et al. 2024). Comparative analyses indicate that astaxanthin derived from yeast or microalgae sources surpasses crude algal feeds in promoting physiological resilience and growth. In Babylonia, dosages of 75–100 mg/kg have demonstrated enhancement in weight gain and antioxidant enzyme levels. Šimat et al. (2022) emphasize astaxanthin function as an effective free radical scavenger that regulates antioxidant enzyme activity and equilibrates immunological responses, hence enhancing stress tolerance in abalone. Li et al. (2024) additionally highlight its influence on coloration, survival, and general developmental performance elements that directly augment the commercial value of gastropods. Natural sources such as *Haematococcus pluvialis* and *Phaffia rhodozyma* generally yield superior tissue deposition and functional advantages compared to unrefined algal biomass, hence endorsing its preferred application in high-value aquaculture systems.

Bivalves (oysters, clams, mussels)

Bivalves, including oysters, clams, and mussels, inherently collect carotenoids such as astaxanthin from diets rich in microalgae; nevertheless, the existing literature on their reaction to direct astaxanthin supplementation is sparse and disjointed. In contrast to crustaceans and gastropods, which have well-documented dose-dependent effects on immunity and growth, bivalve research frequently concentrates solely on larval survival or metamorphosis, with insufficient data on growth, tissue deposition, or functional health outcomes (Jiang et al. 2020).

No standardized dose–response studies for bivalves exist, which is a critical issue. Numerous research utilize mixed algal feeds, complicating the isolation of astaxanthin effects from co-nutrients such as DHA and EPA (Zou et al. 2023). Moreover, species-specific variations in filter-feeding and gastrointestinal absorption are predominantly neglected, despite their probable influence on uptake efficiency. The excessive focus on early life stages overlooks possible advantages in juveniles and adults, including shell integrity, color, and market characteristics. The lack of validated immunological biomarkers in adult bivalves restricts the evaluation of health-related impacts, in contrast to the proven markers utilized in crustaceans (Yu and Liu 2020). The existing evidence is inadequate for definitive conclusions. A pressing necessity exists for species-specific, longitudinal research utilizing established endpoints and economic criteria to assess astaxanthin genuine potential in bivalve aquaculture. This disparity among species suggests that crustaceans and gastropods derive consistent antioxidant and immunological benefits from astaxanthin, whereas bivalves necessitate specific experiments to confirm analogous effects, particularly in later embryonic stages.

Bioactivity of astaxanthin in shellfish

An example is dietary astaxanthin supplementation in *Litopenaeus vannamei* (white leg shrimp), which can significantly increase hemocyte counts, phenol oxidase activity, and superoxide dismutase (SOD) activity, increasing non-specific immune responses. Furthermore, diets enriched with astaxanthin enhance the histological framework and antioxidant ability of juvenile Indian white shrimp (*Fenneropenaeus indicus*) (Eldessouki et al. 2022).

In addition to crustaceans, microbiological sources and nutritional formulations have been investigated to enhance astaxanthin delivery and efficacy in aquaculture. Since aquatic species cannot synthesize astaxanthin, it must be obtained through the diet and is therefore routinely incorporated into commercial aquafeeds (Lim et al. 2018). Due to its greater growth rates and carotenoid synthesis, the Gram-negative bacterium *P. carotinifaciens* is now being sought as a natural source of astaxanthin (Hayashi et al. 2021). Various aquatic species such as crayfish, salmon, trout, and shrimp accumulate dietary carotenoids like astaxanthin (Jannel et al. 2020).

As a potent antioxidant, astaxanthin plays critical roles in minimizing oxidative stress, modulating key cellular pathways, and enhancing aquaculture productivity. Supplementation with dietary pigments represents a practical strategy (Nuntapong et al. 2022). Carotenoids, a class of tetraterpenoid pigments, contribute to both growth and pigmentation, making them valuable additives in aquaculture (Lim et al. 2023). Examples of common carotenoid pigments include astaxanthin and β-carotene, as well as canthaxanthin (Jing et al. 2022). Among them, astaxanthin is the dominant pigment found in shrimp (Chakraborty et al. 2023).

In addition to pigmentation, astaxanthin enhances shrimp health by reducing oxidative stress and supporting immune responses (Xu et al. 2023; Zhao et al. 2022). Astaxanthin is the strongest natural antioxidant so far because it can neutralize the effect of free radicals produced by exogenous stress by activating the Keap1-Nrf2 system (Zhao et al. 2023). There was also an effect on fatty acid profiles by astaxanthin (Wang et al. 2019). Due to this, besides acting as a pigment and antioxidant, astaxanthin has a significant regulatory effect on lipid metabolism.

When combined, cross-species synthesis demonstrates consistent immunological and antioxidant benefits but inconsistent growth effects. These inconsistencies likely stem from interspecies differences in nutrient absorption, feeding physiology, and experimental variability. In the case of industry, this highlights the necessity of aligning the dosage and source choice to the desired endpoints, i.e., survival, pigmentation, or immune resilience, instead of focusing on the expected growth enhancement across taxa.

Comparison of productive results by using astaxanthin as a feed additive for shellfish

Astaxanthin has been used in crab aquaculture since ancient times to provide these species with their characteristic pink-red colour. There is also the fact that astaxanthin is a nutrient-rich substance, and the tendency to consume it has been increasing in recent years. (Yu and Liu 2020). The Pacific white shrimp, *Litopenaeus vannamei*, is a tropical species that is most commonly grown and rich in astaxanthin. Most crustaceans, e.g., shrimp, can absorb dietary astaxanthin directly into the body and can turn dietary β-carotene into astaxanthin (Maoka 2020).

Diaz-Jimenez et al. (2019) find that 2-carotene and astaxanthin were useful in ensuring survival and enhancing the egg quality in peppermint shrimp and have potential in shaping the aquaculture process in peppermint shrimp (*Lysmata wurdemanni*). All treatment groups had similar growth rates, which implies that carotenoids have no significant effect on growth in this case but only increase survival. Body accumulation had a negative relationship with dietary astaxanthin, whereas 2-carotene had a positive relationship with body accumulation, implying that there are different metabolic pathways between these carotenoids. The study offers useful information in designing sustainable aquaculture guidelines on ornamental shrimp (Diaz-Jimenez et al. 2019).

Eldessouki et al. (2022) corroborated prior research by showing that feeding astaxanthin at 100–200 mg/kg boosted growth and immunity in *L. vannamei,* while also dramatically increasing post-challenge survival to 82.7% at 200 mg/kg after *Vibrio harveyi* infection. Yu et al. (2021) reported that astaxanthin extracted from *Haematococcus pluvialis* (HP) significantly enhanced immune-related gene expression in shrimp. Shrimp administered diets with 20.49 mg/kg (HP-35) and 40.98 mg/kg (HP-70) astaxanthin exhibited enhanced expression of Toll, IMD, PO, and Lysozyme genes after 7 days, with additional increases noted by day 15. The expression of Myd88 was much higher in the HP-35 group, which exhibited greater immunological enhancement relative to HP-70. These findings underscore the dose-dependent regulation function of natural astaxanthin on innate immunity genes (Yu et al. 2021).

The researchers Wiener et al. (2015) reached the conclusion that the use of astaxanthin demonstrated significant increases in many performance indicators in young *Eriocheir sinensis*, such as growth, antioxidant capacity, immunity, and coloring. To balance between development and stress resistance, the optimum dietary concentration of micro-algal astaxanthin was determined to be around 60 mg/kg. These findings provide valuable data for the development of effective diets that can enhance *E. sinensis* aquaculture. Chinese mitten crabs (*Eriocheir sinensis*) raised 756,877 tons per year in 2018, which is an economically valuable species in aquaculture. Despite the established benefits of dietary astaxanthin, particularly that of *Haematococcus pluvialis*, in health and stress resistance in a variety of crustacean species, nothing is known regarding its effects on juvenile *Eriocheir sinensis*. No observed differences were present across treatments, although there were trends in which there were better growth parameters as dietary astaxanthin supplementation improved. Though there were higher survival rates in astaxanthin-supplied groups than controls, the rates were not statistically significant (Jiang et al. 2020).

Su et al. (2020) examine the effects of dietary astaxanthin from synthetic sources and its natural sources (*Haematococcus pluvialis*) on the carotenoid content in different body parts of *Eriocheir sinensis*. The researchers noted that the levels of carotenoids were interchangeable by metabolic conversion as the dietary astaxanthin enhanced the levels of β-carotene in the hepatopancreas. The results reveal that astaxanthin is not simply absorbed, but can be transformed in the process of the *Eriocheir sinensis* metabolism. Such results promote the utilization of natural sources of astaxanthin as a nutritional supplement in aquaculture to enhance the quality and safety of aquatic products. The research paper also validated that various tissues in *E. sinensis* selectively accumulate certain carotenoids, with astaxanthin being predominant in the epithelium and carapace. *Hematococcus pluvialis* powder proved to be more efficient than synthetic sources in adding astaxanthin and, thus, it could be used as a better dietary supplement (Su et al. 2020).

Deng et al. (2024) found in their research that the growth of swimming crabs was significantly improved by the addition of astaxanthin to the diet. Crabs fed diets free of AST supplementation contained the lowest concentrations of glutathione (GSH), total antioxidant capacity (T-AOC), superoxide dismutase (SOD), and peroxidase (POD). The level of astaxanthin consumed had no significant effect on the lipid content of muscle or the activity of carnitine palmitoyl transferase (CPT) in the hepatopancreas, but crabs fed diets with no AST supplement contained lower lipid content and fatty acid synthetase (FAS) activity in the hepatopancreatic tissue. Overall, astaxanthin stimulated hemolymph antioxidant and immunological functions and significantly stimulated the accumulation of hepatopancreatic lipid (Deng et al. 2024). Even though the sea clam market is large and growing currently, the future of shellfish cultivation is not assured. The breeding process has not caused the shellfish production cost to increase with the price of the fish. The problem of economic over-cultivation has arisen as a problem producers have to cope with. Commercial cultivation of microalgae comprises a major part of the marine renewable bioresource industry and supplements the inexpensive cultivation of bivalve shellfish, such as oysters, mussels, clams, and scallops (Cheng et al. 2020).

Compared to microalgae-free diets, Yang et al. (2021) discovered that bivalve mollusk diets that combined the use of microalgae with other foods increased the ingestion and digestion of dwarf surf clams, *Mulinia lateralis*, resulting in high growth, survival, and metamorphosis. Bivalves may be either facultative deposit feeders, grazing the surface of sediments, or suspension feeders, sieving suspended particles of organic matter out of the water column. In fact, the amount and quality of food are connected to the ability of different bivalve species to eliminate suspended solids (Yusoff and Wong 2023). Due to their feeding and digestion depending on the bivalve species and stage of life, the mixed microalgae species are the most suitable food to culture bivalve mollusks (Yang et al. 2021). A number of studies have demonstrated that diets containing a combination of microalgae species are more appropriate for bivalve growth and survival as compared to diets containing a single species.

Carotenoid in bivalves promotes the antioxidant system to counteract ROS and free radicals with the help of immunity-related enzymes such as SOD and CAT. Water and sediments in the intertidal ecosystem are also rich in fucoxanthin, a carotenoid of diatoms present throughout the year. Such carotenoids increase tolerance to stress, as observed in pearl oysters (*Pinctada fucata*), which survive better when exposed to high temperatures. Lipids play an important role in bivalve larvae, as a source of energy and as a part of the membrane. Bivalves, however, are unable to synthesize PUFAs such as EPA and DHA but take them up in the diet, especially in microalgae. When consumed in the form of a microalgae diet, there is an increased DHA growth in bivalve membranes, which are stimulated to develop and withstand stress (Yusoff and Wong 2023). Information regarding bivalves' reaction to optimum doses of astaxanthin is very sparse.

Li et al. (2024) found that the flesh-shell ratio (FSR), viscerosomatic index (VSI), and soft tissue index (STI) remained unchanged, but the weight gain rate (WGR), specific growth rate (SGR), and survival rate (SR) of juvenile Babylonia also rose with the increase in astaxanthin concentration of the meal. Astaxanthin at 75-100mg/kg produced significant increases in total antioxidant capacity (T-AOC) and acid phosphatase (ACP), as well as a reduction in malondialdehyde (MDA). It also enhanced muscle crude protein and the hepatopancreatic antioxidant enzymes (AKP, SOD, and CAT). It also improved ammonia stress tolerance and increased hepatopancreatic genes (SOD, Cu/ZnSOD, ferritin, ACP, and CYC). In general, astaxanthin enhanced the immunity of *B. areolata*, stress resistance, muscle quality, and growth (Li et al. 2024).

Zou et al. (2023) conducted a study to identify the most appropriate source of dietary astaxanthin to feed abalone (*Haliotis discus*) by testing *Gracilaria lemaneiformis* (GL), synthetic astaxanthin (SA80), *P. rhodozyma* (PR80), *and H. pluvialis* (HP120). The study evaluated survival, growth, immunological response, antioxidant activity, heat resistance, disease resistance, and gut microbiota. Findings demonstrated that SA80, PR80, and HP120 were superior to GL in terms of survival, growth, immunity, and resistance to stress. PR80 or HP120 also outperformed SA80 in terms of growth. It is important to note that PR80 was found to be the most resilient to heat stress and bacterial stress. On the basis of these findings, the study has suggested *Phaffia rhodozyma* (PR80) as the most efficient source of astaxanthin to improve the efficiency of abalone production and profits (Zou et al. 2023). Table 1 presents comparative results of shellfish, with strong support of crustaceans and weak and inconclusive support of bivalves.

As the table shows, crustaceans consistently demonstrate enhanced immunity and survival, while gastropods exhibit improved pigmentation and stress tolerance. In contrast, bivalve data remain inconclusive, underscoring species-specific responses and research gaps.

Bioavailability of astaxanthin in aquaculture; Current status and strategies to reduce cost production

The astaxanthin, which has low bioavailability by nature, is a lipid-soluble nutritionally and functionally significant substance that encounters significant challenges in aquaculture. The primary factors that lead to its reduced bioavailability are its low water solubility, chemical instability, and poor absorption efficiency of aquatic organisms. Astaxanthin is a lipophilic chemical that is not easily soluble in water. This is particularly an issue in aquatic systems, whereby water-based formulations are widely utilized to deliver nutrients. Thus, in aquatic animals, the low level of solubility is a serious constraint on intestinal absorption and biological action (Liu et al. 2019).

The absorption through the intestine requires that astaxanthin be emulsified by food lipids and then in-

Table 1 Comparative outcomes of dietary astaxanthin in shellfish (growth, immunity, pigmentation, survival) (Eldessouki et al. 2022)

Species (life stage)	Astaxanthin source	Dose (mg/kg feed)	Duration	Key outcomes	Quantitative results (if reported)
Litopenaeus vannamei (juvenile shrimp)	Synthetic / microalgal	100–200	6–8 weeks	↑ SOD, CAT, PO activity; ↑ survival after *Vibrio* challenge	Survival up to 82.7% at 200 mg/kg
Eriocheir sinensis (Chinese mitten crab)	Microalgal and synthetic	~60	6 weeks	↑ antioxidant enzymes; ↑ pigmentation	Growth ↑ but survival NS
Portunus trituberculatus (swimming crab)	Synthetic	24.2	8 weeks	↑ shell coloration; ↑ lipid metabolism	Improved coloration
Babylonia areolata (ivory shell)	*H. pluvialis*-derived	75–100	8 weeks	↑ weight gain rate (WGR), ↑ specific growth rate (SGR), ↑ total antioxidant capacity (T-AOC), ↓ MDA	Significant growth at 100 mg/kg
Haliotis discus hannai (abalone)	PR80 vs HP120 vs SA80	12 weeks	12 weeks	PR80 > HP120 > SA80 for growth, immunity	Best stress resistance with PR80 diet

Table 2 An analysis of the estimated bioavailability and manufacturing costs of various astaxanthin resources (Nur et al. 2022)

Source	Type	Cost range (USD/kg)	Relative bioavailability	Advantages	Limitations
Haematococcus pluvialis	Microalgae	1500–7000	High	Natural stereoisomer, strong tissue deposition	High cost, scaling difficult
Phaffia rhodozyma	Yeast	1000–3000	Medium	Natural, lower cost vs algae	Extraction/purification costs
Chemical synthesis	Synthetic	500–1000	Low	Cheap, consistent purity	Racemic mix, lower absorption
Crustacean by-products	Waste	100–500	Low–Medium	Sustainable, cheap raw material	Low extraction yield
Engineered microbes	Biotechnology	500–2000	Medium–High	Potential scalability	Regulatory barriers

corporated in bile salt micelles, without which the intestinal epithelial cells cannot absorb astaxanthin. The impaired bioavailability is further caused by the disruptions in lipid digestion or micelle production. Positive health impacts of the astaxanthin could be reduced in aquatic organisms, where the digestive system might not be the most appropriate to fully absorb fat-soluble substances (Geng et al. 2020).

In order to handle these difficulties, several solutions have been suggested to enhance the stability and bioavailability of astaxanthin in aquaculture systems. Liposome encapsulation and microencapsulation technologies are among the most promising ones. These encapsulation systems protect astaxanthin molecules against the negative environmental forces, such as heat, light, oxidation, and acidic pH, that form protective layers around the molecules. As a result, gastrointestinal absorption and chemical stability of astaxanthin are enhanced (Huang et al. 2022).

Astaxanthin delivery systems can be divided into two broad groups: micron-scale and nano-scale based on their particle size. Astaxanthin carriers can further be classified into various types based on the encapsulating materials, the production process, and the final architecture structures or morphologies used, which include: liposomes, nanoemulsions, microcapsules, nanoparticles, and nanostructured lipid carriers (NLCs). Both of these administration modes have their advantages and can be employed to enhance the stability of astaxanthin, its bioavailability, and efficacy (Sun et al. 2023).

The other useful strategy is the association of astaxanthin and lipid or astaxanthin and protein complex. The presence of carrier molecules such as proteins, phospholipids, or fatty acids with astaxanthin has been found to enhance water dispersibility and intestinal absorption of astaxanthin. These compounds enhance the solubility and emulsification capacity of astaxanthin, which enhances its micellar absorption and improves its bioavailability in aquatic life (Zhang et al. 2022).

In recent years, a powerful approach to addressing the problems of solubility and stability of astaxanthin has been the delivery technologies based on nanotechnology. Surrounding astaxanthin in nanoparticles, which may be polymeric nanoparticles, nanoliposomes, or nanoemulsions, is beneficial in a number of ways. Such benefits are better dispersion in water, selective dispersion, controlled dispersion, and better bioavailability (Hwang et al. 2024).

Its low water solubility may be overcome by dissolving astaxanthin in an oil phase to make it an emulsion. Then, further stabilization of the emulsion through biopolymer encapsulation can be applied. High encapsulation rates and biocompatibility of liposomes and drug-loading efficiency of nanostructured lipid carriers, respectively. To make the best out of astaxanthin, future research should be devoted to the enhancement of safety tests, targeted delivery, and drug-loading capabilities. It is hoped that these comprehensive solutions will address the poor stability and solubility of astaxanthin, increase its bioavailability and efficacy when applied in aquaculture (Peng et al. 2025).

Microalgae, especially *H. pluvialis,* are the main industrial producers of astaxanthin due to their high efficiency of synthesis. Nonetheless, scalability issues, dependence on raw materials, and expensive prices are all barriers to commercial production. In order to overcome these limitations, scientists are investigating alternative supplies and optimization of the process. Table 2 is a comparative study of the relative bioavailability and cost of production of different astaxanthin sources (Ahmadkelayeh and Hawboldt 2020).

Regarding the industry angle, the decision between the synthetic and natural astaxanthin is an economic decision balancing cost and efficacy. The commercial feed is dominated by synthetic sources because it is cheap and the supply is predictable, yet there is lower tissue deposition and consumer preference with synthetic compared to natural algal-derived astaxanthin. Its adoption in the future will not only rely on the enhancement of the delivery technologies but also on the open cost-effective studies that will establish under which production conditions natural astaxanthin will be more pertinent than its synthetic counterpart. Incorporating bioavailability solutions with economical sources specific to each species group may address existing performance gaps and facilitate broader industry adoption.

Importance of astaxanthin in the commercial feed market

Presently, synthetic astaxanthin supplies most of the feed market, reaching more than 95 percent of the commercial market since it is economical (Stachowiak and Szulc 2021). Nonetheless, the global market of astaxanthin, whose value reached USD 1.0 billion in 2019, is expected to expand with a compound annual growth rate (CAGR) of 16.2% between 2019 and 2027, reaching USD 3,398.8 million by 2027. This is supported by the rise in demand for natural astaxanthin in the pharmaceutical, cosmetic, and food sectors due to its proven health-promoting properties and safety profile (Silva et al. 2021).

The use of astaxanthin is essential as an antioxidant, anti-inflammatory, and immune-enhancing compound, as well as for improving growth performance. Research has shown that astaxanthin dietary supplementation helps to alleviate oxidative stress, enhance immune responses, improve resistance to disease, and improve the growth of several fish and crustacean species (Li et al. 2020). In turn, the addition of astaxanthin to aquaculture activities improves the resistance of aquatic animals, decreases the rate of death, and minimizes antibiotic use (Lu et al. 2021). Table 3 shows few delivery systems for astaxanthin in aquafeeds.

Industry implications

This analysis emphasizes that although astaxanthin regularly offers physiological advantages in shellfish aquaculture, its effects are significantly depending on species and developmental stage. Crustaceans, especially shrimp and crabs, exhibit significant enhancements in immunological responses and stress resilience with dietary astaxanthin supplementation. Nonetheless, growth outcomes continue to exhibit variability. This variance may arise from variations in feed formulation, the supply of astaxanthin (natural versus synthetic), and challenge settings, indicating the necessity for species-specific nutritional solutions instead of a universal approach.

Gastropods, including abalone and ivory shell, demonstrate enhanced stress resilience, antioxidant capacity, and pigmentation, especially when utilizing natural sources of astaxanthin. Nonetheless, diversity in bioavailability persists as a challenge, likely affected by disparities in digestive physiology and feed matrices.

Conversely, evidence about bivalves is sparse and inconsistent, frequently concentrating on early developmental phases or without uniform techniques. The lack of dose-response trials and functional biomarker evaluations impedes definitive results, highlighting the necessity for additional focused study in this population.

From an industrial standpoint, the prevalence of synthetic astaxanthin is attributed to its cost-effectiveness and scalability, although its worse bioavailability and less efficient tissue deposition. Natural sources such as *H. pluvialis* and *P. rhodozyma* provide enhanced functional benefits but are economically unfeasible for extensive application. Future advancements will rely on the equilibrium between efficacy and cost, potentially achieved through enhanced delivery technologies or engineered microbial production. In summary, maximizing astaxanthin utilization in aquaculture necessitates the alignment of source selection and dose with species-specific objectives be it immunological resilience, pigmentation, or market value. A critical synthesis indicates that aligning source and delivery methods with taxon-specific objectives such as immunity in shrimp or coloring in gastropods will be essential for maximizing astaxanthin utilization in aquafeeds.

Future prospects of astaxanthin in aquaculture

While technological advances have made food production more efficient, aquaculture still faces sustainability concerns particularly its dependence on fishmeal and land-based feed inputs (Luthman et al. 2022). In

Table 3 Delivery systems for astaxanthin in aquafeeds (Rivera Hernández et al. 2024)

Delivery system	Mechanism	Stability	Benefits	Challenges
Nanoemulsions	Oil-in-water nanoscale	Good	↑ dispersibility, absorption	Requires high-shear equipment
Liposomes	Phospholipid bilayers	High	↑ encapsulation, controlled release	High cost, storage issues
Nanostructured lipid carriers	Solid + liquid lipid	Very high	↑ bioavailability, sustained release	Manufacturing complexity
Biopolymer encapsulation (alginate, chitosan)	Matrix entrapment	Good	Protects from oxidation	Depends on matrix
Protein–lipid complexes	Protein binding	Moderate	Improves emulsification	Raw-material dependent

Table 4 Recommended dose ranges and knowledge gaps (Li et al. 2024)

Taxon	Suggested dose (mg/kg feed)	Evidence strength	Knowledge gaps
Crustaceans (shrimp, crab)	24–200	Moderate	Standardized long-term trials; source/life-stage comparisons
Gastropods (abalone, ivory shell)	60–120	Low–Moderate	Reproductive performance; growth consistency
Bivalves (oysters, clams, mussels)	Data insufficient	Low	Dose–response trials; larval survival; tissue deposition

response, natural alternatives such as algal meal rich in astaxanthin are gaining traction due to their demonstrated benefits on growth, immunity, pigmentation, and survival in aquatic species. Algal meal rich in astaxanthin has emerged as a viable natural alternative, which displays many advantages with respect to the aquatic species, such as improved growth rate, disease resistance, fertility, pigmentation, and survival rates. In addition, natural astaxanthin is under investigation to revolutionize productivity and health in aquaculture and livestock production as an environmentally friendly feed supplement. Its natural source, absence of residue, antioxidant effect, and strengthening immunity make it a perfect green alternative, taking into account the growing limitations on the use of antibiotics (Nishida et al. 2023).

With the increasing food safety issues and stricter regulations on the use of pharmaceuticals in aquaculture, astaxanthin has become a critical feed supplement given its natural, non-toxic, and side-effect-free properties. The problem with its popularization, however, its high production cost, reaching USD 718 per kilogram, remains a major barrier. In turn, this means that optimization of extraction and production processes is a pressing concern of future research. In the future, The range of applications in aquaculture is expected to expand as research progresses, as the potential of the compound and its effects in the field are likely to increase with more research and technology (Hu et al. 2025). By resolving these research and implementation deficiencies, astaxanthin might transition from a promising although inconsistently utilized addition to a strategically integrated solution that promotes the sustainability, resilience, and economic value of shellfish aquaculture. Table 4 shows some recommended dose ranges and knowledge gaps.

The review will involve a comparative and critical synthesis of the research, which highlights gaps in the research and suggests a roadmap towards future work:
Undertake species-specific, standard dose response, life-stage trials.
Establish and test immunological and functional bacterial biomarkers.
Carry out economic studies to inform adoption in the industry, between natural and synthetic sources.
Discover new delivery methods (nano-encapsulation, protein lipid complex, engineered microbes) to circumvent bioavailability and cost considerations.

By covering these knowledge gaps, astaxanthin might become a promising but inconsistently used additive that becomes a strategic, evidence-based intervention to improve the resilience and sustainability of shellfish aquaculture and increase their commercial value.

Conclusion

Astaxanthin is a promising functional feed supplement in aquaculture, especially for shellfish like crabs and gastropods. Its physiological advantages include enhanced pigmentation, immune modulation, antioxidant defense, stress resilience, and overall productivity. Astaxanthin administration has consistently enhanced health and performance metrics in species such as *Litopenaeus vannamei, Haliotis discus,* and *Babylonia areolata*. However, data on bivalves remain limited and fragmented, particularly regarding optimal dosages, life-stage-specific responses, and bioaccumulation dynamics.

Despite its effectiveness, the application of astaxanthin encounters obstacles pertaining to low bioavailability, elevated production costs, and unpredictability in species responses. Emerging delivery technologies such as microencapsulation and nanotechnology, combined with microbial or alternative natural production sources, offer a more sustainable trajectory. Species-specific and life-stage-specific feeding strategies must be formulated to enhance utilization. Standardized, long-term dose-response studies and comparative trials among various astaxanthin sources and administration modalities are necessary. Economic assessments are essential to support the cost-effective integration of astaxanthin into commercial aquafeeds. Although the promise of astaxanthin in shellfish aquaculture is clear, it is crucial to address existing knowledge gaps through focused research to enhance its efficacy and promote the sustainability and profitability of the sector. The strategic alignment of astaxanthin type, dosage, and administration with species-specific requirements provides the most effective approach to optimizing both biological efficacy and economic viability.

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