sustainability

MDPI

Review

Astaxanthin in Food Systems: From Natural Sources and Stability Challenges to Emerging Functional Applications

Toni Jurić Šolto, Martina Čagalj and Vida Šimat *

Faculty of Marine Sciences, University of Split, 21000 Split, Croatia
* Correspondence: vida@more.unist.hr

Abstract

Astaxanthin is a high-value xanthophyll carotenoid known for its antioxidant activity and potential health benefits that is becoming increasingly important in food, nutraceutical, and health-related applications. In recent years, growing interest in natural bioactive compounds has driven research on astaxanthin sources, bioactivity, functional properties, and its applications in food, nutraceutical, and health-related subjects. This review synthesizes current knowledge on the natural sources, extraction methods, stability, biological activities, and food applications of astaxanthin, with particular attention to challenges and opportunities relevant to food systems. The review discusses a food science-oriented perspective that connects molecular properties and biological functionality with processing stability, formulation strategies, and regulatory considerations. Special emphasis is given to emerging extraction and encapsulation methods, interactions with complex food matrices, and technological limitations affecting bioavailability and consumer acceptance. The review also highlights recent advances in sustainable production, valorization of marine by-products, and the potential role of astaxanthin in personalized nutrition and precision health frameworks. These approaches contribute to circular food systems by reducing food-processing waste, replacing synthetic antioxidants with natural alternatives, and supporting more resource-efficient and environmentally sustainable food production.

Keywords: astaxanthin; functional foods; natural antioxidants; food stability; food coloring; encapsulation; bioavailability; personalized nutrition

1. Introduction

Astaxanthin is a naturally occurring, fat-soluble ketocarotenoid belonging to the xanthophyll group, distinguished by its intense red color. Its molecular structure ($C_{40}H_{52}O_4$) features a long-conjugated polyene chain with alternating double and single bonds, enabling efficient electron delocalization and providing exceptional free radical scavenging capacity. The conjugated structure has been reported to have higher antioxidant activity than that reported for several other dietary carotenoids. The first reports on astaxanthin date to the 1930s, when the pigment was isolated from crab and salmon tissues. However, its chemical identity and structure were initially misinterpreted and were only later clarified through advanced analytical techniques and structural standardization [1,2].

Due to the presence of hydroxyl and keto functional groups at both ends of the molecule, astaxanthin exhibits higher antioxidant efficiency than many other carotenoids, including β-carotene, lutein, and lycopene [3]. In addition to its antioxidant activity, astaxanthin demonstrates anti-inflammatory effects by modulating redox-sensitive signaling

Check for updates

Academic Editor: Ilija Djekic

Received: 12 June 2026
Revised: 9 July 2026
Accepted: 19 July 2026
Published: 21 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

pathways, including NF-κB, Nrf2 and MAPK, thereby reducing oxidative stress and inflammatory responses [4]. These properties have led to growing scientific interest in both natural and synthetic astaxanthin, and increasing research interest in astaxanthin applications (Figure 1) in cardiovascular, neuroprotective, ophthalmic, dermatological, food, and aquaculture over the past five years [1,5], along with its global market size, which is estimated to reach USD 1.96 billion in 2025, with a projected CAGR of 9.5% by 2033 [6]. Natural astaxanthin remains substantially more expensive than synthetic alternatives, with reported market prices approaching USD 15,000 kg^{-1} depending on purity and source [7].

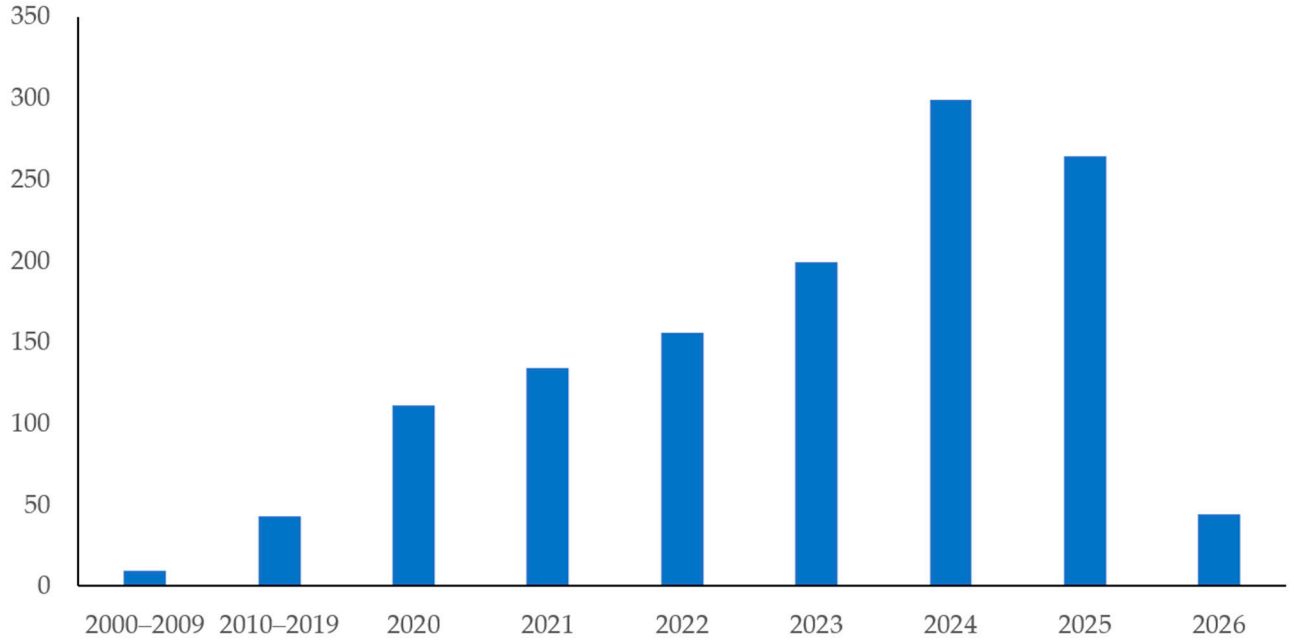

Figure 1. Overview of the number of research papers on astaxanthin from 2000 to March 2026 (search conducted up to 13 March 2026) in the SCOPUS/WOS database using search terms related to astaxanthin application in the food, feed, and health sectors: "astaxanthin", "functional foods", "food supplements", "natural antioxidants", "feed", "health benefits", "application" applied to article titles, abstracts, and keywords written in English.

This review critically evaluates recent advances in astaxanthin chemistry, natural and synthetic production, extraction technologies, stabilization strategies, bioavailability, biological activities, food applications, and regulatory aspects. Particular emphasis is placed on factors influencing astaxanthin stability in food systems, sustainable production approaches, and current research gaps limiting broader industrial application. It is based on a comprehensive literature search conducted to identify peer-reviewed publications relevant to the chemistry, production, stability, biological activities, and food applications of astaxanthin. The literature search was performed using the Scopus, Web of Science Core Collection, and PubMed databases. The search primarily covered peer-reviewed literature published between 2000 and March 2026, while selected seminal publications from 1992–1999 were included to provide historical context and describe the early development of the field. The search strategy combined keywords related to astaxanthin and its applications using Boolean operators. Representative search terms included "astaxanthin", "natural astaxanthin", "synthetic astaxanthin", "microalgae", "*Haematococcus pluvialis*", "extraction", "encapsulation", "bioavailability", "food applications", "functional foods", "food stability", "antioxidant activity", "biological activity", and "food systems". Publications were selected based on their scientific relevance, methodological quality, and direct relevance to the scope of this review. Priority was given to original research articles, system-

atic reviews, and high-quality review papers published in peer-reviewed journals. Studies unrelated to food, nutraceutical, or technological applications of astaxanthin, conference abstracts, non-peer-reviewed publications, and studies lacking sufficient methodological information were excluded. Additional relevant references were identified through manual screening of the reference lists of key publications.

Beyond its biological properties and commercial value, astaxanthin has attracted increasing attention because its production and application support several principles of sustainable food processing, including the valorization of food processing by-products, the use of renewable biological resources, the replacement of synthetic additives, and the implementation of green extraction technologies.

Natural Sources of Astaxanthin

Astaxanthin occurs naturally in a limited number of microorganisms and marine organisms, with microalgae representing the richest and most industrially relevant source (Figure 1). Among these, the green microalga *Haematococcus pluvialis* is recognized as the most efficient natural producer of astaxanthin, capable of accumulating from 3 to 7% astaxanthin on a dry weight (DW) basis under stress conditions such as high light intensity, nutrient limitation, and osmotic stress [8,9]. Due to its exceptionally high pigment content and well-established cultivation systems, *H. pluvialis* remains the primary commercial source of natural astaxanthin for food and nutraceutical applications.

Other microalgal species, including *Chlorococcum*, *Asterarcys quadricellulare*, *Chromochloris zofingiensis* (syn. *Chlorella zofingiensis*), *Schizochytrium* sp., and *Neochloris wimmeri* are also capable of producing astaxanthin, although at substantially lower concentrations compared to *H. pluvialis* [3,10–13]. Among them, *C. zofingiensis* has demonstrated the highest production potential, typically accumulating 0.1–0.5% DW [14]. A cultivation strategy under nitrogen deficiency and at glucose concentration of 5 g/L was recently proposed to enhance the production of astaxantin by *C. zofingiensis* [15]. Other mentioned species produce much lower astaxanthin levels, and this production remains poorly characterized due to the limited number of available studies. *H. pluvialis* already benefits from optimized cultivation technologies, regulatory approval, and well-developed commercial supply chains, creating a high barrier to market entry for alternative species. Consequently, their industrial relevance remains limited, despite ongoing efforts to improve productivity through strain selection and biotechnological optimization. Table 1 summarizes the major challenges that currently limit the commercial production of astaxanthin from alternative microalgal species compared with the established production platform based on *H. pluvialis*.

Table 1. Major factors limiting the commercial production of astaxanthin from alternative microalgal species.

Factor	Impact on Commercial Production	References
Low astaxanthin content in the biomass	A substantially larger amount of biomass is required to obtain the same astaxanthin yield, reducing process efficiency and increasing production costs.	[14,16]
Trade-off between cell growth and astaxanthin accumulation	Environmental stress conditions that stimulate astaxanthin biosynthesis simultaneously inhibit cell growth, resulting in lower overall productivity.	[14,17]
High strain-to-strain variability	Considerable differences in astaxanthin productivity among strains limit process standardization and industrial-scale implementation.	[17,18]

Table 1. *Cont.*

Factor	Impact on Commercial Production	References
Accumulation of intermediate ketocarotenoids	The co-production of compounds such as canthaxanthin and adonixanthin decreases product purity and increases downstream purification costs.	[14,16]
Complex cultivation requirements	Efficient production requires precise control of light intensity, nutrient availability, carbon source, temperature, and stress conditions, increasing operational complexity.	[16,17]
High harvesting and extraction costs	Robust cell walls and intracellular pigment localization require energy-intensive cell disruption and extraction processes.	[14,19]
Limited pilot- and industrial-scale validation	Most studies have been conducted at laboratory scale, with insufficient evidence for technical and economic feasibility under industrial conditions.	[14,16]

Yeasts represent another important natural source of astaxanthin. In particular, *Phaffia rhodozyma* (also known as *Xanthophyllomyces dendrorhous*) can accumulate astaxanthin at concentrations of approximately 0.3–0.6% of dry biomass, with reported values reaching up to 10,000 ppm under optimized cultivation conditions [20]. Astaxanthin biosynthesis in yeasts is typically induced by environmental stress, and optimal production is influenced by temperature, pH, oxygen availability, and nutrient composition [21]. Maximum astaxanthin production is generally achieved at 20–22 °C, whereas temperatures above 30 °C markedly reduce pigment accumulation. Optimal cell growth occurs at approximately pH 6.0, while astaxanthin biosynthesis is favored at pH 4.0–5.0. High oxygen availability maintained by intensive aeration and agitation further enhances pigment production, and glucose-based fed-batch cultivation has been reported to increase astaxanthin titers up to 27 mg/L [22]. Also, yeasts such as *Kluyveromyces marxianus* and transformed *Saccharomyces cerevisiae* can produce astaxanthin under laboratory and industrial conditions, demonstrating the potential for reconstructing the biosynthetic pathway in non-producers of the natural pigment [23–25]. Recently, bacteria *Paracoccus carotinifaciens* has also been investigated as a potential source of astaxanthin [26]. Advances in genetic engineering, heterologous gene expression, and mutagenesis have further enhanced pigment yields and highlighted the potential of yeast-based production platforms [21,24,27].

In other aquatic organisms, astaxanthin is either directly accumulated from the diet or formed through metabolic conversion of other carotenoids such as β-carotene and zeaxanthin. Its concentration in tissues depends on species, dietary availability, feeding strategies, absorption efficiency, and storage capacity. Fish, crustaceans, and other aquatic animals acquire astaxanthin by consuming microalgae, plankton, krill, or astaxanthin-containing feed. Wild salmon typically exhibit higher astaxanthin concentrations in muscle tissue than their farmed counterparts, reflecting differences in natural diets and feeding regimes. Reported values range from approximately 26 to 38 mg/kg in wild salmon and from 6 to 8 mg/kg in farmed salmon, although concentrations strongly depend on dietary supplementation [3]. In aquaculture systems, synthetic astaxanthin is frequently added to feed to achieve desirable pigmentation, although this practice represents a significant production cost and requires precise dosage control [28]. In crustaceans such as shrimp and krill, astaxanthin is predominantly present in esterified form and accumulates in the exoskeleton and tissues, contributing to pigmentation, oxidative stress resistance, and commercial quality, with levels strongly influenced by diet and environmental conditions [3,18,28–30]. The by-products generated during the processing of these organisms have been studied as

valuable secondary sources of astaxanthin (Figure 2). While whole fresh shrimp contain approximately 20 mg of astaxanthin/kg [18], fresh shells contain up to 239.96 mg/kg astaxanthin [31]. Recently, by-products of cephalopod (*Doryteuthis singhalensis*) were also reported for an exceptionally high yield (97.48 mg/kg) of astaxanthin [32]. As already established, fish and other aquatic organisms do not synthesize astaxanthin themselves but ingest it through food rich in microalgae and yeast [33–37]. Plankton, krill, and shrimp transport pigment through the food chain, and aquaculture uses astaxanthin preparations to improve vital functions such as meat color, health, and fish growth. Genetically modified plants, such as corn, which also synthesize astaxanthin, can be used as ingredients in fish feed, allowing meat pigmentation comparable to that achieved with synthetic pigment applications [38,39]. The stability of astaxanthin in fish tissue depends mainly on its esterified form, while direct extraction from fish meat remains impractical due to its low pigment content [40–42]. Natural astaxanthin from microalgae, yeasts, and by-products of marine organisms is a valuable bioactive compound with applications in the food, pharmaceutical, and cosmetic industries. Future research should prioritize scalable extraction technologies that improve pigment recovery while reducing solvent consumption and production costs.

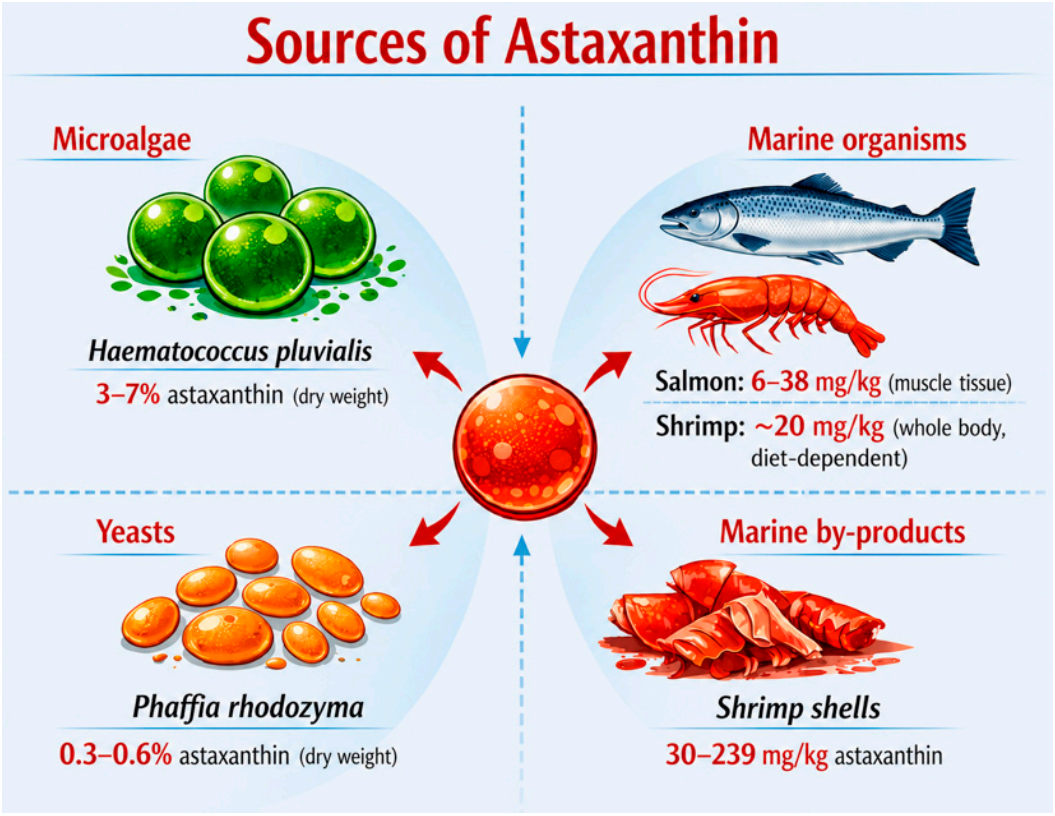

Figure 2. Major natural sources of astaxanthin and reported concentration ranges. Data adapted from [3,18,30,31] (created using ChatGPT (GPT-5.5, OpenAI, San Francisco, CA, USA, July 2026 version).

Overall, the chemical structure, isomeric composition, and esterification state of astaxanthin critically influence its stability, bioavailability, and biological activity. These physicochemical properties underpin its functional role in biological systems and determine its suitability for use in food, nutraceutical, and pharmaceutical products.

From a sustainability perspective, the selection of astaxanthin sources extends beyond pigment production alone. Increasing attention has been directed toward marine processing by-products, particularly shrimp shells and crustacean waste, which are generated in large

quantities by the seafood industry. Their valorization enables the recovery of high-value compounds from materials that would otherwise require disposal, thereby improving biomass utilization and supporting circular bioeconomy principles. At the same time, the development of economically viable extraction technologies remains essential for translating laboratory-scale recovery into sustainable industrial practice.

2. Extraction Methods

The pigment extraction is carried out using organic or green solvents (ethanol, methanol, ethyl acetate, n-hexane) and methods such as supercritical CO_2 extraction, ultrasonic assistance, high-pressure processing and enzymatic fermentation, which increase the yield and stability of the pigment [34–38]. Encapsulation of the extract further improves stability and bioavailability, enabling the pigment's application in the food, pharmaceutical, and cosmetic industries. These approaches contribute to the circular economy by turning waste into a valuable resource.

2.1. Extraction Conditions

The efficiency of astaxanthin extraction and the quality of the resulting extract are strongly influenced by process conditions, solvent selection, and biomass characteristics. Astaxanthin is highly sensitive to environmental factors such as temperature, light, pH, and oxygen, making strict control of extraction conditions essential to preserve its chemical stability and biological activity.

Temperature is one of the most critical parameters affecting astaxanthin extraction efficiency and stability. Numerous studies have shown that low extraction temperatures, typically around 4 °C, significantly reduce pigment degradation and help preserve antioxidant activity, whereas elevated temperatures accelerate oxidative and thermal decomposition [43,44]. However, with increasing extraction temperature, solvent diffusivity and its cell wall disruption ability are enhanced, increasing astaxanthin recovery. Astaxanthin contains a highly unsaturated polyene chain, thus high temperatures accelerate E/Z isomerization, oxidative degradation, and cleavage of conjugated double bonds, leading to significant losses in pigment concentration and antioxidant activity. Extraction processes are optimized to balance extraction efficiency with pigment preservation. Recent studies showed that moderate temperatures (typically 40–65 °C for supercritical CO_2 extraction and 25–50 °C for ultrasound-assisted extraction) provide the best compromise between recovery and stability, whereas temperatures above 70 °C markedly increase thermal degradation [45–48]. Duan et al. [49] investigated the effect of four temperatures (35, 45, 55 and 65 °C) during high-pressure SC-CO_2 extraction of astaxanthin from *H. pluvialis*. The temperature of 55 °C produced the highest astaxanthin extraction yield. Increasing the temperature to 65 °C reduced CO_2 density and no further improvement in recovery was observed despite improved diffusion. Authors found that pressure had an even stronger effect, with extraction at 65 MPa producing 1.25-fold and 2.32-fold higher yields than 45 MPa and 25 MPa, respectively. Kaya et al. [50] optimized the astaxanthin extraction temperature from red giant shrimp (*Aristaeomorpha foliacea*) processing waste using ultrasonication-assisted extraction and found the optimum extraction temperature of 41 °C. The effective extraction of astaxanthin from *H. pluvialis* using ultrasound-assisted extraction was recorded at 41.1 °C [51].

Extraction time plays a dual role in astaxanthin recovery. Insufficient extraction time may limit pigment release from the biomass, particularly in microalgae with rigid cell walls, while prolonged exposure increases the risk of oxidative degradation. Optimized extraction durations thus represent a compromise between maximizing yield and minimizing degradation, with reported optimal times varying depending on the extraction

method and solvent system used [3]. Recent studies have investigated extraction times ranging from 90 s for MAE to 25–90 min for UAE and organic solvent extractions [46–52]. Luo et al. [52] demonstrated that astaxanthin extraction from *H. pluvialis* increased with extraction time up to 70 min, reaching a maximum yield of 10,761.9 μg g^{-1} at 60 °C. Further prolongation of extraction resulted in a rapid decline in astaxanthin recovery, indicating thermal degradation of the pigment. Di Sanzo et al. [53] demonstrated that approximately 90% of astaxanthin could be recovered within the first 40 min of SC-CO_2 extraction (550 bar, 50 °C, 3.62 g CO_2 min^{-1}), whereas maximum extract purity (≈83%) was achieved after 80 min. Extending extraction beyond this period provided limited additional recovery, while higher temperatures (65–80 °C) significantly reduced astaxanthin recovery due to thermal degradation [3].

pH conditions generally have a less pronounced effect on astaxanthin stability compared to temperature and oxygen exposure. However, neutral to mildly acidic environments (pH 5–6) have been reported to favor pigment stability, while strongly acidic conditions and alkaline conditions (pH 9) accelerate isomerization and degradation reactions [43,46,54]. Maintaining controlled pH conditions is therefore recommended, particularly during aqueous or enzymatic extraction processes.

Light and oxygen exposure are additional critical factors contributing to astaxanthin degradation [55]. Light-induced photooxidation leads to cis-trans isomerization and breakdown of the polyene structure, while oxygen promotes oxidative reactions that reduce pigment stability. Niamnuy et al. [56] showed that the rate of astaxanthin degradation during storage was significantly lower in samples stored in the dark, with the effect becoming more pronounced as storage temperature increased. For this reason, extraction and storage are commonly performed under dark conditions, and where feasible, in inert atmospheres such as nitrogen to limit oxidative damage [44]. There has been a small number of original scientific articles in past years that investigated the degradation of astaxanthin under specific light and oxygen conditions during storage. Dewanti et al. [57] showed that astaxanthin stored at room temperature under light had a higher degradation rate and shorter half-life than when stored at the same temperature without light. At conditions without light, astaxanthin had higher degradation and shorter half-life when stored at room temperature than in a refrigerator (4 °C). Li et al. [58] investigated the stability of astaxanthin during the refrigerated storage of ready-to-eat shrimp and showed that exposure to oxygen during storage promoted progressive oxidation.

Beyond these physicochemical parameters, solvent selection plays a decisive role in extraction efficiency. Conventional organic solvents, including acetone, ethanol, and methanol, are widely used due to their ability to disrupt cell membranes and efficiently dissolve carotenoids. However, their use is associated with potential solvent residues and increased risk of pigment degradation due to heat and oxygen exposure [59,60]. These limitations have driven growing interest in alternative extraction approaches, which are discussed in subsequent sections.

Green Extraction Approaches and Analytical Considerations

Besides extraction efficiency, the environmental performance of extraction technologies is becoming an increasingly important selection criterion. Driven by safety, sustainability, and regulatory requirements, green extraction methods are increasingly being developed for astaxanthin recovery. Among these, supercritical carbon dioxide (SC-CO_2) extraction has gained particular attention, as it enables the selective extraction of astaxanthin without residual toxic solvents and produces high-purity extracts. The use of co-solvents such as ethanol or vegetable oils significantly enhances extraction efficiency, with soybean and olive oil reported to markedly improve astaxanthin yield [60]. SC-CO_2 extraction has been

investigated primarily for recovering astaxanthin from *H. pluvialis*, with extraction efficiency primarily influenced by pressure, temperature, extraction time, and CO_2 flow rate.

Recent studies have focused primarily on optimizing extraction pressure, temperature, CO_2 flow rate, extraction time, and the use of polar modifiers such as ethanol. High extraction pressures (50–65 MPa) consistently improve astaxanthin recovery by increasing CO_2 density and solubility, whereas extraction temperatures above approximately 60–65 °C promote thermal degradation despite improved mass transfer. Extraction yield was highest at 65 MPa, 1.25-fold higher than at 45 MPa, and 2.32-fold higher than at 25 MPa. The optimum extraction temperature was 55 °C [49,53,61]. Aravena et al. [61] demonstrated that the presence of water delayed astaxanthin extraction because the initial extraction stage was dominated by water removal before efficient pigment recovery could occur. Their study also demonstrated that biomass moisture significantly influenced extraction kinetics and should therefore be considered during raw material preparation. The authors compared extractions at 35–55 MPa and 40–70 °C. Despite these advantages, the main limitation of SC-CO_2 extraction is the high capital investment required for industrial-scale equipment [59].

Enzyme-assisted extraction has been recognized as a promising green extraction technology, however, only a limited number of original studies have investigated its application for astaxanthin recovery, and no significant number of new experimental studies were published during 2023–2025. Zhao et al. [62] evaluated the use of cellulase and pectinase for the extraction of astaxanthin from *H. pluvialis*. The authors optimized enzyme type, pH, hydrolysis temperature, and hydrolysis time, and reported that pectinase resulted in a significantly higher astaxanthin yield than cellulase. Wang et al. [63] applied protease-assisted hydrolysis to shrimp shells prior to solvent extraction and purification, using enzymatic degradation of the protein matrix to facilitate astaxanthin recovery from crustacean by-products. The authors concluded that enzymatic pretreatment improved the accessibility of the pigment before downstream purification. Enzymatic approaches are often combined with organic solvents or SC-CO_2 extraction to achieve higher overall yields [64].

The use of vegetable oils is another viable alternative, allowing the direct extraction of astaxanthin without prior biomass drying. While high extraction yields can be achieved, oil viscosity may limit mass transfer and extraction kinetics [65,66].

Accurate characterization of astaxanthin and its esterified forms requires complementary analytical techniques. High-performance liquid chromatography (HPLC), particularly with C_{30} columns, enables the efficient separation of free astaxanthin, monoesters, diesters, and geometric isomers [67]. Coupling HPLC with mass spectrometry (LC-MS) allows for the reliable identification of ester forms based on molecular mass and fragmentation patterns [68]. UV/Vis spectrophotometry with diode-array detection facilitates differentiation between cis- and trans-isomers, while nuclear magnetic resonance (NMR) and GC-MS provide detailed structural information, including the fatty acid composition of astaxanthin esters [69,70].

An integrated approach combining optimized process conditions, appropriate extraction strategies, and advanced analytical techniques is essential to maximize astaxanthin yield while preserving its bioactivity. This multidisciplinary optimization forms the basis for the efficient application of astaxanthin in the food, nutraceutical, and cosmetic industries.

Overall, most of the studies were conducted using *H. pluvalis*. The most efficient extraction was suggested to be SC-CO_2 extraction, which enables extraction under relatively mild operating conditions. Although the range of astaxanthin recoveries from *H. pluvalis* using SC-CO_2 was reported to be from 51–97% [59], an even higher astaxanthin recovery

(98.6%, corresponding to 19.72 mg g^{-1} dry biomass) was obtained at 550 bar, 50 °C, a CO_2 flow rate of 3.62 g min^{-1}, and an extraction time of 80 min [53]. For shrimp by-products, conventional solvent extractions and ultrasound-assisted extraction methods have proposed, using solvents such as ethanol [71], a hexane and hexane-isopropanol mixture [72], acetone [71,72] and even vegetable oil [66]. Although recoveries are reported from 36–235 µg astaxanthin/g, these data are not directly comparable because they differ with respect to shrimp species, type of by-product used (shells or mixed processing by-products), and raw material pretreatment.

2.2. Stability of Astaxanthin During Extraction, Processing, and Storage

The stability of astaxanthin during extraction, processing, and storage is a major challenge limiting its industrial application. Because of its highly unsaturated polyene structure, astaxanthin is especially susceptible to degradation caused by heat, oxygen, light, and acidic conditions. These factors can trigger oxidative cleavage of the conjugated chain, trans-cis isomerization, and the formation of apocarotenoids with reduced biological activity [3,73]. For this reason, recent research has explored encapsulation technologies, nanoemulsions, liposomal systems, and biopolymer-based delivery matrices designed to minimize oxygen diffusion and light penetration while preserving the biological activity and bioavailability of astaxanthin [48].

Thermal and oxidative degradation are among the most significant pathways affecting astaxanthin stability during processing. High temperatures accelerate oxidation reactions and promote structural breakdown, especially during drying operations. Comparative studies have shown that lyophilization provides substantially better pigment retention than spray drying, with astaxanthin recovery reported to be about 40% higher in freeze-dried *H. pluvialis* biomass [45]. This improvement is mainly attributed to the absence of high temperatures and reduced oxygen exposure. Although spray drying offers economic and technological advantages, it often results in considerable pigment losses unless protective strategies are used.

After extraction and drying, storage conditions play a decisive role in preserving astaxanthin stability. Temperature and oxygen availability are the main factors governing long-term degradation. Storage at low temperatures (−20 °C or 4 °C), combined with vacuum packaging or inert atmospheres, significantly reduces pigment loss compared to storage at ambient conditions in the presence of air [45,74]. In addition, light exposure accelerates photooxidation and isomerization, highlighting the importance of opaque or light-protective packaging.

The chemical form of astaxanthin also strongly influences its stability. Esterified astaxanthin, which predominates in natural sources such as microalgae and crustaceans, shows greater resistance to oxidative degradation than the free form, especially when dispersed in lipid matrices [74]. This enhanced stability has important implications for formulation strategies in food and nutraceutical systems.

To address stability limitations during processing and storage, various encapsulation and delivery systems have been developed. Among these, Pickering emulsions have attracted particular attention due to their ability to form a physical barrier at the oil–water interface, limiting oxygen diffusion. Encapsulation of astaxanthin in Pickering emulsions has been shown to significantly reduce pigment loss during spray drying and improve stability during storage [75]. Similarly, zein-based and sodium alginate-stabilized Pickering emulsions exhibited good stability over a temperature range of 10–50 °C and at pH values between 3 and 7, whereas alkaline conditions (pH 9) significantly accelerated astaxanthin degradation [54].

Overall, astaxanthin stability is governed by a complex interplay between processing conditions, chemical form, and storage environment. The use of mild drying techniques, low-temperature and oxygen-controlled storage, and advanced encapsulation systems is an effective strategy to preserve astaxanthin bioactivity and extend shelf life. These stabilization approaches are essential for the successful incorporation of astaxanthin into food, nutraceutical, and pharmaceutical products.

2.3. Challenges and Optimization Strategies

Despite its pronounced biological activity and growing commercial relevance, the large-scale application of astaxanthin remains limited by several technological, economic, and bioprocessing challenges. Key limitations include low bioavailability, high production costs, process instability, and limited scalability of current production and extraction systems [40]. Genetic engineering of key biosynthetic genes has increased carotenoid titers and pathway efficiency [54], and recent reviews highlight that the efficient microbial biosynthesis of carotenoids can be achieved through the optimization of culture conditions, stress responses, and strain selection across yeasts, bacteria, and microalgae [76].

One of the primary challenges associated with astaxanthin utilization is its poor bioavailability, which results from its strong lipophilic character and low water solubility. Efficient intestinal absorption requires emulsification and incorporation into mixed micelles in the presence of dietary lipids and bile salts. Inadequate emulsification significantly limits uptake by enterocytes, reducing systemic availability and biological efficacy [40]. These limitations highlight the need for optimized formulation and delivery strategies, including emulsification, encapsulation, and lipid-based carrier systems.

From a production perspective, natural astaxanthin biosynthesis is associated with high costs and process complexity. Microalgae such as *H. pluvialis*, the richest natural source of astaxanthin, require strictly controlled cultivation conditions, high energy input, and multistep downstream processing. Additional challenges include seasonal variability, inconsistent biomass productivity, and fluctuations in pigment yield, all of which negatively affect economic sustainability [40,77].

Optimization of the upstream cultivation process remains a critical bottleneck. Astaxanthin biosynthesis in microalgae is typically induced under stress conditions such as high light intensity, nutrient limitation, and salinity stress, which are unfavorable for biomass growth. The widely applied two-stage cultivation strategy, comprising a "green phase" focused on biomass accumulation and a "red phase" inducing carotenoid synthesis, requires precise control to balance cell growth and pigment production. Excessive stress can severely reduce biomass productivity and overall astaxanthin yield [78]. Environmental parameters, including light intensity and spectrum, temperature, nutrient availability, and salinity, strongly influence astaxanthin accumulation. While nitrogen and carbon limitation act as key signals for carotenogenesis, overly harsh conditions promote oxidative damage and pigment degradation rather than accumulation. Optimizing these parameters is essential to maximize productivity while maintaining cellular viability [78].

Downstream processing presents additional challenges. The robust cell walls of microalgae hinder efficient pigment release, while conventional cell disruption and extraction methods often lead to oxidative degradation. There is a growing need for more efficient, scalable, and environmentally friendly cell disruption and extraction technologies that enhance pigment recovery while minimizing structural damage and bioactivity loss [77].

To address these challenges, research increasingly focuses on integrated optimization strategies combining biological and process engineering approaches [79]. Advances in metabolic and genetic engineering enable the modulation of key enzymes in the carotenoid biosynthetic pathway, increasing flux toward astaxanthin production. The development of

engineered microbial platforms and "microbial factories" supported by synthetic biology offers improved stability, predictability, and scalability of pigment production [80].

In parallel, process engineering innovations, including the optimization of fermentation parameters, energy-efficient extraction techniques, and integration of green and circular economy principles, contribute to reduced production costs and environmental impact. The coordinated optimization of upstream cultivation, downstream processing, and formulation strategies is essential for the sustainable and competitive production of astaxanthin for food, nutraceutical, and pharmaceutical applications [77,80].

The long-term sustainability of astaxanthin production will depend not only on increasing pigment yields, but also on improving process efficiency throughout the entire production chain. Future optimization should therefore integrate upstream cultivation, energy-efficient downstream processing, solvent recovery, waste minimization, and the utilization of renewable raw materials. Such integrated approaches are expected to improve both the environmental and economic sustainability of astaxanthin production.

3. Synthetic Production of Astaxanthin

The development of synthetic astaxanthin production has enabled a large-scale, economically viable supply that is independent of biological sources. In practice, two main approaches are used: total chemical synthesis, in which astaxanthin is constructed from petrochemical precursors, and semi-synthesis, where structurally related carotenoids such as canthaxanthin or zeaxanthin are chemically modified to yield astaxanthin [20].

3.1. Chemical Synthesis Routes

Chemical synthesis of astaxanthin relies on multistep organic reactions designed to construct the characteristic C_{40} polyene backbone and introduce hydroxyl and keto functional groups at the terminal β-ionone rings. Key reactions include hydroxylation, oxidation, and Wittig-type condensation that assemble polyenic fragments into the final carotenoid structure. In semi-synthetic routes, canthaxanthin is hydroxylated, while zeaxanthin undergoes oxidation to introduce keto groups, yielding astaxanthin [20].

The first successful syntheses of astaxanthin were reported in the late 1960s; however, industrial-scale production became feasible in the 1980s after Hoffmann-La Roche's development of robust total synthesis pathways. This method, based on Wittig condensation between C_{15} phosphonium salts and C_{10} dialdehydes, remains the foundation of commercial synthetic astaxanthin production, which is used primarily in aquaculture feed today [81].

Despite its scalability and cost-effectiveness, chemical synthesis produces a mixture of stereoisomers and geometric isomers, including 3*S*, 3′*S*; 3*R*, 3′*R*; meso forms, and cis/trans configurations. This heterogeneous isomeric composition is associated with lower biological activity compared to naturally derived astaxanthin, which predominantly occurs in the 3*S*, 3′*S* configuration and in esterified form. Consequently, rigorous quality control using HPLC and UV/Vis spectroscopy is required to monitor isomeric distribution in synthetic products [81].

3.2. Biotechnological Production Approaches

Growing demand for biologically active and sustainable forms of astaxanthin has increased interest in biotechnological production systems based on microbial fermentation and genetic engineering. This approach redirects carotenoid biosynthetic pathways toward astaxanthin synthesis by introducing and regulating key enzymes, primarily β-carotene ketolase (BKT) and β-carotene hydroxylase (CrtR-b) [82].

Genetically engineered microorganisms, including bacteria (*Escherichia coli*), yeasts (*S. cerevisiae*, *Kluyveromyces marxianus*), and microalgae, have been extensively studied as production platforms. Advances in metabolic engineering, gene copy number optimization, and pathway balancing have significantly improved yields and process stability [24,83]. More recently, CRISPR-Cas-based tools have enabled the precise control of biosynthetic networks, allowing for improved regulation of flux distribution and stereoisomeric composition.

Fermentation forms the core technological framework of biotechnological production, with parameters such as pH, temperature, oxygen availability, and nutrient supply optimized and controlled to maximize pigment accumulation. High-yield systems have been reported, with engineered yeast strains producing astaxanthin concentrations exceeding 200 mg/L and product purities above 85%, highlighting the potential of microbial platforms for industrial-scale production [84].

Compared to chemical synthesis, biotechnological production offers several advantages, including greater selectivity for biologically active isomers, reduced reliance on petrochemical inputs, and lower environmental impact. However, challenges related to strain robustness, scalability, and downstream processing efficiency remain and must be addressed before widespread industrial adoption.

The relevance of astaxanthin for food and feed applications differs. Synthetic production continues to play a key role in meeting the global demand for astaxanthin, particularly in feed applications, thus it remains the dominant source for aquaculture and animal feed, primarily because of its lower cost, consistent supply, and regulatory acceptance for non-human use. In contrast, naturally obtained and biotechnologically produced astaxanthin are preferred for human food and nutraceutical applications, where stereochemical purity, esterification state, and consumer preference for "natural" ingredients are key factors.

However, ongoing advances in biotechnological production and a growing emphasis on sustainability are expected to gradually shift the balance toward biologically derived astaxanthin in food-related sectors.

3.3. Comparison with Natural Astaxanthin

Natural astaxanthin is primarily derived from the microalga *H. pluvialis* and the yeast *P. rhodozyma*, where it occurs mainly in esterified form as monoesters and diesters. In contrast, synthetic astaxanthin is produced as a free, non-esterified compound through chemical synthesis. These structural differences significantly affect the stability, bioavailability, biological activity, and cost of astaxanthin in food and biological systems. One of the most important distinctions between natural and synthetic astaxanthin is their stereochemical composition. Natural astaxanthin is predominantly found in the 3S, 3′S configuration, while chemically synthesized astaxanthin consists of a racemic mixture of stereoisomers (3S, 3′S; 3R, 3′R; and meso forms), along with varying proportions of cis and trans isomers. Numerous studies have shown that the naturally occurring stereoisomer exhibits superior antioxidant and biological activity, often attributed to its optimized molecular orientation within cell membranes and enhanced interaction with lipid bilayers [85,86].

In addition to stereochemistry, the esterification state is crucial for stability and functionality. Esterified astaxanthin is more resistant to oxidative and thermal degradation than the free form, especially in lipid-based matrices. This increased stability is particularly beneficial for food applications, where processing and storage conditions can compromise pigment integrity [74]. Moreover, natural astaxanthin extracts often contain additional bioactive compounds, such as tocopherols and other carotenoids, which may have synergistic effects and further enhance antioxidant capacity.

Regarding biological efficacy, natural astaxanthin has been reported to more effectively reduce oxidative stress, upregulate endogenous antioxidant enzymes (e.g., superoxide dismutase and glutathione peroxidase), and modulate cytoprotective signaling pathways compared to synthetic forms [87]. These properties support the preference for natural astaxanthin in nutraceuticals and functional foods intended for human consumption.

Conversely, synthetic astaxanthin offers advantages in production cost, scalability, and supply stability, making it well-suited for aquaculture and animal feed applications, where pigmentation efficiency and economic feasibility are primary considerations. Synthetic astaxanthin also shows relatively high stability during feed processing, including thermal treatments, supporting its widespread use in industrial feed formulations [88].

From an environmental and sustainability perspective, synthetic production may have a lower environmental footprint under certain controlled conditions. However, natural and biotechnological production systems offer greater potential for integration into circular and sustainable production models, especially when combined with renewable energy sources, waste valorization, and green extraction technologies [89].

Overall, both natural and synthetic astaxanthin play important roles in current markets, with their suitability determined by application-specific requirements. Natural astaxanthin is generally preferred for food and nutraceutical products targeting human health due to its superior biological activity and consumer acceptance, while synthetic astaxanthin remains dominant in feed applications because of its cost-effectiveness and regulatory acceptance. Continued advances in biotechnological production are expected to further bridge the gap between these two sources and expand the availability of high-quality astaxanthin for food-related applications. From a sustainability perspective, the comparison between natural and synthetic astaxanthin extends beyond biological activity and production costs. Natural astaxanthin obtained from renewable biological resources, particularly microalgae and seafood processing by-products, can be integrated into circular production systems through biomass valorization and green extraction technologies. In contrast, synthetic astaxanthin is produced from petrochemical feedstocks but currently remains economically competitive because of its high production efficiency and established industrial infrastructure. Only a limited number of studies have compared the environmental aspects of both production routes [89]. The limited number of life cycle assessments have primarily focused on microalgal production systems, whereas direct comparisons with synthetic production remain scarce. Consequently, further comparative life cycle assessment and techno-economic studies are required to quantify the environmental footprint of natural and synthetic production routes under industrial conditions.

3.4. Regulatory and Safety Considerations

The regulatory status and safety assessment of astaxanthin depend on its source, chemical form, and intended application. Regulatory authorities have generally recognized astaxanthin as safe when used within the established limits; however, clear distinctions are made between natural and synthetic forms, particularly regarding human consumption.

In the European Union, the safety of astaxanthin has been evaluated by the European Food Safety Authority (EFSA). Based on available toxicological, metabolic, and human intervention data, EFSA concluded that astaxanthin derived from the microalga *H. pluvialis* is safe for use in food products and food supplements within specified intake levels. In its most recent assessment, EFSA approved astaxanthin-rich oleoresin from *H. pluvialis* as a novel food under Regulation (EU) 2015/2283, recommending that the daily intake for adults should not exceed 8 mg of astaxanthin, corresponding to approximately 40–80 mg of oleoresin [90].

Earlier EFSA evaluations proposed an acceptable daily intake (ADI) of 2 mg/day, based on toxicological studies using synthetic astaxanthin in animal models [91]. EFSA emphasized that adolescents (14–18 years) consuming 8 mg/day may already reach the ADI, underscoring the need for the careful formulation and labeling of astaxanthin-containing products for younger populations. Analysis of human clinical studies indicates that natural astaxanthin has not been associated with serious adverse effects at doses up to 12 mg/day, although long-term safety data remain limited.

The distinction between natural and synthetic astaxanthin is particularly relevant from a regulatory perspective. Synthetic astaxanthin is approved primarily for use in animal feed, including aquaculture and ornamental fish, where it has been evaluated by the FEEDAP panel and deemed safe and effective within the established inclusion levels. In contrast, synthetic astaxanthin is not authorized for direct human consumption in food supplements in the European Union. Several authors have emphasized that toxicological data obtained using synthetic astaxanthin cannot be directly extrapolated to natural forms due to differences in stereochemistry and esterification state [92].

In the United States, astaxanthin is regulated differently depending on its application. When marketed as a dietary supplement, astaxanthin falls under the Dietary Supplement Health and Education Act (DSHEA) of 1994 [93], under which manufacturers are responsible for ensuring product safety and accurate labeling without prior approval by the Food and Drug Administration (FDA). When used as a food ingredient or additive, astaxanthin is subject to FDA premarket approval requirements. Natural astaxanthin from microalgal sources has achieved Generally Recognized as Safe (GRAS) status for specific applications.

Toxicological studies to date indicate that astaxanthin does not exhibit mutagenic, genotoxic, or carcinogenic effects [93]. Genotoxicity assays in bacterial and mammalian cell models, as well as long-term animal studies, have not reported increased tumor incidence or significant adverse outcomes [94]. Nevertheless, regulatory authorities consistently emphasize the need for continued safety evaluation, particularly regarding long-term consumption, high-dose exposure, and vulnerable population groups.

The existing regulatory frameworks support the safe use of natural astaxanthin in food and nutraceutical products when consumed within recommended limits. However, differences in regulatory status between regions, along with distinctions between natural and synthetic forms, underscore the importance of source-specific safety assessment, standardized labeling, and clear consumer communication. Ongoing research and regulatory harmonization will be essential to facilitate broader and more consistent use of astaxanthin in food systems. Astaxanthin intake from a conventional diet is generally low because only a limited number of foods naturally contain substantial amounts of the pigment, primarily salmonids, trout, shrimp, krill, lobster and microalgae. Consequently, the doses associated with biological effects in human intervention studies (typically 4–12 mg day^{-1}) [95] are difficult to achieve through habitual diets alone. This has stimulated the development of astaxanthin-enriched functional foods, beverages, and dietary supplements. However, its practical application in food systems remains limited by poor water solubility, susceptibility to oxidation and light-induced degradation, and low oral bioavailability, emphasizing the need for suitable encapsulation and delivery strategies.

4. Biological Activities and Health Effects of Astaxanthin

Astaxanthin exhibits a broad spectrum of biological activities primarily due to its unique polar-lipophilic molecular structure, which enables efficient interaction with both aqueous and lipid environments. This structural feature allows astaxanthin to function as a potent antioxidant by neutralizing reactive oxygen species (ROS), binding transition metals, and protecting cell membranes from lipid peroxidation [96,97]. By spanning the

lipid bilayer and stabilizing membrane structure, astaxanthin effectively preserves cellular integrity under oxidative stress.

Experimental studies have demonstrated that astaxanthin supplementation enhances antioxidant capacity and reduces markers of oxidative damage. In aquaculture and animal models, dietary astaxanthin has been shown to increase the total antioxidant capacity (T-AOC) and significantly reduce levels of secondary oxidation products such as malondialdehyde (MDA), which is widely used as an indicator of lipid peroxidation [98]. Beyond its antioxidant effects, astaxanthin exerts pronounced anti-inflammatory activity by modulating key signaling pathways involved in inflammatory responses. It has been shown to downregulate the expression of pro-inflammatory cytokines and inhibit the activity of inducible nitric oxide synthase (iNOS) and cyclooxygenase-2 (COX-2), thereby reducing the production of inflammatory mediators such as nitric oxide (NO) and prostaglandin E_2 (PGE_2) [4,99]. Through these mechanisms, astaxanthin reduces chronic inflammatory processes associated with a wide range of diseases.

The combined antioxidant and anti-inflammatory properties of astaxanthin have been associated with protective effects in several physiological systems. Experimental and preclinical studies indicate beneficial roles in cardiovascular health by reducing lipid oxidation and improving endothelial function, as well as in neuroprotection by limiting oxidative damage and inflammatory activation in neural tissues [96,100]. While preclinical studies provide strong mechanistic support, further long-term, well-designed human studies are required to clarify its clinical efficacy, optimal dosage, and role in cardiovascular disease prevention and management. Additionally, astaxanthin has shown protective effects in ocular tissues, where it reduces inflammatory mediator production in retinal cells and mitigates light-induced oxidative stress, helping prevent inflammation-related eye disorders [101,102]. Skin and ocular tissues are particularly vulnerable to oxidative damage caused by ultraviolet (UV) radiation, environmental stressors, and aging-related inflammatory processes, making them relevant targets for astaxanthin-based interventions.

In skin health, astaxanthin has shown significant photoprotective effects. Clinical and experimental studies indicate that astaxanthin supplementation reduces oxidative stress and inflammation in skin cells exposed to UV radiation. In a controlled human study, daily intake of 6–12 mg of astaxanthin over 16 weeks resulted in decreased expression of matrix metalloproteinase-1 (MMP-1) and lower levels of inflammatory cytokines in keratinocytes, confirming its role in protecting against UV-induced skin damage [95].

It was also found to be a neuroprotective compound with the ability to simultaneously modulate oxidative stress, neuroinflammation, and mitochondrial dysfunction, central mechanisms underlying neurodegenerative disorders and acute neuronal injury. Evidence from preclinical studies indicates that astaxanthin exerts antioxidant, anti-inflammatory, and anti-apoptotic effects while preserving mitochondrial integrity and blood–brain barrier function [82]. Its ability to cross the blood–brain barrier distinguishes astaxanthin from many other dietary antioxidants, enabling direct interaction with neural tissues and supporting its potential neuroprotective effects in experimental models of neurodegenerative disorders [79,83]. In addition, astaxanthin plays an important role in modulating neuroinflammatory responses, reducing the expression of pro-inflammatory cytokines and suppressing excessive activation of microglia, thereby limiting secondary inflammatory damage in neural tissues [103,104]. These effects are particularly relevant in chronic neurodegenerative conditions, where sustained neuroinflammation accelerates neuronal loss and disease progression.

Most of the reported biological effects have been demonstrated in animal models and human supplementation studies rather than following the consumption of conventional foods. Natural dietary intake of astaxanthin is generally limited because only a small num-

ber of seafood products naturally contain substantial amounts of the pigment, whereas most reported biological effects have been demonstrated using purified astaxanthin supplements. Consequently, translating these findings into food systems requires the development of stable food matrices capable of protecting astaxanthin during processing and storage while maintaining its bioavailability after gastrointestinal digestion. Current evidence therefore supports the incorporation of astaxanthin into functional foods targeting oxidative stress and inflammation; however, further studies are required to determine whether comparable physiological effects can be achieved through astaxanthin-enriched foods under realistic dietary intake conditions. Table 2 summarizes different types of evidence for the mechanisms of action and recorded effects of astaxanthin, from in vitro studies to human trials, but does not clearly distinguish the strength of evidence for each effect. This should be taken into consideration to avoid overinterpretation of some biological activities.

Table 2. Overview of the reported biological activities of astaxanthin, their mechanisms of action, and evidence from experimental and clinical studies.

Action Area	Main Effects	Mechanism of Action	Model/Population	Level of Evidence	Literature
Antioxidant effect	Reduction in oxidative stress, inhibition of lipid peroxidation, reduction in MDA	ROS neutralization, transition metal binding, membrane stabilization	Obese and overweight healthy individuals, healthy non-smoking males, healthy male athletes; fishes and crustaceans (aquaculture)	In vitro, animal studies, human intervention studies	[96–98,105]
Anti-inflammatory effect	Reduction in inflammatory cytokines and mediators, and improving immunity	Inhibition of iNOS and COX-2, modulation of signaling pathways; Reduction in pro-inflammatory cytokines, oxidative stress and improvement of immune system function	Rats, mice, rabbits, asthmatic guinea-pigs, fish, healthy adult female individuals	In vitro, human intervention studies	[3,4,36,99, 106–109]
Cardiovascular health	Reduction in LDL oxidation, improved lipid profile, possible antihypertensive effect; prevention of atherosclerosis, reduction in hypertension	Increased antioxidant enzyme activity, greater NO availability, oxidative stress reduction, reduced inflammation, blood vessel function improvement	Rat, mice, rabbit, dog, fish, human patients with heart disease, healthy adult men, participants with type 2 diabetes, heart failure patients	Animal studies, human intervention studies	[96,107,110, 111]

Table 2. *Cont.*

Action Area	Main Effects	Mechanism of Action	Model/Population	Level of Evidence	Literature
Neuroprotective effects	Neuronal protection, apoptosis reduction, mitochondrial stability, cognitive function improvement and protection against neurodegeneration	ROS neutralization, microglia inhibition, anti-apoptotic pathways; oxidative stress reduction in the brain, neuroinflammation inhibition, and brain cell function improvement	Mice, rats, human population (older men)	In vitro, animal studies, human intervention studies	[100,103,104,112]
Anti-diabetic activity	Lowering blood pressure, glucose metabolism improvement	Reduction in oxidative stress, insulin function improvement, inflammation reduction and vascular function improvement	Patients with type 2 diabetes mellitus	Human intervention studies	[113]
Anti-carcinogenic effect	Adjuvant therapeutic agent in the treatment of cancer (prostate, skin)	Oxidative stress and inflammation reduction, tumor cell growth inhibition, and improvement of the effectiveness of chemotherapy	Mice, healthy people, healthy female participants	In vitro, animal studies, human intervention studies	[114]
Skin and eye health	Improvement of skin elasticity, reduction in wrinkles, protection of the retina, and dry eye; reduced UV damage, improved visual function, and lowered risk of cataracts; reduced risk of eye diseases	Inhibition of MMP-1, reduction of NO, PGE2 and TNF-α, improved microcirculation; reduction in oxidative stress in the eyes and improvement of retinal function	Mice, rats, patients with nonadvanced age-related macular degeneration (AMD), patients with AMD, healthy people over 40 years	Animal studies, human intervention studies	[8,95,101,102,115]
Sports performance enhancer	Physical and mental performance improvement	Reduction in oxidative stress that occurs during physical exertion, endurance improvement and fatigue reduction	Healthy male athletes	Human intervention studies	[105]

MDA—malondialdehyde; ROS—reactive oxygen species; LDL—low-density lipoprotein.

5. Use of Astaxanthin in Food Products

Astaxanthin has attracted growing interest as a functional ingredient in food products because of its antioxidant activity, coloring capacity, and potential health benefits. Incorporating it into food systems aims to enhance nutritional value, oxidative stability, shelf life, and visual quality. However, successful application depends on formulation strategies, processing conditions, and regulatory constraints. Recent advances in astaxanthin use as an antioxidant in food applications have been reviewed by Dang et al. [87].

5.1. Outlook for Food Applications

Overall, astaxanthin is a promising functional ingredient for food applications, especially in products targeting oxidative stability, visual appeal, and added health value. Continued advances in stabilization technologies, cost-effective production methods, and delivery systems are expected to facilitate its broader incorporation into diverse food matrices. However, challenges related to stability, bioavailability, cost, and regulatory compliance must be addressed to fully realize the potential of astaxanthin in food systems. An overview of the main food application areas of astaxanthin, along with associated functional benefits and technological limitations, is summarized in Table 3.

Table 3. Food applications of astaxanthin: functionality, benefits, and technological constraints—general overview.

Application Area	Representative Food Matrices	Functional Role	Functional Benefits	Technological and Regulatory Limitations	Literature
Functional foods and beverages	Fruit juices, sports beverages, fermented dairy and plant-based drinks	Antioxidant, natural colorant	Reduced oxidative degradation, extended shelf life, enhanced nutritional value	Sensitivity to light, heat, and oxygen; need for stabilization	[3,87,116]
Nutraceuticals	Capsules, tablets, powders	Antioxidant and anti-inflammatory activity	Support of cardiovascular, skin, eye, and immune health	High cost of natural astaxanthin; dosage and regulatory restrictions	[87,96,117]
Dairy products	Yogurts, cheeses	Antioxidant enrichment	Improved nutritional value and oxidative stability	Potential color and flavor interactions	[20,87]
Bakery products	Whole-grain biscuits, baked goods	Antioxidant, color enhancement	Reduced lipid oxidation during storage	Thermal instability during baking	[3,87]
Meat and poultry products	Enriched meat products, eggs	Antioxidant, pigmentation	Improved color stability and freshness	Cost of dietary supplementation	[87,117]
Fish and seafood	Salmon, trout, shrimp	Pigmentation, antioxidant protection	Improved visual quality and oxidative stability	Regulatory limits on inclusion levels	[20,87]

5.2. Food Categories Incorporating Astaxanthin

Direct consumption of astaxanthin-rich food sources limits its health benefits and bioactivity to a small number of foods such as some types of fish, crabs, and microalgae.

Indirectly, astaxanthin has been investigated in a wide range of food categories, including functional foods and beverages, nutraceuticals, dairy products, bakery products, and foods of animal origin (Table 4). In functional foods and beverages, astaxanthin is mainly used as a natural antioxidant and colorant. It has been applied in fruit juices, sports and energy drinks, fermented dairy products, and plant-based beverages, where it improves oxidative stability, extends shelf life, and enhances nutritional profiles. However, its sensitivity to light, heat, and oxygen requires appropriate stabilization strategies during processing and storage [3,117,118].

Recent studies have demonstrated the successful incorporation of astaxanthin into a wide range of food products, where it primarily functions as a natural antioxidant and colorant while improving product stability during processing and storage. The effectiveness of astaxanthin depends on the food matrix, its concentration, and the formulation used. In dairy products such as yogurts and cheeses, astaxanthin has been explored as a functional ingredient to enhance antioxidant capacity and nutritional value. While promising results have been reported, challenges related to color intensity, potential flavor interactions, and pigment stability during fermentation and storage must be carefully addressed [119]. Li et al. [120] investigated the incorporation of astaxanthin-rich egg yolk into set yogurt and evaluated the influence of different pasteurization regimes. The study demonstrated that pasteurization at 65 °C for 30 min resulted in the highest astaxanthin retention together with improved texture and higher antioxidant activity after 21 days of refrigerated storage. The study focused on the influence of processing conditions rather than consumer acceptance, and only one yogurt formulation containing astaxanthin-rich egg yolk was evaluated. Earlier, Cerezal Mezquita et al. [121] evaluated the stability of astaxanthin oleoresin incorporated into yogurt to simulate an apricot color. The authors added 0.055 g astaxanthin oleoresin to 750 g of yogurt and reported no significant decrease in astaxanthin concentration after 28 days of refrigerated storage. Color remained stable throughout storage, while the fat content did not significantly influence pigment stability. The study focused on color stability and did not evaluate antioxidant activity or sensory acceptance. Astaxanthin from shrimp by-products has also shown considerable potential in dairy products. Dmytrów et al. [122] incorporated an astaxanthin lipid extract from shrimp shells into acid curd cheese at concentrations of 0.25%, 0.5% and 1%. The addition improved color, increased antioxidant activity, reduced lipid oxidation, and enhanced pH stability during refrigerated storage. Among the tested formulations, 0.5% provided the highest sensory acceptance, whereas the 1% formulation produced an undesirable foreign aftertaste. The authors described the work as a preliminary experiment, indicating that further optimization and consumer studies are still required. In seafood products, Zhu et al. [123] investigated the application of astaxanthin extract recovered from shrimp processing by-products in ready-to-cook shrimp surimi products. The formulation containing 30 g/kg astaxanthin extract exhibited lower lipid and protein oxidation, improved textural properties, higher redness and better overall sensory acceptability during frozen storage compared with the control. The extract contained 23.23 μg/g of astaxanthin, indicating that the observed effects resulted from the combined action of astaxanthin and other bioactive compounds present in the extract rather than purified astaxanthin alone. Similarly, Seo et al. [124] demonstrated that astaxanthin can replace synthetic antioxidants in emulsified pork sausages. Astaxanthin significantly reduced peroxide value and TBARS formation, preserved thiol groups, and improved redness during 21 days of refrigerated storage. Samples containing astaxanthin also received higher scores for redness and overall acceptability than the control. Applications have also been extended to lipid-rich foods. Draghici et al. [125] evaluated astaxanthin extracted from shrimp by-products as a natural antioxidant in lard and identified an optimum concentration of approximately 3 mg/g.

At this concentration, astaxanthin provided the highest oxidative stability and the lowest peroxide and TBARS values during 30 days of storage, while color was influenced primarily by the presence of astaxanthin rather than by its concentration. The application of astaxanthin in bakery products has received considerably less attention. Incorporating astaxanthin into products such as whole-grain biscuits and baked goods has been shown to improve lipid oxidative stability and enhance color characteristics. However, thermal sensitivity during baking remains a major limitation, often requiring encapsulation or protective matrices to minimize pigment degradation [87]. Hossain et al. [126] incorporated *H. pluvialis* biomass into wholemeal cookies, significantly enhancing the total phenolic content, antioxidant capacity and reducing in vitro glucose release. The study used whole microalgal biomass rather than purified astaxanthin, making it difficult to attribute the observed effects exclusively to astaxanthin. The available studies indicate that astaxanthin can be successfully incorporated into foods, however, most published studies have been conducted at laboratory scale using a limited number of formulations, and relatively few have evaluated long-term consumer acceptance, industrial-scale processing or commercial shelf-life under real production conditions [3,87,117–119]. Nutraceutical products are the most established application area for astaxanthin intended for human consumption. Astaxanthin is commonly formulated as capsules, tablets, or powders and is valued for its antioxidant and anti-inflammatory properties, as well as its reported benefits for cardiovascular, skin, eye, and immune health. In this category, controlled dosage, bioavailability, and regulatory compliance are critical factors influencing product development and market acceptance [127].

Astaxanthin also plays a prominent role in foods of animal origin. In poultry production, dietary supplementation enhances yolk and skin pigmentation, while in aquaculture, it is essential for achieving the characteristic pink coloration of salmonids and shrimp. Beyond pigmentation, astaxanthin contributes to improved feed conversion ratios in aquaculture [40] and oxidative stability, product freshness, and nutritional quality of meat and seafood during storage [87,123,128]. Although microalgal biomass application in feed can improve the nutritional quality and lipid profile of different food products [129], relevant aspects related to the direct application of astaxanthin has rarely been investigated.

Table 4. Effect of astaxanthin on quality characteristics in food products.

Food Product	Astaxanthin Type/Source	Concentration	Main Effects/Limitations	Literature
Wholemeal cookies	Dried microalgae *Hematococcus pluvialis*	Replacement of the flour with astaxanthin powder 5%, 10% and 15%	Better antioxidant properties, positive color change, lower glucose release.	[126]
Raw ground pork	Extracts of *H. pluvialis* rich in astaxanthin	0.15, 0.3, or 0.45 g/kg of meat	Application of 0.3 and 0.45 g/kg of the extract delayed the lipid oxidation and improved the color stability of the meat.	[130]
Pork sausages	Synthetic astaxanthin	400 mg/kg	Higher redness values and greater overall acceptability scores. Higher oxidation stability, lower MDA content.	[124]

Table 4. *Cont.*

Food Product	Astaxanthin Type/Source	Concentration	Main Effects/Limitations	Literature
Frankfurter-type sausages	5% astaxanthin oil extracted from *H. pluvialis*	200 mg/kg	Significantly lower peroxide value and a higher antioxidant capacity.	[131]
Formulated cookies	*H. pluvialis* powder	10%, 15%, and 20%	Astaxanthin could stabilize lipid oxidation in cookies. The cookies' hardness significantly decreased as the astaxanthin percentage was increased. The taste acceptability was not affected.	[86]
Rainbow trout	*Adonis aestivalis* extract	50, 100, and 200 mg/kg	The extract improved the flesh color and the antioxidative status.	[132]
Minced Tilapia	Shrimp wastes	Astaxanthin extracted using flaxseed oil	The microbiological quality improvement and extension of the minced fish shelf-life.	[133]
Tilapia fillets	*H. pluvialis*	3% of astaxanthin doses of 100 and 200 mg/kg of feed	Tilapia supplemented with astaxanthin can reduce lipid oxidation index.	[134]
Coral trout	*H. pluvialis* powder	0, 0.5, 1.0, and 2.0 g/kg	Improvement of the activity of antioxidant enzymes as well as the total antioxidant capacity of coral trout, and significantly reduced MDA content.	[135]
Ready to cook shrimp surimi products	Shrimp (*Trachypenaeus curvirostris*) by-product extract	23.23 mg/kg astaxanthin in extract; 30 g of extract/kg of surimi	Higher oxidative stability, higher redness values and greater overall acceptability and texture properties after cooking.	[123]
Black Tiger Prawn	Synthetic astaxanthin	0.02%, 0.04%, 0.08%, and 0.16% added to feed	Improvement of the growth, body color, antioxidant capacity, and nonspecific immunity of *Penaeus monodon*.	[136]
Meatballs	*H. pluvialis* extract with 5% pure astaxanthin	0.5% and 1% *w*/*w*	The oxidative stability and the color properties improvement.	[137]

Table 4. *Cont.*

Food Product	Astaxanthin Type/Source	Concentration	Main Effects/Limitations	Literature
Lamb patties	1% astaxanthin extracted from *H. pluvialis*	20, 40, 60, and 80 mg/kg of astaxanthin	Reduction in lipid oxidation, lower MDA content, and decreased oxysterols levels compared to control. The amount of volatiles released from the cooked patties was reduced.	[128]
Lard	Shrimp by-product extract	4 mg/g	After 30 days of storage, lard with extract showed higher oxidative stability and lower MDA content compared to control sample.	[125]
Male broilers	*H. pluvialis*	0, 20, 40, and 80 ppm astaxanthin supplementation	Lowered MDA in leg muscle, decreased hyperthermic stress level, and improved meat quality and antioxidant status of chickens.	[138]
Egg	*Paracoccus carotinifaciens* powder	8 mg/kg in the diet of laying hens	Increased concentrations of valuable carotenoids (astaxanthin, adonirubin, and adonixanthin) in egg yolk, which enhanced the pigmentation.	[139]
Egg	10% oil extract of astaxanthin from *H. pluvialis*	10, 20, and 30 mg/kg in the diet of laying hens	The carotenoid content and color of the egg yolks was higher.	[140]
Chia oil	*H. pluvialis*	400 μg/g oil	Blends of chia oil and astaxanthin stored at 25 °C showed good stability.	[141]
Avocado oil	Bacterium *Paracoccus carotinifaciens*	550 μg/mL	Enhanced the oxidative stability of avocado oil.	[142]
Model beverage	Shrimp waste	Emulsion	The encapsulated astaxanthin extract imparted a highly stable color to the product. However, the astaxanthin concentration was highly affected by time and partially affected by light and temperature.	[143]

Table 4. *Cont.*

Food Product	Astaxanthin Type/Source	Concentration	Main Effects/Limitations	Literature
Turkish delight	Clementine peels extract	3.75, 7.50, 11.25, and 15 mg	Antioxidant activity improvement.	[144]
Curd cheese (Tvarog)	Shrimp (*Pandalus borealis*) by-product extract	0.25%, 0.5%, and 1% (*w*/*w*)	The highest extract concentration reduced lipid oxidation and MDA content in cheese. The cheese color was improved, however, the higher extract concentration caused a foreign aftertaste.	[122]
Yogurt	*H. pluvialis*	0.055 ± 0.001 g in 750 g yogurt	The color parameters remained very stable over the four weeks of yogurt storage.	[121]
Yogurt	Astaxanthin-rich eggs (16 mg/100 g of astaxanthin)	Fortified with astaxanthin-rich yolk	The pasteurization conditions of 65 °C for 30 min can be used to prepare a functional yogurt with stable quality and antioxidant activity.	[120]

MDA—malondialdehyde.

Through the addition of astaxanthin to various food products, positive results in terms of food quality preservation, reduced lipid oxidation, and higher nutritional value of the product were achieved. The use of astaxanthin in different forms, such as powder, extract or synthetic additive, has been shown to contribute to extending the shelf life, improving the color as well as increasing the antioxidant value of the final product. In order to overcome the limitations of astaxanthin use as a food additive (odor, flavor, light, and temperature sensitivity), researchers have introduced a number of stabilization techniques such as emulsification and encapsulation, that have shown promising results for its application and effectiveness.

Besides improving product quality, the incorporation of astaxanthin into food products may also contribute to more sustainable food production. Its biological potential is to extend the product shelf life and potentially reduce food losses associated with oxidative deterioration. Nevertheless, most available studies have been performed under laboratory conditions, and further industrial-scale validation is required to confirm their environmental and economic sustainability.

5.3. Technological Advantages and Limitations

From a technological perspective, astaxanthin offers several advantages as a food ingredient, including high antioxidant potency, compatibility with lipid-based food systems, and the potential to replace synthetic colorants. Its incorporation can delay lipid oxidation, improve product stability, and extend shelf life, particularly in fat-rich matrices.

Despite these advantages, several limitations restrict its broader application in food products. Natural astaxanthin is associated with relatively high production costs, and its chemical instability under processing conditions poses formulation challenges. Additionally, its lipophilic nature results in limited bioavailability, requiring delivery systems

such as emulsions, liposomes, or encapsulation technologies to enhance absorption and functional performance [3,145].

Consumer perception is another constraint. Intense coloration, potential marine-associated flavors, and higher product prices may limit acceptance, especially in plant-based or vegetarian food products. Strategies such as taste masking, controlled dosing, and appropriate formulation design are essential to facilitate successful market integration [146].

The effective use of astaxanthin in food systems depends on integrating stabilization technologies, optimizing formulation strategies, and carefully considering regulatory and consumer-related factors. These technological aspects are closely linked to the stability and encapsulation approaches discussed in Sections 2.2 and 2.3.

5.4. Regulatory Considerations in Food Applications

The use of astaxanthin in food products is subject to regulatory restrictions regarding source, purity, and maximum allowable intake. In the European Union, only astaxanthin derived from approved natural sources, such as *H. pluvialis*, is authorized for use in food and food supplements within the established intake limits. These regulations directly influence formulation strategies, labeling requirements, and target consumer groups. Compliance with regulatory frameworks, along with transparent labeling and scientifically substantiated health claims, is essential to ensure consumer safety and trust. As regulatory approval remains source- and region-specific, food manufacturers must carefully consider the legal status of astaxanthin when developing new products.

6. Recommendations and Directions for Future Research

This section synthesizes current research gaps and outlines key future directions for astaxanthin research and application. Despite substantial progress in understanding the biological activity and technological potential of astaxanthin, several scientific and industrial challenges must still be addressed to enable its broader and more sustainable use in food systems. Future research is expected to focus on improving production efficiency, stability, bioavailability, and regulatory harmonization while aligning astaxanthin-based applications with emerging trends in functional foods and sustainable nutrition.

One of the most important research directions is the development of cost-effective and scalable production systems. Although microalgae-based production remains the primary source of natural astaxanthin, advances in metabolic engineering, synthetic biology, and controlled fermentation are expected to improve yields, process robustness, and consistency. Integrating renewable energy sources, waste valorization, and circular economy principles into cultivation and downstream processing may further enhance the environmental and economic sustainability of astaxanthin production.

From a food technology perspective, stability and delivery continue to represent critical bottlenecks. Future studies should prioritize designing food-grade encapsulation systems that protect astaxanthin during processing and storage while enabling controlled release and enhanced intestinal absorption. Developing multifunctional delivery systems that simultaneously improve stability, bioavailability, and sensory compatibility across diverse food matrices is likely to play a central role in expanding food applications.

Another key area of interest is the interaction of astaxanthin with complex food matrices. While its antioxidant activity has been extensively studied in isolated systems, limited data are available on its behavior in real foods, where interactions with proteins, lipids, carbohydrates, and food microstructure may influence stability, bioaccessibility, and efficacy. Addressing these knowledge gaps will be essential for translating laboratory-scale findings into industrially relevant food products.

Future research should also place greater emphasis on human intervention studies relevant to the food-based delivery of astaxanthin. Although existing clinical evidence supports its safety and biological activity, further well-designed trials are required to clarify dose–response relationships, long-term effects, and the impact of food matrix composition on bioavailability. Such studies are particularly important for substantiating health-related claims and supporting evidence-based regulatory approval.

An emerging and underexplored opportunity for astaxanthin lies in its potential application within personalized nutrition and precision healthcare frameworks. Inter-individual variability in lipid metabolism, oxidative stress status, inflammatory responses, and gut microbiota composition may significantly influence astaxanthin bioavailability and physiological efficacy [147]. Advances in nutrigenomics, metabolomics, and digital health technologies provide new tools to stratify populations based on metabolic phenotype, genetic background, and lifestyle factors, enabling more targeted and effective astaxanthin-based dietary interventions. Future research integrating omics-driven approaches with food-based delivery systems could support the development of personalized functional foods and nutrition strategies optimized for specific health outcomes.

From a regulatory and consumer perspective, harmonization of standards and transparent communication will be increasingly important. Differences in regulatory status between regions and between natural and synthetic forms of astaxanthin may limit global market expansion. Clear labeling, standardized quality criteria, and improved consumer education regarding source, functionality, and sustainability will support informed choice and market acceptance.

Overall, astaxanthin represents a promising bioactive compound at the interface of food science, nutrition, and sustainability. Continued interdisciplinary research integrating biotechnology, food engineering, nutrition science, and regulatory frameworks will be essential to unlock its full potential and support the development of safe, effective, and sustainable astaxanthin-enriched food products.

Author Contributions: Conceptualization, V.Š.; methodology, V.Š.; writing—original draft preparation, V.Š., T.J.Š. and M.Č.; writing—review and editing, V.Š. and M.Č.; supervision, V.Š.; project administration, V.Š. and M.Č.; funding acquisition, V.Š. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the PRIMA Program under project InnoSol4Med (Project ID 1836) supported by the European Union, with co-funding from the Ministry of Science and Education—MSE.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: During the preparation of this manuscript/study, the authors used ChatGPT (GPT-5.5, OpenAI, San Francisco, CA, USA, July 2026 version) for the purposes of generating a figure. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Davinelli, S.; Saso, L.; D'Angeli, F.; Calabrese, V.; Intrieri, M.; Scapagnini, G. Astaxanthin as a Modulator of Nrf2, NF-KB, and Their Crosstalk: Molecular Mechanisms and Possible Clinical Applications. *Molecules* **2022**, *27*, 502. [CrossRef] [PubMed]
2. Martínez-Álvarez, Ó.; Calvo, M.M.; Gómez-Estaca, J. Recent Advances in Astaxanthin Micro/Nanoencapsulation to Improve Its Stability and Functionality as a Food Ingredient. *Mar. Drugs* **2020**, *18*, 406. [CrossRef] [PubMed]
3. Ambati, R.; Phang, S.-M.; Ravi, S.; Aswathanarayana, R. Astaxanthin: Sources, Extraction, Stability, Biological Activities and Its Commercial Applications—A Review. *Mar. Drugs* **2014**, *12*, 128–152. [CrossRef] [PubMed]
4. Fakhri, S.; Abbaszadeh, F.; Dargahi, L.; Jorjani, M. Astaxanthin: A Mechanistic Review on Its Biological Activities and Health Benefits. *Pharmacol. Res.* **2018**, *136*, 1–20. [CrossRef] [PubMed]
5. Bjørklund, G.; Gasmi, A.; Lenchyk, L.; Shanaida, M.; Zafar, S.; Mujawdiya, P.K.; Lysiuk, R.; Antonyak, H.; Noor, S.; Akram, M.; et al. The Role of Astaxanthin as a Nutraceutical in Health and Age-Related Conditions. *Molecules* **2022**, *27*, 7167. [CrossRef] [PubMed]
6. Grand View Research. *Astaxanthin Market (2026–2033)*; Grand View Research: San Francisco, CA, USA, 2026.
7. Sathasivam, R.; Ki, J.-S. A Review of the Biological Activities of Microalgal Carotenoids and Their Potential Use in Healthcare and Cosmetic Industries. *Mar. Drugs* **2018**, *16*, 26. [CrossRef] [PubMed]
8. Giannaccare, G.; Pellegrini, M.; Senni, C.; Bernabei, F.; Scorcia, V.; Cicero, A.F.G. Clinical Applications of Astaxanthin in the Treatment of Ocular Diseases: Emerging Insights. *Mar. Drugs* **2020**, *18*, 239. [CrossRef] [PubMed]
9. Sun, H.; Kong, Q.; Geng, Z.; Duan, L.; Yang, M.; Guan, B. Enhancement of Cell Biomass and Cell Activity of Astaxanthin-Rich *Haematococcus pluvialis*. *Bioresour. Technol.* **2015**, *186*, 67–73. [CrossRef] [PubMed]
10. Huang, W.; Lin, Y.; He, M.; Gong, Y.; Huang, J. Induced High-Yield Production of Zeaxanthin, Lutein, and β-Carotene by a Mutant of *Chlorella zofingiensis*. *J. Agric. Food Chem.* **2018**, *66*, 891–897. [CrossRef] [PubMed]
11. Minyuk, G.; Sidorov, R.; Solovchenko, A. Effect of Nitrogen Source on the Growth, Lipid, and Valuable Carotenoid Production in the Green Microalga *Chromochloris zofingiensis*. *J. Appl. Phycol.* **2020**, *32*, 923–935. [CrossRef]
12. Park, J.-E.; Zhang, S.; Han, T.H.; Hwang, S.-J. The Contribution Ratio of Autotrophic and Heterotrophic Metabolism during a Mixotrophic Culture of *Chlorella sorokiniana*. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1353. [CrossRef] [PubMed]
13. Singh, D.P.; Khattar, J.S.; Rajput, A.; Chaudhary, R.; Singh, R. High Production of Carotenoids by the Green Microalga *Asterarcys quadricellulare* PUMCC 5.1.1 under Optimized Culture Conditions. *PLoS ONE* **2019**, *14*, e0221930. [CrossRef] [PubMed]
14. Yang, S.; Lu, X.; Wang, J.; Liu, Y.; Nie, M.; Liu, J.; Sun, H. Astaxanthin from *Haematococcus pluvialis* and *Chromochloris zofingiensis*: Biosynthetic Pathways, Engineering Strategies, and Industrial Prospects. *Mar. Drugs* **2025**, *23*, 485. [CrossRef] [PubMed]
15. Ma, R.; Ma, X.; Qiao, Y.; Wang, B.; Ho, S.-H.; Chen, J.; Xie, Y. Improved Production of Astaxanthin in Heterotrophic *Chromochloris zofingiensis* through Optimized Culture Conditions Incorporating an Efficient Fed-Batch Strategy. *Algal Res.* **2025**, *86*, 103895. [CrossRef]
16. Wood, E.E.; Ross, M.E.; Jubeau, S.; Montalescot, V.; Stanley, M.S. Progress towards a Targeted Biorefinery of *Chromochloris zofingiensis*: A Review. *Biomass Convers. Biorefin.* **2024**, *14*, 8127–8152. [CrossRef] [PubMed]
17. Bhardwaj, R.A.; Yadav, A.; Swapnil, P.; Meena, M. Characterization of Microalgal β-Carotene and Astaxanthin: Exploring Their Health-Promoting Properties under the Effect of Salinity and Light Intensity. *Biotechnol. Biofuels Bioprod.* **2025**, *18*, 18. [CrossRef] [PubMed]
18. Elbahnaswy, S.; Elshopakey, G.E. Recent Progress in Practical Applications of a Potential Carotenoid Astaxanthin in Aquaculture Industry: A Review. *Fish. Physiol. Biochem.* **2024**, *50*, 97–126. [CrossRef] [PubMed]
19. Ritu, J.R.; Ambati, R.R.; Ravishankar, G.A.; Shahjahan, M.; Khan, S. Utilization of Astaxanthin from Microalgae and Carotenoid Rich Algal Biomass as a Feed Supplement in Aquaculture and Poultry Industry: An Overview. *J. Appl. Phycol.* **2023**, *35*, 145–171. [CrossRef]
20. Higuera-Ciapara, I.; Félix-Valenzuela, L.; Goycoolea, F.M. Astaxanthin: A Review of Its Chemistry and Applications. *Crit. Rev. Food Sci. Nutr.* **2006**, *46*, 185–196. [CrossRef] [PubMed]
21. Mussagy, C.U.; Pereira, J.F.B.; Dufossé, L.; Raghavan, V.; Santos-Ebinuma, V.C.; Pessoa, A. Advances and Trends in Biotechnological Production of Natural Astaxanthin by *Phaffia rhodozyma* Yeast. *Crit. Rev. Food Sci. Nutr.* **2023**, *63*, 1862–1876. [CrossRef] [PubMed]
22. Hu, Z.-C.; Zheng, Y.-G.; Wang, Z.; Shen, Y.-C. PH Control Strategy in Astaxanthin Fermentation Bioprocess by *Xanthophyllomyces dendrorhous*. *Enzym. Microb. Technol.* **2006**, *39*, 586–590. [CrossRef]
23. Jiang, G.; Yang, Z.; Wang, Y.; Yao, M.; Chen, Y.; Xiao, W.; Yuan, Y. Enhanced Astaxanthin Production in Yeast via Combined Mutagenesis and Evolution. *Biochem. Eng. J.* **2020**, *156*, 107519. [CrossRef]
24. Lin, Y.-J.; Chang, J.-J.; Lin, H.-Y.; Thia, C.; Kao, Y.-Y.; Huang, C.-C.; Li, W.-H. Metabolic Engineering a Yeast to Produce Astaxanthin. *Bioresour. Technol.* **2017**, *245*, 899–905. [CrossRef] [PubMed]
25. Ukibe, K.; Hashida, K.; Yoshida, N.; Takagi, H. Metabolic Engineering of *Saccharomyces cerevisiae* for Astaxanthin Production and Oxidative Stress Tolerance. *Appl. Environ. Microbiol.* **2009**, *75*, 7205–7211. [CrossRef] [PubMed]

26. Mussagy, C.U.; Duarte, J.L.; Tashiro, F.M.; Medeiros, C.C.B.; Sorrechia, R.; Pietro, R.C.L.R.; Chorilli, M.; Guzmán-Flores, J.M.; Caicedo-Paz, A.V. *Paracoccus carotinifaciens* as a Bacterial Source of Astaxanthin for Food Applications: Integrated Experimental and in Silico Analysis Reveals a Safe Non-Antibacterial Profile and Weak Selective Fungistatic Activity. *Food Biosci.* **2026**, *76*, 108277. [CrossRef]
27. Gomes, S.M.; Rebelo, B.A.; Abranches, R. Unlocking the Potential of Medicago Truncatula A17 Cell Suspension Cultures for Bioproduction of Astaxanthin and Canthaxanthin. *Biotechnol. Bioeng.* **2025**, *122*, 2228–2240. [CrossRef] [PubMed]
28. Chien, Y.-H.; Jeng, S.-C. Pigmentation of Kuruma Prawn, *Penaeus japonicus* Bate, by Various Pigment Sources and Levels and Feeding Regimes. *Aquaculture* **1992**, *102*, 333–346. [CrossRef]
29. Hamre, K.; Micallef, G.; Hillestad, M.; Johansen, J.; Remø, S.; Zhang, W.; Ødegård, E.; Araujo, P.; Prabhu Philip, A.J.; Waagbø, R. Changes in Daylength and Temperature from April until August for Atlantic Salmon (*Salmo salar*) Reared in Sea Cages, Increase Growth, and May Cause Consumption of Antioxidants, Onset of Cataracts and Increased Oxidation of Fillet Astaxanthin. *Aquaculture* **2022**, *551*, 737950. [CrossRef]
30. Turujman, S.A.; Wamer, W.G.; Wei, R.R.; Albert, R.H. Rapid Liquid Chromatographic Method to Distinguish Wild Salmon from Aquacultured Salmon Fed Synthetic Astaxanthin. *J. AOAC Int.* **1997**, *80*, 622–632. [CrossRef]
31. Hu, J.; Lu, W.; Lv, M.; Wang, Y.; Ding, R.; Wang, L. Extraction and Purification of Astaxanthin from Shrimp Shells and the Effects of Different Treatments on Its Content. *Rev. Bras. Farmacogn.* **2019**, *29*, 24–29. [CrossRef]
32. Anguchamy, V.; Jianping, W.; Muthuvel, A. Valorization of Cephalopod (*Doryteuthis singhalensis*) by-Products through Astaxanthin Recovery and Antioxidant Assessment. *Sep. Purif. Technol.* **2026**, *382*, 135969. [CrossRef]
33. Dalei, J.; Sahoo, D. Extraction and Characterization of Astaxanthin from the Crustacean Shell Waste from Shrimp Processing Industries. *Int. J. Pharm. Sci. Res.* **2015**, *6*, 2532–2537.
34. Prameela, K.; Venkatesh, K.; Immandi, S.B.; Kasturi, A.P.K.; Rama Krishna, C.; Murali Mohan, C. Next Generation Nutraceutical from Shrimp Waste: The Convergence of Applications with Extraction Methods. *Food Chem.* **2017**, *237*, 121–132. [CrossRef] [PubMed]
35. Punbusayakul, N.; Panpranot, S.; Srisopa, K.; Phimolsiripol, Y.; Wangtueai, S.; Thuengtung, S.; Yarnpakdee, S.; Kaewprachu, P.; Chakrabandhu, Y.; Kingwascharapong, P.; et al. Valorization of Mantis Shrimp By-Product through Integrated Extraction-Encapsulation Approach for Astaxanthin Production. *LWT* **2025**, *232*, 118428. [CrossRef]
36. Šimat, V.; Rathod, N.B.; Čagalj, M.; Hamed, I.; Generalić Mekinić, I. Astaxanthin from Crustaceans and Their Byproducts: A Bioactive Metabolite Candidate for Therapeutic Application. *Mar. Drugs* **2022**, *20*, 206. [CrossRef] [PubMed]
37. Wang, J.; Yu, Z.; Yin, F.; Li, D.; Liu, H.; Song, L.; Zhou, D. Comparison of Different Solvents for Extraction of Oils from By-products of Shrimps *Penaeus vannamei* and *Procambarus clarkia*. *J. Food Process. Preserv.* **2021**, *45*, e15754. [CrossRef]
38. Breitenbach, J.; Nogueira, M.; Farré, G.; Zhu, C.; Capell, T.; Christou, P.; Fleck, G.; Focken, U.; Fraser, P.D.; Sandmann, G. Engineered Maize as a Source of Astaxanthin: Processing and Application as Fish Feed. *Transgenic Res.* **2016**, *25*, 785–793. [CrossRef] [PubMed]
39. Weeratunge, W.K.O.V.; Perera, B.G.K. Formulation of a Fish Feed for Goldfish with Natural Astaxanthin Extracted from Shrimp Waste. *Chem. Cent. J.* **2016**, *10*, 44. [CrossRef] [PubMed]
40. Peng, L.; Zhang, Z.; Li, Q.; Yang, H. Current Challenges and Issues in the Application of Astaxanthin. *Fishes* **2025**, *10*, 159. [CrossRef]
41. Stachowiak, B.; Szulc, P. Astaxanthin for the Food Industry. *Molecules* **2021**, *26*, 2666. [CrossRef] [PubMed]
42. Zhu, Y.; Li, X.; Wu, S. Biological Function of Astaxanthin and Its Application in Aquatic Animal Feeding. *Food Chem. X* **2025**, *32*, 103319. [CrossRef] [PubMed]
43. Safari, R.; Mirbakhsh, M.; Ghaffari, H.; Reyhani Poul, S.; Rahmati, R.; Ebrahimzadeh, M.). Effect of Temperature, PH, and Time Factors on the Stability and Antioxidant Activity of the Extracted Astaxanthin from *Haematococcus* Microalgae (*Haematococcus pluvialis*). *Iran. Sci. Fish. J.* **2022**, *31*, 109–120.
44. Anarjan, N.; Tan, C.P. Effects of Storage Temperature, Atmosphere and Light on Chemical Stability of Astaxanthin Nanodispersions. *J. Am. Oil Chem. Soc.* **2013**, *90*, 1223–1227. [CrossRef]
45. Ahmed, F.; Li, Y.; Fanning, K.; Netzel, M.; Schenk, P.M. Effect of Drying, Storage Temperature and Air Exposure on Astaxanthin Stability from *Haematococcus pluvialis*. *Food Res. Int.* **2015**, *74*, 231–236. [CrossRef] [PubMed]
46. Bustos-Garza, C.; Yáñez-Fernández, J.; Barragán-Huerta, B.E. Thermal and PH Stability of Spray-Dried Encapsulated Astaxanthin Oleoresin from *Haematococcus pluvialis* Using Several Encapsulation Wall Materials. *Food Res. Int.* **2013**, *54*, 641–649. [CrossRef]
47. Feizi, P.; Jafari, S.M. Optimization of Astaxanthin Extraction from Red (*Gracilaria corticata*) and Brown (*Sargassum polycystum*) Macroalgae through Ultrasonication and Microwave Processing. *Ultrason. Sonochem.* **2025**, *121*, 107556. [CrossRef] [PubMed]
48. Oninku, B.; Lomas, M.W.; Burr, G.; Aryee, A.N.A. Astaxanthin: An Overview of Its Sources, Extraction Methods, Encapsulation Techniques, Characterization, and Bioavailability. *J. Agric. Food Res.* **2025**, *21*, 101869. [CrossRef]
49. Duan, M.; Zhou, X.; Fang, T.; Zhou, D.; Shi, Q.; Ge, F.; Wang, W. Efficient Supercritical Carbon Dioxide Extraction of Astaxanthin from *Hematococcus pluvialis* at High Pressure. *J. Supercrit. Fluids* **2024**, *205*, 106145. [CrossRef]

50. Kaya, A.; Ural, G.N.; Topuz, O.K. Optimization of Ultrasonication-Assisted Astaxanthin Extraction Conditions from Red Giant Shrimp (*Aristaeomorpha foliacea*) Processing Waste. *J. Aquat. Food Product. Technol.* **2025**, *34*, 82–91. [CrossRef]
51. Zou, T.-B.; Jia, Q.; Li, H.-W.; Wang, C.-X.; Wu, H.-F. Response Surface Methodology for Ultrasound-Assisted Extraction of Astaxanthin from *Haematococcus pluvialis*. *Mar. Drugs* **2013**, *11*, 1644–1655. [CrossRef] [PubMed]
52. Luo, F.; Wang, S.; Zhang, X.; Liu, Z.; Zhu, R.; Xue, W. Extraction of Astaxanthin from *Haematococcus pluvialis* and Preparation of Astaxanthin Liposomes. *Molecules* **2024**, *29*, 3320. [CrossRef] [PubMed]
53. Di Sanzo, G.; Mehariya, S.; Martino, M.; Larocca, V.; Casella, P.; Chianese, S.; Musmarra, D.; Balducchi, R.; Molino, A. Supercritical Carbon Dioxide Extraction of Astaxanthin, Lutein, and Fatty Acids from *Haematococcus pluvialis* Microalgae. *Mar. Drugs* **2018**, *16*, 334. [CrossRef] [PubMed]
54. Xu, Y.; Jia, Z.; Wang, J.; Sun, J.; Song, R. Property and Stability of Astaxanthin Emulsion Based on Pickering Emulsion Templating with Zein and Sodium Alginate as Stabilizer. *Int. J. Mol. Sci.* **2022**, *23*, 9386. [CrossRef] [PubMed]
55. Sun, L.; Li, Y.; Yang, A.; Xie, M.; Xiong, R.; Huang, C. Astaxanthin: A Comprehensive Review of Synthesis, Biological Activities and Applications. *Food Chem.* **2025**, *488*, 144847. [CrossRef] [PubMed]
56. Niamnuy, C.; Devahastin, S.; Soponronnarit, S.; Vijaya Raghavan, G.S. Kinetics of Astaxanthin Degradation and Color Changes of Dried Shrimp during Storage. *J. Food Eng.* **2008**, *87*, 591–600. [CrossRef]
57. Dewanti, P.R.; Rochmadi; Rohman, A.; Budiman, A. Degradation Rate of Astaxanthin from *Haematococcus pluvialis*. *Food Res.* **2022**, *6*, 254–258. [CrossRef] [PubMed]
58. Li, N.; Fan, X.; Wang, Y.; Zhang, K.; Liu, R.; Xu, Y.; Tan, Z.; Xu, W.; Zhou, D.; Li, D. Investigation of Isomerization and Oxidation of Astaxanthin in Ready-to-Eat *Litopenaeus vannamei* during Accelerated Storage. *Food Res. Int.* **2024**, *195*, 114983. [CrossRef] [PubMed]
59. Reyes, F.A.; Mendiola, J.A.; Ibañez, E.; del Valle, J.M. Astaxanthin Extraction from *Haematococcus pluvialis* Using CO_2-Expanded Ethanol. *J. Supercrit. Fluids* **2014**, *92*, 75–83. [CrossRef]
60. Torres-Carvajal, L.K.; Gonzalez-Delgado, A.D.; Barajas-Solano, A.F.; Suarez-Gelvez, J.H.; Urbina-Suarez, N.A. Astaxanthin Production from *Haematococcus pluvialis*: Effects of Light Wavelength and Salinity. *Contemp. Eng. Sci.* **2017**, *10*, 1739–1746. [CrossRef]
61. Aravena, R.I.; del Valle, J.M.; de la Fuente, J.C. Supercritical CO_2 Extraction of Aqueous Suspensions of Disrupted *Haematococcus pluvialis* Cysts. *J. Supercrit. Fluids* **2022**, *181*, 105392. [CrossRef]
62. Zhao, X.; Zhang, X.; Liu, H.; Zhu, H.; Zhu, Y. Enzyme-Assisted Extraction of Astaxanthin from *Haematococcus pluvialis* and Its Stability and Antioxidant Activity. *Food Sci. Biotechnol.* **2019**, *28*, 1637–1647. [CrossRef] [PubMed]
63. Wang, L.; Hu, J.; Lv, W.; Lu, W.; Pei, D.; Lv, Y.; Wang, W.; Zhang, M.; Ding, R.; Lv, M. Optimized Extraction of Astaxanthin from Shrimp Shells Treated by Biological Enzyme and Its Separation and Purification Using Macroporous Resin. *Food Chem.* **2021**, *363*, 130369. [CrossRef] [PubMed]
64. Shah, M.M.R.; Liang, Y.; Cheng, J.J.; Daroch, M. Astaxanthin-Producing Green Microalga *Haematococcus pluvialis*: From Single Cell to High Value Commercial Products. *Front. Plant Sci.* **2016**, *7*, 531. [CrossRef] [PubMed]
65. Ruen-ngam, D.; Shotipruk, A.; Pavasant, P. Comparison of Extraction Methods for Recovery of Astaxanthin from *Haematococcus pluvialis*. *Sep. Sci. Technol.* **2010**, *46*, 64–70. [CrossRef]
66. Panagiotakopoulos, I.; Nasopoulou, C. Extraction Methods, Encapsulation Techniques, and Health Benefits of Astaxanthin. *Sustainability* **2024**, *16*, 10859. [CrossRef]
67. Holtin, K.; Kuehnle, M.; Rehbein, J.; Schuler, P.; Nicholson, G.; Albert, K. Determination of Astaxanthin and Astaxanthin Esters in the Microalgae *Haematococcus pluvialis* by LC-(APCI)MS and Characterization of Predominant Carotenoid Isomers by NMR Spectroscopy. *Anal. Bioanal. Chem.* **2009**, *395*, 1613–1622. [CrossRef] [PubMed]
68. Todorović, B.; Grujić, V.J.; Krajnc, A.U.; Kranvogl, R.; Ambrožič-Dolinšek, J. Identification and Content of Astaxanthin and Its Esters from Microalgae *Haematococcus pluvialis* by HPLC-DAD and LC-QTOF-MS after Extraction with Various Solvents. *Plants* **2021**, *10*, 2413. [CrossRef] [PubMed]
69. Miao, F.; Lu, D.; Li, Y.; Zeng, M. Characterization of Astaxanthin Esters in *Haematococcus pluvialis* by Liquid Chromatography–Atmospheric Pressure Chemical Ionization Mass Spectrometry. *Anal. Biochem.* **2006**, *352*, 176–181. [CrossRef] [PubMed]
70. García-de Blas, E.; Mateo, R.; Viñuela, J.; Alonso-Álvarez, C. Identification of Carotenoid Pigments and Their Fatty Acid Esters in an Avian Integument Combining HPLC–DAD and LC–MS Analyses. *J. Chromatogr. B* **2011**, *879*, 341–348. [CrossRef] [PubMed]
71. Sharayei, P.; Azarpazhooh, E.; Zomorodi, S.; Einafshar, S.; Ramaswamy, H.S. Optimization of Ultrasonic-Assisted Extraction of Astaxanthin from Green Tiger (*Penaeus semisulcatus*) Shrimp Shell. *Ultrason. Sonochem.* **2021**, *76*, 105666. [CrossRef] [PubMed]
72. Dave, D.; Liu, Y.; Pohling, J.; Trenholm, S.; Murphy, W. Astaxanthin Recovery from Atlantic Shrimp (*Pandalus borealis*) Processing Materials. *Bioresour. Technol. Rep.* **2020**, *11*, 100535. [CrossRef]
73. Naguib, Y.M.A. Antioxidant Activities of Astaxanthin and Related Carotenoids. *J. Agric. Food Chem.* **2000**, *48*, 1150–1154. [CrossRef] [PubMed]

74. Miao, F.; Geng, Y.; Lu, D.; Zuo, J.; Li, Y. Stability and Changes in Astaxanthin Ester Composition from *Haematococcus pluvialis* during Storage. *Chin. J. Oceanol. Limnol.* **2013**, *31*, 1181–1189. [CrossRef]
75. Burgos-Díaz, C.; Opazo-Navarrete, M.; Soto-Añual, M.; Leal-Calderón, F.; Bustamante, M. Food-Grade Pickering Emulsion as a Novel Astaxanthin Encapsulation System for Making Powder-Based Products: Evaluation of Astaxanthin Stability during Processing, Storage, and Its Bioaccessibility. *Food Res. Int.* **2020**, *134*, 109244. [CrossRef] [PubMed]
76. Saubenova, M.; Rapoport, A.; Venkatachalam, M.; Dufossé, L.; Yermekbay, Z.; Oleinikova, Y. Production of Carotenoids by Microorganisms. *Fermentation* **2024**, *10*, 502. [CrossRef]
77. Tambat, V.S.; Singhania, R.R.; Sumathi, Y.; Chen, C.-W.; Dong, C.-D.; Michaud, P.; Patel, A.K. Astaxanthin: Nature's Multifunctional Molecule, Natural Sources, Health Benefits, and Process Advancements. *Crit. Rev. Biotechnol.* **2026**, *46*, 61–79. [CrossRef] [PubMed]
78. Oslan, S.N.H.; Shoparwe, N.F.; Yusoff, A.H.; Rahim, A.A.; Chang, C.S.; Tan, J.S.; Oslan, S.N.; Arumugam, K.; Ariff, A.B.; Sulaiman, A.Z.; et al. A Review on *Haematococcus pluvialis* Bioprocess Optimization of Green and Red Stage Culture Conditions for the Production of Natural Astaxanthin. *Biomolecules* **2021**, *11*, 256. [CrossRef] [PubMed]
79. Cheng, J.; Shen, S.; Yang, H.; Tang, D.; Wang, X.; Lin, Y.; Liu, X. Improved Physicochemical Stability and Bioaccessibility of Astaxanthin-Loaded Oil-in-Water Emulsions by a Casein-Caffeic Acid–Glucose Ternary Conjugate. *Food Res. Int.* **2023**, *163*, 112153. [CrossRef] [PubMed]
80. Zhu, X.; Meng, C.; Sun, F.; Wei, Z.; Chen, L.; Chen, W.; Tong, S.; Du, H.; Gao, J.; Ren, J.; et al. Sustainable Production of Astaxanthin in Microorganisms: The Past, Present, and Future. *Crit. Rev. Food Sci. Nutr.* **2023**, *63*, 10239–10255. [CrossRef] [PubMed]
81. Nishida, Y.; Berg, P.; Shakersain, B.; Hecht, K.; Takikawa, A.; Tao, R.; Kakuta, Y.; Uragami, C.; Hashimoto, H.; Misawa, N.; et al. Astaxanthin: Past, Present, and Future. *Mar. Drugs* **2023**, *21*, 514. [CrossRef] [PubMed]
82. Wang, C.; Hong, Z.; Song, M.; Zheng, H.; Zhou, Q.; Yang, H.; Li, H.; Huang, D. Production of Astaxanthin with High Purity and Activity Based on Engineering Improvement Strategies. *J. Biotechnol.* **2025**, *405*, 139–149. [CrossRef] [PubMed]
83. Han, D.; Li, Y.; Hu, Q. Astaxanthin in Microalgae: Pathways, Functions and Biotechnological Implications. *ALGAE* **2013**, *28*, 131–147. [CrossRef]
84. Jin, J.; Wang, Y.; Yao, M.; Gu, X.; Li, B.; Liu, H.; Ding, M.; Xiao, W.; Yuan, Y. Astaxanthin Overproduction in Yeast by Strain Engineering and New Gene Target Uncovering. *Biotechnol. Biofuels* **2018**, *11*, 230. [CrossRef] [PubMed]
85. Capelli, B.; Bagchi, D.; Cysewski, G.R. Synthetic Astaxanthin Is Significantly Inferior to Algal-Based Astaxanthin as an Antioxidant and May Not Be Suitable as a Human Nutraceutical Supplement. *Nutrafoods* **2013**, *12*, 145–152. [CrossRef]
86. Al-Tarifi, B.Y.; Mahmood, A.; Assaw, S.; Sheikh, H.I. Application of Astaxanthin and Its Lipid Stability in Bakery Product. *Curr. Res. Nutr. Food Sci. J.* **2020**, *8*, 962–974. [CrossRef]
87. Dang, Y.; Li, Z.; Yu, F. Recent Advances in Astaxanthin as an Antioxidant in Food Applications. *Antioxidants* **2024**, *13*, 879. [CrossRef] [PubMed]
88. Zhao, W.; Guo, Y.-C.; Huai, M.-Y.; Li, L.; Man, C.; Pelletier, W.; Wei, H.-L.; Yao, R.; Niu, J. Comparison of the Retention Rates of Synthetic and Natural Astaxanthin in Feeds and Their Effects on Pigmentation, Growth, and Health in Rainbow Trout (*Oncorhynchus mykiss*). *Antioxidants* **2022**, *11*, 2473. [CrossRef] [PubMed]
89. Aldaghi, S.A.; Ubais, R.; Schmitt, I.; Wendisch, V.F.; Costamagna, M.; Perucca, M. Life Cycle Assessment of Bacterial, Algal, and Synthetic Approaches for Astaxanthin Production at a Laboratory Scale: Comparative Environmental Analysis and Sensitivity of Energy Sources. *Processes* **2023**, *11*, 2911. [CrossRef]
90. Turck, D.; Bohn, T.; Castenmiller, J.; De Henauw, S.; Hirsch-Ernst, K.I.; Maciuk, A.; Mangelsdorf, I.; McArdle, H.J.; Naska, A.; Pelaez, C.; et al. Safety of a Change in Specifications of the Novel Food Oleoresin from *Haematococcus pluvialis* Containing Astaxanthin Pursuant to Regulation (EU) 2015/2283. *EFSA J.* **2023**, *21*, e08338. [CrossRef] [PubMed]
91. Turck, D.; Castenmiller, J.; de Henauw, S.; Hirsch-Ernst, K.I.; Kearney, J.; Maciuk, A.; Mangelsdorf, I.; McArdle, H.J.; Naska, A.; Pelaez, C.; et al. Safety of Astaxanthin for Its Use as a Novel Food in Food Supplements. *EFSA J.* **2020**, *18*, e05993. [CrossRef] [PubMed]
92. Brendler, T.; Williamson, E.M. Astaxanthin: How Much Is Too Much? A Safety Review. *Phyther. Res.* **2019**, *33*, 3090–3111. [CrossRef] [PubMed]
93. United States Congress. *Dietary Supplement Health and Education Act of 1994*; United States Congress: Washington, DC, USA, 1994.
94. Edwards, J.A.; Bellion, P.; Beilstein, P.; Rümbeli, R.; Schierle, J. Review of Genotoxicity and Rat Carcinogenicity Investigations with Astaxanthin. *Regul. Toxicol. Pharmacol.* **2016**, *75*, 5–19. [CrossRef] [PubMed]
95. Davinelli, S.; Nielsen, M.E.; Scapagnini, G. Astaxanthin in Skin Health, Repair, and Disease: A Comprehensive Review. *Nutrients* **2018**, *10*, 522. [CrossRef] [PubMed]
96. Fassett, R.G.; Coombes, J.S. Astaxanthin in Cardiovascular Health and Disease. *Molecules* **2012**, *17*, 2030–2048. [CrossRef] [PubMed]
97. Bjerkeng, B. Carotenoids in Aquaculture: Fish and Crustaceans. In *Carotenoids*; Birkhäuser Basel: Basel, Switzerland, 2008; pp. 237–254. [CrossRef]

98. Sun, Y.; Zong, W.; Wang, J.; He, J.; Zhang, J.; Han, T. Astaxanthin Enhances Antioxidant Capacity to Alleviate Thermal Stress-Induced Liver Inflammation in Largemouth Bass (*Micropterus salmoides*): A Multi-Omics Insight into Glutathione Metabolism Remodeling. *Front. Mar. Sci.* **2025**, *12*, 1595039. [CrossRef]
99. Choi, S.K.; Park, Y.S.; Choi, D.K.; Chang, H.I. Effects of Astaxanthin on the Production of NO and the Expression of COX-2 and INOS in LPS-Stimulated BV2 Microglial Cells. *J. Microbiol. Biotechnol.* **2008**, *18*, 1990–1996. [CrossRef]
100. Galasso, C.; Orefice, I.; Pellone, P.; Cirino, P.; Miele, R.; Ianora, A.; Brunet, C.; Sansone, C. On the Neuroprotective Role of Astaxanthin: New Perspectives? Mar. *Drugs* **2018**, *16*, 247. [CrossRef] [PubMed]
101. Ohgami, K.; Shiratori, K.; Kotake, S.; Nishida, T.; Mizuki, N.; Yazawa, K.; Ohno, S. Effects of Astaxanthin on Lipopolysaccharide-Induced Inflammation In Vitro and In Vivo. *Investig. Opthalmology Vis. Sci.* **2003**, *44*, 2694. [CrossRef] [PubMed]
102. Yamashita, E. Let Astaxanthin Be Thy Medicine. *PharmaNutrition* **2015**, *3*, 115–122. [CrossRef]
103. Fakhri, S.; Yosifova Aneva, I.; Farzaei, M.H.; Sobarzo-Sánchez, E. The Neuroprotective Effects of Astaxanthin: Therapeutic Targets and Clinical Perspective. *Molecules* **2019**, *24*, 2640. [CrossRef] [PubMed]
104. Masoudi, A.; Dargahi, L.; Abbaszadeh, F.; Pourgholami, M.H.; Asgari, A.; Manoochehri, M.; Jorjani, M. Neuroprotective Effects of Astaxanthin in a Rat Model of Spinal Cord Injury. *Behav. Brain Res.* **2017**, *329*, 104–110. [CrossRef] [PubMed]
105. Wu, L.; Sun, Z.; Chen, A.; Guo, X.; Wang, J. Effect of Astaxanthin and Exercise on Antioxidant Capacity of Human Body, Blood Lactic Acid and Blood Uric Acid Metabolism. *Sci. Sports* **2019**, *34*, 348–352. [CrossRef]
106. Boskabady, M.H.; Karimi, G.R.; Samarghandian, S.; Farkhondeh, T. Tracheal Responsiveness to Methacholine and Ovalbumin; and Lung Inflammation in Guinea Pigs Exposed to Inhaled Lead after Sensitization. *Ecotoxicol. Environ. Saf.* **2012**, *86*, 233–238. [CrossRef] [PubMed]
107. Cheng, C.-H.; Guo, Z.-X.; Ye, C.-X.; Wang, A.-L. Effect of Dietary Astaxanthin on the Growth Performance, Non-Specific Immunity, and Antioxidant Capacity of Pufferfish (*Takifugu obscurus*) under High Temperature Stress. *Fish. Physiol. Biochem.* **2018**, *44*, 209–218. [CrossRef] [PubMed]
108. Kohandel, Z.; Farkhondeh, T.; Aschner, M.; Pourbagher-Shahri, A.M.; Samarghandian, S. Anti-Inflammatory Action of Astaxanthin and Its Use in the Treatment of Various Diseases. *Biomed. Pharmacother.* **2022**, *145*, 112179. [CrossRef] [PubMed]
109. Cheng, J.; Eroglu, A. The Promising Effects of Astaxanthin on Lung Diseases. *Adv. Nutr.* **2021**, *12*, 850–864. [CrossRef] [PubMed]
110. Pereira, C.; Souza, A.; Vasconcelos, A.; Prado, P.; Name, J. Antioxidant and Anti-inflammatory Mechanisms of Action of Astaxanthin in Cardiovascular Diseases (Review). *Int. J. Mol. Med.* **2020**, *47*, 37–48. [CrossRef] [PubMed]
111. Kato, T.; Kasai, T.; Sato, A.; Ishiwata, S.; Yatsu, S.; Matsumoto, H.; Shitara, J.; Murata, A.; Shimizu, M.; Suda, S.; et al. Effects of 3-Month Astaxanthin Supplementation on Cardiac Function in Heart Failure Patients with Left Ventricular Systolic Dysfunction-A Pilot Study. *Nutrients* **2020**, *12*, 1896. [CrossRef] [PubMed]
112. Lu, Y.-P.; Liu, S.-Y.; Sun, H.; Wu, X.-M.; Li, J.-J.; Zhu, L. Neuroprotective Effect of Astaxanthin on H_2O_2-Induced Neurotoxicity in Vitro and on Focal Cerebral Ischemia in Vivo. *Brain Res.* **2010**, *1360*, 40–48. [CrossRef] [PubMed]
113. Mashhadi, N.S.; Zakerkish, M.; Mohammadiasl, J.; Zarei, M.; Mohammadshahi, M.; Haghighizadeh, M.H. Astaxanthin Improves Glucose Metabolism and Reduces Blood Pressure in Patients with Type 2 Diabetes Mellitus. *Asia Pac. J. Clin. Nutr.* **2018**, *27*, 341–346. [CrossRef] [PubMed]
114. Catanzaro, E.; Bishayee, A.; Fimognari, C. On a Beam of Light: Photoprotective Activities of the Marine Carotenoids Astaxanthin and Fucoxanthin in Suppression of Inflammation and Cancer. *Mar. Drugs* **2020**, *18*, 544. [CrossRef] [PubMed]
115. Chalyk, N.E.; Klochkov, V.A.; Bandaletova, T.Y.; Kyle, N.H.; Petyaev, I.M. Continuous Astaxanthin Intake Reduces Oxidative Stress and Reverses Age-Related Morphological Changes of Residual Skin Surface Components in Middle-Aged Volunteers. *Nutr. Res.* **2017**, *48*, 40–48. [CrossRef] [PubMed]
116. Yuan, J.; Peng, J.; Yin, K.; Wang, J. Potential Health-promoting Effects of Astaxanthin: A High-value Carotenoid Mostly from Microalgae. *Mol. Nutr. Food Res.* **2011**, *55*, 150–165. [CrossRef] [PubMed]
117. Guerin, M.; Huntley, M.E.; Olaizola, M. Haematococcus Astaxanthin: Applications for Human Health and Nutrition. *Trends Biotechnol.* **2003**, *21*, 210–216. [CrossRef] [PubMed]
118. Cao, Y.; Yang, L.; Qiao, X.; Xue, C.; Xu, J. Dietary Astaxanthin: An Excellent Carotenoid with Multiple Health Benefits. *Crit. Rev. Food Sci. Nutr.* **2023**, *63*, 3019–3045. [CrossRef] [PubMed]
119. Lim, K.C.; Yusoff, F.M.; Shariff, M.; Kamarudin, M.S. Astaxanthin as Feed Supplement in Aquatic Animals. *Rev. Aquac.* **2018**, *10*, 738–773. [CrossRef]
120. Li, Z.; Zhang, T.; Zhou, R.; Zhang, X.; Ren, J.; Diao, M. Effects of Pasteurization on Set Yogurt Fortified with Astaxanthin-Rich Yolk: Evaluation of Physicochemical Properties, Stability, and Biological Activity. *J. Dairy Sci.* **2025**, *108*, 3499–3514. [CrossRef] [PubMed]
121. Mezquita, P.C.; Barragán-Huerta, B.E.; Ramírez, J.P.; Hinojosa, C.O. Stability of Astaxanthin in Yogurt Used to Simulate Apricot Color, under Refrigeration. *Food Sci. Technol.* **2014**, *34*, 559–565. [CrossRef]
122. Dmytrów, I.; Szymczak, M.; Szkolnicka, K.; Kamiński, P. Development of Functional Acid Curd Cheese (Tvarog) with Antioxidant Activity Containing Astaxanthin from Shrimp Shells Preliminary Experiment. *Foods* **2021**, *10*, 895. [CrossRef] [PubMed]

123. Zhu, K.; Yan, W.; Dai, Z.; Zhang, Y. Astaxanthin Extract from Shrimp (*Trachypenaeus curvirostris*) By-Products Improves Quality of Ready-to-Cook Shrimp Surimi Products during Frozen Storage at −18 °C. *Foods* **2022**, *11*, 2122. [CrossRef] [PubMed]
124. Seo, J.-K.; Parvin, R.; Park, J.; Yang, H.-S. Utilization of Astaxanthin as a Synthetic Antioxidant Replacement for Emulsified Sausages. *Antioxidants* **2021**, *10*, 407. [CrossRef] [PubMed]
125. Draghici, O. Astaxanthin from Shrimp By-Products Enhances Oxidative Stability of Lard During Storage. *Foods* **2025**, *14*, 2585. [CrossRef] [PubMed]
126. Hossain, A.K.M.M.; Brennan, M.A.; Mason, S.L.; Guo, X.; Zeng, X.A.; Brennan, C.S. The Effect of Astaxanthin-Rich Microalgae "*Haematococcus pluvialis*" and Wholemeal Flours Incorporation in Improving the Physical and Functional Properties of Cookies. *Foods* **2017**, *6*, 57. [CrossRef] [PubMed]
127. Capelli, B.; Talbott, S.; Ding, L. Astaxanthin Sources: Suitability for Human Health and Nutrition. *Funct. Foods Health Dis.* **2019**, *9*, 430. [CrossRef]
128. Carballo, D.E.; Caro, I.; Andrés, S.; Giráldez, F.J.; Mateo, J. Assessment of the Antioxidant Effect of Astaxanthin in Fresh, Frozen and Cooked Lamb Patties. *Food Res. Int.* **2018**, *111*, 342–350. [CrossRef] [PubMed]
129. Mostafa, H.S.; Hashem, M.M. Microalgae as a Source of Carotenoids in Foods, Obstacles and Solutions. *Phytochem. Rev.* **2025**, *24*, 4295–4337. [CrossRef]
130. Pogorzelska, E.; Godziszewska, J.; Brodowska, M.; Wierzbicka, A. Antioxidant Potential of *Haematococcus pluvialis* Extract Rich in Astaxanthin on Colour and Oxidative Stability of Raw Ground Pork Meat during Refrigerated Storage. *Meat Sci.* **2018**, *135*, 54–61. [CrossRef] [PubMed]
131. Bošnjak, S.; Vasilev, D.; Stajković, S.; Vejnović, B.; Miletić, N.; Čobanović, N.; Grković, N.; Pajičić, Đ.; Suvajdžić, B. Influence of Astaxanthin on the Quality and Shelf Life of Frankfurter-Type Sausages with Reduced Nitrite Content. *Ann. Anim. Sci.* **2026**. [CrossRef]
132. Zhang, C.; Yao, W.; Wen, D.; Li, X.; Wu, S.; Leng, X. Dietary Adonis. Aestivalis Extract Improved the Flesh Pigmentation, Antioxidative Status and Shelf-life of Rainbow Trout (*Oncorhynchus mykiss*). *Aquac. Nutr.* **2020**, *26*, 2032–2042. [CrossRef]
133. El-Bialy, H.A.A.; Abd El-Khalek, H.H. A Comparative Study on Astaxanthin Recovery from Shrimp Wastes Using Lactic Fermentation and Green Solvents: An Applied Model on Minced Tilapia. *J. Radiat. Res. Appl. Sci.* **2020**, *13*, 594–605. [CrossRef]
134. Aracati, M.F.; Rodrigues, L.F.; de Oliveira, S.L.; Rodrigues, R.A.; Conde, G.; Cavalcanti, E.N.F.; Borba, H.; Charlie-Silva, I.; Fernandes, D.C.; Eto, S.F.; et al. Astaxanthin Improves the Shelf-life of Tilapia Fillets Stored under Refrigeration. *J. Sci. Food Agric.* **2022**, *102*, 4287–4295. [CrossRef] [PubMed]
135. Zhu, X.; Hao, R.; Zhang, J.; Tian, C.; Hong, Y.; Zhu, C.; Li, G. Dietary Astaxanthin Improves the Antioxidant Capacity, Immunity and Disease Resistance of Coral Trout (*Plectropomus leopardus*). *Fish. Shellfish Immunol.* **2022**, *122*, 38–47. [CrossRef] [PubMed]
136. Chen, Q.; Huang, S.; Dai, J.; Wang, C.; Chen, S.; Qian, Y.; Gong, Y.; Han, T. Effects of Synthetic Astaxanthin on the Growth Performance, Pigmentation, Antioxidant Capacity, and Immune Response in Black Tiger Prawn (*Penaeus monodon*). *Aquac. Nutr.* **2023**, *2023*, 6632067. [CrossRef] [PubMed]
137. Bingol, M.; Brennan, C.; Zeng, M.; Oz, F. Effect of the Fortification with Astaxanthin on the Quality Parameters and Heterocyclic Amines Content of Meatballs. *Int. J. Food Sci. Technol.* **2022**, *57*, 7653–7665. [CrossRef]
138. Hosseindoust, A.; Oh, S.M.; Ko, H.S.; Jeon, S.M.; Ha, S.H.; Jang, A.; Son, J.S.; Kim, G.Y.; Kang, H.K.; Kim, J.S. Muscle Antioxidant Activity and Meat Quality Are Altered by Supplementation of Astaxanthin in Broilers Exposed to High Temperature. *Antioxidants* **2020**, *9*, 1032. [CrossRef] [PubMed]
139. Honda, M.; Kawashima, Y.; Hirasawa, K.; Uemura, T.; Jinkun, S.; Hayashi, Y. Possibility of Using Astaxanthin-Rich Dried Cell Powder from *Paracoccus carotinifaciens* to Improve Egg Yolk Pigmentation of Laying Hens. *Symmetry* **2020**, *12*, 923. [CrossRef]
140. Shevchenko, L.V.; Iakubchak, O.M.; Davydovych, V.A.; Honchar, V.V.; Ciorga, M.; Hartung, J.; Kołacz, R. Influence of Lycopene and Astaxanthin in Feed on Metabolic Parameters of Laying Hens, Yolk Color of Eggs and Their Content of Carotenoids and Vitamin A When Stored under Refrigerated Conditions. *Pol. J. Vet. Sci.* **2021**, *24*, 525–535. [CrossRef] [PubMed]
141. Espinaco, B.Y.; Niizawa, I.; Marino, F.; Zorrilla, S.E.; Sihufe, G.A. Storage Stability of Chia (*Salvia Hispanica* L.) Oil Incorporated with Astaxanthin. *J. Food Process. Preserv.* **2021**, *45*, e15184. [CrossRef]
142. Paz, A.V.C.; Mesa, M.C.M.; Franco, M.; Galan, J.P.M.; Farias, F.O.; Mussagy, C.U. Innovative Approaches for Improving Avocado Oil Quality Using All-E-Rich Astaxanthin from *Paracoccus carotinifaciens* as Bacterial-Based Antioxidants. *Innov. Food Sci. Emerg. Technol.* **2025**, *106*, 104285. [CrossRef]
143. Bassijeh, A.; Ansari, S.; Hosseini, S.M.H. Astaxanthin Encapsulation in Multilayer Emulsions Stabilized by Complex Coacervates of Whey Protein Isolate and Persian Gum and Its Use as a Natural Colorant in a Model Beverage. *Food Res. Int.* **2020**, *137*, 109689. [CrossRef] [PubMed]
144. Ibrahim, E.A.; Omran, A.A.; Salama, Z.A. Evaluation of Turkish Delight Prepared With Pigments And Essential Oils Extracted From Clementine (*Citrus clementine*) Peels As Natural Antioxidants. *Baghdad Sci. J.* **2022**, *19*, 0745. [CrossRef]
145. Yang, L.; Qiao, X.; Gu, J.; Li, X.; Cao, Y.; Xu, J.; Xue, C. Influence of Molecular Structure of Astaxanthin Esters on Their Stability and Bioavailability. *Food Chem.* **2021**, *343*, 128497. [CrossRef] [PubMed]

146. Francezon, N.; Tremblay, A.; Mouget, J.L.; Pasetto, P.; Beaulieu, L. Algae as a Source of Natural Flavors in Innovative Foods. *J. Agric. Food Chem.* **2021**, *69*, 11753–11772. [CrossRef] [PubMed]
147. Zeevi, D.; Korem, T.; Zmora, N.; Israeli, D.; Rothschild, D.; Weinberger, A.; Ben-Yacov, O.; Lador, D.; Avnit-Sagi, T.; Lotan-Pompan, M.; et al. Personalized Nutrition by Prediction of Glycemic Responses. *Cell* **2015**, *163*, 1079–1094. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.