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Trends in Bioplastics from Marine Resources

Airon D. Dulay[1], Therese Elaine B. Enad[1], and Marco Nemesio E. Montaño[2,3*]

[1] Department of Biology, University of San Carlos;
[2*] Marine Science Institute University of the Philippines Diliman; and
[3] Mathematical and Physical Sciences Division, National Academy of Science and Technology Philippines

Correspondence:
Marco Nemesio E. Montaño
coke.montano2@gmail.com

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ORCID
Marco Nemesio E. Montaño
https://orcid.org/0000-0003-0189-8126

ABSTRACT

Marine-derived bioplastics have emerged as a promising class of sustainable materials capable of addressing the environmental and resource limitations associated with conventional petroleum-based plastics and first-generation bio-based polymers. This review synthesizes recent advances in the development of bioplastics derived from marine biomass, including seaweeds, fishery byproducts, and marine microorganisms. Key biopolymers such as agar, alginate, carrageenan, ulvan, chitin, and polyhydroxyalkanoates (PHAs) exhibit favorable properties, including biodegradability, biocompatibility, and functional versatility for applications in packaging, biomedical devices, and industrial materials. In addition, marine-based biocomposites incorporating natural reinforcements—such as chitosan, fish scales, and seashell-derived fillers—demonstrate enhanced mechanical performance and barrier properties. Using a systematic review approach guided by PRISMA, this study evaluates material characteristics, processing technologies, and application domains, while identifying key trends in research, innovation, and early-stage commercialization. The findings highlight the growing integration of marine bioplastics into circular economy frameworks, particularly through the valorization of marine waste streams and the expansion of seaweed-based production systems. However, large-scale adoption remains constrained by high production costs, feedstock variability, and limitations in mechanical and thermal performance relative to conventional plastics. Future progress will depend on advancements in extraction and processing technologies, improved material engineering, and stronger alignment between policy, industry, and research systems. Addressing these challenges is essential to enable the transition of marine bioplastics from emerging innovations to scalable and economically viable alternatives within global materials markets.

Keywords: Marine bioplastics, Biodegradable polymers, Seaweed-based plastics, Sustainable packaging, Marine biocompositesç

Abbreviations: PLA, Polylactic Acid; PHA, Polyhydroxyalkanoates; PBS, Polybutylene Succinate; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; PMMA, Polymethyl Methacrylate; $CaCO_3$, Calcium Carbonate; PVA, Polyvinyl Alcohol; GO, Graphene Oxide; TPSA, Thermoplastic Sugar Palm Starch–Agar; PP, Polypropylene; EPR, Extended Producer Responsibility; TRL, Technology Readiness Level.

INTRODUCTION

Plastic pollution remains one of the most persistent and complex environmental challenges of the twenty-first century, driven by the exponential growth of petroleum-based plastic production and its inadequate end-of-life management (Iroegbu et al. 2021). Global initiatives have attempted to mitigate this issue through recycling systems, waste management improvements, bans on single-use plastics, and the development of bio-based alternatives such as polylactic acid (PLA) and starch-derived polymers (Jha et al. 2024). Despite these interventions, plastic waste continues to accumulate across terrestrial and marine ecosystems due to low recycling rates, material heterogeneity, and the inherent durability of conventional plastics. Even first-generation bioplastics, while derived from renewable feedstocks, present limitations including competition with food resources, dependence on arable land, and in some cases, limited biodegradability under natural environmental conditions (Ghosh and Jones 2021). These constraints highlight that although existing solutions are significant, they remain insufficient to curb the escalating plastic crisis.

In this context, marine-derived bioplastics have emerged as a promising and relatively underexplored alternative that addresses several limitations of both conventional plastics and terrestrial bioplastics. Derived from abundant and renewable marine biomass such as seaweed, crustacean shells, and fishery byproducts, these materials do not compete with food systems and require minimal freshwater and land resources. However, despite increasing research interest, the field remains fragmented, with limited synthesis of advancements in material properties, production technologies, scalability, and real-world applications. Furthermore, critical challenges—including economic feasibility, industrial scalability, and performance optimization—have not been comprehensively evaluated within a unified framework. (Nagarajan et al. 2024).

This review therefore aims to bridge this gap by systematically synthesizing current trends in marine-derived bioplastics and biocomposites, critically assessing their advantages over existing materials, and identifying key technological and industrial barriers. It provides a timely and cohesive perspective on why marine bioplastics are not only relevant but necessary in advancing sustainable material solutions in the face of a worsening global plastic pollution problem.

Materials and Methods

This systematic review, conducted in accordance with PRISMA guidelines, evaluated the potential of marine resources such as algae, marine microorganisms, and other marine-derived materials for bioplastic production. Employing a structured and transparent methodology, the review consolidated current research in this emerging field and identified prevailing trends and future opportunities.

Eligibility and Search Strategy

This review included peer-reviewed primary research articles, reviews, and case studies published in English that focused on marine-derived resources for bioplastics. Non-peer-reviewed literature and studies not related to marine resources or bioplastics were excluded. A comprehensive search of the CAPES Journal database was conducted using targeted keywords such as “marine bioplastics,” “biodegradable plastics,” “biopolymer,” “marine biocomposite,” “seaweed,” “fish waste,” “marine resources,” “marine algae,” and “shell waste.” Boolean operators were applied to combine these keywords and enhance the search results. The

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search covered publications from the inception of the databases through November 2024, with additional studies identified through backward citation searches.

PRISMA Guideline and Study Selection Process

The PRISMA framework offers a standardized flow diagram and checklist to document the identification, screening, eligibility, and inclusion of studies (Figure 1). Employing PRISMA in this review was critical to ensure methodological transparency and reproducibility. The selected studies constituted the evidence base for analyzing trends in marine-derived bioplastics and biocomposites.

Marine Resources

Major feedstocks for marine bioplastics include seaweed biomass, crustacean shells, fishery residues, and microbial sources, each providing distinct polymers and functional compounds (Figure 2). Among these, marine resources offer strong potential as sustainable alternatives to petroleum-based plastics, with seaweed being particularly promising because it contains natural biopolymers such as agar, alginate, carrageenan, and ulvan that can be processed into biodegradable films and packaging materials (Narayanan et al. 2023; Khalil et al. 2017). Red, green, and brown seaweed species are especially valuable for producing bioplastics with good strength, flexibility, and faster degradation in natural environments.

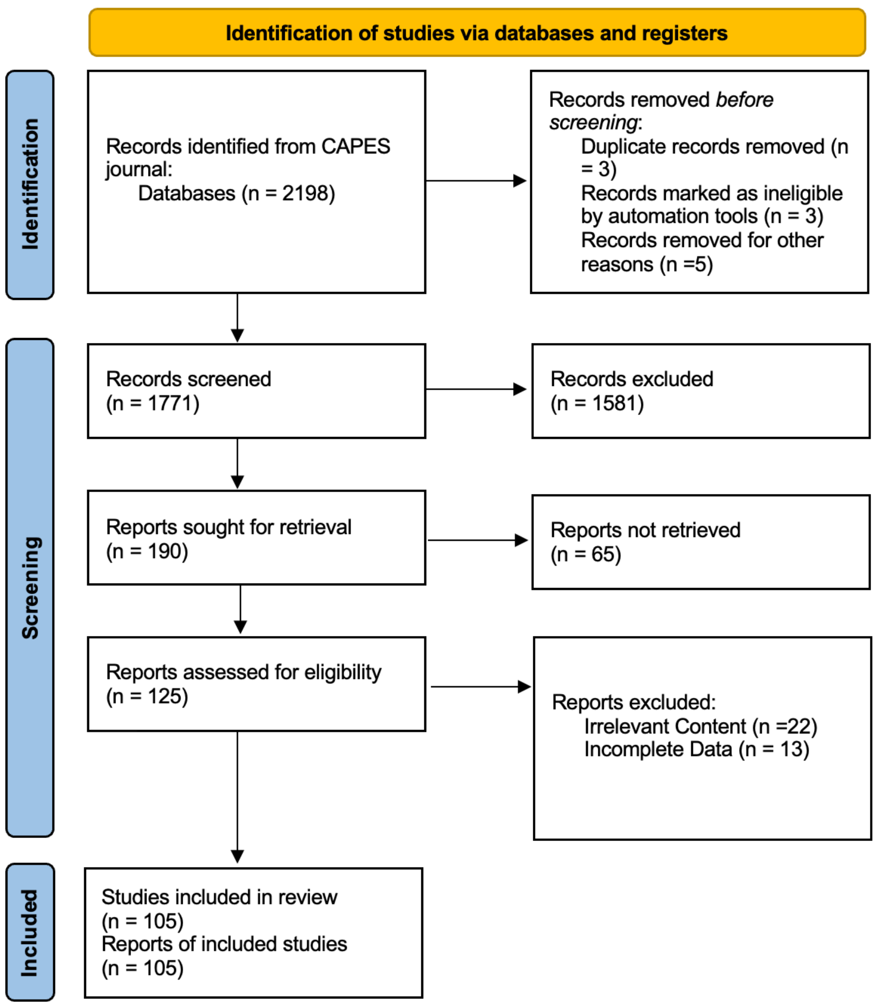

Figure 1. Flowchart based on the PRISMA model with the result of the search carried out in the database (2000-2025) using the keyword "marine bioplastics"

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Figure 2. Common resources for marine bioplastics. (Images via Canva.com).

Crustacean shells represent a significant marine resource due to their content of chitin and its derivative, chitosan. These natural polymers, found in shrimp, crab, and lobster shells, are biodegradable and possess antimicrobial properties, which make them highly suitable for bioplastic production. Chitosan-based materials have been extensively studied for applications in food packaging, medical products, and agricultural films (Kumari and Kishor 2020). Additionally, fishery byproducts such as fish scales and collagen are utilized as raw materials for bioplastics. Collagen extracted from fish skin and scales can be processed into gelatin-based bioplastics that are both flexible and biodegradable. These materials are applied in medicine, including wound dressings and drug delivery systems, as well as in food packaging (Lionetto and Esposito Corcione 2021).

Agar-Based Bioplastics

Agar, a gel-forming polysaccharide extracted from red seaweed, has long been used in food and pharmaceutical applications and is now increasingly recognized as a biodegradable material that can help reduce plastic waste (Armisen R and Galatas 1987; Mostafavi and Zaeim 2020). Commercial production is mainly derived from red algae such as *Gelidiella*, *Gracilaria*, and *Pterocladia*, which are valued for their high polysaccharide yield and superior gel quality (Figure 3).

Alginate Bioplastics

Brown seaweed is a major source of alginate, a polymer composed of mannuronic and guluronic acids that forms hydrogels when combined with calcium ions and water (King 2019). After extraction and purification, it is commonly converted into sodium alginate for diverse applications, including films, hydrogels, packaging systems, drug delivery, and edible coatings due to its biocompatibility (Saji et al. 2022; Santana et al. 2024). Major industrial sources include brown algae such as *Laminaria*, *Macrocystis*, and *Sargassum* (Figure 4).

Carrageenan Bioplastics

Carrageenan, a gelling and stabilizing agent extracted from red seaweed, has three principal forms with distinct structural and functional properties that determine their applications in bioplastics (Therkelsen 1993). Kappa (κ) carrageenan forms rigid gels with potassium ions and is blended with sorbitol or polyethylene glycol to improve material strength, while iota (ι) carrageenan forms elastic gels with calcium ions and is used in biodegradable composites with modified starch (Krishnan et al. 2024; Abdillah and Charles 2021). Lambda (λ) carrageenan functions mainly as a thickener in liquid products and biodegradable films and is often combined with bioactive additives to extend shelf life (Mathew et al. 2024). These differences make carrageenan suitable for rigid, elastic, or thickening applications in marine bioplastics (Figure 5).

Ulvan

Ulvan, a sulfated polysaccharide found in green seaweed of the genus Ulva, is composed of sugars and sulfate groups and is a key material for biodegradable film development (Lahaye and Robic 2007). These films are typically produced by dissolving dried ulvan in water and blending it with plasticizers, with the type of plasticizer strongly influencing the final bioplastic

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Figure 3. Red algae that are commercially sources of agar A. *Gelidiella*, B. *Gracilaria*, C. *Pterocladia*. (Photos courtesy of Dr. Ganzon-Fortes 2026).

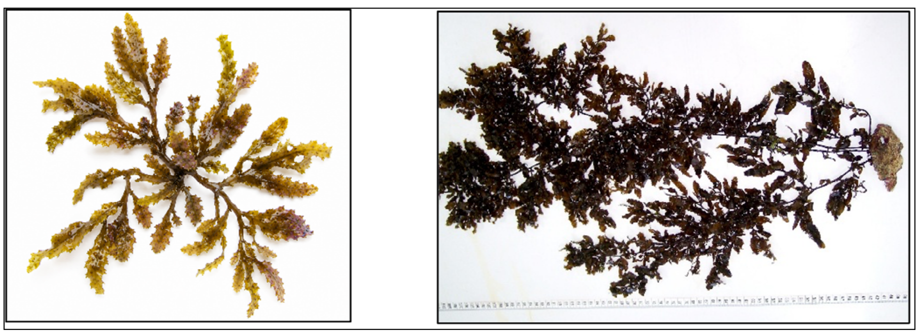

Figure 4. Brown alga *Sargassum*, a commercially important source of alginate. (Photos courtesy of Dr. Ganzon-Fortes 2026).

properties (Guidara et al. 2020; Ganesan et al. 2018). Green seaweeds of the genus Ulva are the principal commercial source of ulvan (Figure 6).

Fish and Shellfish Waste-Based Bioplastics

Fish and shell waste, which are rich sources of collagen, chitin, and chitosan, can be processed into biodegradable biopolymers (Espinales et al. 2023). The extraction process typically includes cleaning, demineralization, and either chemical or enzymatic treatment (Saravanan et al. 2023). Chitosan, obtained from chitin, finds applications in medicine, agriculture, and packaging (Hisham et al. 2024). Marine collagen, extracted using acid or enzymatic methods, exhibits film-forming properties but often requires further modification to enhance water resistance (Harris et al. 2021). The incorporation of additives such as antioxidants can improve the mechanical strength and barrier properties of food packaging materials (Luo et al. 2022).

Chitin and Chitosan-Based Bioplastics

Chitin is a structural polysaccharide found in the shells of crustaceans such as crabs, shrimp, and lobsters, as well as in mollusks, and is composed of N-acetyl-D-glucosamine (Iber et al. 2022). Its deacetylated derivative, chitosan, contains both N-acetyl-glucosamine and glucosamine units and has gained major interest as an abundant, low-cost biopolymer (Kasaai 2009). Through chemical or biological processing, chitin and chitosan can be modified with plasticizers, crosslinkers, polymers, or nanofillers such as graphene oxide to improve their mechanical and functional properties (Hejazi et al. 2018; Mishra et al. 2018). Their strong film-forming ability, biodegradability, limited permeability, biological activity, and antibacterial effects make them valuable for edible films, packaging, sutures, and biomedical applications such as bone tissue healing (Priyadarshi and Rhim 2020; Lee et al. 2023). Chitin and chitosan possess closely related structures that underpin these properties (Figure 7).

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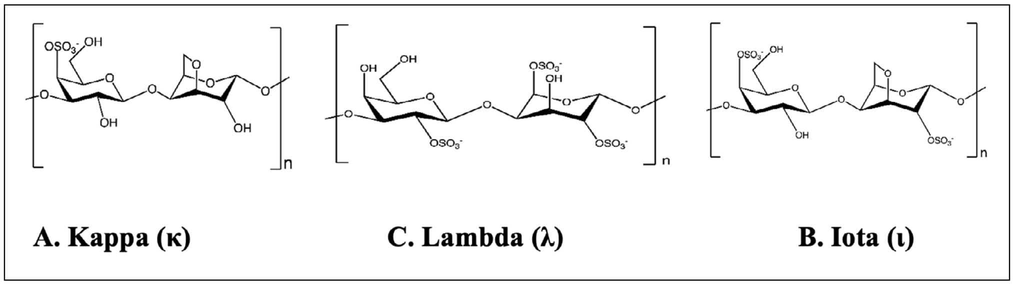

Figure 5. Chemical structure of different types of carrageenan

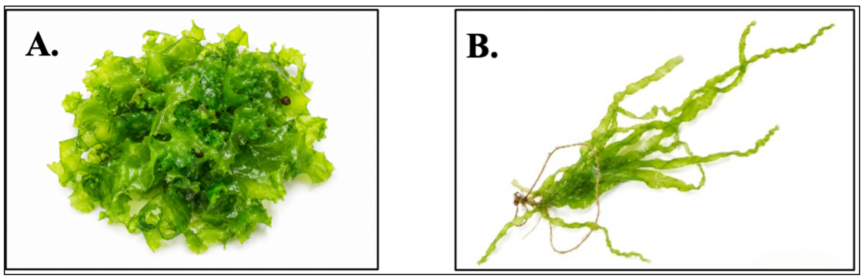

Figure 6. Commercially sourced seaweed of ulvan: A. *Ulva lactuca* and B. *Ulva intestinalis*. (Photos courtesy of AD Dulay)

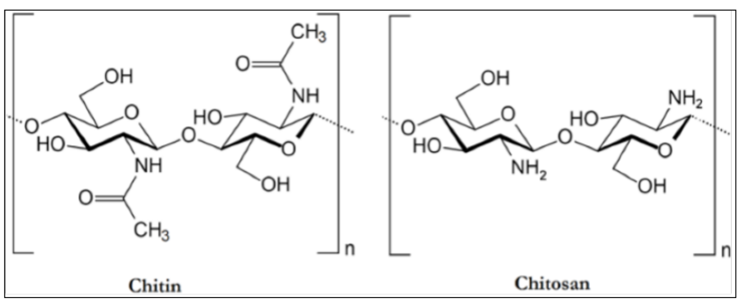

Figure 7. Chemical structure of chitin and chitosan.

Application of Marine Bioplastics

Marine-derived polysaccharides such as ulvan, alginate, carrageenan, and chitosan possess strong mechanical and optical properties that support applications in food packaging, edible cutlery, biomedical materials, and absorbent medical packaging made from thermoplastic starch derived from marine algae (Dybka-Stępień et al. 2021; Dang et al. 2022). Marine biomaterials are also important in tissue engineering, where seaweed-based scaffolds, fish collagen, chitin-based bioplastics, hyaluronan, and polyhydroxyalkanoates (PHAs) are used for skin, bone, cartilage regeneration, wound healing, drug delivery, sutures, and stents because of their biocompatibility, biodegradability, and ethical advantages over land-animal sources (Venkatesan et al. 2015; Liu et al. 2022; Shamshina et al. 2019; Chang et al. 2024; Sharma et al. 2021).

Startups are accelerating the commercialization of these materials through seaweed-based packaging and single-use alternatives. Companies such as Notpla, B'Zeos, Sway, C-Combinator, FlexSea, Oceanium, Loliware, Evoware, SoluBlue, and Kelpi are producing compostable films, biodegradable bags, straws, polymer sheeting, and composite packaging that provide scalable alternatives to petroleum-based plastics while creating economic opportunities in coastal regions (Nagarajan et al. 2024; Patel 2019; Raghunathan et al. 2022; Ayyakkalai

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et al. 2024). Current commercial outputs include packaging films, edible sachets, cutlery, biomedical materials, and molded consumer products derived from marine polymers as illustrated in Figure 8.

Conversion of marine biomass into bioplastics involves a sequential process consisting of extraction, purification, compounding, and final shaping through molding or casting (Figure 9). This pathway begins with biomass collection and pretreatment, including cleaning, sorting, and size reduction to remove salts, sand, and other impurities, thereby improving extraction efficiency and product purity (Torrejon et al. 2025). Depending on chemical composition, marine feedstocks are then processed through distinct routes: polysaccharide-rich materials such as alginate, carrageenan, agar, chitin, and cellulose undergo chemical, thermal, or enzymatic extraction followed by purification and drying, while protein-based materials are typically processed via solubilization, precipitation, and crosslinking to enable film or composite formation. Further modification and compounding steps, such as deacetylation, hydrolysis, or blending, are applied to optimize polymer properties before final fabrication into usable bioplastic products (de Souza Vandenberghe et al. 2023).

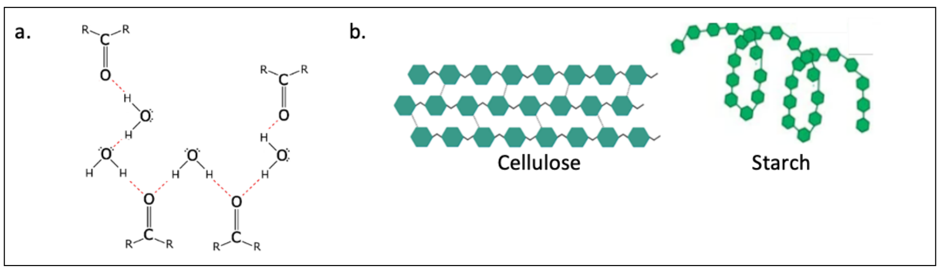

Figure 8. Example products of marine bioplastics. (Images via Canva.com)

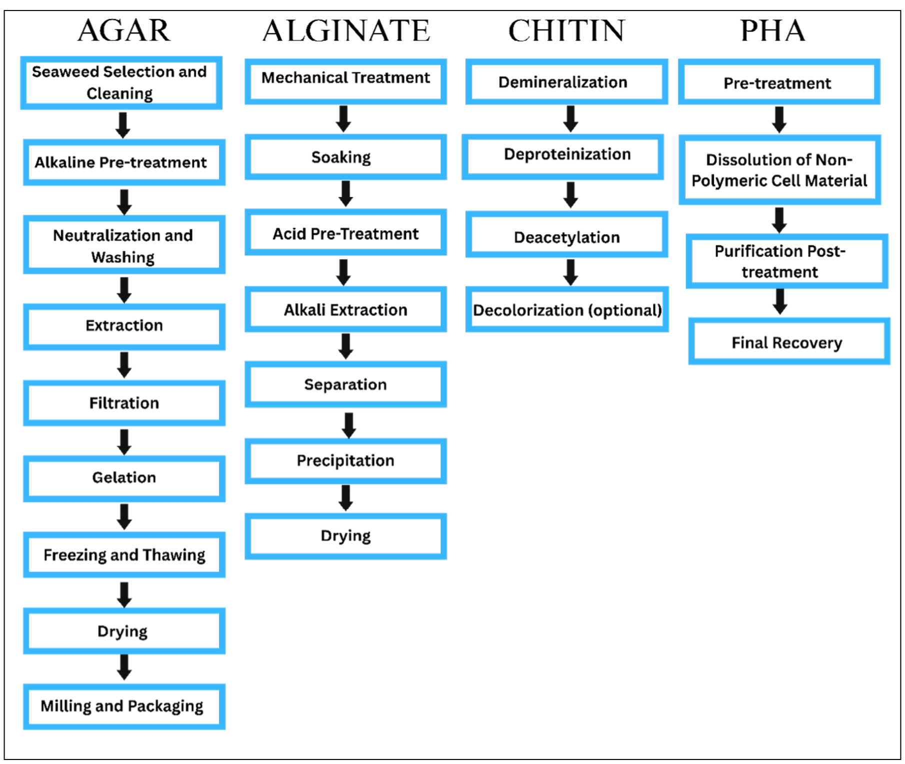

Figure 9. Extraction and conversion workflow for common primary structural material of marine bioplastics.

Marine Biocomposites

Natural reinforcements, including fish scales, crab shell particles, seashell nanopowders, chitosan, and seaweed, have been widely studied for their capacity to improve mechanical properties, thermal stability, and water resistance in polymer composites. These bio-based fillers provide sustainable alternatives to synthetic reinforcements and contribute to the development of high-performance, environmentally friendly materials (Gopi and Gopi 2022).

Fish Scale Composites

Studies on fish-scale-reinforced polymer composites indicate that mechanical properties are influenced by the volume fraction of fish scales within the polymer matrix (Razi et al. 2019). Composites with lower concentrations of fish scales exhibit high impact strength and superior hardness, while excessive fish scale content leads to non-uniform dispersion and reduced mechanical performance. These results suggest that fish scale fillers enhance polymer composites most effectively up to an optimal concentration (Obiechefu et al. 2024).

Crab Shell-Particles

Crab shell particles have been reported to increase the tensile and flexural strength of polymer composites (Prasad et al. 2021). Fourier-transform infrared spectroscopy has confirmed the compatibility of these fillers by identifying similar crystalline structures in both crab shell particles and fiber reinforcements. Additionally, composites containing crab shell particles demonstrate improved water resistance and hardness, supporting their application in a variety of fields (Soundhar and Kandasamy 2021).

Seashell Nanopowders

The incorporation of seashell nanopowders into PMMA-based denture composites has been shown to improve wear resistance and reduce frictional forces (Ali Sabri et al. 2021). Optimal performance was observed at 12% filler content, while higher concentrations led to decreased microhardness. Similarly, unsaturated polyester composites reinforced with 10% seashell particles demonstrated significant improvements in flexural strength, stiffness, and impact resistance. The integration of seashell powders with waste plastics resulted in biocomposites with minimal water absorption and high wear resistance, indicating their suitability for applications such as automotive components and window panels (Bakri et al. 2022).

Chitosan-Polymer

Chitosan, obtained from crab shells, has been investigated as a reinforcing agent in polymer composites. Studies on polylactic acid (PLA) composites containing chitosan microparticles found that 6% chitosan yielded optimal mechanical reinforcement, while 10% chitosan enhanced wear resistance (Daramola et al. 2021). Excessive chitosan content, however, resulted in particle clustering and reduced composite performance. Research on chitosan-based nanocomposite films combined with graphene oxide (GO) reported improved thermomechanical properties, ultraviolet resistance, and barrier effectiveness, supporting their use in food packaging (Pires et al. 2021). Additionally, chitosan composites blended with montmorillonite and polyvinyl alcohol (PVA) demonstrated increased tensile strength and decreased wettability, highlighting their potential for a range of material applications (Mohsen et al. 2024).

Seaweed and Algae-Based Composites

Numerous studies have explored seaweed as a sustainable reinforcement in polymer composites. For example, blending seaweed with sugar palm starch-agar (TPSA) reduces moisture content but increases water solubility, suggesting that enhanced hydrophobicity is required (Irianto et al. 2024). In polypropylene (PP) composites, sulfuric acid-treated green algae reinforcements significantly improve mechanical and thermal stability (Zhang et al. 2019). Research on poly(lactic) acid (PLA) indicates that while algae reinforcements increase Young's modulus, they can decrease tensile strength at higher concentrations (Bulota and Budtova 2015). Furthermore, cellulose from *Cladophora* algae blended with starch produces biocomposite films with the mechanical strength and water resistance necessary for sustainable packaging (Steven et al. 2020). While algae fiber-epoxy composites with high fiber content show marked improvements in flexural and tensile strength, managing porosity remains a technical challenge (Constante and Pillay 2018).

Application of Marine Biocomposites

Marine-based polymer biocomposites are highly valued across multiple industries for their high strength, low weight, durability, and resistance to environmental stressors (Andrew and Dhakal 2022) (Figure 10). In the automotive sector, these materials are essential for producing tires, belts, and body components. Recent technological advancements in these composites have enabled ultra-hard protective finishes for vehicles and reduced tire friction, ultimately enhancing longevity and performance (Muhammad et al. 2021). Similarly, the aerospace and marine industries favor these composites for their superior strength-to-density and stiffness-to-weight ratios (Rahman et al., 2023). They successfully reduce aircraft weight without compromising durability and are increasingly replacing traditional carbon and glass fibers in boat construction due to their resilience in harsh aquatic environments (Castegnaro et al. 2017). Furthermore, these biocomposites play a crucial role in the medical field for the development of advanced biomedical devices (Udayakumar et al. 2021).

Beyond transportation and medicine, these materials are transforming the packaging, construction, and energy sectors. The packaging industry utilizes marine-based polymer nanocomposites to create high-barrier films that block gases and water vapor, effectively extending food freshness (Xue et al. 2023). Ongoing research is further enhancing these films with antimicrobial properties and intelligent nanosensors for spoilage detection (Adak et al. 2024; Sharma et al. 2023). In construction and electronics, the materials' high strength-to-weight ratio is utilized for structural reinforcement, wind turbine blades, and electronic casings; certain nanocomposites even function as structural stress sensors (Rajak et al. 2019). The oil and gas industry relies heavily on these biocomposites for offshore platforms, pipelines, and storage tanks because they offer superior corrosion resistance and lower weight compared to metals (Dhandapani et al. 2024). Additionally, fiber-reinforced thermoset polymers provide a highly cost-effective alternative to metals for repairing and restoring transport infrastructure in this sector (Diniță et al. 2023).

Global Trends in Marine Bioplastics Research, Development and Commercialization

As marine bioplastics transition toward commercialization, significant cost and scalability constraints emerge. Regional commercialization pathways differ according to policy support, infrastructure maturity, and industrial incentives (Figure 11; Table 2). High production expenses are primarily driven by the complexity of converting marine biomass into consistent, industrial-grade feedstock (Possidónio et al. 2025). Scaling lab-level technologies requires heavy capital investment to ensure economic viability, while the inherent seasonality and environmental variability of seaweed harvesting hinder a steady supply, making these materials less competitive than traditional petroleum-based plastics (Amponsah et al. 2024).

Underdeveloped distribution networks and the specialized infrastructure required to prevent biomass degradation during transport and storage complicate logistics (Peng and Sadaghiani 2023). This progress is geographically uneven; regions with extensive coastlines and supportive policy frameworks are better equipped for efficient production, while others face higher input costs and logistical inefficiencies that limit market access (Torrejon et al. 2025).

The development of marine bioplastics is shaped by regional policies that reflect national priorities and industrial capacities. In Asia, Japan advances a roadmap for resource circulation through research initiatives like COI-NEXT (Likely Misinterpretation) and BCNF, (Boyce-Codd Normal Form). While Thailand utilizes national roadmaps, tax incentives, and university partnerships to establish itself as a global hub for polylactic acid (PLA) production. These pathways emphasize structured growth and sector-specific integration to facilitate commercialization.

European nations adopt a regulation-driven approach aligned with circular economy principles. Germany utilizes the Circular Economy Act, the Packaging Act, and lignocellulosic biorefineries to drive feedstock innovation, while France employs the AGEC Law and extended producer responsibility (EPR) to promote algae-based bioplastics. Italy similarly integrates EPR with extensive composting infrastructure, maintaining leadership in starch-based and PBAT (polybutylene adipate terephthalate) materials through specialized

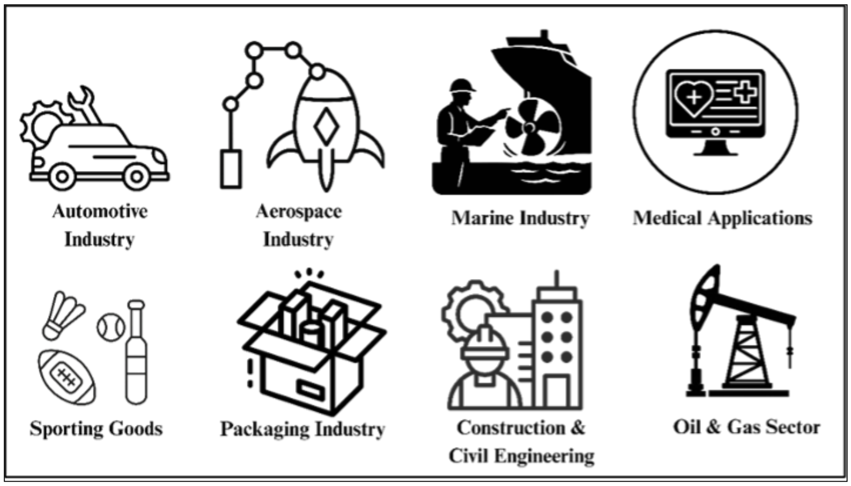

Figure 10. Applications of marine-based polymer biocomposites across industries. (Images via Canva.com)

Table 1. Comparison of marine-derived bioplastics.

Bioplastic type	Source	Properties	Applications	Benefits	Disadvantages
Marine Algae-Based Bioplastics	Macroalgae (seaweed) and microalgae	Biodegradable, film-forming, good mechanical strength	Packaging, agriculture, biomedical applications	Renewable, biodegradable,	Limited mechanical properties, moisture sensitivity
Fish and Shellfish Waste-Based Bioplastics	Fish skin, bones, scales, shellfish exoskeletons	High tensile strength, biocompatible, biodegradable	Packaging, medical devices, agricultural films	Utilizes waste materials, biodegradable, high mechanical strength	Potential allergenicity, variable quality due to raw material sources
Chitin and Chitosan-Based Bioplastics	Crustacean exoskeletons, fungi	Biodegradable, biocompatible, antimicrobial properties	Wound dressings, drug delivery, packaging	Biocompatible, antimicrobial, sustainable	Expensive extraction process, solubility issues
Marine Biocomposites	Biopolymers combined with marine-based fibers and bio-aggregates	Enhanced mechanical properties, biodegradable	Automotive parts, construction materials, packaging	Renewable resources, improved mechanical properties, biodegradable	Potential variability in raw material quality, processing challenges

co-collection systems. These strategies prioritize closed-loop material recovery as the central pillar of their industrial models.

Other regions leverage market incentives and adaptive policy designs to stimulate scalability. The United Kingdom uses EPR schemes and packaging taxes to drive demand, whereas the Netherlands utilizes its logistics networks to foster PLA/PHA innovation clusters. Malaysia employs a hybrid Roadmap combining green procurement with ASTM/ISO standards and phased EPR. Meanwhile, Australia's National Plastics Plan 2.0 and New Zealand's voluntary standards promote certified compostable packaging and FOGO (food organics and garden organics) systems. However, infrastructure gaps remain a significant constraint, as evidenced by only 28% of Australian households currently having access to FOGO services.

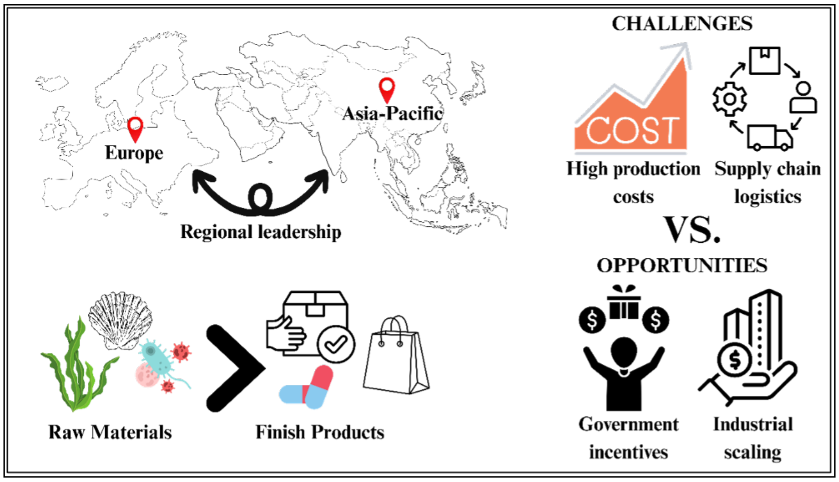

Figure 11. Development and commercialization in marine bioplastics. (Images via Canva.com)

Table 2. Policy instruments and commercialization strategies across regions.

Country	Policy Instruments	Infrastructure	Industry Support	Research, Development and Innovation	Commercialization Strategy
Japan	Roadmap for Bioplastics, Resource Circulation Strategy	Advanced composting and recycling	Government procurement, public awareness	COI-NEXT, BCNF research	Sector-specific bioplastic integration
Thailand	National Roadmap, Tax incentives, Standards	Industrial composting, ISO-certified labs	Investment incentives, MOUs	University partnerships, PLA production	Export-oriented, global hub
Malaysia	Plastics Sustainability Roadmap, EPR	Waste segregation, informal sector integration	Green procurement targets	Standards based on ASTM/ISO	Phased EPR, labeling, voluntary to mandatory
Chile	EPR Law, Organic Waste Strategy	Waste picker integration, composting targets	Fee structures, landfill taxes	Focus on downstream management	Domestic circular economy focus.
Germany	Circular Economy Act, Packaging Act	Dense composting and recycling network	Public-private partnerships	Lignocellulosic biorefinery integration	High recycling rates, feedstock innovation
France	AGEC Law, Packaging Law, EPR	Municipal composting expansion	Retailer mandates, bulk sales	SEABIOPLUS, algae-based bioplastics	Home composting, reusable packaging
Italy	Composting laws, EPR	360 composting plants	Novamont leadership	Starch-based and PBAT innovation	Co-collection of food and bioplastics
UK	EPR, Plastic Packaging Tax	Recycling and composting	Brand procurement mandates	Market incentives, startup support	Rapid adoption of renewable resins
Netherlands	EPR, Circular Economy Focus	Logistics and export hub	Innovation clusters	PLA/PHA plant development	Export-oriented, supply chain integration

Stakeholder Responsibilities for Marine Bioplastics

The adoption of marine bioplastics requires a coordinated, interdependent system of stakeholders linked by regulatory, technological, and market-driven feedback loops. Governments are responsible for establishing standards for biodegradability and ethical sourcing while incentivizing seaweed farming and seafood waste c through policy and procurement (Khalil et al. 2017). Industry participants, including farmers and packaging converters, must focus on sustainable cultivation and technological innovations to address current mechanical and water-resistance limitations (Santana et al. 2024; Pires et al. 2021). This industrial progress relies heavily on academic research to optimize extraction methods and improve polymer properties, which is essential for overcoming cost and scalability barriers (Samalens et al. 2022; Tennakoon et al. 2023; Ghosh and Jones 2021).

Financial institutions and NGOs enable the scaling of these innovations by providing capital and ethical frameworks that support coastal communities (Cooney et al. 2023). These investment decisions are often contingent upon the regulatory stability provided by governments and the technological feasibility demonstrated by academia. Consumers and retailers drive the market pressure necessary for commercial viability; through labeling initiatives and composting participation, they incentivize industry adoption and guide policy direction (Xue et al. 2023). The transition to marine bioplastics depends on this collective participation, as even the most advanced technologies require consumer acceptance to succeed (Gao and Shao 2022).

The commercial adoption pathway for marine bioplastics begins with foundational research and industrial collaboration focused on marine-derived feedstocks and biodegradability (Figure 12). This stage transitions into pilot production and demonstration, where facilities test feasibility through life-cycle assessments, cost-benefit analyses, and practical applications in sectors like packaging, fisheries, and coastal industries (Santana et al. 2024). Subsequently, policy frameworks and certification standards become essential, with government incentives and national plastic reduction strategies driving industry growth and product reliability (Igwe et al. 2024). Market scaling is then accelerated through private sector partnerships and global supply chain expansion, supported by consumer awareness to drive mainstream demand. Long-term sustainability and cost-efficiency requires continuous innovation and full integration into circular economy firewords (Agrawal et al. 2024).

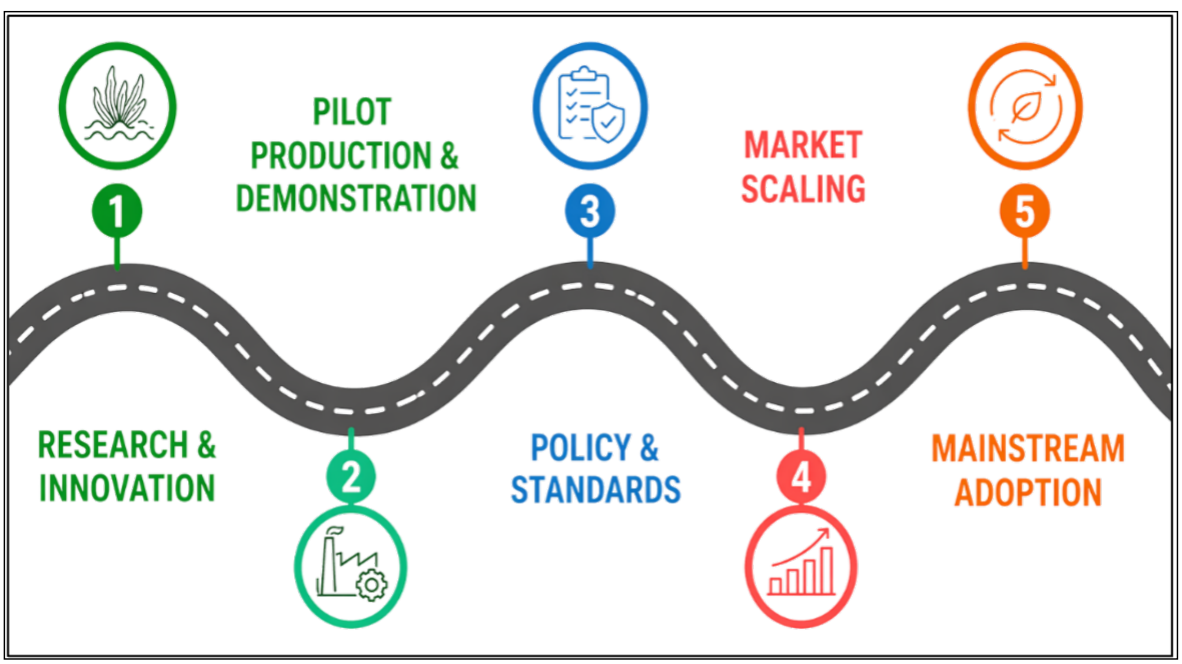

Figure 12. Roadmap to commercial adoption of marine bioplastics. (Images via Canva.com)

Cost and Scalability Challenges in Commercial Adoption

Marine-derived bioplastics remain economically constrained due to their high production costs and energy-intensive processing requirements, making them less competitive than conventional and established bio-based plastics (Mostafavi and Zaeim 2020; Saji et al. 2022; Hasanzadeh et al. 2022). These challenges become more pronounced at industrial scales, where inefficiencies lead to increased costs and variability in product quality (Irianto et al. 2024; Zhang et al. 2019).

Scalability is further affected by the variability and sustainability of marine biomass feedstocks. Dependence on seasonal and geographically limited resources creates supply instability, while the need to prevent overexploitation requires investments in controlled cultivation and resource management systems (Khalil et al. 2017; Cooney et al. 2023; Lomartire et al. 2022; Narayanan et al. 2023).

Overall, the combination of low conversion efficiency, high energy demand, and technological immaturity limits commercial readiness. Advancing processing technologies and improving supply chain stability will be critical to achieving cost competitiveness and enabling large-scale adoption (Guidara et al. 2020; Hejazi et al. 2018; Pires et al. 2021; Coltelli et al. 2023; Sarker and Kaparaju 2025).

Policy and regulatory frameworks play a decisive role in bridging these gaps (Figure 13). In the absence of targeted subsidies, tax incentives, or mandates favoring biodegradable materials, marine bioplastics are often perceived as high-risk investments (Patel 2019; Raghunathan et al. 2022). Strategic government intervention is therefore essential to offset production costs, incentivize infrastructure development, and promote innovation in processing technologies. Coordinated efforts among academia, industry, and policymakers are required to optimize feedstock utilization, improve conversion efficiencies, and establish standardized production systems. Collectively, the integration of economic, technological, and regulatory strategies will determine whether marine-derived bioplastics can transition from niche innovations to scalable, commercially viable alternatives in the global materials market (Ayyakkalai et al. 2024).However, their application in bioplastics requires careful formulation to ensure chemical stability against oxidation, hydrolysis, and UV radiation, which will ensure color retention and compatibility with the biopolymer and other additives. Some of these natural product colorants are included in Figure 20. Non-toxic mineral colorants are also used, such as iron oxides, copper salts, and TiO_2.

Table 3. Challenges in the commercial application of marine-derived bioplastics.

Aspect	Key Issue	Implication
High Production Cost	Complex processing and high energy use (Mostafavi and Zaeim 2020; Saji et al. 2022)	More expensive than conventional plastics (Hasanzadeh et al. 2022)
Scale-Up Limitations	Inefficiencies in industrial production (Irianto et al. 2024; Zhang et al. 2019)	Higher costs and inconsistent quality
Feedstock Variability	Seasonal and location-dependent biomass (Khalil et al. 2017; Cooney et al. 2023)	Unstable supply chain
Sustainability & Supply	Risk of overuse; need for aquaculture systems (Lomartire et al. 2022; Narayanan et al. 2023)	Increased operational costs
Low Efficiency & High Energy Demand	Moderate yields and energy-intensive processes (Guidara et al. 2020; Hejazi et al. 2018; Pires et al. 2021)	Reduced economic viability
Technological & Infrastructure Gaps	Early-stage development and facility mismatch (Coltelli et al. 2023; Sarker and Kaparaju 2025)	Limited large-scale commercialization

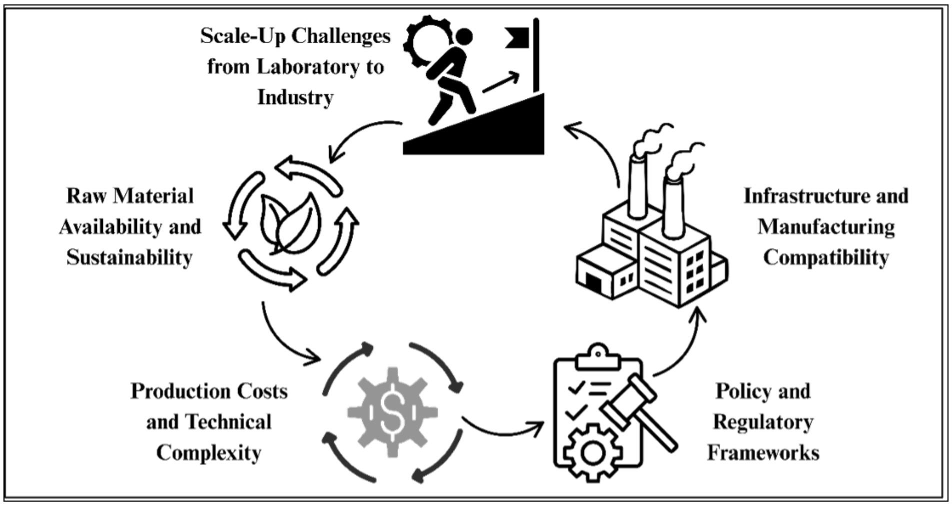

Figure 13. Challenges to commercial adoption of marine-derived bioplastics. (Images via Canva.com)

Environmental Impact and Pollution Reduction Potential of Marine Bioplastics

The environmental benefits of marine bioplastics are increasingly evident as they replace conventional plastics across multiple sectors, advancing circular economy principles by converting fishery byproducts and cultivated seaweed into valuable materials that safely re-enter natural cycles (Cooney et al. 2023; Narayanan et al. 2023; Liu et al. 2022). In the food and beverage industry, companies like Notpla and Evoware utilize naturally biodegradable seaweed for sachets, straws, and films, effectively eliminating toxic residues in waterways (Patel 2019; Raghunathan et al. 2022). Medically, fish collagen and chitosan mitigate synthetic waste through their use in biodegradable wound dressings and sutures (Lionetto and Esposito Corcione 2021; Mishra et al. 2018). Industrially, marine biocomposites reinforced with fish scales or seashell powders provide a necessary balance of durability and biodegradability for packaging and automotive components (Obiechefu et al. 2024; Bakri et al. 2022).

Despite their immense potential to reduce fossil fuel dependence and plastic pollution, immediate scalability is constrained by high production costs linked to limited infrastructure (Coltelli et al. 2023), mechanical drawbacks such as reduced tensile strength and water resistance (Bulota and Budtova 2015), and variable, environmentally dependent degradation rates (El-Araby et al. 2024). Overcoming these processing and material challenges through targeted research, industry collaboration, and policy support is crucial. Continued innovation will allow these renewable marine resources to fully realize their role as a viable, sustainable alternative, significantly enhancing both ecosystem health and long-term societal sustainability.

Outlook and Perspectives

Transitioning marine-derived bioplastics from laboratory innovation to industrial adoption requires overcoming significant economic and technical hurdles. Future research must prioritize cost reduction and process optimization by improving extraction efficiency and energy consumption through greener technologies like enzymatic extraction and biorefinery approaches (Nanda et al. 2022; Nguyen et al. 2022). Ensuring a consistent feedstock supply is equally vital; while seaweed offers rapid growth without requiring arable land, it necessitates large-scale, year-round cultivation systems (Campbell et al. 2019). Similarly, enhancement of crustacean waste and metabolic engineering for microbial PHAs are essential to enhance productivity (Venugopal 2021). To bridge the commercialization gap, material performance—specifically mechanical strength and thermal stability—must be bolstered through nanomaterials and hybrid systems, supported by standardized evaluation frameworks (Abd El-malek et al. 2020). Adoption depends on policy incentives

Table 4. Summary of comparative advantages of marine bioplastics over conventional plastics.

Material Type	Source	Biodegradation Potential	Environmental Benefit
Agar-based films	Red seaweed (Gelidium, Gracilaria)	Weeks to months in compost/ seawater (Irianto et al. 2024)	Reduces single-use packaging waste
Alginate composites	Brown seaweed (Laminaria, Sargassum)	Rapid hydrolysis in marine conditions (Santana et al. 2024)	Biocompatible, safe for food and medical use
Carrageenan plastics	Red seaweed	Variable depending on type (Krishnan et al. 2024; Abdillah and Charles 2021)	Provides biodegradable stabilizers for packaging
Chitosan bioplastics	Crustacean shells	Enzymatic breakdown in seawater (Samalens et al. 2022)	Converts seafood waste into value-added products
PHAs	Marine microorganisms	Complete biodegradation in soil and marine environments (Sharma et al. 2021)	Reduces long-term accumulation of plastics

like subsidies and carbon pricing, alongside holistic, interdisciplinary collaborations that integrate technical and economic dimensions across the entire value chain (Jiao et al. 2025; Omer et al. 2025).

CONCLUSION

Marine-derived bioplastics represent a significant advancement in sustainable materials, offering clear advantages over conventional petroleum-based plastics and first-generation bio-based alternatives. Marine biomass—including seaweeds, fishery byproducts, and marine microorganisms—provides a diverse and renewable feedstock capable of producing biodegradable, biocompatible, and functionally versatile biopolymers. Their growing application across packaging, biomedical, and industrial sectors, along with the development of marine biocomposites, underscores their increasing relevance within circular economy systems. The valorization of marine waste streams and the expanding involvement of startups and industry further highlight a strong and accelerating momentum toward commercialization.

Despite this progress, large-scale adoption remains constrained by economic, technical, and infrastructural barriers, including high production costs, energy-intensive processing, scale-up inefficiencies, and feedstock variability. Limitations in mechanical and thermal performance, coupled with supply chain instability and uneven policy support, continue to restrict broader implementation. Overcoming these challenges requires integrated technological innovation, improved feedstock management, and stronger alignment among policy, industry, and research sectors. With sustained interdisciplinary efforts and targeted investments, marine bioplastics have strong potential to transition from emerging innovations to commercially viable and sustainable alternatives in the global materials market.

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- Airon D. Dulay — conceptualization, design, analysis, discussion, writing, revision, finalization of paper;
- Therese Elaine B. Enad — design, analysis, discussion, writing, revision, finalization of paper
- Marco Nemesio E. Montaño — provided overall direction, conceptualization, design, discussion, revision, finalization of paper.

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Some images included in this work were generated or enhanced using AI tools, but they serve only illustrative purposes and do not alter the substance of the research.

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