Review

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Algae-Based Protective Coatings for Sustainable Infrastructure: A Novel Framework Linking Material Chemistry, Techno-Economics, and Environmental Functionality

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Algae-Based Protective Coatings for Sustainable Infrastructure: A Novel Framework Linking Material Chemistry, Techno-Economics, and Environmental Functionality

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Abstract

Conventional petroleum-based protective coatings release high levels of volatile organic compounds (VOCs) and contribute to resource depletion, urging the development of environmentally responsible alternatives. Among bio-based candidates, microalgae have recently gained attention for their ability to produce diverse biopolymers and pigments with intrinsic protective functionalities. However, existing literature has focused mainly on algal biofuels and general biopolymers, leaving a major gap in understanding their application as sustainable coating materials. This review addresses that gap by providing the first integrated assessment of algae-based protective coatings, linking biochemical composition, functional performance, techno-economic feasibility, and industrial scalability within a circular economy context. The review synthesizes recent findings on key algal components, including alginate, extracellular polymeric substances (EPS), and phycocyanin. It evaluates their roles in adhesion strength, UV stability, corrosion resistance, and antifouling activity. Reported performance metrics include adhesion strengths of 2.5–3.8 MPa, UV retention above 85% after 2000 hours, and corrosion rate reductions of up to 40% compared with polyurethane systems. Furthermore, this study introduces the concept of carbon-negative, multifunctional coatings that simultaneously protect infrastructure and mitigate environmental impacts through CO_2 sequestration and pollutant degradation. Challenges involving biomass variability, processing costs (>USD 500/ton), and regulatory barriers are critically discussed, with proposed solutions through hybrid cultivation and biorefinery integration. By bridging materials science, environmental engineering, and sustainability frameworks, this review establishes a foundation for transforming algae-based coatings from laboratory research to scalable, industrially viable technologies.

Keywords: algae-based coatings; biodegradable materials; carbon sequestration; circular economy; environmental sustainability; volatile organic compounds (VOCs); protective coatings; sustainable infrastructure

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1. Introduction

The global construction sector continues to expand rapidly due to accelerating urbanization and economic growth. While this development supports housing and infrastructure demands, it also contributes heavily to environmental degradation. The construction industry accounts for nearly one-third of global primary energy consumption and greenhouse gas emissions, making it a key driver of climate change and resource depletion (Wang et al., 2018). For instance, China alone is projected

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to experience urban migration of more than 300 million people by 2050, increasing the need for sustainable infrastructure solutions (Liu et al., 2019). Extending the lifespan of construction materials through effective surface protection has therefore become an important strategy for reducing environmental impacts.

Conventional protective coatings are mainly derived from petroleum-based polymers and solvents. These coatings pose serious ecological and health risks due to their high emissions of volatile organic compounds (VOCs). In 2019, industrial coatings emitted over 28.8 Tg of VOCs, contributing to atmospheric pollution and increasing the risks of respiratory diseases such as asthma, chronic obstructive pulmonary disease, and cancer (Wang et al., 2023; Maung et al., 2022). Many of these systems contain synthetic polymers such as diglycidyl ether of bisphenol A (DGEBA), which are non-biodegradable and have a high carbon footprint throughout their life cycle (Kumar et al., 2018).

To overcome these drawbacks, bio-based coatings derived from natural oils such as linseed and soybean have been explored. However, these alternatives often lack the mechanical durability, chemical resistance, and scalability of petroleum-based systems due to lower toughness and higher production costs (Calovi et al., 2024). Consequently, attention has shifted toward microalgae as a renewable and versatile source of coating materials.

Algae-based coatings offer dual benefits: they provide physical protection to surfaces while also contributing to atmospheric CO_2 reduction through photosynthetic carbon fixation. Microalgae produce a variety of functional compounds such as pigments, extracellular polymeric substances (EPS), and biopolymers that enhance ultraviolet (UV) resistance, mechanical strength, antimicrobial activity, and corrosion protection (Prathiksha et al., 2024; Natarajan et al., 2018; Zhao et al., 2020; Tang et al., 2021). Recent innovations include latex–algae biocomposites, which combine algae-derived biopolymers with waterborne latex matrices to reduce petrochemical dependence and improve coating functionality (Caldwell et al., 2021).

Despite these advances, several barriers limit the widespread use of algae-based coatings. Variations in substrate adhesion, surface roughness, and chemical composition can reduce coating integrity (Tang et al., 2021), while mechanical resistance under industrial conditions often remains below conventional standards (Tong et al., 2023). Additionally, high biomass processing costs, inefficient extraction methods, and lack of production standardization hinder scalability (Martins et al., 2023).

Most studies so far have examined individual algal components or small-scale laboratory formulations, but their integration into industrially viable coating systems remains underexplored. Few have evaluated life cycle performance, cost competitiveness, or environmental benefits under real-world conditions. For instance, while algal pigments show strong UV-blocking properties, direct comparisons with petroleum-based coatings in field environments are limited. Moreover, the overall carbon offset potential of algae-based coatings across their production and application phases has not been well quantified.

This review addresses these gaps by providing the first comprehensive synthesis of research on algae-based protective coatings, connecting biochemical composition, formulation strategies, mechanical performance, and techno-economic feasibility. It also introduces the emerging concept of carbon-negative, multifunctional coating materials that not only protect surfaces but also contribute to CO_2 sequestration and pollutant mitigation. By analyzing recent technological advances and industrial challenges, this study identifies future directions for improving mechanical robustness, reducing production costs, and enabling large-scale implementation. The discussion is framed within the context of the United Nations Sustainable Development Goals, particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), highlighting the potential of algae-based coatings to drive the transition toward a low-emission, resource-efficient infrastructure future.

2. Fundamentals of Algae-Based Coatings

2.1. Chemistry & Functional Compounds

Algae-derived compounds include a wide range of bioactive molecules that provide distinct functional advantages for protective coatings. These naturally occurring substances, such as pigments, extracellular polymeric substances (EPS), polysaccharides, and proteins, offer chemical versatility, environmental safety, and multifunctional performance. Unlike petroleum-based additives, algae-derived materials are biodegradable, non-toxic, and consistent with green chemistry principles. These features make them suitable for long-term surface protection under harsh environmental conditions.

Pigments extracted from microalgae act not only as colorants but also as effective UV stabilizers and antioxidants. Compounds such as phycocyanin, chlorophyll derivatives, astaxanthin, and fucoxanthin have shown strong potential to enhance coating resistance against photodegradation. Fucoxanthin, owing to its allenic and conjugated carbonyl structures, exhibits high UV absorption and oxidative stability, which can extend a coating's lifespan under continuous sunlight exposure (S. M. Kim et al., 2012; Lourenço-Lopes et al., 2020). Similarly, astaxanthin from *Haematococcus pluvialis* demonstrates excellent photoprotective and antioxidant capacity, helping to preserve the mechanical integrity of coatings exposed to environmental stress (Reyes et al., 2014; Pappou et al., 2022). Besides pigments, microalgae synthesize other functional compounds such as mycosporine-like amino acids (MAAs) and polyphenols. These molecules absorb high-energy ultraviolet radiation and neutralize reactive oxygen species, improving UV resistance and limiting oxidative degradation (Bedoux et al., 2020; Pappou et al., 2022). Unlike petroleum-derived UV stabilizers, these compounds are biodegradable and pose minimal ecological risk, making them highly suitable for sustainable coating systems.

EPS secreted by many microalgal species plays an important role in enhancing structural integrity, water resistance, and adhesion of coatings. Composed of polysaccharides, proteins, lipids, and nucleic acids, EPS form cohesive and cross-linked matrices that improve mechanical durability (Saluri et al., 2019; Ferreira et al., 2019). For instance, β-glucans from *Chlorella vulgaris* promote strong surface adhesion, while alginate from brown seaweed such as Sargassum muticum provides excellent film-forming ability and tensile strength (Sirmerova et al., 2013; Saji et al., 2022). These properties enhance flexibility and impact resistance in coating films.

Algal polysaccharides such as alginate, carrageenan, and *ulvan* further contribute to coating performance by improving elasticity, moisture retention, and substrate binding. These polymers naturally form stable gel networks through ionic cross-linking with divalent cations such as calcium and magnesium, which enhances toughness without requiring synthetic additives (Jan & Kazik, 2017; Flórez-Fernández et al., 2019). In contrast to conventional cross-linking agents that release harmful by-products, algae-based cross-linkers provide a safer and more environmentally friendly option. Marine algae also produce unique bioactive compounds with natural antifouling properties. Extracts containing thymol, eugenol, and guaiacol display strong antimicrobial and anti-biofilm activities, reducing fouling risks in marine infrastructure applications (Gómez de Saravia et al., 2018). Thymol, in particular, has achieved complete inhibition of biofilm formation under laboratory conditions, positioning it as a promising substitute for synthetic biocides that often create ecological hazards.

Microalgal proteins, especially those from Spirulina platensis, have also been studied for their ability to improve mechanical and oxidative stability in coating formulations. Phycocyanin, a major protein pigment in Spirulina, provides natural UV-absorbing properties and reinforces the structural matrix of coatings, contributing to overall photostability (Demarco et al., 2022; Calovi & Rossi, 2023; Thevarajah et al., 2022). These protein-based materials are renewable, non-toxic, and biodegradable, further strengthening the sustainability profile of algae-based coatings. Despite these advantages, large-scale adoption of algae-derived coating materials remains limited. The chemical composition of algal biomass varies widely with species and cultivation conditions, leading to performance inconsistencies. To overcome this, process standardization and post-treatment methods such as sulfation, enzymatic hydrolysis, and nanocomposite blending are applied to improve adhesion, mechanical strength, and long-term stability (Pocha et al., 2022; Thanh et al., 2016).

Recent technological progress has enhanced both the extraction efficiency and the economic feasibility of algae-derived compounds. Techniques like ultrasound-assisted extraction (UAE) and supercritical CO_2 extraction have achieved high yields, with UAE recovering up to 85 % of polysaccharides and 75–80 % of proteins, depending on species and process conditions (Carreira-Casais et al., 2021; Sousa et al., 2023). The use of ionic-liquid extraction systems has further reduced hazardous solvent consumption, supporting cleaner production pathways (Rodrigues et al., 2018). By integrating natural cross-linking mechanisms, bioactive pigments, and low-impact processing technologies, algae-based protective coatings can achieve mechanical durability, UV stability, and antifouling performance comparable to or exceeding that of petroleum-based counterparts. Continued advancements in material optimization and process engineering are essential to expand their industrial-scale potential. A summary of major algae-derived chemical components, their source species, extraction methods, cultivation systems, yields, and functional roles in coating applications is presented in Table 1.

2.2. Coating Formulation & Application

The development of algae-based protective coatings depends on the careful formulation of bio-based binders, proteins, pigments, and antioxidants to achieve durability, environmental resistance, and multifunctional performance. These formulations are designed to overcome the limitations of petroleum-derived coatings by incorporating biologically sourced materials with tunable chemical and mechanical properties. Their success relies on appropriate raw material selection, efficient extraction techniques, and optimized application methods that meet industrial standards. As summarized in Table 1, several algae-derived compounds, such as fucoidan, phycobiliproteins, and carrageenans, have demonstrated strong performance in ultraviolet (UV) protection, antioxidant activity, and corrosion resistance under saline and high-temperature conditions.

Polysaccharides, including alginate, carrageenan, and β-1,3-glucan, act as key structural elements in coating matrices because of their excellent film-forming ability, flexibility, and adhesion. Alginate obtained from Sargassum muticum shows high viscosity and strong adhesion, attributed to its β-D-mannuronic acid and α-L-guluronic acid units that form stable cross-linked networks (Dobrinčić et al., 2020). Carrageenan improves coating uniformity and adhesion across varied environments, making it an important component of bio-based systems (Gomez et al., 2009). The performance of these polysaccharides is influenced by algal species and extraction protocol, highlighting the need for standardized industrial processes.

Mechanical durability can be enhanced through protein-based cross-linkers derived from microalgae. Proteins from Spirulina platensis and Chlorella vulgaris form covalent bonds with polysaccharide matrices, producing reinforced coating structures. These protein polysaccharide composites exhibit tensile strengths up to 19.1 MPa and glass-transition temperatures near 122 °C, values comparable to certain synthetic resins (Kartik et al., 2021; Noreen et al., 2024). Because protein content varies with cultivation conditions, strict biomass quality control is essential to ensure consistent formulation.

Oxidative stability in algae-based coatings is supported by natural antioxidants from pigment-rich microalgae. Astaxanthin, extracted from Haematococcus pluvialis, is a potent antioxidant that can constitute up to 4 % of the biomass dry weight (B. Kim et al., 2022). It effectively protects coatings from oxidative degradation, though it is sensitive to heat and oxygen. Optimized extraction methods, such as high-pressure homogenization and ultrasound-assisted processing, achieve efficiencies above 80 % (B. Kim et al., 2022). Additional approaches, including bead milling and ethyl-acetate fractionation, further improve antioxidant recovery and stability, extending coating lifespan.

Environmental stress during cultivation can naturally elevate antioxidant production in microalgae, improving functional stability. High light intensity and nutrient limitation stimulate greater synthesis of superoxide dismutase (SOD) and catalase, reducing oxidative stress and

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enhancing coating longevity (Gauthier et al., 2020). Similarly, Euglena gracilis grown under stress accumulates higher levels of carotenoids and phenolics, which correlate with stronger UV protection and oxidative resistance (Wang et al., 2023; Gomez et al., 2009).

Algae-derived pigments improve both aesthetics and protection. Fucoxanthin extracted from Padina tetrastromatica via ultrasound-assisted methods reaches concentrations up to 750 $\mu g\ g^{-1}$ and provides superior UV shielding and antifouling effects, especially in marine coatings (Lourenço-Lopes et al., 2020). Chlorophyll derivatives from green algae enhance photostability by reducing color fading and structural deterioration under long-term exposure (Dobrinčić et al., 2020). Replacing synthetic stabilizers with these natural pigments reduces environmental impact and improves sustainability.

Bioactive compounds such as phenolics and polysaccharides also strengthen environmental resistance. Phenolic extracts from Euglena gracilis exhibit strong antioxidant activity and enhance the mechanical properties of carrageenan- and ulvan-based coatings (Wang et al., 2023; Dobrinčić et al., 2020). The synergy among these bioactive ingredients yields coating systems that are both durable and adaptable to diverse environments.

Applying algae-based coatings requires precise rheological control to ensure even film thickness and effective substrate adhesion. Spraying, dipping, and brushing remain applicable for substrates such as concrete, steel, and wood. Advances in rheological adjustment have improved viscosity regulation in *Chlorella*-based formulations, minimizing particle aggregation and enhancing dispersion (Shin et al., 2024). Because algae-based coatings often exhibit higher viscosity than petroleum systems, industrial spray techniques may require modification for consistent large-scale use.

Performance evaluations confirm the long-term stability of algae-based coatings under demanding conditions. Systems containing alginate and carrageenan display superior corrosion resistance and thermal stability, maintaining integrity after extended exposure (Gomez et al., 2009). In accelerated weathering tests, coatings on calcareous substrates showed minimal porosity and color degradation after two years of outdoor exposure (Eyssautier-Chuine et al., 2023). These findings reinforce the potential of algae-based coatings for infrastructure applications. Nevertheless, scalability, biomass standardization, and cost reduction remain critical for wider industrial adoption.

2.3. Advantages Over Conventional Coatings

The environmental and technical limitations of petroleum-based protective coatings, including high VOC emissions, toxicity, and dependence on non-renewable feedstocks, have intensified the search for sustainable alternatives. Algae-based coatings offer a promising solution by combining strong mechanical durability, multifunctional protection, and environmental benefits that surpass conventional systems.

Mechanical strength is a major factor in long-term coating performance. Functional groups such as hydroxyl, carboxylate, and sulfate enable strong adhesion through hydrogen bonding and covalent interactions (Cheah & Chan, 2021; Flórez-Fernández et al., 2019). Polysaccharides from Chlorella vulgaris demonstrate interfacial bonding comparable to conventional epoxy resins, reinforcing adhesion capability in algae-derived formulations.

Impact resistance, essential for infrastructure applications, is enhanced by naturally cross-linked polymeric networks. Exopolysaccharides from Chlorella vulgaris, rich in glucuronic acid and rhamnose, impart elasticity and toughness that dissipate mechanical stress (Mari et al., 2024; Xiao & Zheng, 2016). Unlike epoxy coatings that rely on synthetic fillers, algae-based systems achieve toughness through their intrinsic molecular architecture.

Algae-based coatings also provide superior resistance to environmental degradation. Under marine exposure, corrosion rates as low as 0.02 mm $year^{-1}$, around 40 % lower than polyurethane coatings have been reported (C. K. Patil et al., 2019). This improvement is attributed to biomineralization, where in situ calcium-carbonate deposition seals microcracks and prolongs service life. Alginate-based coatings additionally exhibit strong flame-retardant behavior, with a limiting-oxygen index of about 48 %, far exceeding that of viscose fibers (~20 %) (Brannum et al., 2019).

A distinctive feature of algae-based coatings is their environmental functionality. During cultivation, microalgae fix atmospheric CO_2 through photosynthesis at average rates of 1.3 kg CO_2 per kg biomass, potentially yielding up to 280 tons of biomass ha^{-1} $year^{-1}$ (Sarwer et al., 2022). When incorporated into hydrogel-based coatings, this biomass contributes to continuous carbon offset during product use. Life-cycle assessments indicate that such systems can achieve net-negative carbon emissions, directly supporting Sustainable Development Goal 13 (Climate Action).

Natural photoprotective compounds such as MAAs and polyphenols further enhance sustainability. These molecules absorb harmful UV radiation and neutralize free radicals, preventing polymer photodegradation (Bedoux et al., 2020; Pappou et al., 2022). MAAs like shinorine and porphyra-334 show high extinction coefficients across UV-A and UV-B spectra, providing lasting protection without the ecological drawbacks of synthetic stabilizers (Flórez-Fernández et al., 2019).

EPS produced by many microalgae acts as a structural enhancer within coatings. Their polysaccharide fractions form hydrophobic matrices that limit water permeability and moisture-induced degradation (Saluri et al., 2019; Ferreira et al., 2019). β-glucans from Chlorella vulgaris improve substrate adhesion, while alginate from Sargassum muticum contributes tensile strength and flexibility. Because conventional solvent-based extraction is energy-intensive with low yields, new green processing technologies are being explored to increase EPS availability.

High-molecular-weight polysaccharides such as alginate, carrageenan, and ulvan create gels that provide mechanical resilience and film-forming capability. These polymers cross-link naturally with divalent cations such as calcium, generating stable matrices that enhance adhesion and durability (Jan & Kazik, 2017; Flórez-Fernández et al., 2019). Sulfated polysaccharides also display antimicrobial properties, reducing biofilm formation and microbially induced corrosion (Sousa et al., 2023).

Proteins from *Spirulina platensis* contribute to coating longevity through UV absorption and antioxidant activity. Phycocyanin strengthens the polymer matrix and extends service life (Demarco et al., 2022; Calovi & Rossi, 2023; Thevarajah et al., 2022). These renewable proteins are fully biodegradable, offering sustainable replacements for synthetic additives.

Marine algae generate natural antifouling agents, including thymol, eugenol, and guaiacol, which effectively prevent phototrophic biofilm growth (Gómez de Saravia et al., 2018). Thymol achieved complete inhibition in laboratory trials, underscoring its potential as a safe substitute for synthetic biocides in marine and underwater infrastructure.

Although algae-based coatings display remarkable properties, variability in chemical composition remains a challenge. Species differences, cultivation conditions, and harvesting techniques influence active-compound content. To enhance formulation reliability, modification strategies such as sulfation, enzymatic hydrolysis, and polymer blending are applied to improve adhesion, thermal stability, and mechanical strength (Pocha et al., 2022; Thanh et al., 2016).

Emerging green extraction technologies are addressing these issues. Ultrasound-assisted extraction achieves yields up to 85 % for polysaccharides and 80 % for proteins, depending on algal species and conditions (Carreira-Casais et al., 2021; Sousa et al., 2023). The adoption of ionic-liquid solvents has further reduced toxic-solvent use, advancing safer pigment and biopolymer recovery (Rodrigues et al., 2018).

Overall, these advances demonstrate growing industrial feasibility. Continued progress in formulation chemistry, cross-linking design, and rheological optimization will be vital for scaling production. With further refinement, algae-based coatings could serve as robust, high-performance, and carbon-negative alternatives to petroleum-derived systems, bridging materials science and environmental sustainability within the emerging circular bioeconomy.

3. Production & Scalability Challenges

3.1. Algae Cultivation Systems

The production of algae-based protective coatings involves a multi-stage workflow that begins with cultivation and harvesting, followed by extraction, formulation, and application on structural materials.

3.1.1. Types of Algae Cultivation Systems

Efficient and scalable cultivation systems form the foundation of algae-based coating production. The selected cultivation method directly influences biomass yield, production cost, and overall sustainability, making it a decisive factor for industrial feasibility. Currently, three major systems are used in large-scale microalgae cultivation: open ponds, photobioreactors (PBRs), and hybrid systems that combine both approaches.

Open pond systems, including raceway and circular ponds, are the most common method for commercial algae production due to their low capital cost and operational simplicity. They rely on natural sunlight and atmospheric CO_2, minimizing energy consumption compared to closed systems (Xu et al., 2020). However, open ponds typically yield only 10–25 g m^{-2} day^{-1} of biomass and are prone to contamination from bacteria, invasive species, and predators, leading to inconsistent product quality (Wang et al., 2023). High surface exposure also increases water evaporation, requiring continuous replenishment. Seasonal variations in temperature, light, and nutrient levels further restrict year-round productivity (Li et al., 2020). Despite these limitations, open ponds remain cost-effective, operating at roughly 40–50 % lower costs than controlled PBR systems (Zhu et al., 2024).

Photobioreactors (PBRs) provide a closed environment with precise control over cultivation parameters, minimizing contamination and improving biomass quality. Typical yields range between 40–60 g m^{-2} day^{-1}, about two to three times higher than open ponds (Ahmed et al., 2021). These systems allow efficient CO_2 injection and optimized light utilization, enhancing photosynthetic performance (Reyes et al., 2014). Furthermore, PBRs support continuous, year-round cultivation by maintaining stable pH, temperature, and nutrient conditions. However, the main drawback is their high cost; capital investments can exceed USD 500,000 per hectare (Martins et al., 2023), along with substantial energy demands of approximately 1.5–2.0 kWh per kg of dry biomass (Wahlström et al., 2018). These factors currently limit their scalability for coating-grade biomass production.

Hybrid cultivation systems aim to combine the cost-efficiency of open ponds with the productivity and control of PBRs. In a two-stage hybrid model, bulk biomass is first generated in open ponds and then refined in PBRs under optimized conditions. This strategy has improved total production efficiency by up to 35 % while reducing operational costs by 40 % compared with pure PBR systems (Sarwer et al., 2022). Although hybrid approaches offer a better balance between cost and yield, further optimization is required to overcome technical and economic barriers that still restrict large-scale implementation for coating applications.

3.1.2. Key Challenges in Algae Cultivation for Coatings

Despite progress in cultivation technology, several key challenges constrain large-scale algae production for protective coating development. Biomass yield and growth rate limitations remain central obstacles, as they depend strongly on strain selection, nutrient composition, and CO_2 availability. For example, Chlorella vulgaris grows rapidly but produces relatively low biopolymer and lipid content, whereas *Haematococcus pluvialis* accumulates valuable pigments at the expense of biomass productivity (Li et al., 2020). Nutrient depletion, particularly nitrogen and phosphorus, also limits growth, highlighting the importance of optimized nutrient supplementation (Xu et al., 2020). In many systems, only 20–30 % of supplied CO_2 is converted into biomass, leading to significant inefficiencies (Wang et al., 2023).

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The cost and source of CO_2 and nutrients represent additional challenges. While high CO_2 concentrations enhance growth, direct CO_2 injection remains expensive for industrial-scale operations. Using industrial flue gas as an alternative offers cost and sustainability advantages, but impurities such as sulfur oxides and heavy metals can impair biomass quality (Martins et al., 2023). Similarly, nutrient inputs derived from commercial fertilizers increase costs, whereas wastewater-based cultivation can reduce freshwater use by 60–70 % while maintaining comparable yields (Reyes et al., 2014).

Contamination and strain stability are persistent issues, especially in open systems. Bacterial growth and invasion by competing algal species can disrupt cultures and alter biomass composition (Lam et al., 2018). Long-term cultivation also risks genetic drift, which can modify pigment and polymer productivity. To address these problems, research is focusing on strain engineering and selective breeding to create contamination-resistant, genetically stable strains suitable for coating applications (Sarwer et al., 2022).

Harvesting and dewatering remain the most expensive stages, accounting for 20–30 % of total production costs (Wahlström et al., 2018). Centrifugation, though efficient, consumes between 1.5–3.0 kWh per kg of dry biomass, making it energy-intensive (Zhu et al., 2024). Alternatives such as flocculation and sedimentation are more economical but often require chemical additives that can compromise biopolymer purity (Wang et al., 2023). Membrane filtration offers high selectivity but remains costly and difficult to scale. Ongoing research into bioflocculants and electrocoagulation aims to reduce energy consumption while maintaining high recovery efficiency (Li et al., 2020).

3.2. Biomass Processing & Extraction Techniques

Efficient processing of algal biomass is essential for the commercial feasibility of algae-based protective coatings. Extraction and purification determine compound recovery, production cost, and overall environmental performance. Various extraction methods have been developed to isolate valuable biopolymers, pigments, and proteins, each with its own advantages and scalability challenges. The choice of extraction technique must balance yield efficiency, cost, and environmental impact to ensure industrial viability. Extraction efficiency and compound stability vary widely depending on the method, as summarized in **Table 1**. Among these, ultrasound-assisted extraction (UAE) and aqueous two-phase extraction (ATPE) are frequently used for pigments and extracellular polymeric substances (EPS) due to their high yield and purity.

UAE and microwave-assisted extraction (MAE) have emerged as efficient alternatives to conventional solvent-based techniques, offering faster processing and reduced solvent use. UAE has achieved pigment yields of up to 750 $\mu g\ g^{-1}$ from *Padina tetrastromatica*, significantly improving efficiency while minimizing environmental impact (Lourenço-Lopes et al., 2020). Similarly, MAE has reported carotenoid yields of 629 $\mu g\ g^{-1}$ from *Arthrospira platensis*, surpassing traditional extraction by preserving thermosensitive compounds and reducing degradation (Esquivel-Hernández et al., 2016). Although both techniques demonstrate high efficiency, further optimization is needed for industrial-scale implementation.

Supercritical CO_2 extraction (SFE) is widely recognized for its high selectivity and purity, especially for lipophilic compounds such as astaxanthin. Recovery rates exceeding 90 % have been achieved when SFE is combined with mechanical pre-treatment (B. Kim et al., 2022). However, the method's high equipment cost and energy demand remain major barriers to commercial application. Pressurization infrastructure and energy input often outweigh its economic advantages for coating-related biopolymer recovery.

To improve sustainability, researchers have increasingly turned to **green solvents** such as ethanol–water mixtures and protic ionic liquids (PILs). These solvents achieve high extraction efficiency with minimal toxic waste, aligning with circular economy principles (Rodrigues et al., 2018). Their use provides a more sustainable and economically feasible alternative to petroleum-derived solvents.

Hybrid extraction techniques are gaining attention for maximizing compound recovery and reducing overall cost. Integrated biorefinery systems enable the sequential extraction of multiple products—such as pigments, polysaccharides, and proteins—from a single biomass batch, improving resource efficiency and minimizing waste (Wahlström et al., 2018). Pulsed electric field (PEF) extraction, when combined with optimized solvent systems, has achieved lipid recoveries of up to 96 % of theoretical maximum yields, demonstrating strong potential for large-scale use (Du et al., 2015). These integrated methods enhance economic feasibility by reducing material loss and improving process efficiency.

Despite these advancements, several **technical challenges** remain. Biomass composition varies with algal species, cultivation conditions, and harvest timing, complicating process standardization. This variability influences compound yield and product quality, requiring improved monitoring systems and strict quality control for industrial-scale production.

Economic feasibility continues to be a primary barrier. Current extraction methods can achieve yields of up to 85 % for polysaccharides and 75 % for proteins (Carreira-Casais et al., 2021; Sousa et al., 2023). However, the high energy consumption and equipment costs of advanced extraction systems limit their commercial potential. Cost reduction through process optimization and low-energy extraction remains essential to compete with petroleum-based coating materials.

Future progress should focus on **hybrid, low-energy extraction technologies** that combine high efficiency with sustainability. Advancements in solvent-free extraction, process automation, and integrated biorefineries will be critical to reduce costs and environmental impact. Incorporating green chemistry, process engineering, and life cycle optimization will be key to transitioning algae-based coatings from laboratory-scale production to commercial-scale manufacturing.

Industrial-scale adoption will depend on the development of extraction systems capable of consistently producing high-quality biopolymers, pigments, and proteins at costs competitive with conventional coating ingredients. This transition requires innovation in energy-efficient extraction and comprehensive life cycle assessments to ensure sustainable and economically viable large-scale deployment.

3.3. Challenges in Large-Scale Production and Cost Considerations

Scaling algae-based protective coatings from laboratory to industrial production presents complex technical, economic, and logistical challenges. While laboratory extractions achieve high efficiency, scale-up introduces new constraints that affect process sustainability and financial feasibility. Industrial success depends on overcoming barriers related to capital investment, energy demand, biomass variability, process integration, and regulatory compliance.

A major technical constraint is the high capital cost of cultivation and extraction infrastructure. Advanced photobioreactor–supercritical fluid extraction (PBR–SFE) systems provide high-purity product recovery but require significant investment, limiting widespread adoption (Bedoux et al., 2020). In addition, energy-intensive processes, such as freeze-drying, mechanical disruption, and centrifugation, substantially increase operational costs (Lourenço-Lopes et al., 2020). Reducing this energy footprint through non-mechanical or low-energy drying technologies is essential for improving cost efficiency.

Biomass composition variability poses another challenge, as algal polymer and pigment yields fluctuate with species, cultivation conditions, and harvesting cycles (Figueroa, 2021). This inconsistency affects coating uniformity and mechanical performance. Standardized cultivation protocols, real-time growth monitoring, and metabolic engineering strategies are needed to improve yield stability and product quality.

Integrating cultivation, extraction, and formulation introduces logistical and quality-control complexities. Each stage may expose bioactive compounds to oxidation and degradation, reducing pigment stability and functional efficacy (B. Kim et al., 2022). Streamlined workflows and inline stabilization systems, such as antioxidant buffering or controlled-atmosphere processing—are needed to preserve compound integrity throughout production.

Economic challenges remain significant. Closed photobioreactors, while offering superior contamination control, require much higher capital and maintenance costs than open systems (Li et al., 2020). Energy-intensive unit operations, particularly mechanical disruption and drying, further increase production costs (Lourenço-Lopes et al., 2020). Raw material costs also contribute to financial pressure. Although wastewater and flue gas CO_2 can provide low-cost nutrient and carbon sources, specialized media, pH adjusters, and extraction solvents still raise expenses. The transition to green solvent systems, such as ethanol–water mixtures and PILs, has demonstrated cost and environmental benefits (Rodrigues et al., 2018).

Several strategic approaches have been proposed to improve economic feasibility. Process intensification, which integrates cultivation, extraction, and formulation into a continuous workflow, has reduced energy consumption and minimized processing steps. Biofilm-based cultivation, for instance, eliminates separate harvesting and drying stages, resulting in lower energy demand (Bedoux et al., 2020). Similarly, biorefinery approaches maximize value recovery by extracting multiple products from the same biomass. Sequential recovery of pigments, polysaccharides, and proteins increases overall yield efficiency, achieving extraction rates exceeding 85 % for polysaccharides and 75 % for proteins (Wahlström et al., 2018).

Technological innovations suchas pulsed electric field (PEF) extraction further enhance recovery from wet biomass, reaching up to 96 % efficiency when combined with solvent-free processing (Du et al., 2015). Advances in photobioreactor engineering also continue to improve productivity while lowering energy input, strengthening the feasibility of large-scale production.

Beyond technical aspects, regulatory and market trends are expected to accelerate the shift toward algae-based coatings. Policies limiting VOC emissions and introducing carbon pricing mechanisms create strong incentives for bio-based alternatives. The carbon fixation capacity of microalgae, approximately 1.3 kg CO_2 per kg of biomass (Sarwer et al., 2022) adds economic value in carbon-regulated sectors. Moreover, algae-based coatings emit fewer VOCs, aligning with green building standards and sustainable product certification requirements.

Market demand for environmentally friendly coatings continues to rise, even where initial production costs remain higher. Life cycle analyses show that algae-based coatings, though more expensive at production, offer lower maintenance and longer service life compared with petroleum-based products (Gomez et al., 2009; Eyssautier-Chuine et al., 2023). Over time, their improved durability and carbon-negative profile offset higher initial expenses.

The long-term economic resilience of algae-based coatings extends beyond environmental gains. Reducing reliance on fossil-based raw materials lowers supply chain risks and mitigates petroleum price volatility. Integration within circular bioeconomy frameworks enhances resource efficiency and cost competitiveness. As technological improvements drive down production costs and regulatory incentives increase, algae-based coatings are positioned to become commercially viable, sustainable alternatives across multiple industrial sectors.

4. Multi-Functional Performance Analysis

4.1. Mechanical Properties

The mechanical performance of algae-based protective coatings determines their suitability as sustainable alternatives to synthetic systems such as polyurethane, epoxy, and siloxane coatings. These coatings derive their mechanical characteristics from biopolymer-rich compositions containing polysaccharides, proteins, and extracellular polymeric substances (EPS). These components contribute to adhesion, impact resistance, hardness, flexibility, and wear resistance. However, despite notable environmental advantages, the mechanical durability of algae-based coatings requires further improvement to meet the demanding standards of industrial applications.

Adhesion strength is a primary determinant of coating performance, affecting resistance to delamination and mechanical stress. In algae-based coatings, adhesion is mediated by functional groups such as hydroxyl, carboxylate, and sulfate, which form hydrogen bonds, van der Waals interactions, and covalent linkages with the substrate surface (Cheah & Chan, 2021). These mechanisms are comparable to those of epoxy coatings but eliminate the need for petroleum-based adhesion promoters. While polyurethane and epoxy coatings reach adhesion strengths of up to 7.2 MPa and 7.51 MPa respectively, algae-based coatings currently exhibit values between 2.5 and 3.8 MPa (Chattopadhyay & Raju, 2007; Kampa et al., 2022). The reduced polymer chain entanglement and lack of reactive cross-linkers limit substrate bonding. Emerging strategies such as plasma surface activation, enzyme-assisted cross-linking, and nanocellulose reinforcement have demonstrated potential to increase surface reactivity and enhance interfacial adhesion.

Impact resistance in algae-based coatings is largely governed by their polysaccharide network, which dissipates mechanical energy through its flexible structure. Exopolysaccharides extracted from *Chlorella vulgaris*, rich in glucuronic acid and rhamnose, provide natural elasticity and energy absorption, improving coating toughness (Mari et al., 2024). Unlike synthetic epoxies that rely on inorganic fillers such as silica or carbon nanotubes to enhance strength, algae-based systems achieve impact resistance through intrinsic polymeric resilience (Xiao & Zheng, 2016). Current impact resistance values range from 18 to 22 J/cm^2, compared with 50 J/cm^2 for epoxy coatings (Kampa et al., 2022). Incorporating graphene oxide, biopolymer-reinforced composites, or layered nanostructures could improve impact tolerance, especially in applications demanding high mechanical endurance.

Hardness and abrasion resistance are key to long-term performance in marine coatings, flooring, and industrial surfaces. Algae-derived polyurethane formulations exhibit pencil hardness values up to 5H, comparable to standard polyurethane systems, though below reinforced epoxies, which achieve Shore D hardness around 80.2 ± 3.06 (Patil et al., 2019; Kampa et al., 2022). The modulus of elasticity of algae-based coatings, between 0.07 and 0.26 GPa, aligns with modified polyurethane systems (0.26 GPa) but remains below that of high-strength polythiourethane/ZnO composites (0.952 GPa) (Chattopadhyay & Raju, 2007). To enhance surface hardness and wear resistance, researchers are exploring silica nanoparticle reinforcement, chitosan-polymer cross-linking, and bio-nanocomposite formulations that improve surface density and extend coating life.

Flexibility and crack resistance are also critical for coatings exposed to dynamic mechanical stress and thermal expansion. Algae-based coatings display high elasticity and retain structural integrity under 10 mm mandrel bend tests, showing no visible cracking (C. K. Patil et al., 2019). The elastomeric characteristics of alginate and chitosan enable efficient strain absorption, reducing brittle failure. Polyurethane coatings typically show elongation at fracture between 14% and 65%, while epoxy coatings exhibit lower values due to their rigid cross-linked networks (Chattopadhyay & Raju, 2007; Kampa et al., 2022). The elasticity of algae-based formulations positions them as suitable candidates for bridge coatings, expansion joints, and thermal barrier applications where flexibility is essential.

Despite encouraging progress, algae-based coatings must overcome certain limitations before they can fully substitute synthetic systems. Adhesion strength remains below industrial benchmarks, while wear resistance is insufficient for high-friction or load-bearing environments. Potential improvements include the integration of amphiphilic polymers, nanocomposite reinforcements, and bio-inspired self-healing materials that enhance both mechanical strength and sustainability. Long-term testing under industrial conditions, including accelerated weathering, chemical exposure, and field trials, is needed to validate real-world durability.

Future research should prioritize hybrid formulations that blend algae-derived polymers with bio-based elastomers, improving mechanical performance while maintaining biodegradability. The incorporation of self-repairing biopolymers, UV-stabilized bioadditives, and nanocellulose-enhanced matrices could further improve resilience and service life. Advancements in scalable production technologies will be essential to ensure cost-effective manufacturing. Through these developments, algae-based coatings could achieve the dual goals of high mechanical performance and environmental sustainability.

4.2. Protective Properties

Algae-based protective coatings provide multiple functional benefits, including corrosion resistance, antimicrobial protection, UV stability, and fire retardancy. These coatings present sustainable alternatives to conventional petroleum-based systems such as polyurethane and epoxy, addressing both environmental and performance challenges. Their protective behavior is derived from a combination of polysaccharides, EPS, and bioactive compounds, which impart long-term stability, self-repairing capacity, and resistance to environmental degradation (C. K. Patil et al., 2019).

Corrosion resistance is among the most notable advantages of algae-derived coatings, especially in marine and humid environments. Electrochemical Impedance Spectroscopy (EIS) studies show barrier resistance values between 10^9 and 10^{10} $\Omega\cdot cm^2$, outperforming typical epoxy coatings that range from 10^7 to 10^8 $\Omega\cdot cm^2$ (Habib-ur-Rahman et al., 2022). Field trials report corrosion rates as low as 0.02 mm/year, representing a 40% improvement compared with polyurethane-based coatings in chloride-rich conditions (C. K. Patil et al., 2019). This performance is attributed to biomineralization, where in situ calcium carbonate forms protective layers that seal microcracks and slow corrosion. These self-repairing features distinguish algae-based coatings from synthetic ones, which often degrade irreversibly over time (Banerjee et al., 2011).

Antimicrobial activity adds further value by preventing biofilm formation and microbial-induced corrosion (MIC), critical in marine and industrial environments. Unlike conventional coatings containing toxic biocides, algae-based systems employ natural bioactive molecules and nanoparticle additives for protection. Incorporating silver-hydroxyapatite (Ag-HAP) nanoparticles into algae-derived matrices has achieved 86% inhibition of corrosion-related microbial colonies, substantially reducing substrate degradation (C. K. Patil et al., 2019). In laboratory tests, these coatings reduced *Escherichia coli* and *Staphylococcus aureus* populations by more than 90%, outperforming commercial antimicrobial coatings that lose efficiency over time (Alvira et al., 2022; Wong & Chiu, 2011; Dec et al., 2020). The non-toxic antimicrobial nature of these systems supports their application in water treatment, pipelines, and submerged structures.

The UV and weathering resistance of algae-based coatings further enhances their outdoor performance. Natural photoprotective molecules such as carotenoids and mycosporine-like amino acids (MAAs) absorb high-energy radiation, minimizing polymer degradation. Accelerated UV exposure tests show that algae-based coatings retain approximately 85% of their mechanical integrity after 2000 hours, compared with 65–70% retention for polyurethane and epoxy coatings (Vega et al., 2021; Lambert & Wagner, 2017). Dense polysaccharide cross-linking contributes to UV shielding by limiting chain scission and pigment photodegradation, improving long-term stability.

Algae-based coatings also demonstrate strong **thermal cycling resistance**, maintaining structural integrity between -40°C and +80°C (Li et al., 2020). Their elastomeric flexibility prevents microcracking and delamination under repeated temperature changes (Xu et al., 2020). This property provides a distinct advantage for outdoor infrastructure, aerospace structures, and equipment exposed to fluctuating thermal conditions.

Fire-retardant performance represents another key benefit. Alginate-based coatings form stable char layers during combustion, reducing heat release and improving flame resistance (Brannum et al., 2019). The limiting oxygen index (LOI) of alginate coatings is reported at 48%, significantly higher than polyurethane and viscose fibers, which average around 20% (Brannum et al., 2019). Bentonite addition further strengthens flame resistance by increasing char yield and thermal stability.

Despite these advantages, large-scale adoption faces challenges. Long-term field validation over multiple years is required to confirm performance consistency under variable climates (Li et al., 2020). Biomass variability also impacts reproducibility, emphasizing the need for raw material standardization. Economically, algae-based formulations currently cost more than synthetic coatings due to high extraction and processing expenses (Reyes et al., 2014). Hybrid strategies combining algae-derived polymers with selective synthetic additives can optimize performance while preserving sustainability (Rodrigues et al., 2018). Future research should focus on developing application-specific formulations for example, corrosion-resistant marine coatings or UV-protective architectural layers to meet both technical and regulatory requirements (Wahlström et al., 2018).

Table 1. Functional Components Extracted from Algae for Protective Coating Applications: Species, Extraction Methods, Cultivation Systems, and Performance Metrics.

Chemical Component	Algae Species	Extraction Method	Cultivation System	Yield (% Dry Weight)	Function in Coating	Performance Metrics	Reference
β-Glucans	*Arthrospira platensis*	Enzymatic hydrolysis using Megazyme kits	Closed photobioreactors; semi-continuous mode	20–34%	Enhances structural integrity and mechanical stability	Improved durability, antifouling properties	(Markou et al., 2021)
Carbohydrates	*Nannochloropsis spp.*	Acid hydrolysis followed by HPLC analysis	Batch systems; mixotrophic and photoautotrophic	14–21% β-glucans	Acts as a biopolymer for hydrophobicity and adhesion	Increased resistance to degradation	(Jan & Kazik, 2017a)
Polysaccharides	*Chlorella vulgaris*	Biochemical extraction (e.g., precipitation methods)	Aquaculture systems with stress adaptation	~88% carbohydrates	Forms biopolymeric layers for barrier protection	High antioxidant and UV resistance	(Abdelhamid et al., 2020)
Lipids (Accessory)	*Nannochloropsis spp.*	Organic solvent extraction (chloroform-methanol)	Photoautotrophic with controlled salinity	~40%	Imparts water resistance and flexibility	Improved water repellency	(Jan & Kazik, 2017b)
Pigments (e.g., Chlorophylls, Carotenoids)	*Chlorella vulgaris*	Solvent-based extraction	Freshwater aquaculture	~5%	UV protection and color stability	High UV absorbance, durability	(Abdelhamid et al., 2020)
Alginate	*Sargassum muticum*	Ultrasound-assisted extraction	Open pond	13.6%–25.6%	Film-former, structural integrity, biopolymer matrix	High thermo-rheological stability	(Flórez-Fernández et al., 2019)

Phycobiliproteins	*Spirulina platensis*	Ultrasound-assisted with PILs	Photobioreactor /Open pond	0.68%–0.80% (wet wt.)	UV resistance, pigment for aesthetic coatings	Fluorescence stability at pH 6.0	(Rodrigues et al., 2018)
R-Phycoerythrin	*Furcellaria lumbricalis*	Enzymatic treatment + HPLC	Open marine systems	0.13%–0.43%	UV shielding, light energy absorption	Fluorescence efficiency, thermal stability	(Saluri et al., 2019)
C-Phycocyanin	*Spirulina platensis*	Ultrasonication	Photobioreactor /Open pond	0.75%	Antioxidant, UV-protection additive	Strong absorption at 615 nm	(Rodrigues et al., 2018) (Saluri et al., 2019)
Extracellular Polymeric Substances (EPS)	*Sargassum species*	Enzyme-assisted extraction	Open pond	~10%-15%	Corrosion resistance, adhesion enhancer	Mechanical stability in marine environments	(Flórez-Fernández et al., 2019)
Fucoidan	*Sargassum muticum*	Ultrasound-assisted extraction	Open pond	~15% (short extraction times)	Antimicrobial, antifouling layer in coatings	Antifouling efficacy under saline exposure	(Flórez-Fernández et al., 2019)
Alginate	*Sargassum muticum*	Acid pre-treatment, alkali extraction, ethanol precipitation	Wild harvest (seaweed)	13.57%	Film formation, thickening	High viscosity, gel strength	(Mazumder et al., 2016)
Alginate	*Macrocystis pyrifera*	Ethanol, HCl, CaCl2 routes	Wild harvest (seaweed)	25%-34% (depending on route)	Structural integrity, binder	Molecular weight, M/G ratio	(Gomez et al., 2009)
C-Phycocyanin, APC	*Spirulina platensis*	Aqueous Two-Phase Extraction (ATPE)	Photobioreactor (microalgae)	C-PC: 78.58%, APC: 51.73%	UV-blocking, pigmentation	Purity: C-PC (4.02), APC (1.5)	((Patil et al., 2008))
Kappa-carrageenan	*Kappaphycus alvarezii*	Ultrasound-Assisted (UAE)	Land-based Hatchery	76.7%	Film-forming, stabilizer, binder	Viscosity: 658.7 cP	(Mendes et al., 2024)

Kappa-carrageenan	*Kappaphycus alvarezii*	Conventional Alkali	Open Sea Farming	~44.5%	Gel-forming, mechanical support	Gel Strength: 926–4946 dyne/cm^2	(Mendes et al., 2024)
Beta-carrageenan	*Eucheuma gelatinae*	Maceration-Stirred	Sea-based Farming	42.68%	Antioxidant, UV protection, binder	Antioxidant Activity: 71.95 mg/g	(Ha et al., 2022)
Sulfated Polysaccharides	*Kappaphycus alvarezii*	Supercritical Fluid (SFE)	Controlled Hatchery	~70%	UV protection, anti-corrosion	High sulfate content, low pH	(Mendes et al., 2024)
Carrageenan Blend	*Eucheuma spp.*	Enzymatic-assisted	Seaweed Aquaculture	Not Reported	Adhesion enhancer, film thickness control	Gel Strength: 487.5 g/cm^2	(Ha et al., 2022)
Fucoxanthin	*Phaeodactylum tricornutum*	Ultrasound-Assisted Extraction (UAE)	Tubular Photobioreactor	1.0–2.5%	UV protection, antioxidant properties, structural stability	Superior UV resistance; enhanced antioxidant activity	(Pocha et al., 2022)
Fucoxanthin	*Padina tetrastromatica*	UAE	Open Pond	0.075%	UV resistance and oxidative stability	Improved light absorption; anti-oxidative effects	(Lourenço-Lopes et al., 2020)
Extracellular Polymeric Substances (EPS)	*Phaeodactylum tricornutum*	Ethanol-based extraction	Flat-Panel Photobioreactor	Not specified	Improved adhesion strength; corrosion resistance	Increased substrate binding; reduced metal oxidation	(Kim et al., 2012)
Biopolymers (e.g., alginate)	*Laminaria japonica*	Microwave-Assisted Extraction (MAE)	Photobioreactor or Open Pond	2.67%	Hydrophobicity and barrier properties	Enhanced water resistance; reduced permeability	(Lourenço-Lopes et al., 2020)

Lipids	*Phaeodactylum tricornutum*	Solvent-Based Extraction (Ethanol)	Tubular Photobioreactor	18%	Hydrophobic coating layers to enhance anti-corrosion	Improved water resistance; reduced moisture absorption	(Pocha et al., 2022)
Pigments (e.g., carotenoids)	*Chaetoceros calcitrans*	Soxhlet Extraction	Raceway Pond	Not specified	UV protection and color stability	Reduced pigment degradation under UV exposure	(Pocha et al., 2022)
Bioplastics	*Isochrysis galbana*	Solvent-Based Extraction (Methanol)	Closed Photobioreactor	Not specified	Flexibility, durability, eco-friendly alternative to resins	Increased mechanical flexibility; lower environmental footprint	(Lourenço-Lopes et al., 2020)
Polysaccharides	*Sargassum duplicatum*	Enzyme-Assisted Extraction (EAE)	Open Pond	0.657%	Enhanced mechanical strength and biocompatibility	Increased tensile strength; compatibility with sustainable materials	(Lourenço-Lopes et al., 2020)
Ulvans (Sulfated Polysaccharides)	*Ulva lactuca*	Aqueous ethanol (70:30 v/v)	Phototrophic (raceway ponds)	15–65	Enhances film elasticity and adhesion	Improved mechanical stability, water resistance	(Pappou et al., 2022)
Astaxanthin	*Haematococcus pluvialis*	Supercritical CO_2 with ethanol	Closed photobioreactors (PBRs)	~5	Provides UV resistance and antioxidant properties	Increased UV stability; reduced oxidative degradation	(Reyes et al., 2014)
Carotenoids (e.g., Lutein)	*Haematococcus pluvialis*	Pressurized liquid extraction	Two-phase: PBRs + stress phase	2–3	Adds color and photoprote	UV absorption; enhanced durability	(Li et al., 2020)

					ctive properties		
Polyphenols	*Ulva lactuca*	Ethanol-water mixture (70:30)	Raceway ponds	10–15	Antioxidant and antimicrobial functions	Reduction in fouling and microbial growth	(Pappou et al., 2022)
Extracellular Polymeric Substances (EPS)	*Various microalgae*	Wet biomass extraction (DME)	Heterotrophic systems	Not specified	Improves film-forming ability	Increased cohesion and surface coverage	(Li et al., 2020)
Polysaccharides (General)	*Ulva spp.*	Thermal aqueous extraction	Open raceway ponds	49.9	Enhances viscosity and structural integrity	Improved coating thickness and adhesion	(Pappou et al., 2022)
Ulvan (Sulfated Polysaccharides)	*Ulva lactuca*	Hot water extraction, alcohol precipitation	Open systems (coastal waters)	15%	Film-forming, UV resistance, antifouling	Enhanced mechanical stability, moderate adhesion strength	(Thanh et al., 2016)
Polysaccharides	*Ulva fasciata*	Hot-water reflux, ethanol precipitation	Coastal harvesting	43.66%	Structural reinforcement, corrosion resistance	High antioxidant activity (DPPH scavenging ~85%)	(Barakat et al., 2022)
Carotenoids	*Ulva lactuca*	Ethanol/water extraction (70:30 v/v)	Cultivated in non-arable lands	10–15%	UV protection, antioxidant properties	Improved durability, enhanced UV-blocking capacity	(Pappou et al., 2022)
Phenolics	*Ulva lactuca*	Ethanol/water extraction (70:30 v/v), solvent screening	Cultivated in non-arable lands	Not specified	Antimicrobial properties, oxidative stability	High antioxidant potential, moderate antibacterial activity	(Pappou et al., 2022)

Lipids	*Ulva lactuca*	Chloroform/methanol extraction	Open systems (coastal waters)	3.5%	Hydrophobic coatings, moisture resistance	Moderate improvement in hydrophobicity	(Pappou et al., 2022)
Ash/Minerals	*Ulva lactuca*	Direct incineration for mineral ash calculation	Open systems (coastal waters)	27.7%	Structural enhancement, catalytic surface functionality	Improved corrosion resistance, mechanical support	(Pappou et al., 2022)
Mycosporine-like Amino Acids (MAAs)	*Porphyra columbina*	Water or mild ethanol solutions	IMTA system with fishpond effluents	~10.4	UV protection, antioxidant	UV absorbance at 330 nm; photostability	(Bedoux et al., 2020)
Pigments (e.g., chlorophyll, carotenoids)	*Palmaria palmata*	Sequential water and methanol	Bioreactor or open pond	~6.93 (seasonal)	Enhanced color stability, UV protection	UV absorption (310-365 nm); antioxidant activity	(Figueroa, 2021)
Biopolymers (e.g., alginate, EPS)	*Gracilaria tenuistipitata*	Mild ethanol extraction	Mesocosm or open tank	1.5–4.3	Mechanical stability, adhesion improvement	Increased adhesion strength; tensile stability	(Bedoux et al., 2020)
Shinorine (a specific MAA)	*Chondrus crispus*	HPLC with distilled water	Indoor controlled light systems	~3.0 (gametophytes)	UV resistance, surface protection	UV absorbance at 330 nm; durability under UV-B exposure	(Bedoux et al., 2020)
Porphyran (sulfated polysaccharide)	*Porphyra umbilicalis*	Hydroethanolic extraction	Outdoor cultivation under solar exposure	~11	Water resistance, biopolymer matrix stabilization	Reduced water permeability; increased coating durability	(Figueroa, 2021)

Asterina-330 (a specific MAA)	*Gracilaria cornea*	Aqueous methanol extraction	Semi-controlled IMTA system	~12.8	Photoprotective enhancement, durability	UV absorbance peak at 330 nm; oxidative stability under UV stress	(Bedoux et al., 2020)
Fucoxanthin (carotenoid)	*Grateloupia lanceola*	Sequential extraction (ethanol, acetone)	Indoor tank cultivation under variable light	3.5–4.4	UV-blocking properties, color enhancement	High antioxidant activity; photostability	(Bedoux et al., 2020)
Fucoidan	*Fucus vesiculosus*	Hot water extraction	Natural cultivation in marine habitats	2.5%–7%	Enhances UV resistance, provides antifouling properties	UV stability, antifouling effectiveness	(Ferreira et al., 2019)
Phlorotannins	*Fucus vesiculosus*	Hot water extraction, mild acid extraction	Natural coastal collection	Up to 12%	Antioxidant, improves coating stability and durability	Longevity, antioxidant activity	(Cabral et al., 2021)
Laminarins	*Ecklonia maxima, Laminaria pallida*	Acid extraction	Coastal and aquaculture systems	8%–10%	Strengthens structural integrity of coatings	Mechanical stability, anti-corrosion	(January et al., 2019)
Sulfated Polysaccharides	*Splachnidium rugosum*	Salt extraction	Offshore cultivation	~5%	Improves adhesion and water resistance	Adhesion strength, water barrier properties	(January et al., 2019)
Fucoxanthin	*Fucus vesiculosus*	Supercritical fluid extraction	Coastal algae farms	~0.5%	Provides UV protection and pigmentation	UV absorbance, color stability	(Ferreira et al., 2019)

Biopolymers	*Laminaria pallida*	Microwave-assisted extraction	Marine cultivation systems	~15%	Enhances biofilm formation and reduces surface fouling	Biofilm stability, antifouling performance	(Cabral et al., 2021)
Porphyran	*Porphyra umbilicalis*	Sequential alkaline-acidic extraction	Indoor tank, controlled conditions	~20%	Improves film formation, antioxidant properties	UV resistance, antioxidant activity	(Wahlström et al., 2018)
Carrageenan	*Porphyra umbilicalis*	Alkaline extraction (90°C, 4h, pH 9.5)	Indoor tank, controlled conditions	~20%	Cross-linking agent, gel formation	Mechanical stability, structural reinforcement	(Wahlström et al., 2018)
Pectin	*Porphyra umbilicalis*	Acidic extraction (90°C, 4h, pH 2)	Indoor tank, controlled conditions	~15%	Binding properties, thermal stability	Heat resistance, adhesive strength	(Wahlström et al., 2018)
Cellulose	*Porphyra umbilicalis*	Alkaline and HCl treatment	Indoor tank, controlled conditions	~10%	Reinforcement additive in polymer matrices	Enhanced tensile strength	(Wahlström et al., 2018)
Sulfated Polysaccharides	*Porphyra haitanensis*	Hot water and alcohol precipitation	Not mentioned	~40%	Antioxidant, anti-fouling properties	Oxidative stability, surface properties	(Qiu et al., 2021)
EPS (Extracellular Polymeric Substances)	*Porphyra species*	Enzymatic extraction	Not mentioned	Not specified	Biofilm formation, enhances adhesion	Adhesion strength, mechanical durability	(Qiu et al., 2021)
Proteins	*Porphyra umbilicalis*	Cold alkaline extraction	Indoor tank, controlled conditions	~15%	Supplementary mechanical strength	Increased elasticity and durability	(Wahlström et al., 2018)

4.3. Environmental Impact

Algae-based protective coatings represent a new generation of sustainable materials that merge environmental remediation with conventional protective functions. Unlike synthetic coatings that primarily act as passive barriers and contribute to pollution through volatile organic compound (VOC) emissions and microplastic generation, algae-based coatings offer active environmental benefits. These include carbon sequestration, air purification, and water treatment capabilities. Such functionalities arise from the photosynthetic activity of embedded microalgae, their bioactive metabolites, and adsorption mechanisms that continue to operate during use. In this way, algae-based coatings contribute not only to surface protection but also to continuous environmental improvement. However, large-scale implementation requires overcoming challenges in long-term biological stability, material standardization, and economic scalability. Many of the algae-derived compounds summarized in Table 1 are produced through low-impact cultivation systems such as open ponds, photobioreactors, and integrated multi-trophic aquaculture (IMTA), reinforcing their environmental sustainability.

One of the most significant advantages of algae-based coatings is their ability to sequester carbon, aligning directly with global decarbonization efforts. Microalgae can fix approximately 1.3 kg of CO_2 per kg of dry biomass, with optimized cultivation systems producing up to 280 tons of biomass per hectare annually (Sarwer et al., 2022). In contrast to conventional coatings with high embodied carbon footprints, algae-based coatings incorporate microalgal biomass within polymer or hydrogel matrices, enabling continued CO_2 fixation throughout their service life. Experimental data indicate that these coatings can reduce net CO_2 levels by 51–73% over their functional lifespan (Cole et al., 2023). Additionally, the integration of pyrolytic conversion processes allows for the transformation of algal residues into biochar, ensuring permanent carbon sequestration without the need for energy-intensive storage infrastructure. Life cycle assessments (LCA) show that while epoxy coatings emit around 2.5 tons of CO_2 per ton of product, algae-derived coatings exhibit net-negative carbon emissions (C. K. Patil et al., 2021). This carbon-negative potential strengthens their relevance in carbon-regulated markets and green certification systems such as LEED.

Beyond carbon mitigation, algae-based coatings actively contribute to air purification by degrading airborne pollutants such as nitrogen oxides (NOx) and VOCs. Conventional epoxy and polyurethane coatings are major VOC emitters, collectively releasing about 28.84 Tg per year, which contributes to ground-level ozone and smog formation (Cruz et al., 2019). In contrast, algae-derived coatings use photocatalytic and bioadsorptive mechanisms to remove VOCs from surrounding air. Poly(3-hydroxybutyrate) (PHB) coatings derived from *Spirulina sp.* have demonstrated VOC degradation efficiencies above 60% within 24 hours (Cruz et al., 2019). Moreover, C-phycocyanin extracted from *Spirulina* exhibits dual antioxidant and antimicrobial activity, reducing microbial proliferation while enhancing indoor and outdoor air quality. This multifunctionality transforms algae-based coatings into “living” protective systems capable of improving environmental health in polluted urban settings.

Algae-based coatings also play a role in water purification and environmental remediation. Their bioactive and adsorptive properties enable the removal of heavy metals and pollutants from stormwater and industrial effluents. Unlike synthetic coatings, which may release microplastics or toxic leachates, algae-integrated coatings act as biological filters. Field-scale applications have reported removal efficiencies of 75–85% for metals such as lead (Pb), cadmium (Cd), and arsenic (As) (Sarwer et al., 2022). These coatings also support biofilm regeneration, which enhances long-term adsorption performance and reduces maintenance requirements compared with conventional membrane filtration systems. This self-renewing capability contributes to lower operational costs and sustainable water treatment, particularly in urban runoff management and wastewater reuse applications.

Despite their clear environmental benefits, several challenges limit the widespread adoption of algae-based coatings. A key issue is maintaining long-term photosynthetic viability within coating matrices. Exposure to UV radiation, temperature variations, and biofouling can reduce CO_2 fixation efficiency after three to five years of use. Additionally, while life cycle assessments have demonstrated environmental superiority, comprehensive cradle-to-grave evaluations are still needed to assess the overall impact of cultivation energy demands, extraction emissions, and end-of-life biodegradability. Biological variability across algal species and cultivation conditions also complicates material standardization. Seasonal fluctuations and strain-specific biochemical profiles influence biopolymer and pigment yields, affecting consistency in coating performance (Li et al., 2020). Establishing uniform cultivation protocols and advanced quality control measures will be essential to achieve reliable large-scale production.

To enhance durability and scalability, future research should focus on encapsulation techniques that preserve algal photosynthetic activity within coatings while minimizing degradation under environmental stress. Hybrid formulations that combine algae-derived biopolymers with limited synthetic reinforcements can balance mechanical durability with eco-functionality. Further, establishing standardized evaluation protocols for carbon sequestration, VOC degradation, and water purification performance will support regulatory approval and commercial certification. Such frameworks will be vital for integrating algae-based coatings into green infrastructure and sustainable construction standards.

Algae-based coatings redefine the traditional concept of protective surfaces. They shift from passive protection toward active environmental enhancement by simultaneously sequestering carbon, purifying air, and filtering water. This multifunctionality represents a major step forward in sustainable materials engineering. As global sustainability policies and carbon regulations tighten, algae-based coatings stand out as viable next-generation materials capable of reducing emissions, mitigating pollution, and supporting circular economy principles within construction and industrial sectors.

5. Economic Viability & Industrial Adoption

5.1. Cost Analysis vs. Petroleum-Based Coatings

The economic feasibility of algae-based protective coatings remains a major factor determining their industrial potential. Although these coatings provide clear environmental advantages and promising material performance, production costs remain high compared to conventional petroleum-based alternatives. Key cost drivers include biomass cultivation, extraction efficiency, and large-scale processing logistics. Despite recent technological progress, current cost analyses indicate that algae-based coatings still face economic challenges that restrict their commercialization. A detailed evaluation of cost components, covering biomass production, extraction, formulation, quality assurance, and regulatory compliance, helps identify strategies to enhance their economic competitiveness.

Biomass cultivation is the primary cost contributor. Open pond and photobioreactor (PBR) systems offer different cost-performance trade-offs. Open ponds require 40–60% less capital investment than PBRs but have lower productivity (20–25 $g/m^2/day$) and higher risks of contamination and seasonal yield fluctuations (Xu et al., 2020). PBRs provide controlled conditions and higher productivity up to 60 $g/m^2/day$ but involve high setup costs, often exceeding USD 500,000 per hectare (B. R. Kumar et al., 2021). Hybrid systems that use open ponds for bulk cultivation followed by refinement in PBRs have improved production efficiency by 35% and reduced costs by about 40% (Sarwer et al., 2022). Even so, improving energy efficiency and optimizing process integration remain essential for achieving economic sustainability at larger scales.

Extraction and processing add significant costs, largely due to energy-intensive methods. Conventional solvent-based extraction and drying consume large amounts of energy and may degrade bioactive compounds that are critical to coating functionality (Xu et al., 2020). Advanced technologies such as supercritical fluid extraction (SFE) and microwave-assisted extraction (MAE) improve recovery efficiency. SFE achieves over 90% recovery for astaxanthin, while MAE enhances polysaccharide yields by about 33% compared with traditional extraction (Esquivel-Hernández et al., 2016; Zuber et al., 2017). However, both techniques require high capital investment. Alternative methods, such as bio-flocculation and electrocoagulation harvesting, have demonstrated potential to reduce energy costs while maintaining high recovery efficiency (Sosa-Hernández et al., 2019).

Quality assurance also contributes to overall costs. Unlike petroleum-based coatings that rely on standardized petrochemical feedstocks, algae-based formulations require strict quality control due

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to natural biomass variability. Differences in strain, nutrient supply, and growth conditions affect coating consistency, necessitating advanced monitoring systems. Analytical methods such as Fourier Transform Infrared (FTIR) and UV–Vis spectroscopy help verify chemical structure and functional group uniformity, particularly in polysaccharide-based polyurethane coatings (Gieroba et al., 2023). Although these quality controls add expense, they ensure product reliability and performance stability. Moreover, algae-derived polymers can be customized for improved adhesion, hydrophobicity, and corrosion resistance, providing long-term savings by extending service life and reducing reapplication frequency (C. K. Patil et al., 2019; Gieroba et al., 2023).

Material optimization strongly influences final costs. Additives such as silica–titania nanoparticles improve scratch resistance, while calcium–alginate cross-linked networks enhance adhesion (Verma et al., 2018; Xiao & Zheng, 2016). Although these additives increase initial costs, they significantly extend coating durability, improving long-term cost efficiency. Continued innovation in biopolymer stabilization and bio-nanocomposite integration may further enhance performance while reducing energy consumption during production.

The biorefinery approach offers an effective pathway to improve economic feasibility. By sequentially extracting multiple high-value compounds such as biopolymers, pigments, and proteins from a single biomass batch, waste is minimized and overall revenue increases (Mouga & Fernandes, 2022). Additionally, integrating algae cultivation with wastewater treatment reduces nutrient costs and generates secondary income through pollutant remediation services. The use of renewable energy, such as solar-powered PBRs, has achieved operational cost reductions of 25–30%, further improving economic potential (Wilson et al., 2021).

Despite the cost gap, algae-based coatings offer long-term economic advantages due to sustainability incentives and regulatory trends. Carbon pricing and VOC restrictions are driving industries toward bio-based products. With microalgae capable of fixing about 1.3 kg of CO_2 per kg of biomass, algae-based coatings can benefit from carbon credit schemes valued at $50–70 per ton of CO_2 sequestered (Sarwer et al., 2022). In addition, demand for low-VOC coatings in LEED-certified and green infrastructure projects is increasing, enhancing market appeal (Cole et al., 2023).

Life cycle assessments (LCA) highlight further economic potential. While petroleum-based coatings offer lower upfront costs, algae-derived formulations provide superior durability and longer service life, lowering overall maintenance and reapplication expenses. Studies show that alginate- and carrageenan-based coatings demonstrate enhanced corrosion and weathering resistance, outperforming conventional products (Gomez et al., 2009; Eyssautier-Chuine et al., 2023). Combined with tightening environmental regulations, this long-term resilience strengthens their market competitiveness.

To achieve cost parity, ongoing improvements are needed in cultivation productivity, extraction efficiency, and material performance. Scaling up biomass production, adopting renewable energy, and refining stabilization methods will reduce costs further. Strategic investment in biorefinery technologies, government incentives, and public–private partnerships will accelerate the transition of algae-based coatings from niche innovations to commercially viable products. With continued technological progress, algae-based coatings are positioned to become cost-effective, high-performance, and sustainable alternatives in the protective coatings industry.

5.2. Market Readiness & Commercial Barriers

Despite the progress achieved in formulation and process optimization, several critical barriers still hinder the large-scale commercialization of algae-based coatings. The transition from laboratory-scale studies to industrial-scale production is constrained by scalability, quality control, infrastructure adaptation, workforce training, and regulatory readiness. Addressing these limitations is crucial for algae-based coatings to compete with petroleum-derived systems.

Scalability is one of the major constraints. Current cultivation technologies struggle to maintain high productivity at low cost. Advances in photobioreactor (PBR) systems have shown promise, with cyclic-flow PBRs capturing 30% of CO_2 emissions from a 1 MW coal power plant and producing 1,280

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tons of biomass per year (Wilson et al., 2021). However, extending such systems beyond pilot scale remains challenging due to high capital costs and operational inefficiencies. Hybrid open-pond–PBR models have achieved 40% cost reductions while maintaining stable productivity (B. R. Kumar et al., 2021), but further optimization is needed for continuous, year-round operation. Artificial intelligence (AI)-assisted control has reduced biomass variability to below 5%, improving process consistency (Sahu et al., 2024). Yet, implementation at scale is limited by infrastructure expenses and technology transfer issues.

Quality control represents another barrier. Biomass composition varies depending on species and cultivation conditions, affecting coating uniformity (C. K. Patil et al., 2019). Advanced analytical techniques such as FTIR, SEM-EDS, and UV–Vis spectroscopy are required to ensure structural integrity and functional stability (Di Fazio et al., 2024). However, industrial-scale use of these methods requires costly instruments and trained personnel. In contrast to synthetic resins, which exhibit uniform molecular structures, algae-based formulations demand rigorous quality management, increasing production time and costs.

Infrastructure adaptation also presents challenges. Although additives like silica–titania nanoparticles improve adhesion compatibility (Verma et al., 2018), algae-derived coatings have higher viscosity and require modified rheological control to ensure uniform application. Traditional methods such as spraying and dip-coating must be adapted to accommodate these materials (D. Kim & Kang, 2020). The lack of standardized application protocols discourages manufacturers from transitioning to bio-based systems, as it requires additional investment in process calibration and operator retraining.

Workforce training is an additional barrier. Unlike petroleum-based coatings, which rely on established chemical synthesis processes, algae-based coatings require knowledge of biopolymer stabilization, enzymatic curing, and hydrogel handling (Cole et al., 2023). Specialized training is necessary to prevent polymer degradation and contamination during production. Handling bioactive components and chelating agents such as EDTA and sodium citrate also demands strict safety protocols. Simulation-based training and machine learning-assisted process monitoring have shown potential to reduce errors and improve productivity (Bin Abu Sofian et al., 2024), yet the current lack of skilled professionals remains a bottleneck.

Economic constraints and market dynamics further limit adoption. Although algae-based coatings can remove up to 73% of atmospheric CO_2 and reduce marine biofouling (D. Kim & Kang, 2020; Cole et al., 2023), their production remains more expensive than petroleum-based systems. Established synthetic coating industries benefit from economies of scale and decades of optimization. Moreover, regulatory standards are still tailored to petrochemical-based formulations, lacking clear guidelines for biodegradability, carbon offset performance, and bio-based certification (Patil et al., 2019; Xu et al., 2020; Prathiksha et al., 2024). This regulatory gap slows approval and discourages manufacturers from investing in large-scale production.

To overcome these commercialization barriers, several strategies can be pursued. Financial incentives such as tax credits for carbon-negative coatings, green subsidies for bio-based production, and inclusion in LEED-certified construction programs can accelerate adoption. Collaboration between research institutions and established coating manufacturers will help develop hybrid formulations that combine algae-derived biopolymers with limited synthetic additives, balancing performance and cost. Regulatory agencies should create dedicated standards for bio-based coatings that address their unique biodegradability and carbon capture characteristics, ensuring fair evaluation and faster certification.

Ultimately, achieving full market readiness will depend on aligning technological, economic, and policy frameworks. By improving scalability, enhancing quality control, providing specialized training, and implementing regulatory incentives, algae-based coatings can evolve from emerging technologies into mainstream industrial solutions. As global industries continue to prioritize low-carbon and eco-efficient materials, algae-based coatings have the potential to become a cornerstone of sustainable infrastructure development.

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5.3. Regulatory Standards & Future Implementation Strategies

The absence of standardized regulatory frameworks for algae-based coatings remains one of the most significant barriers to large-scale commercialization. Current industrial and environmental coating standards, including those developed by the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM), primarily address petroleum-derived coatings and fail to accommodate the unique characteristics of bio-based alternatives (Patil et al., 2019; Xu et al., 2020). Existing regulations emphasize volatile organic compound (VOC) limits, durability, and chemical resistance but lack evaluation criteria for biodegradability, carbon sequestration, and environmental remediation capabilities, which are key performance attributes of algae-based coatings (Cole et al., 2023; Prathiksha et al., 2024). This regulatory gap complicates approval processes, increasing both compliance costs and time-to-market for manufacturers seeking to scale bio-based formulations.

The lack of globally recognized certification pathways further restricts industrial adoption. Although algae-based coatings provide net-negative carbon emissions and low environmental toxicity, they do not fit within existing eco-labeling systems such as EU Ecolabel or Green Seal, which were designed for conventional petroleum coatings (Cole et al., 2023). As a result, producers face extended certification timelines and additional compliance expenses. Studies indicate that regulatory approval for bio-based coatings can increase initial production costs by 20–30% due to the need for extensive validation trials, safety assessments, and long-term performance testing (Xu et al., 2020). Without dedicated certification standards and streamlined approval mechanisms, algae-based coatings remain at a structural disadvantage compared to synthetic systems that have benefited from decades of regulatory optimization.

Several policy initiatives have begun addressing these regulatory shortcomings. In the European Union (EU), programs under the European Green Deal promote the use of bio-based industrial materials, potentially granting algae-derived coatings priority access to research funding and fast-track certification (Prathiksha et al., 2024). In the United States, agencies such as the Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA) are developing sustainability-focused criteria for coatings that prioritize low-VOC content and carbon capture capacity (Cole et al., 2023). These initiatives reflect growing recognition of biotechnology-based materials but still lack explicit inclusion of algae-based coatings, delaying full regulatory integration.

Beyond regulatory frameworks, future implementation strategies must address **scalability, cost-efficiency, and performance optimization**. Automation in photobioreactor (PBR) systems and AI-assisted cultivation control has achieved biomass yield improvements of 25–30%, reducing variability and operational costs (Xu et al., 2020; B. R. Kumar et al., 2021). The adoption of biorefinery-based processing, which enables the sequential extraction of polysaccharides, pigments, and proteins, enhances economic feasibility by maximizing value recovery from each biomass batch (Mouga & Fernandes, 2022). These integrated systems improve both cost competitiveness and sustainability, making them more attractive within evolving regulatory and commercial contexts.

Ongoing research should also prioritize improving the **mechanical durability and weathering stability** of algae-based coatings to meet industrial-grade standards. Although current formulations exhibit good adhesion and impact resistance, more robust cross-linking mechanisms are needed to maintain long-term performance under harsh environmental conditions (Xiao & Zheng, 2016; Mari et al., 2024). Encapsulation strategies using nano-additives, including silica–titania composites and chitosan-reinforced matrices, have demonstrated potential to preserve bioactive functionality while enhancing structural stability (Sosa-Hernández et al., 2019). Continued advancements in these areas are essential for aligning algae-based coatings with established industrial benchmarks.

The integration of algae-based coatings into **smart infrastructure systems** offers another promising direction for future implementation. Emerging bioelectronic interfaces now enable real-time environmental monitoring, allowing coatings to self-adjust in response to humidity, temperature, and pollutant exposure (Prathiksha et al., 2024). These capabilities align with Industry

4.0 technologies and may significantly enhance coating durability and service life. Additionally, research on **self-healing bio-coatings**, where algae-infused hydrogel matrices autonomously repair microcracks, presents new opportunities to reduce maintenance costs and extend functional lifespan (Cole et al., 2023).

To achieve widespread industrial adoption, it is crucial to establish **global certification standards** tailored specifically to bio-based coatings. Harmonized testing methodologies should include biodegradability assessment, carbon sequestration validation, and environmental impact evaluation. Government-backed incentive programs, including tax benefits and research grants, can encourage investment and accelerate regulatory approval. Large-scale demonstration projects and cross-industry collaborations will also be vital to verify commercial viability and real-world performance.

By bridging regulatory gaps, optimizing production systems, and enhancing mechanical resilience, algae-based coatings can progress from emerging sustainable innovations to mainstream industrial materials. Their alignment with international sustainability targets and carbon-neutral goals positions them as practical, scalable, and environmentally responsible alternatives to petroleum-based coatings (Cole et al., 2023; Prathiksha et al., 2024).

6. Conclusions

This review demonstrates that algae-based protective coatings represent a transformative advancement in sustainable materials engineering by merging functional surface protection with active environmental remediation. Unlike conventional petroleum-derived coatings, which are primarily passive barriers contributing to VOC emissions and microplastic pollution, algae-based coatings play an active role in sequestering carbon, degrading air pollutants, and filtering contaminants from water systems. This dual functionality positions them as next-generation materials that not only protect infrastructure but also contribute directly to ecosystem restoration and carbon-neutral development.

The novelty of this work lies in establishing a comprehensive techno-economic and sustainability framework for algae-based protective coatings, integrating insights from cultivation systems, biomass processing, coating formulation, environmental performance, and regulatory readiness. Previous studies often focused on isolated aspects such as pigment extraction or biopolymer performance, but this review unifies these fragmented domains into a single analytical model, highlighting the interconnections between technical innovation, process economics, and environmental outcomes. By presenting an integrated roadmap from laboratory-scale synthesis to industrial-scale implementation, this study provides the first holistic synthesis of technological, regulatory, and sustainability dimensions of algae-based coatings.

The paper further emphasizes the potential of algal biorefineries as economic enablers for scalable coating production. Through sequential extraction of polysaccharides, pigments, and proteins, biorefineries improve cost efficiency while supporting circular economy principles. The analysis of hybrid photobioreactor–open pond systems, solvent-free extraction, and AI-assisted process control reveals practical pathways toward cost reduction and industrial feasibility. These strategies collectively redefine algae-based coatings as viable, carbon-negative materials capable of competing with petroleum-based systems in both performance and economic resilience.

From an environmental standpoint, algae-based coatings offer measurable sustainability advantages. Their proven ability to fix up to 1.3 kg of CO_2 per kilogram of biomass, combined with VOC degradation efficiencies exceeding 60%, establishes them as active contributors to emissions reduction and air purification. In addition, their capacity to remove up to 85% of heavy metals from runoff water introduces a new class of multifunctional environmental materials that go beyond passive sustainability claims to deliver real ecosystem benefits.

However, achieving full industrial integration requires targeted progress in several areas. Standardization of algal biomass quality, development of encapsulation strategies to preserve photosynthetic activity, and creation of regulatory frameworks that define performance criteria for bio-based coatings are immediate priorities. The establishment of unified certification protocols addressing biodegradability, carbon sequestration, and environmental remediation potential will be essential for building global market credibility. Furthermore, close collaboration among materials scientists, environmental engineers, and policymakers will be vital to translate laboratory-scale advances into commercial success.

Looking ahead, algae-based coatings align strongly with the Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Their integration into future infrastructure and building systems could accelerate the shift toward carbon-negative and self-regenerative materials in construction and manufacturing. As global policies and markets increasingly prioritize sustainability, algae-based coatings have the potential to redefine surface protection, transforming it from an environmental burden into a regenerative and multifunctional solution for a circular and climate-resilient future.

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