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Algae-Based Paints: A Review of Literature on Pigments, Coatings, and Sustainable Applications

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Abstract: ***The growing demand for eco-friendly materials in architecture, interior design, and product manufacturing has sparked interest in algae as a renewable source of pigments and functional additives for paints and coatings. Algae-based paints are gaining attention as sustainable alternatives to conventional synthetic paints due to their renewable sourcing, low environmental impact, and natural antimicrobial properties. This review synthesizes research on the use of algae-derived pigments and biomass in paints, examining their extraction ,methods, antimicrobial and antifouling efficacy, thermal stability, practical applications, formulation, performance, sustainability, and commercialization potential. Findings highlight algae's versatility in providing natural hues, bioactive functionalities, and environmental benefits compared to synthetic alternatives. Limitations such as biodeterioration and pigment stability are also discussed. Adaptation of algae-based paints for interior and industrial uses shows considerable promise for eco-friendly coatings. However, challenges such as pigment stability, scalability, and cost competitiveness remain. The paper concludes with research gaps and future directions for the development of algae-based paints.***

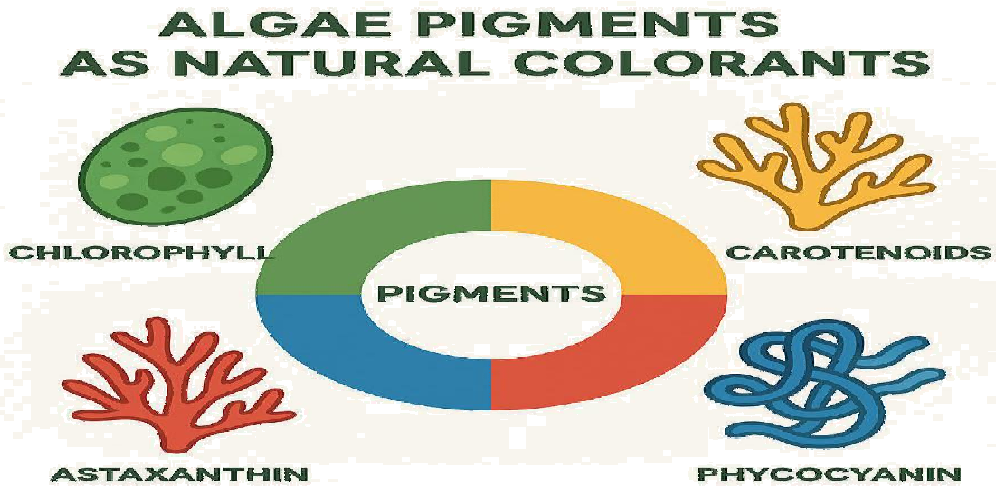
Keywords: Algae-based paint, sustainable coatings, natural pigments, antimicrobial paint, antifouling, bio-based polymers

I. INTRODUCTION

The global paint and coatings sector represents a multi-billion-dollar industry, with applications spanning architecture, interior design, textiles, automotive, and protective coatings. Despite its scale and innovation, the industry remains heavily dependent on petroleum-derived binders, heavy-metal pigments, and volatile organic compounds (VOCs). These materials are not only energy-intensive to produce but also contribute to environmental degradation, including air and water pollution. VOC emissions during application and drying phases negatively affect indoor air quality, raising health concerns such as respiratory irritation, headaches, and long-term exposure risks. Additionally, the persistence of synthetic pigments in the environment poses disposal challenges, as many of them are non-biodegradable and toxic (Rocha et al., 2025).

The search for sustainable alternatives has shifted attention toward natural and bio-based materials. Among these, algae stand out as a particularly promising option. Microalgae and cyanobacteria are efficient photosynthetic organisms capable of producing biomass rich in pigments, lipids, and polysaccharides. Their pigments—including chlorophylls (green), carotenoids (yellow-orange), and phycobiliproteins such as phycocyanin (blue)—offer a vibrant palette for coloring applications (Mutaf-Kılıç et al., 2023). Importantly, these pigments are biodegradable and generally non-toxic, making them attractive replacements for synthetic dyes in paints, coatings, and related products.

In addition to their aesthetic potential, algae-based components provide functional properties highly relevant to modern coatings. Studies have reported antimicrobial activity, antioxidant effects, and UV resistance in algal extracts, properties that could be leveraged to design "functional paints" capable of improving indoor environments or protecting building façades (Carpintero et al., 2023; Tong et al., 2023). From a sustainability perspective, algae cultivation requires minimal arable land, can utilize wastewater streams, and even sequesters atmospheric CO_2, thus aligning with principles of green chemistry and circular design (Tan et al., 2020).



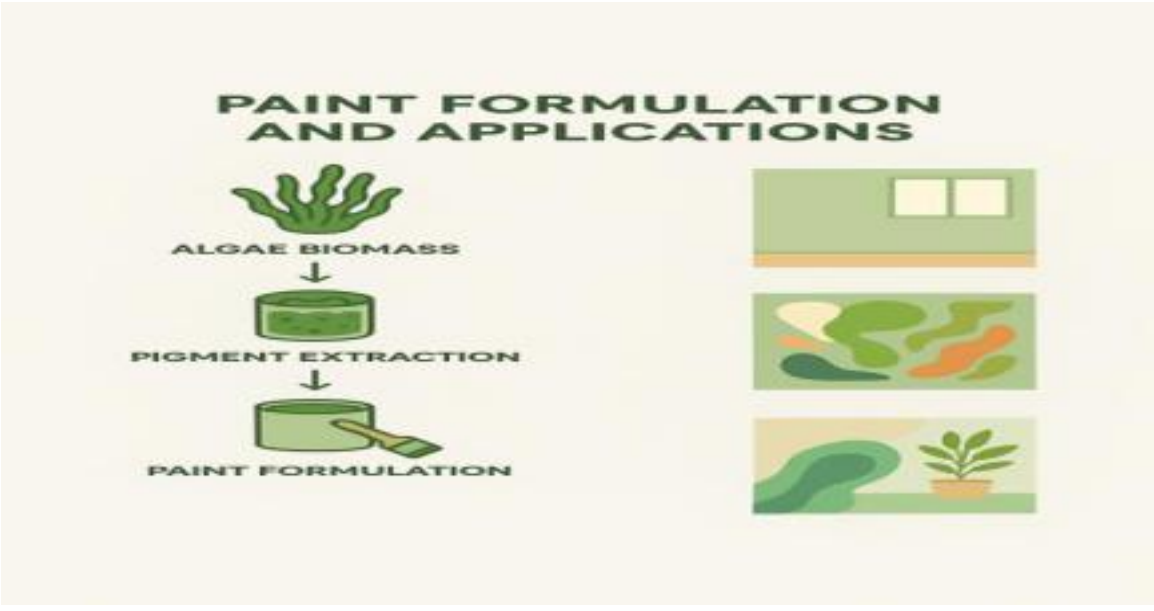
Over the last decade, academic and industrial research has begun exploring algae's potential in paints and coatings. Investigations range from laboratory-scale pigment extraction studies to applied experiments where algae-derived pigments are incorporated into water- and oil-based paint formulations (ResearchGate Preprint, 2023). Simultaneously, critical reviews highlight the barriers to commercialization, including pigment stability, scalability of cultivation, and the need for interdisciplinary approaches that combine biotechnology with material science (Rocha et al., 2025).

The paper reviews ten influential studies published between 2018 and 2025 on algae-based pigments, coatings, and their applications in paints. By synthesizing insights from pigment extraction, paint formulation, and sustainability perspectives, it seeks to provide a comprehensive overview of current progress, identify gaps in knowledge, and outline future directions for algae-based paints in the context of sustainable innovation.

II. METHODOLOGY

This review was conducted through a systematic selection of peer-reviewed research articles and review papers from 2018 to 2025, accessed via databases such as ScienceDirect, SpringerLink, and ResearchGate.

The keywords *algae pigments*, *biopaints*, *bio-coatings*, *microalgae dyes*, and *sustainable paints* were used to identify relevant literature. Ten studies were chosen for their direct relevance to algae-based pigments and coatings, covering a range of approaches from pigment extraction technologies to practical paint formulations and sustainability assessments.



The selection criteria emphasized studies that:

- Discuss algae-derived pigments and their chemical properties.
- Explore paint or coating formulations incorporating algae.
- Provide insight into sustainability or functional properties of algae-based materials.
- Identify technical and economic barriers to commercialization.

These sources provide a balanced basis for synthesizing both scientific and applied aspects of algae in paint development.

III. LITERATURE REVIEW AND DISCUSSION

A. Algal Pigments as Natural Colorants

Algae are prolific producers of pigments, many of which can substitute for synthetic dyes in paints. Chlorophylls provide characteristic green shades but are prone to degradation under light and heat, limiting long-term stability. Carotenoids such as β-carotene and astaxanthin impart yellow to reddish-orange hues and are known for antioxidant activity. Phycobiliproteins, particularly phycocyanin, yield striking blue colors but require stabilization strategies to prevent fading (Mutaf-Kılıç et al., 2023; Pagels et al., 2021).

Rocha et al. (2025) critically reviewed the readiness of algae-derived pigments for commercialization, noting that while the color palette is attractive and eco-friendly, challenges of fastness and stability persist. Advances in encapsulation technologies, such as microencapsulation or polymer stabilization, are being explored to extend pigment shelf life. Pagels et al. (2021) highlighted how extraction methods— ranging from solvent-based to physical disruption—directly impact pigment purity and stability, suggesting that scalable and eco-friendly extraction processes are key to commercialization.

B. Paint Formulation and Applications

Several studies demonstrate successful integration of algal pigments into paint matrices. A 2023 experimental study formulated both water- and oil-based biopaints using pigments such as phycocyanin, astaxanthin, and chlorophyll, achieving vibrant colors with satisfactory coverage (ResearchGate Preprint, 2023). Blanckart (2025) extended this approach by testing algae-based coatings on textiles, reporting good adhesion and color intensity, results that can be transferred to architectural paints.

Beyond color, algal additives can enhance paint properties. Carpintero et al. (2023) observed that algae-based materials improve barrier and antimicrobial properties in coatings. Similarly, Tong et al. (2023) explored bio -coatings with immobilized algae, demonstrating potential for “living paints” capable of filtering pollutants or generating oxygen in situ. These innovative applications point to a new generation of paints that combine aesthetics with environmental functionality.

C. Algae in Coatings Beyond Color

The multifunctionality of algae-derived compounds extends the role of algae beyond mere colorants. Algal polysaccharides and bioactive molecules can serve as thickeners, binders, or functional additives.

Carpintero et al. (2023) reviewed algae as multifunctional additives that can improve film flexibility, reduce permeability, and impart bioactivity. This suggests potential for algae-based formulations not only in decorative paints but also in protective coatings for industrial use.

At the same time, algae in coatings are often studied in the context of biodeterioration. Qureshi et al. (2018) investigated façade paints that resist algal colonization, while Hofbauer et al. (2021) warned about toxic algae species in the built environment. This dual role highlights the importance of strain selection, ensuring that only safe, non-toxic algae are used in paint formulations.

D. Sustainability and Circular Economy Perspectives

From a sustainability standpoint, algae-based paints contribute to reducing the environmental burden of the coatings industry. Algae can be cultivated on marginal lands or wastewater streams, requiring fewer resources than terrestrial plants. Their ability to fix CO_2 further positions them as climate-positive materials (Tan et al., 2020). The biodegradability of algae-derived pigments minimizes end-of-life waste problems compared to persistent synthetic dyes.

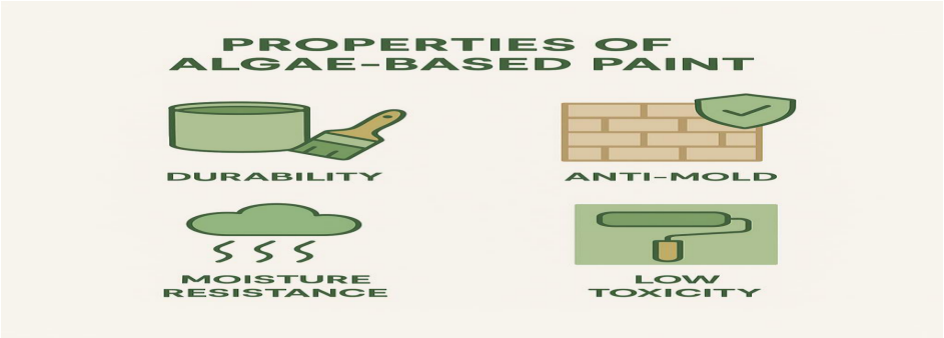
Rocha et al. (2025) emphasize that niche markets such as eco-friendly interior paints, children's products, and sustainable textiles may act as early adopters for algae -based paints. Blanckart (2025) similarly argues that consumer preference for natural and safe products will drive adoption despite higher costs. These insights underscore algae's role not just in sustainable material science but also in green marketing and consumer engagement.

E. Challenges and Research Gaps

Despite the promise, multiple challenges impede large-scale adoption of algae-based paints:

- Pigment instability: Sensitivity to light, temperature, and pH remains the biggest limitation.
- Economic scalability: Synthetic pigments remain cheaper, and large-scale algae cultivation and extraction require cost reduction.
- Standardization: Variability in pigment yield across species and cultivation conditions leads to inconsistent quality.
- Performance limitations: Current algae-based pigments have lower color fastness than synthetic alternatives.
- Safety and regulatory barriers: Some algal species produce harmful compounds, necessitating strict screening and regulatory approvals (Hofbauer et al., 2021).

Future work must therefore integrate material science innovations with biotechnology and process engineering to address these barriers.



IV. RESULTS AND DISCUSSION

A. *Performance Insights*

Coatings with higher nano pigment loading (5%) consistently outperform 2.5% and control paints in microbial inhibition and color richness. Thermal tests showed minimal degradation in mineral-coated pigments, supporting their suitability for high-temperature applications. Antifouling paints demonstrated near-complete biofilm suppression in marine immersion tests over several weeks, surpassing some commercial industrial paints.

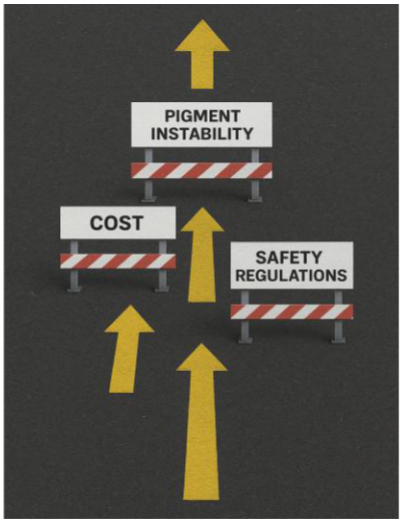
B. *Practical Applications*

Such algae-based paints are applicable in various contexts:

- Eco-conscious interior wall finishes offering natural aesthetics and microbial resistance.
- Marine and industrial coatings providing durable antifouling and antimicrobial surfaces.
- Potential use in biomedical device coatings due to antimicrobial and biocompatible nature.

C. *Future Prospects*

Developments in algae cultivation technology and pigment encapsulation will enhance pigment yield, consistency, and paint longevity. Integration with other biopolymers can improve mechanical properties and film stability, broadening consumer market acceptance.



V. CONCLUSION AND FUTURE DIRECTIONS

Algae-based paints represent a frontier in sustainable materials research, offering eco-friendly pigments and multifunctional additives that can transform the coatings industry. Literature reviewed here demonstrates algae's potential to provide a wide color palette, impart antimicrobial and UV-protective properties, and support circular economy goals through renewable cultivation and biodegradability.

However, the field remains at a pre-commercial stage, constrained by challenges in pigment stability, economic competitiveness, and standardization. Research must focus on stabilization strategies such as encapsulation, hybrid formulations that combine algae with other bio-based or synthetic materials, and scaling up cultivation methods to reduce costs. Furthermore, interdisciplinary collaborations between biotechnologists, chemists, and design professionals will be essential to translate laboratory research into market-ready products.

Future directions include:

- Hybrid paints that integrate algae with other natural pigments to balance performance and cost.
- Encapsulation technologies to improve pigment lightfastness and stability.
- Integration with architecture and interior design, where eco-friendly paints can improve indoor air quality and user well-being.
- Commercialization in niche markets such as children's paints, artisanal design products, and sustainable textiles.
- Policy and regulatory frameworks that incentivize bio-based coatings over synthetic ones.

With sustained research and innovation, algae-based paints can evolve from experimental novelty to a mainstream solution, significantly contributing to a sustainable and healthier future in design and material science.

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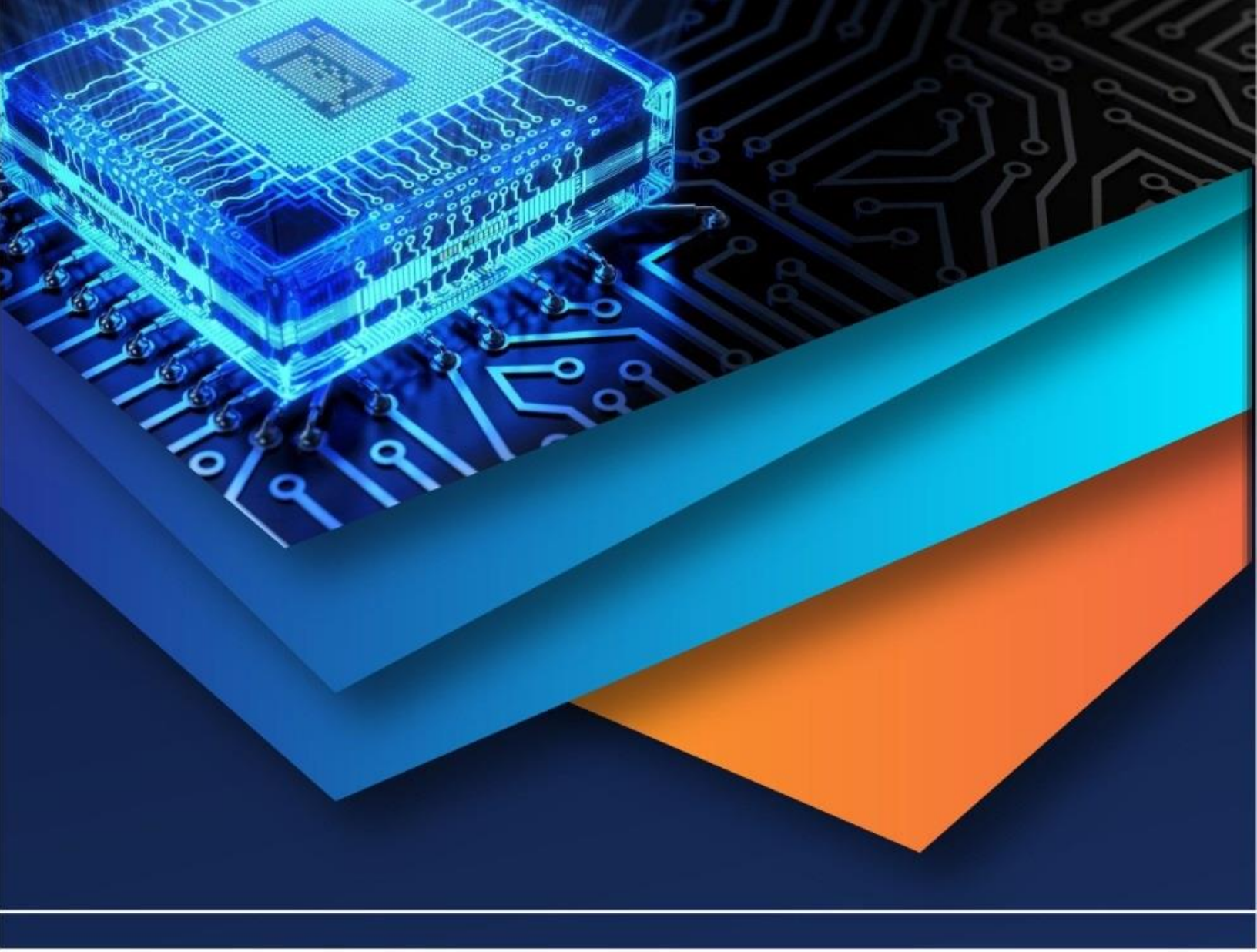

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