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Algae-based bioplastics from biomass to functional materials: Processing, structure–property relationships, environmental fate and scale-up challenges

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Abstract
The search for renewable alternatives to petroleum-derived plastics has increased interest in algae as a versatile biomass feedstock for biopolymer production. Algal biomass contains polysaccharides, proteins, lipids and, in selected microorganisms, biosynthesized polyhydroxyalkanoates that can contribute to the development of films, coatings, blends and composite materials. However, the sustainability and practical performance of algae-based bioplastics depend not only on biomass composition but also on cultivation, harvesting, pretreatment, extraction, formulation, processing and end-of-life conditions. This review critically examines algae-based bioplastics using an integrated feedstock–process–structure–property perspective. Particular attention is given to macroalgal hydrocolloids such as alginate, agar and carrageenan; microalgal and cyanobacterial biomass; direct use of whole biomass; extraction-based polymer recovery; and indirect routes involving fermentation-derived polymer precursors. The review further discusses film formation, plasticization, blending, reinforcement, mechanical and barrier performance, thermal behavior, biodegradation and environmental aging. Economic and environmental considerations are examined with emphasis on energy-intensive downstream processing, feedstock variability, life-cycle assessment, biorefinery integration and scale-up. Evidence indicates that whole-biomass utilization and integrated valorization strategies may reduce purification requirements, whereas polymer extraction and material modification can provide improved control over functionality. Future progress will depend on standardized characterization and biodegradation protocols, low-energy processing, improved compatibility between algal fractions and polymer matrices, and pilot-scale validation. Overall, algae-based bioplastics should be considered as a class of tunable bio-based materials whose environmental value depends on the complete production and end-of-life system rather than on feedstock origin alone.

Keywords: Algae, bioplastics, biopolymers, biodegradable materials, polymer processing, sustainable materials

Introduction

The continued dependence on petroleum-derived plastics has created a demand for materials that combine functional performance with improved resource efficiency and appropriate end-of-life behavior. Bioplastics have consequently received increasing attention as alternatives or complements to conventional polymeric materials. However, the terms bio-based, biodegradable and compostable are not interchangeable. A polymer may be derived from renewable carbon without being biodegradable, while biodegradation itself depends on polymer chemistry, formulation and environmental conditions [13, 14].

Among renewable feedstocks, algae have attracted considerable interest because both microalgae and macroalgae contain structurally diverse biochemical fractions that can be converted into materials or polymer precursors. Macroalgae are particularly rich in hydrocolloids such as alginate, agar, carrageenan, ulvan, fucoidan and laminarin, many of which possess film-forming and gel-forming characteristics [5 ,8]. Microalgae and cyanobacteria can provide carbohydrate- and protein-rich biomass, while selected organisms and engineered systems have been investigated for production of polyhydroxyalkanoates (PHAs) or for generation of fermentation substrates for polymer precursors [1, 3, 4].

The attraction of algal biomass is therefore not simply its renewable origin. A major opportunity lies in matching the biochemical composition of a specific feedstock with the intended polymer architecture and manufacturing route. For example, a seaweed rich in alginate may be suitable for hydrocolloid-based films, whereas whole microalgal biomass may be more appropriate as a filler or functional component in a polymer matrix. Likewise, an algal carbohydrate fraction may be converted into fermentable intermediates rather than used directly as a polymer.

Recent reviews have already examined the global research landscape, commercialization trends and broad technological potential of algal bioplastics [1, 4]. Other studies have focused specifically on seaweed polysaccharides, macroalgal films and microalgal bioplastics [5, 6, 8]. These contributions demonstrate the rapid expansion of the field but also reveal an important unresolved issue: improved biomass productivity, extraction yield or biodegradability does not necessarily translate into a superior final material or a more sustainable production system.

For polymer applications, the relevant question is therefore not whether algae can produce biodegradable materials, but

how feedstock composition, process conditions and polymer formulation interact to determine material performance, environmental behavior and economic feasibility. This review adopts this perspective and organizes the available evidence from biomass cultivation through processing and final material performance.

Review methodology and scope

The available evidence was critically synthesized across key thematic dimensions, including feedstock characteristics, polymer composition, processing routes, potential applications, environmental implications and technological limitations. The review adopts a narrative approach and is intended to provide a critical overview of the current state of knowledge rather than a systematic review or meta-analysis.

Recent peer-reviewed literature was prioritized, while foundational studies were retained where necessary to explain established polymer-processing concepts. The evidence base included research and review literature concerning macroalgae, microalgae and cyanobacteria; algal polysaccharides and other polymer-forming fractions; biomass harvesting and pretreatment; polymer extraction; film formation and composite processing; mechanical, thermal and barrier properties; biodegradation; environmental assessment; and techno-economic considerations.

Algal feedstocks and polymer-forming fractions

1. Microalgae and cyanobacteria

Microalgae and cyanobacteria offer rapid biomass generation and can be cultivated in controlled systems or integrated with nutrient-recovery processes. Species investigated for bioplastic-related applications include Chlorella, Scenedesmus, Chlamydomonas and several cyanobacterial genera [1, 3, 4].

The biochemical composition of microalgal biomass varies substantially with organism, cultivation system and environmental conditions. Carbohydrates, proteins and lipids may therefore serve different functions during material production. Whole biomass can be incorporated into polymer matrices, while selected fractions can be extracted or converted into precursor molecules.

Cyanobacteria deserve separate consideration because some strains possess metabolic pathways associated with intracellular PHA accumulation. In this context, PHA should not be treated as a universal "algal polymer." Rather, PHA production is associated with specific microorganisms and cultivation or metabolic-engineering strategies. Similarly, polylactic acid (PLA) is not directly synthesized by algae; algal carbohydrates may instead serve as a renewable carbon source for fermentation to lactic acid, followed by polymer synthesis [3, 4].

These distinctions are important because the upstream cultivation and downstream processing requirements differ substantially between direct algal-polymer utilization and indirect conversion routes.

2. Macroalgae and seaweed-derived polymers

Macroalgae provide a particularly attractive platform for polymer development because several commercially established hydrocolloids can be isolated from different taxonomic groups. Brown seaweeds are important sources of alginate, whereas red seaweeds are major sources of agar and carrageenan. Other polysaccharides, including ulvan, fucoidan and laminarin, have also been investigated for material applications [5, 8].

Alginate forms gels through ionic interactions and can generate films with useful transparency and flexibility. Carrageenan provides film-forming and gel-forming properties and can be modified through blending and plasticization. Agar is also capable of forming coherent films but may require formulation changes to overcome brittleness and moisture sensitivity.

The chemical structure, molecular weight, degree of substitution or sulfation, monomer composition and extraction history influence polymer behavior. Consequently, "seaweed-based bioplastic" is not a single material class but a family of materials whose performance depends strongly on polymer chemistry.

3. Feedstock selection as a polymer-design decision

Feedstock selection should be based on more than biomass productivity. Important parameters include carbohydrate and protein content, polysaccharide type, ash and mineral content, moisture, pigment concentration, cell-wall structure, contaminant levels and seasonal variability. These parameters influence harvesting requirements, extraction efficiency, molecular integrity and subsequent processing behavior.

A feedstock rich in a target polymer may reduce purification requirements, whereas a whole-biomass route may avoid extraction but produce a less homogeneous material. Conversely, extensive purification may increase polymer purity while simultaneously increasing water, chemical and energy consumption.

Table 1: Relationship between algal feedstocks, polymer fractions and material-production strategies

Feedstock	Principal relevant fraction	Major material route	Potential advantage	Principal limitation
Brown macroalgae	Alginate and other polysaccharides	Extraction followed by film or composite formation	Established polymer chemistry and gel formation	Moisture sensitivity and extraction requirements
Red macroalgae	Agar, carrageenan	Direct extraction and film formation	Strong film-forming and gel-forming behavior	Brittleness or water sensitivity depending on formulation
Green macroalgae	Ulvan and mixed polysaccharides	Extraction, blending or composite formation	Structural diversity and renewable origin	Feedstock variability and less-established processing routes
Microalgae	Proteins, carbohydrates, lipids	Whole biomass, extraction or precursor conversion	Rapid cultivation and process flexibility	Dilute biomass and costly harvesting
Cyanobacteria	Biomass and selected intracellular PHAs	Direct biomass use or biosynthetic PHA route	Potential for intracellular polymer production	Species-specific biology and scale-up challenges
Mixed or residual algal biomass	Multiple fractions	Whole-biomass composites or biorefinery route	Reduced purification requirements	Heterogeneous composition

Conversion of algal biomass into bioplastic materials

1. Cultivation

Cultivation represents the first major stage in the production chain. Light intensity, temperature, pH, carbon dioxide availability and nutrient supply influence biomass productivity and biochemical composition [7]. Production systems may include open ponds, closed photobioreactors and other controlled cultivation configurations.

Nutrient limitation can alter intracellular carbohydrate, lipid or other metabolite accumulation. Two-stage cultivation strategies can therefore separate biomass generation from metabolic enrichment. Biomass may initially be produced under favorable conditions and subsequently exposed to controlled stress to increase the concentration of a target component.

However, increased intracellular metabolite concentration does not automatically improve process economics. Stress conditions can reduce overall biomass productivity and may increase the cultivation time or resource requirement per unit of final product. Consequently, optimization should consider both biomass productivity and target-component productivity.

For industrial polymer production, stable biomass composition may be as important as maximum biomass yield because large variations in composition can influence extraction, formulation and final material properties.

2. Harvesting and biomass concentration

Harvesting is particularly important for microalgae because the biomass concentration in culture systems is generally low. Centrifugation, filtration, membrane separation, sedimentation and flocculation are among the methods used for biomass concentration [8, 9].

The choice of harvesting technology affects downstream polymer production. Residual culture medium, salts and extracellular components may interfere with extraction or modify the composition of the final material. Mechanical concentration can provide relatively clean biomass but may require considerable energy, whereas flocculation may reduce energy demand but introduce additional chemicals or require subsequent purification.

Recent work on algal dewatering emphasizes that membrane and concentration technologies should be selected according to the intended downstream product rather than treated as independent process steps [9].

3. Drying and pretreatment

Following harvesting, biomass may be dried or processed in a wet state. Drying improves storage stability and facilitates handling but introduces an additional energy-intensive operation. Where downstream processing permits, wet-biomass processing may reduce the need for complete drying.

Pretreatment is used to disrupt cell structures, alter biomass accessibility or facilitate recovery of intracellular components. Mechanical, chemical, thermal and enzymatic methods have all been investigated [7]. The selection of pretreatment depends on the intended production route.

A pretreatment that is appropriate for carbohydrate hydrolysis may be unsuitable for recovery of an intact polymer because excessive temperature, pH or chemical exposure can alter molecular weight or promote degradation. Therefore, pretreatment should be considered in relation to the **required polymer integrity**, not solely extraction yield.

4. Extraction and recovery of biopolymers

Extraction represents a major differentiation between algal material platforms. Seaweed-derived polysaccharides such as alginate, agar and carrageenan can be obtained through established extraction routes, while intracellular components from microalgae may require cell disruption followed by aqueous, solvent-based or enzymatic recovery [3, 5].

Extraction efficiency should be evaluated using more than percentage yield. Important metrics include polymer purity, molecular-weight retention, solvent consumption, water demand, chemical usage, energy input and waste generation. Enzyme-assisted and other lower-severity extraction strategies are increasingly attractive because they may improve selectivity while reducing some of the limitations associated with harsh chemical treatment [5]. Nevertheless, enzyme cost, reaction time and process control remain important considerations.

An integrated biorefinery approach can improve overall resource utilization by assigning different biomass fractions to different products. A polysaccharide fraction can be directed to polymer production, while proteins, pigments, lipids or residual solids may be valorized through additional routes. This approach reduces the burden placed on a single product to support the economics of the complete process [3, 7].

5. Direct biomass utilization and precursor-based routes

Three broad pathways can be distinguished.

Direct biomass route. Whole or partially processed biomass is incorporated into a polymer matrix. This pathway minimizes purification and can improve resource efficiency, but material composition may be heterogeneous.

Extracted-biopolymer route: Target polymers such as alginate, agar or carrageenan are recovered and formulated into films, coatings or composites. This provides greater control over polymer chemistry but increases downstream processing requirements.

Indirect precursor route: Algal carbohydrates or other biomass fractions are converted into monomers or microbial polymer products. Examples include fermentation-derived lactic acid for PLA production or biosynthetic PHA systems. Such routes can produce more conventional polymer structures but require additional biological or chemical conversion stages [3, 4].

The economically preferred route is therefore feedstock- and application-specific. A highly purified polymer is not necessarily the most sustainable option when a whole-biomass composite can provide adequate performance with substantially fewer processing steps.

6. Film formation and polymer processing

Recovered algal polymers can be fabricated by solvent casting, compression molding, extrusion, thermoforming or related processing techniques. Solvent casting is widely used at laboratory scale because it allows relatively simple preparation of thin films, whereas extrusion and molding are more relevant to continuous industrial manufacturing.

Plasticizers such as glycerol and sorbitol can increase chain mobility and flexibility in hydrophilic polysaccharide- and protein-based systems. However, greater plasticizer concentration may also reduce tensile strength, increase water uptake and alter dimensional stability [5, 8].

7. Blends and composite materials

Blending and composite formation provide practical strategies for overcoming weaknesses in single-component algal materials. Hydrophilic algal polymers can be combined with other biodegradable polymers, fibers, nanomaterials, proteins or hydrophobic components to modify mechanical, thermal and barrier properties [5, 8].

Whole algal biomass may also be used as a filler or reinforcing phase. This strategy can reduce purification requirements and increase biomass utilization efficiency. However, poor interfacial compatibility between algal particles and the polymer matrix may reduce tensile performance.

Surface modification, compatibilization, particle-size control and cross-linking can improve matrix–filler interactions. The resulting material should nevertheless be assessed in terms of the complete environmental burden because an additive that improves performance may introduce additional synthesis, toxicity or end-of-life considerations.

The broader principle of converting heterogeneous biomass residues into value-added bioplastic materials has also been demonstrated using agricultural wastes. Biswas *et al.* reported approaches for preparation of bioplastics from agricultural and food-processing residues, illustrating the potential of biomass valorization as a complementary strategy to algal feedstock utilization [16].

Structure–property relationships in algae-based bioplastics

1. Mechanical properties

Mechanical performance is one of the principal barriers to wider use of algae-based materials. Important parameters include tensile strength, elongation at break, Young's modulus, impact resistance and flexibility.

Mechanical behavior depends on polymer molecular weight, crystallinity, intermolecular interactions, plasticizer concentration, moisture content, filler distribution and processing conditions. In algal composites, increasing biomass loading may improve biodegradation potential or reduce polymer consumption but may also decrease tensile strength when matrix–filler adhesion is poor [1, 12].

Accordingly, mechanical performance should not be reported without consideration of composition. Comparisons between studies are difficult when specimens differ in thickness, moisture content, test conditions, plasticizer concentration or conditioning humidity.

2. Barrier properties

Water-vapor permeability and oxygen permeability are particularly relevant for packaging applications. Many algal polysaccharides are hydrophilic, resulting in high sensitivity to humidity and water.

Approaches used to improve barrier performance include cross-linking, incorporation of hydrophobic components, polymer blending, surface coating and addition of reinforcing nanoparticles [5, 8]. However, an improvement in water resistance may be accompanied by reduced flexibility or altered biodegradation.

For food-packaging applications, the appropriate material should therefore be optimized for the intended food matrix and storage environment rather than evaluated using a single universal barrier criterion.

3. Thermal and morphological properties

Thermal stability determines the range of processing conditions that can be applied during extrusion, molding or thermal conversion. Thermal analysis, including thermogravimetric analysis and differential scanning calorimetry, can be used to evaluate degradation behavior and thermal transitions [14, 15].

Morphological analysis provides information on surface roughness, porosity, phase separation, filler dispersion and matrix–filler interaction. These structural characteristics can help explain differences in tensile and barrier behavior.

The polymer-processing-property relationship is particularly important for algal materials because the same chemical composition may produce markedly different properties when processed under different drying, plasticization, cross-linking or thermal conditions.

4. Biodegradation and environmental aging

Biodegradation is a functional property that should be interpreted alongside service-life requirements. A packaging film must remain sufficiently stable during intended use but should degrade under an appropriate end-of-life pathway.

The rate and mechanism of degradation depend on polymer chemistry, crystallinity, molecular weight, water availability, temperature, microbial community, oxygen availability and formulation [13, 14]. Industrial composting, soil exposure, freshwater, marine environments and landfill conditions can therefore produce substantially different outcomes.

Recent literature emphasizes that claims of biodegradability should specify the environmental conditions and test methodology rather than treating “biodegradable” as an intrinsic universal property [13]. Environmental aging may also occur through moisture, ultraviolet radiation, thermal exposure and mechanical stress before biological degradation becomes dominant [14].

Table 2: Principal processing variables and their expected influence on material performance

Processing variable	Primary effect	Potential benefit	Potential trade-off
Cultivation conditions	Alters biomass composition	Higher target fraction	Reduced total biomass under stress
Harvesting method	Determines biomass purity and moisture	Efficient concentration	Energy or chemical demand
Drying temperature	Controls moisture removal	Improved storage stability	Thermal damage and energy use
Pretreatment severity	Controls accessibility of intracellular material	Improved recovery	Polymer degradation

Extraction conditions	Determines purity and molecular integrity	Higher polymer recovery	Solvent, water and energy demand
Plasticizer concentration	Changes chain mobility	Higher flexibility	Lower strength and higher water sensitivity
Cross-linking	Restricts polymer-chain mobility	Improved stability and barrier properties	Lower flexibility and possible reduced biodegradation rate
Filler loading	Changes matrix structure	Reduced polymer use or reinforcement	Agglomeration and reduced tensile strength
Processing temperature	Controls melt or structural formation	Industrial processability	Thermal degradation
Surface coating	Alters surface chemistry	Improved moisture barrier	Additional processing and end-of-life complexity

Potential applications

1. Food and flexible packaging

Food packaging represents one of the most frequently investigated applications because algal polysaccharides can form films and may also provide functional properties such as antioxidant or antimicrobial activity [5, 8]. However, the performance requirements of food packaging extend beyond biodegradability.

The material must provide adequate mechanical integrity, oxygen and moisture control, resistance to handling and storage conditions, and appropriate food-contact safety. Water sensitivity remains an important barrier for many polysaccharide-based materials.

Active packaging is a particularly promising area because bioactive compounds can potentially be incorporated into algal matrices. Nevertheless, migration behavior, dose control, sensory effects and regulatory compliance require rigorous evaluation before practical food applications.

2. Agricultural materials

Biodegradable films and coatings may have applications in agricultural systems where temporary functionality is required. Potential uses include mulch films, seed coatings and controlled-release matrices.

For these applications, degradation rate becomes an important design parameter. Excessively slow degradation can leave persistent residues, whereas excessively rapid degradation may compromise functionality. Soil type, moisture, temperature and microbial activity should therefore be considered during material evaluation.

3. Biomedical and pharmaceutical materials

Alginate, agar and carrageenan possess properties that make algal polymers relevant to biomedical research, including gel formation and biocompatibility. Potential applications include wound-dressing matrices, encapsulation systems and controlled-release materials [5, 8].

However, biomedical deployment requires substantially more stringent characterization than conventional packaging applications. Purity, endotoxin or contaminant content, sterilization stability, cytocompatibility and controlled degradation must be established for the intended use.

4. Short-lived consumer and disposable materials

Algal composites may also be suitable for selected disposable items, coatings, trays and molded products where the intended service life is short and the desired end-of-life route is compatible with the material chemistry.

The suitability of these applications depends on balancing mechanical performance, moisture resistance, processability and degradation behavior.

Environmental sustainability and circularity

1. Environmental advantages and limitations

Algal cultivation can potentially utilize non-arable land, saline water or nutrient-containing waste streams, reducing competition with some terrestrial resources. Algae also assimilate carbon dioxide during growth. These characteristics create opportunities for lower-impact biomass production [1, 3, 7].

However, a carbon-uptake claim at the cultivation stage does not by itself establish a lower overall environmental footprint. Cultivation energy, mixing, aeration, pumping, nutrient supply, harvesting, drying, chemical extraction and downstream processing can substantially influence the total impact.

Consequently, algae-based bioplastics should be assessed over their entire life cycle rather than on cultivation characteristics alone.

2. Life-cycle assessment

Life-cycle assessment (LCA) is particularly important because environmental performance can change with system boundaries, energy sources, allocation methods, functional units and coproduct assumptions.

A recent systematic assessment of microalgal valorization found substantial variation among reported LCA outcomes and identified concerns involving limited impact categories, data quality and transparency [12]. These findings are directly relevant to algal bioplastic research.

For future studies, LCA should preferably report at least cultivation, harvesting, downstream extraction or conversion, polymer processing and end-of-life stages. Sensitivity analysis should identify the process variables with the largest environmental influence.

3. Techno-economic considerations

Economic feasibility is another critical issue. Algal bioplastics may face high costs because of dilute biomass, harvesting, drying, extraction and purification requirements.

Techno-economic work has shown that integrated algal biorefineries can improve the economic outlook by assigning multiple value streams to the biomass [11]. Similar conclusions have emerged from reviews emphasizing that whole-biomass utilization can avoid some downstream purification costs [3].

Therefore, future development should not focus solely on maximizing the yield of one polymer. The economic value of proteins, pigments, lipids, fertilizers, feed components, energy products and other coproducts may be essential to support the overall system.

4. Circular use of biomass

A circular strategy can be represented as:

cultivation → biomass recovery → high-value fraction recovery → polymer/material production → use → biological or material recovery → residual biomass valorization

Such integration may increase resource productivity while reducing waste streams.

The use of agricultural residues in parallel with algal biomass further illustrates the broader concept of converting underutilized renewable feedstocks into functional polymeric materials [16]. Hybrid systems combining algae with agricultural waste or other biopolymer sources may therefore represent an important future direction.

Technological limitations and scale-up challenges

1. Feedstock variability

Biochemical composition may change with species, season, geographical origin and cultivation conditions. Such variation complicates quality control and may alter extraction yield and final material properties.

Industrial production will therefore require defined feedstock specifications for moisture, ash, target polymer concentration, contaminants and relevant physicochemical properties.

2. Energy-intensive downstream operations

Harvesting and drying can become major energy-demanding operations, especially for dilute microalgal cultures [7, 9]. Strategies that reduce the number of dewatering and drying stages may consequently provide major environmental and economic benefits.

3. Extraction versus direct utilization

Purification improves control over polymer chemistry but adds processing complexity. Direct utilization minimizes processing but increases heterogeneity.

The optimal route should therefore be selected according to the performance requirements of the final product rather than assuming that highly purified polymer is always preferable.

4. Mechanical and moisture limitations

Many algal polysaccharide materials exhibit a combination of good film-forming capacity and poor moisture resistance. Plasticizers can improve flexibility but may reduce strength and increase water sensitivity.

Blending, cross-linking, surface modification and reinforcement offer solutions, but these interventions also increase formulation complexity.

5. Standardization of biodegradation testing

Comparative biodegradation studies are difficult when researchers use different soil types, temperatures, humidity levels, inocula, sample dimensions and test durations. A standardized framework is therefore necessary for meaningful comparison [13, 14].

Biodegradation should ideally be accompanied by mass loss, mechanical-property retention, structural or chemical changes and, where appropriate, mineralization measurements.

6. Regulatory and market barriers

Commercial use also depends on food-contact requirements, compostability standards, chemical migration limits, labeling rules and waste-management infrastructure.

Regulatory acceptance should be considered during material design rather than after material development is complete.

Table 3: Key barriers to commercialization and research priorities

Barrier	Consequence	Priority research direction
Low biomass concentration	High harvesting cost	Low-energy concentration technologies
Variable feedstock composition	Batch-to-batch property variation	Standardized biomass specifications
Costly drying	Increased energy demand	Wet-biomass processing routes
Harsh extraction	Polymer degradation and waste	Aqueous and enzyme-assisted extraction
Poor moisture resistance	Limited packaging performance	Cross-linking, coatings and hydrophobic blends
Weak matrix–filler adhesion	Reduced strength	Compatibilization and surface modification
Limited pilot-scale evidence	Uncertain industrial feasibility	Pilot and demonstration-scale trials
Inconsistent degradation testing	Poor cross-study comparability	Standardized environmental protocols
Limited LCA/TEA data	Uncertain sustainability	Integrated LCA–TEA studies
End-of-life complexity	Risk of environmental mismanagement	Application-specific disposal and recovery systems

Emerging technologies and future research directions

1. Integrated biorefinery platforms

The most promising development pathway is likely to involve integrated biorefineries rather than single-product processes. By recovering several marketable fractions from the same biomass, the economic burden of cultivation and harvesting can be distributed across multiple products [3, 7, 11].

In such systems, polymer production would represent one component of biomass valorization rather than the sole source of revenue.

2. Wastewater-integrated cultivation

Cultivation systems coupled with wastewater treatment may provide nutrients while simultaneously generating biomass. This approach has potential to reduce freshwater and nutrient inputs but requires careful assessment of contaminants, biomass quality and suitability for the final application [7].

Biomass grown on contaminated streams may be inappropriate for food-contact or biomedical applications unless adequate purification and safety assessment are demonstrated.

3. Low-energy extraction and processing

Future research should prioritize aqueous extraction, enzyme-assisted processing, membrane-based concentration and other low-severity processes. Reducing solvent and energy consumption may provide greater sustainability gains than modest improvements in polymer recovery.

4. Advanced blending and nanocomposite design

Nanofillers, fibers, bio-based compatibilizers and surface coatings can be used to tune strength, barrier properties and

thermal behavior [5, 8]. Future work should evaluate these modifications simultaneously with biodegradation and environmental safety rather than optimizing mechanical performance in isolation.

5. Digital process optimization

Artificial intelligence, machine learning and sensor-based process control are emerging tools for cultivation and material development. These methods may assist in predicting biomass composition, optimizing cultivation conditions and linking formulation variables with material properties [12].

However, reliable machine-learning applications require standardized, high-quality datasets. Greater experimental harmonization is therefore a prerequisite for meaningful predictive modeling.

6. Standardized structure–property databases

A shared database linking species, biochemical composition, extraction conditions, polymer molecular characteristics, plasticizer content, processing conditions and measured material properties would facilitate cross-study comparisons.

Such a framework could eventually enable predictive formulation of algal materials for specific applications.

Conclusions

Algae-based bioplastics represent a diverse class of renewable polymeric materials rather than a single homogeneous technology. Their performance is determined by the interaction among feedstock composition, cultivation conditions, biomass recovery, pretreatment, polymer extraction, formulation and processing. Macroalgal polysaccharides such as alginate, agar and carrageenan provide established platforms for film and gel formation, whereas microalgal and cyanobacterial biomass offers opportunities for whole-biomass composites, extraction of functional fractions and precursor-based polymer production.

The major technical challenge is the trade-off between process simplicity, material performance and environmental burden. Purification can improve polymer consistency but increase energy, solvent and water requirements. Whole-biomass utilization can reduce processing intensity but may introduce compositional variability. Similarly, plasticization, cross-linking and reinforcement can improve functional properties but may alter moisture sensitivity, recyclability or degradation behavior.

The environmental advantages of algae-based bioplastics should therefore not be assumed from renewable feedstock origin alone. Life-cycle performance depends strongly on cultivation energy, harvesting, drying, extraction, formulation, processing and end-of-life conditions. Economic viability likewise depends on process integration and efficient use of coproducts.

Future progress will require integrated biorefinery models, low-energy downstream processing, standardized material characterization, application-specific biodegradation testing and pilot-scale validation. A feedstock–process–structure–property–environment framework provides a useful basis for designing algae-derived materials that are not only biodegradable or bio-based, but also technically credible and environmentally meaningful.

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Conflict of interest

The authors declare that there is no conflict of interest associated with this manuscript.

Author Contribution

Sneha Halder contributed to literature collection and preparation of the initial manuscript. Dr. Rupali Dhara Mitra contributed to conceptualization, scientific interpretation, manuscript development and critical revision. Both authors approved the final manuscript.

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