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A Review on Advances in Extraction Technologies, Analytical Characterization, and Various Applications of Astaxanthin Derived from Seafood Waste

Panchakarla Sedyaaw[1], Sravani Kalluri[2], Supriya D. Meshre[3], Varsha R. Bhatkar[4], Darwin Ratnaghosh Bhaladhare[1], Pranali Arun Kamble[1], Sanket Sunil Kawade[5], Shubham Janbandhu[6] and Md. Shadab Alam[7]

[1]Dept. of Fish Processing Technology, [4]Dept. of Aquaculture, [5]Dept. of Aquatic Environment Management, College of Fisheries, Ratnagiri, Maharashtra (415 629), India

[2]Dept. of Fish Processing technology, College of Fishery Science, APFU, Narasapur, Andhra Pradesh (534 275), India

[3]Dept. of Fish Processing Technology, College of Fishery Science, Udgir, Maharashtra (413 517), India

[6]Dept. of Fisheries Resource Management, College of Fisheries Science, Kamdhenu University, Veraval, Gujarat (362 265), India

[7]Dept. of Aquaculture, College of Fisheries, Odisha University of Agriculture and Technology, Bhubaneswar, Odisha (760 007), India

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Corresponding panchakarlasedyaaw@gmail.com

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ABSTRACT

Astaxanthin, a red-orange carotenoid (3,3′-dihydroxy-β, β-carotene-4,4′-dione) with potent antioxidant, anti-inflammatory, and therapeutic effects, is a valuable bioactive compound sustainably extracted from discarded shrimp and crab shells. As seafood industries grow, these by-products pose environmental challenges yet represent an untapped astaxanthin source competing traditional microalgal origins. This review emphasizes astaxanthin's abundance in crustacean shells and the critical role of handling and processing in preserving yield and integrity. Traditionally sourced from *Haematococcus pluvialis*, its commercial use is limited by high cultivation costs. Recently, shrimp and crab shells-common seafood waste-have emerged as sustainable, cost-effective alternatives. The review rigorously discusses extraction methods including ethanol-based, ultrasonic, supercritical CO_2, enzymatic, and emerging green solvents, evaluating yields, sustainability, cost, and scalability. Ethanol-based ultrasound-assisted extraction achieved efficient, eco-friendly yields up to 239.96 µg g^{-1} in *Procambarus clarkii* shells. Silica gel chromatography enhanced purity to 85.1%, enabling use in functional foods, cosmetics, and pharmaceuticals. Purification techniques employing advanced chromatographic and spectrophotometric assays convert crude extracts into pharmaceutical-grade astaxanthin. Applications span food systems-emulsions, microcapsules, antioxidant films-and cosmetics featuring liposomes, nanoemulsions, and cyclodextrins to optimize stability and bioavailability. Each technology balances bioactivity, shelf-life, and safety compliance. The review concludes by highlighting the imperative for safe, effective, and economically viable astaxanthin recovery from seafood waste, aiming to advance sustainable, high-value compound production for food, pharmaceutical, and cosmetic sectors while mitigating environmental impact.

KEYWORDS: Astaxanthin, extraction techniques, supercritical CO_2, nutraceutical, microalgae, antioxidant

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1. INTRODUCTION

The seafood processing industry generates a large quantity of waste, however, these wastes contain valuable bioactive compounds such as astaxanthin, a red-orange carotenoid (3,3′-dihydroxy-β,β-carotene-4′-dione), renowned for its potent antioxidant properties. Notably, the concentration of astaxanthin varies widely among species; for instance, Procambarus clarkii shells contain the highest recorded level at 239.96 μg g^{-1}, whereas Argentine red shrimp shells contain only 1.86 μg g^{-1}, reflecting significant species-specific variation (Hu et al., 2019). The methods of pretreatment and processing greatly affect astaxanthin recovery, with fresh shells yielding significantly higher than sun-dried or boiled shells (Sun et al., 2010; He et al., 2017; Dong et al., 2014; Zhang et al., 2014; Radzali et al., 2014). Consequently, improper disposal of such wastes exacerbates environmental issues loosing economic opportunities.

Astaxanthin is a xanthophyll carotenoid characterized by a polyene chain and terminal hydroxyl and keto groups (Hu et al., 2019). The molecule's conjugated double bonds facilitate potent antioxidative activity, while its polar end groups enhance interactions with cellular membranes, enabling it to span lipid bilayers and protect lipids and proteins from oxidative damage (Papa et al., 2015; Visioli and Artaria, 2017; Zuluaga et al., 2018). Structurally, the rigidity and molecular symmetry of the polyene chain contribute to astaxanthin's greater antioxidant efficacy relative to related carotenoids such as β-carotene and lutein (Wu et al., 2015). Advanced analytical techniques, particularly high-performance liquid chromatography (HPLC) using specialized C30 columns, have been developed to accurately quantify astaxanthin content and purity, albeit with higher operational costs (Sun et al., 2017).

Beyond its chemical properties, astaxanthin exhibits a broad spectrum of biological activities, including anti-inflammatory, and neuroprotective effects; antioxidant that of vitamin E by over 500-fold enabling effective neutralization of free radicals and protection of cellular components against oxidative stress (Dong et al., 2014; Papa et al., 2015). It has shown promise in attenuating cognitive impairments induced by chemotherapy and neurodegenerative diseases (Elagamy et al., 2018; Wu et al., 2015) and provides cardiovascular benefits by improving lipid profiles and reducing arterial plaque formation (Visioli and Artaria, 2017). Due to its amphiphilic nature, possessing both lipophilic and hydrophilic domains, astaxanthin exhibits enhanced biological interactions, including membrane integration that stabilizes its antioxidant activity (Higuera et al., 2006; Guerin et al., 2003; Yuan et al., 2011). This multifaceted functionality underpins its growing application across pharmaceutical, nutraceutical, cosmetic, and food industries. In particular, astaxanthin derived from seafood waste contributes to applications in aquaculture as a pigment enhancer and immunostimulant (Dong et al., 2014), while in food systems it acts as a stable natural colorant and preservative (Papa et al., 2015). Moreover, dietary oils enhance astaxanthin bioavailability; co-supplementation with fish oil improves immune parameters and antioxidant enzyme activities, further amplifying health benefits (Barros et al., 2012; Otton et al., 2012; Ranga et al., 2010, 2013a, 2013b). Astaxanthin's bioavailability has been validated in animal and human studies, demonstrating tissue accumulation and metabolic transformation, supporting its efficacy as a health-promoting agent (Page et al., 2002; Oster et al., 2000; Okada et al., 2009; Olson et al., 2004).

A recent review that thoroughly gathers and assesses extraction, purification, characterization, and application strategies that specifically consider shrimp and crab waste and the benefits of these sources over conventional sources is lacking, even though seafood waste is becoming more widely acknowledged as a source of sustainable astaxanthin. Therefore, the goal of this review is to examine and gather recent developments in the extraction and characterization of astaxanthin from by-products of seafood processing, assess the overall sustainability of extraction and purification techniques, and highlight advancements in formulations and commercial applications.

2. SOURCES OF ASTAXANTHIN

2.1. Sources and natural types of astaxanthin

Astaxanthin (3,3′-dihydroxy-β,β-carotene-4,4′-dione) is a red-orange xanthophyll carotenoid that occurs naturally in a variety of marine organisms. Its most concentrated and commercially exploited source is the microalga *Haematococcus pluvialis*, which can accumulate astaxanthin up to 4% of its dry weight. However, large-scale cultivation of this alga remains technically challenging and costly (Dong et al., 2014; Li et al., 2015; Papa et al., 2015; Elagamy et al., 2018). Seafood processing by-products, particularly crustacean shells (e.g., shrimp and crabs), present an abundant and low-cost alternative, rich in esterified astaxanthin (Zhang et al., 2014; Radzali et al., 2014; Wu et al., 2015; Visioli and Artaria, 2017). Specific crustaceans like *Procambarus clarkii*, *Portunus crab*, *Argentine red shrimp*, and *Pandalus borealis* have been identified as viable sources. In fact, *P. clarkii* demonstrated the highest recorded content at 239.96 μg g^{-1} in processed samples (Hu et al., 2019).

2.2. Availability and processing impact on astaxanthin

The availability of astaxanthin-rich biomass is significantly influenced by seafood industry waste streams. Shrimp and crab shells discarded during food processing can serve as cost-effective, renewable sources for astaxanthin recovery

(Dong et al., 2014; Zhang et al., 2014; Radzali et al., 2014; He et al., 2017). However, the preservation and processing methods play a crucial role in determining the final yield of astaxanthin. Hu et al. (2019) showed that fresh *P. borealis* shells retained 50.32 μg g^{-1} of astaxanthin, while sun-drying and boiling reduced this to as low as 2.69 μg g^{-1} due to oxidative degradation. This underlines the importance of handling practices, as astaxanthin is highly sensitive to heat, oxygen, and UV light (Zuluaga et al., 2018; Sun et al., 2010; Sun et al., 2017; Visioli and Artaria, 2017). Selecting fresh biomass and optimizing storage conditions are, therefore, vital to maximize extraction efficiency and product quality.

2.3. Extraction methods and optimization strategies

Several extraction methodologies are employed to isolate astaxanthin from natural sources. These include oil-soluble extraction, solvent extraction, and supercritical carbon dioxide (SC-CO_2) extraction (Dong et al., 2014; Zhang et al., 2014; Li et al., 2015; He et al., 2017). Among these, ethanol-based solvent extraction has emerged as the most efficient, scalable, and environmentally friendly option. Hu et al. (2019) optimized the extraction from shrimp shells using ultrasound-assisted ethanol extraction at 50°C for 20 minutes and a solid-liquid ratio of 1:7, achieving a yield of 43.7 μg g^{-1}. In contrast, SC-CO_2 offers high purity and safety but requires expensive equipment (Radzali et al., 2014; Papa et al., 2015; Zuluaga et al., 2018). Ethyl acetate extraction from prawn shells has also been attempted, yielding up to 30.258 μg g^{-1} (He et al., 2017). Such comparisons underscore the trade-off between yield, purity, cost, and environmental sustainability.

2.4. Purification techniques and industrial applications

After extraction, astaxanthin purification is important because of the presence of different, but similar carotenoids. Silica gel column chromatography has successfully purged crude extracts, thus increasing purity levels from 0.34% to 85.1% (Hu et al., 2019). Despite minor irreversible adsorption (~14%), silica remains a preferred medium due to its affordability and separation efficiency (Sun et al., 2017; Wu et al., 2015; Zuluaga et al., 2018; Elagamy et al., 2018). C18 or C30 columns are commonly used in high-performance liquid chromatography (HPLC) to measure astaxanthin in both crude and purified extracts. Notably, C30 offers better baseline separation but is costlier. The highly pure astaxanthin thus extracted finds applications in nutraceuticals, cosmetics, pharmaceuticals, and functional foods, owing to its antioxidant, anti-inflammatory, and neuroprotective properties (Visioli and Artaria, 2017; Wu et al., 2015; Dong et al., 2014; Papa et al., 2015). Table 1 lists the several astaxanthin sources, extraction techniques, and content.

3. EXTRACTION TECHNIQUES

3.1. Solvent extraction

Solvent extraction is a popular technique for obtaining astaxanthin from shrimp shells because it is easy to use and reasonably priced. This technique involves dissolving astaxanthin using organic solvents such as ethanol, acetone, or hexane. Among these, ethanol has emerged as the preferred choice due to its low toxicity and environmental compatibility. Studies have shown that ethanol extraction can achieve astaxanthin yields as high as 85.1% when optimized with solid–liquid ratios, extraction time, and temperature conditions (Hu et al., 2019). The process is particularly effective when using fresh shrimp shells, as pre-treatment such as boiling or drying can significantly degrade astaxanthin content through oxidation or thermal decomposition. Ethanol's polarity makes it highly efficient in extracting polar xanthophylls like astaxanthin, although excessive heat during evaporation may lead to degradation (Dong et al., 2014). The method's limitations include residual solvent issues and the need for post-extraction purification. However, it remains the most practical for small-to medium-scale operations due to low costs and simple setup (He et al., 2017; Sun et al., 2010; Zhang et al., 2014).

3.2. Supercritical fluid extraction (SFE)

Supercritical Fluid Extraction (SFE), particularly with carbon dioxide (CO_2), is an advanced technique used for

Table 1: Astaxanthin Sources and Extraction

Source type	Species/Material	Astaxanthin content (μg g^{-1})	Extraction method	Reference
Microalga	*Haematococcus pluvialis*	~40,000 (dry wt)	Oil extraction, SC-CO_2, solvent (e.g., DMSO, ethanol)	Dong et al., 2014
Shrimp shell (fresh)	Pandalus borealis	50.32	Ethanol+ultrasound, 50°C, 20 min	Hu et al., 2019
Shrimp shell (cooked)	*Pandalus borealis*	2.69	Same as above	Hu et al., 2019
Red shrimp shell	*Argentine red shrimp*	1.86	Same as above	Hu et al., 2019
Crayfish shell	*Procambarus clarkii*	239.96	Same as above	Hu et al., 2019
Crab back shell	*Portunus crab*	11.67	Same as above	Hu et al., 2019

extracting astaxanthin without involving harmful solvents. When CO_2 is brought to its supercritical state-above 31.1°C and 73.8 bar-it acts as a tunable solvent with high diffusivity and low viscosity. By adjusting pressure and temperature, researchers can optimize its solvating power for non-polar or slightly polar compounds like astaxanthin. To enhance efficiency, co-solvents like ethanol are often introduced, boosting both yield and purity. The SFE process is highly selective and capable of producing pharmaceutical-grade astaxanthin with minimal oxidation or degradation (Zhang et al., 2014; Dong et al., 2014). Despite its environmental benefits, SFE is not yet widely implemented in industrial settings due to high operational and equipment costs. However, its solvent-free nature and minimal environmental footprint make it an attractive alternative for high-value applications (Papa et al., 2015; Visioli and Artaria, 2017).

3.3. Enzymatic extraction

Enzymatic extraction leverages the use of specific enzymes such as chitinase and protease to degrade the shrimp shell matrix, allowing for more efficient astaxanthin release. This technique is considered a green approach since it operates under mild conditions without harmful solvents. By breaking down proteins and chitin that encapsulate astaxanthin, enzymatic treatments can significantly increase extraction yields (Dong et al., 2014). Moreover, the method preserves the molecular integrity of astaxanthin due to lower thermal stress compared to conventional methods. The efficiency of this technique depends heavily on the type of enzyme, concentration, pH, and incubation time. Enzymatic extraction is also compatible with further downstream processing, such as column chromatography or crystallization, to purify the extracted compound (He et al., 2017; Radzali et al., 2014). Although promising, the high cost of commercial enzymes and longer processing time pose economic and scalability challenges (Zuluaga et al., 2018).

3.4. Microwave-assisted extraction (MAE)

Microwave-Assisted Extraction (MAE) increases the recovery of bioactive compounds, like astaxanthin, through microwave radiation which provides rapid heating of the solvent and biological matrix, rupturing the cell walls and allowing for a fast release of the intracellular compounds. The method dramatically reduces extraction time and increases yield compared to traditional solvent extraction. MAE can be conducted with ethanol or acetone as solvents, yielding high-quality astaxanthin with reduced energy input (Dong et al., 2014). It is particularly suitable for thermally sensitive compounds due to shorter exposure times and uniform heating. Moreover, studies have demonstrated that microwave power and exposure duration are critical factors affecting efficiency and compound stability (Zhang et al., 2014). However, the method's scalability and safety concerns due to pressurized vessels remain barriers to full industrial implementation (Sun et al., 2010; Papa et al., 2015).

3.5. Ultrasonic and green extraction technologies

Ultrasonic-assisted extraction (UAE) and other emerging green extraction methods, such as deep eutectic solvents (DES), represent the frontier in sustainable bio-extraction. In order to improve mass transfer and solvent penetration, UAE uses ultrasonic waves to create cavitation bubbles that rupture the tissues of shrimp shells. This method enhances astaxanthin yield and quality while cutting down on extraction time and energy consumption (Radzali et al., 2014; Zhang et al., 2014). When combined with ethanol or DES, UAE achieves even higher extraction efficiency with lower environmental impact. Green solvents like DES, composed of natural substances such as choline chloride and glycerol, further minimize ecological footprints and are biodegradable (Zuluaga et al., 2018). Although these methods are still under development and limited by high equipment costs, they represent a promising future for environmentally safe and efficient astaxanthin extraction technologies (Papa et al., 2015; Visioli & Artaria, 2017). Table 2 shows the different methods of astaxanthin extraction and the yield obtained.

4. METHODS OF CHARACTERIZATION

4.1. Chromatographic techniques–HPLC and TLC

The purification and measurement of astaxanthin isolated from shrimp shells are common applications for chromatographic techniques including Thin Layer Chromatography (TLC) and High-Performance Liquid Chromatography (HPLC). In the present study, HPLC equipped with a C18 column was employed for its superior separation performance and rapid detection at 474 nm, yielding precise retention times of 9.6 minutes for standard astaxanthin (Hu et al., 2019). This technique allowed accurate measurement even at microgram levels, with a high linearity (R^2=0.9995), confirming its reliability (Sun et al., 2010). Compared to C18 columns, C30 columns offered better resolution and retention for astaxanthin, though they were cost-prohibitive (Sun et al., 2017). For preliminary qualitative assessment, TLC was used as a simpler and cost-effective method. It effectively differentiated astaxanthin from co-extracted pigments on silica gel plates, using petroleum ether/ethanol as eluting solvents (He et al., 2017). The color intensity and Rf values from TLC matched standard references, facilitating easy monitoring during purification (Dong et al., 2014). Combining both HPLC and TLC ensured high purity and identification fidelity in the separation process (Zhang et al., 2014).

4.2. Spectrophotometric assays

Spectrophotometric techniques serve as essential tools

Table 2: Extraction Methods of Astaxanthin

Extraction method	Yield	Purity	Cost	Environmental safety	Reference
Solvent extraction	High (up to 85%)	Moderate	Low	Moderate	Hu et al. (2019); Dong et al. (2014)
Supercritical fluid extraction	Moderate-high	High	High	Very high	Zhang et al. (2014); Papa et al. (2015)
Enzymatic extraction	Moderate	High	Moderate	High	Dong et al. (2014); Zuluaga et al. (2018)
Microwave-assisted extraction	High	Moderate-high	Moderate	Moderate	Dong et al. (2014); Sun et al. (2010)
Ultrasonic and green extraction	High	High	Moderate-high	Very high	Radzali et al. (2014); Zuluaga et al. (2018)

for assessing both the purity and concentration of astaxanthin during the extraction and purification stages. In the referenced study, UV–Visible spectrophotometry was utilized to scan the absorption spectrum of both crude and purified astaxanthin within the range of 200–800 nm (Hu et al., 2019). The absorption peak for pure astaxanthin was observed at 474 nm, consistent with its known spectral characteristics (Zuluaga et al., 2018). The purified sample showed a significantly stronger and narrower absorption band compared to the crude extract, confirming the removal of interfering substances and validating the purification process (Papa et al., 2015). Spectrophotometric methods also helped in determining the irreversible adsorption losses of astaxanthin on silica gel during purification, which was found to be 14.05% (He et al., 2017). The absorbance values correlated well with concentration via Beer-Lambert law, supporting its quantitative use. Additionally, colorimetric comparison with standard astaxanthin solutions validated the visual assessment of sample integrity (Dong et al., 2014). These assays are advantageous due to their simplicity, low cost, and rapid output, making them ideal for routine quality control alongside chromatographic methods (Visioli & Artaria, 2017).

4.3. Structural identification–NMR and MS

Advanced instruments such as Nuclear Magnetic Resonance (NMR) and Mass Spectrometry (MS) are necessary for the full structural elucidation of astaxanthin, whilst chromatographic and spectrophotometric techniques are appropriate for quantification and preliminary analysis. Although the primary study focused on purification using silica gel and HPLC, it referenced the broader scientific context where NMR and MS are used for structural verification of purified astaxanthin (Zhang et al., 2014; Papa et al., 2015). NMR provides insights into the molecular framework, including the identification of characteristic hydroxyl and keto groups at the 3 and 4 positions on each terminal ring of the astaxanthin molecule (Visioli and Artaria, 2017). The presence of 11 conjugated double bonds is confirmed via ^{1}H NMR and ^{13}C NMR spectra, revealing chemical shifts specific to carotenoid structures (Zuluaga et al., 2018). Complementing NMR, MS offers molecular mass data, which aids in verifying the intact mass ($C_{40}H_{52}O_4$, MW=596.84 Da) and detecting any fragmentation patterns due to degradation (Dong et al., 2014). These techniques ensure that the compound isolated is indeed astaxanthin, free from isomers or oxidation products (Sun et al., 2010). Their integration with HPLC enables full-spectrum analysis of compound purity, identity, and stability under industrial or laboratory conditions (He et al., 2017).

5. APPLICATIONS OF ASTAXANTHIN IN FOOD INDUSTRY

5.1. Emulsions

When added directly to food formulations, astaxanthin is extremely sensitive to light, heat, oxygen, and humidity. Additionally, its chemical qualities are unstable and easily deactivated by changes in external conditions, which significantly reduces its functional effects and economic value. For astaxanthin, an emulsion administration method has been progressively used to increase its bio-utilization efficiency. Because astaxanthin is well soluble in oil and can quickly form a mixed micelle structure, loading efficiency, stability, and bioavailability can all be significantly increased using the emulsion production method. Specifically, Bassijeh et al. (2020) focused on the potential of highly concentrated astaxanthin lipid components extracted from shrimp waste. They tested the effectiveness of a model beverage system in a real food setting by adding astaxanthin lipid phases with concentrations ranging from 42.9 to 49.8 g 100 g^{-1}. The results of a 15-day accelerated stability test demonstrated that astaxanthin's stability when emulsified was greatly enhanced, particularly when the whey protein isolate to polyglycerol ester ratio was 1:4, which markedly slowed down the astaxanthin's rate of degradation. Recently,

astaxanthin has been successfully added to beverages Cheng et al. (2023), yogurt (Sun et al., 2022) and other emulsion-type foods (Saechio et al., 2023). In addition, pickering emulsions have also been used to effectively stabilize astaxanthin (Yang et al., 2022; Zhang et al., 2023).

5.2. Microcapsules

Through microencapsulation technology, astaxanthin can be embedded in specific wall materials to form a tiny capsule structure that provides an ideal protection environment for astaxanthin (Pan-utai et al., 2021). For example, Huang et al. (2023) investigated the application of microcapsule technology in astaxanthin protection and release optimization. To create an astaxanthin microcapsule system with high fluidity and encapsulation efficiency, sodium caseinate and κ-carrageenan were used as wall materials. Wet granulation and compression were then used to successfully incorporate these astaxanthin microcapsules into effervescent tablets. The findings of the trial demonstrated that the new microcapsule formulation exhibited exceptional solubility and quick drug release, with the astaxanthin dissolution rate in effervescent tablets containing astaxanthin microcapsules reaching 90% in under two hours. More significantly, astaxanthin's initial antioxidant activity was unaffected by the entire manufacturing procedure or the choice of excipients.

5.3. Film

Thin film, a popular kind of protection, is crucial for stabilizing active substances like astaxanthin that are readily oxidizable. The encapsulation and protection of astaxanthin utilizing thin film technology can successfully increase its stability under a variety of environmental circumstances and ensure that its bioactivity is not adversely compromised, especially in the food science, cosmetics, and pharmaceutical industries. Xu et al. (2020) used an improved casting technique in 2020 to create a novel bio-functional composite membrane. They successfully created a composite film with dual antibacterial and antioxidant capabilities by combining astaxanthin, a by-product of prawns, with gelatin and chitosan, two biodegradable substances with superior film-forming qualities. With an almost 100% inhibition rate, the bio-functional composite membrane demonstrated an impressive efficacy against the putrefaction bacteria linked to *Penaeus alba*. Furthermore, when the composite film was used to package foods that oxidize readily, like maize oil, it demonstrated exceptional antioxidant qualities that can prolong the oxidation of fats and preserve the food's freshness and nutritional content. Moreover, there is growing interest in using edible coating and film technologies to extend the shelf life of fruits (Pavinatto et al., 2020), as they can significantly improve the efficiency of the entire packaging system when attached to the food surface (Jafarzadeh et al., 2021a). Their mechanism of action is reflected at several levels, such as effectively reducing the natural water loss of fruits during storage, reducing respiration and its accompanying oxidation reaction rate, and preventing or reducing various physiological changes that may lead to the decline in fruit quality (Jafarzadeh et al., 2021b). For instance, Mussagy et al. (2023) added astaxanthin to the film, which was effective in preventing strawberries from being oxidized despite the fact that astaxanthin reduces the transparency of the film, thus improving the antioxidant capacity of the film.

5.4. Whole grain foods

Astaxanthin added to the diet can help control blood sugar fluctuations, which has potential benefits for people with diabetes or those concerned with blood sugar management (Hossain et al., 2017). Therefore, the synergistic control of blood glucose with astaxanthin in whole grain foods, represented by whole wheat crackers, has been investigated (Garzon et al., 2020). Hossain et al. (2017) used three whole grain flours, wheat, barley and oats, to make cookies in 2017 and introduced astaxanthin into the formulation. Astaxanthin cookies demonstrated a considerably decreased glucose release rate in in vitro tests that mimicked the internal digestive environment of the human body. Additionally, the cookies' overall phenolic content and antioxidant efficacy were significantly increased. In an experiment conducted in 2020, Yousef et al. (2020) achieved the same outcome. Furthermore, they discovered that astaxanthin greatly enhanced the antioxidant qualities of cookies when mixed with whole wheat flour. Consequently, the addition of astaxanthin with whole wheat flour may have a synergistic impact.

5.5. Seafood

Aquatic products are currently preserved using astaxanthin in a variety of ways. Fish freshness is significantly impacted by this. In a 2020 investigation, El-bialy and associates specifically soaked fish samples in astaxanthin solutions that contained a green solvent extract after subjecting them to radiation treatment. They assessed astaxanthin's antioxidant potential using DPPH free radical scavenging tests. The researchers observed throughout the experiment that the lipid oxidation in the sample was considerably decreased when astaxanthin was introduced to minced tilapia fish and complemented with an appropriate dosage of gamma radiation. Then, in 2022, Zhu et al. (2022) investigated the effect of shrimp by-product astaxanthin extract (AE) on the quality and sensory properties of ready-to-eat surimi shrimp products (RC-SSP) during frozen storage at−18°C. The reduced thio-barbituric acid reactive substance and carbonyl values and increased sulfhydryl and salt-soluble protein quantities in RC-SSP suggest that the addition of AE

could successfully delay lipid and protein oxidation. These experimental findings suggest that astaxanthin has a major impact on the oxidation parameters of fresh seafood and can be utilized as a valuable natural food enhancer. Information regarding the use of different forms of astaxanthin in various food categories is provided in Table 3.

6. APPLICATIONS OF ASTAXANTHIN IN COSMETICS INDUSTRY

6.1. Liposomes

Liposomes are colloidal and vesicular delivery systems, composed of at least one bilayer amphiphilic lipid membrane and a hydrophilic core (Costa and Santos, 2017). There are numerous benefits to these systems. They can contain amphiphilic, hydrophilic, or hydrophobic substances. They also have slow-release qualities and targeted potential. Their resemblance to cell membranes accounts for their biocompatibility. They can also prolong the shelf life of products, are biodegradable, have low toxicity, and are simple to prepare (Tan et al., 2014). The use of liposomes as a drug delivery system allows partially overcoming the problems related to the poor stability, water-solubility, and bioavailability of AST (Pan et al., 2018). Because liposomes may be absorbed via endocytosis, especially by reticuloendothelial system cells, and release encapsulated medicines, they are a great choice for drug delivery in skin therapy applications. Additionally, they can exchange lipids with the cell membrane or fuse with cells (Schäfer-Korting et al., 1989). The creation of effective liposomal formulations is hampered by the decreased vesicle flexibility of liposomes in aqueous solutions. Furthermore, the stratum corneum must be reached for topical treatment to be absorbed by the skin, which makes it difficult to develop novel substitutes that would improve efficiency.

Table 3: Utilisation of various forms of astaxanthin in different types of foods

Type of food product	Form of astaxanthin	Concentration	Benefits	Reference
Salmonid and crustacean feed	Synthetic and natural (Algae, Yeast, Crustacean waste)	50–100 mg kg^{-1} feed (varies by species)	Enhances pigmentation, boosts immunity, aids reproduction, reduces oxidative stress	Higuera-Ciapara et al., 2006
Broiler chicken and egg yolk	Natural (Haematococcus pluvialis)	1.5–2% in algal biomass; 0.1–0.4% in feed	Improves yolk color, fertility, meat pigmentation, reduces salmonella	Akiba et al., 2001
Human dietary supplements	Encapsulated natural extracts (Algae or Yeast)	3.85–19.25 mg day^{-1}	Powerful antioxidant, immune booster, UV protection, cardiovascular and anti-cancer support	Bennedsen et al., 1999
Nutraceutical beverages	Extracts (natural)	Not specified	Reduces LDL oxidation, supports cardiovascular health	Iwamoto et al., 2000

6.2. Emulsions

Microemulsions are thermodynamically stable transparent delivery systems formed by droplets dispersed on a liquid phase, which are capable of forming spontaneously and have low interfacial energy and size, ranging from about 10 nm to 100 nm (Nastiti et al., 2017). Zhou et al. (2015) developed AST oil/water microemulsions and checked the effect of different antioxidants either alone or in combination as additives to improve their stability. A great substitute for better emulsions for AST distribution, the microemulsion made with AST alone, Tween 80 as an emulsifier, and ethanol in buffer solution delayed AST degradation. Nanoemulsions are thermodynamically and kinetically stable systems with nanoscale droplet sizes (100 nm to 400 nm) (Callender et al., 2017), uniform size distribution, and physicochemical and biological properties different from those of other emulsions (>500 nm).

The small droplet size, the scarce probability of coalescence and flocculation, effective delivery of active ingredients, rapid penetration, long-lasting effects, and uniform deposition onto the skin make them suited for use in the personal care, cosmetic, and health science fields (Kim et al., 2012).

6.3. Particulate systems

Nano/microspheres and nano/microcapsules are examples of particulate systems, which are delivery methods. While nano/microspheres are active ingredient dispersions in polymeric matrices, nano/microcapsules are reservoirs that contain separate domains of core and wall material. These formulations create a compatible environment for susceptible molecules and protect them from light, oxygen, pH, heat, enzymatic degradation and other external factors that can affect their stability (Nesterenko et al., 2013). Microencapsulation technologies are widely used in cosmetic products to increase stability, protect against degradation, promote safe administration and allow controlled and

targeted release (Casanova et al., 2016). There is a lot of surface area available to create active substances because particle sizes range from about one micron to a few millimeters. Nanoparticles involve particulate systems in the nano range, providing a larger surface area that is available for adsorption and desorption sites, chemical reactions, light scattering, etc. (Casanova et al., 2016).

6.4. Cyclodextrin

Cyclodextrins (CDs) are a family of cyclic polysaccharides used to form inclusion complexes with a wide variety of substances used in pharmaceuticals, drug delivery systems, cosmetics, and in the food and chemical industries (Carneiro et al., 2019). Their molecular structure is composed of a cavity size, which is determined by the number of glucose units, where the space inside the cyclodextrin molecules allows the formation of inclusion complexes with poorly soluble compounds (Carneiro et al., 2019). The inclusion of guest molecules into CDs can change their physical and chemical properties, as well as increasing their water solubility and stability (Chen et al., 2007). The CDs are an excellent alternative for the inclusion of a variety of natural compounds, such as oils (Magalhães et al., 2020) and other compounds. When used in proportions from 0 to 60% (w/v), a sulfobutyl ether cyclodextrin was shown to complex with crystalline AST. At 60%, AST water solubility has grown by more than 50 times. Using a pre-solubilization process could boost it by 71 times compared to the parent compound in water. Table 4 provides details on the use of astaxanthin in different cosmetics.

7. STORAGE AND STABILITY OF ASTAXANTHIN

The stability of astaxanthin was evaluated under different storage and carrier conditions. *Haematococcus*-derived astaxanthin's stability in a range of edible oils was established (Ranga Rao et al., 2007). Astaxanthin was stable at 70–90 °C in ricebran, gingelly and palm oils with 84%–90% of retention of astaxanthin content which can be used in food, pharmaceutical and nutraceutical applications, whereas astaxanthin content was reduced at 120 and 150 °C (Ranga Rao et al., 2007). Astaxanthin nanodispersions' stability was evaluated in skimmed milk, orange juice and deionized water was used as a control (Anarjan and Tan, 2013). It was discovered that astaxanthin degradation in skim milk was noticeably greater than in orange juice. In another study, stability of astaxanthin biomass was examined after drying and storage at various conditions for nine weeks (Raposo et al., 2012). The findings demonstrated that after nine weeks of storage, astaxanthin degradation in biomass dried at 180/110°C and kept at -21°C under nitrogen was as low as 10%. The stability of astaxanthin from *Phaffia rhodozyma* was studied and it was found that stability was high at pH 4.0 and at a lower temperature (Villalobos-Castillejos et al., 2013). The storage stability of astaxanthin was enhanced at 4°C and 25°C in a complex mixture of hydroxyproply-β-cyclodextrin and water (Yuan et al., 2013). Astaxanthin stability was investigated using microencapsulation with chitosan, polymeric nanospheres, emulsions and β-cyclodextrin as reported by various authors (Tachaprutinun et al., 2009).

8. SAFETY AND DOSE OF ASTAXANTHIN

When taken with food, astaxanthin is safe and has no negative effects. After rats are fed astaxanthin, it is lipid soluble, builds up in animal tissues, and has no harmful effects (Ranga Rao et al., 2013a; Ranga Rao et al., 2013b). Animals with excessive astaxanthin intake have skin that is yellow to reddish in color. The addition of astaxanthin to fish feed causes the skin of the fish to turn crimson.Antioxidant enzymes such as superoxide dismutase, catalase, and glutathione peroxidase levels significantly increased in rats after oral dosage of astaxanthin (Ranga Rao et al., 2013a; Ranga Rao et al., 2013b). A study reported that blood pressure (bp) was reduced in stroke prone rats and in hypertensive rats by feeding 50 mg kg^{-1} astaxanthin for five weeks and 14 days, respectively (Hussein et al., 2005). Astaxanthin was also shown significant protection

Table 4: utilisation of astaxanthin in various cosmetics

Cosmetic type	Concentration/Form	Benefits	References
Anti-aging creams	Liposomal AST (0.01–0.1%)	Reduces wrinkles, improves elasticity	Imokawa (2019)
Sunscreens	AST in nanoemulsions/liposomes	UV protection, photoaging prevention	Hama et al. (2012)
Moisturizers	Nanoemulsions with carboxymethyl chitosan	Enhanced hydration, skin permeability	Hong et al. (2021)
Wound healing films	Collagen-AST films	Promotes healing, antioxidant	Veeruraj et al. (2019)
Daily skincare	Cyclodextrin complexes	Enhanced solubility/stability	Zuluaga et al. (2017)
Serums	Nanostructured lipid carriers (NLCs)	High antioxidant power	Rodriguez-Ruiz et al. (2019)

against naproxen induced gastric, antral ulcer and inhibited lipid peroxidation levels in gastric mucosa (Augusti et al., 2012; Kim et al., 2005). Astaxanthin accumulation in eyes was observed when astaxanthin was fed to rats (Petri et al., 2007). Astaxanthin extracted from *Paracoccus carotinifaciens* showed potential antioxidant and also anti-ulcer properties in murine models as reported by Murata et al. (2012). Astaxanthin bioavailability was increased with supplement of lipid-based formulations (Odeberg et al., 2003). Supratherapeutic concentrations of astaxanthin had no adverse effects on platelet, coagulation and fibrinolytic function (Serebruany et al., 2010). Astaxanthin ingestion in humans and animals has not yet been linked to any serious adverse consequences, according to research. These findings bolster astaxanthin's safety for upcoming clinical research.

It is advised to take astaxanthin with omega-3-rich seed oils like those found in walnuts, almonds, chia, flaxseed, salmon, and nutella. The market offers snacks, soft gels, capsules, and creams that contain astaxanthin (4–8 mg). 2–4 mg of astaxanthin per day is the recommended dosage.A study reported that no adverse effects were found with the administration of astaxanthin (6 mg day^{-1}) in adult human subjects (Spiller and Dewell, 2003). Astaxanthin effects on human blood rheology were investigated in adult men subjects with a single-blind method after administration of astaxanthin at 6 mg day^{-1} for 10 days (Miyawaki et al., 2008).

9. CONCLUSION

Reviewing recent advances, efficient methods for extracting and purifying astaxanthin from shrimp and crab shells-traditionally discarded as waste-are now transforming seafood byproducts into valuable resources. Using ethanol and silica gel chromatography, yields of up to 85.1% have been achieved, with fresh shrimp shells proving especially rich. Optimized, green extraction not only boosts purity but also underscores sustainability, paving the way for high-value applications in food, pharmaceutical, and cosmetic industries while reducing environmental impact.

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