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Marine-derived Bioplastics: Sustainable Solutions from the Ocean

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ABSTRACT

The world's plastic pollution, resulting from over 500 mmt tons of fossil-fuel-based plastics produced annually, has become a pressing environmental challenge, necessitating sustainable solutions. The continuous increase in plastic production has underscored the urgency of adopting alternatives that are both eco-friendly and efficient. This review focuses on marine-derived biopolymers and bioplastics obtained from renewable resources such as marine algae, fishery by-products, and microorganisms. These materials are not only biodegradable under specific conditions but also exhibit lower carbon footprints and require less energy for production compared to conventional petroleum-based plastics. This review focuses on marine-derived biopolymers and biopolymers obtained from renewable resources such as marine algae, fishery by-products, and microorganisms. These materials are not only biodegradable under specific conditions but also exhibit lower carbon footprints and require less energy for production compared to conventional petroleum-based plastics. By using processes such as extracting chitin and chitosan from crustacean shells, fermenting microbial polymers like polyhydroxyalkanoates (PHA), and utilizing whole algal biomass, these marine-derived bioplastics show how innovation can drive sustainable manufacturing, turn waste into valuable resources, and support responsible stewardship of our oceans, offering hope in the fight against plastic pollution. Overall, this review illustrates how marine-derived bioplastics can drive innovation in sustainable manufacturing, waste valorization, and responsible resource management, offering a comprehensive perspective on their role in mitigating the global plastic pollution crisis.

KEYWORDS: Sustainability, algae, waste, bioplastic, biodegradable, bio-based

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1. INTRODUCTION

The Food and Agriculture Organization defines bioplastics as materials derived from renewable biological resources, mainly marine and fishery by-products, such as fish scales, crustacean shells, and algae. These materials are either bio-based (made from biomass), biodegradable (capable of breaking down naturally under specific conditions), or both. It emphasizes its role in promoting sustainability by repurposing seafood waste into benificial products, reducing reliance on finite natural fuel resources, and addressing plastic pollution in marine environments. Bioplastics have various advantages, like lower carbon footprints due to their renewable resource base and decreased use of carbon-based energy (Saharan and Kharb, 2022). Many are biodegradable, breaking down into water, CO_2, and biomass under specific conditions, thereby minimizing long-term pollution. Additionally, their production often requires less energy than conventional plastics, thereby enhancing energy efficiency; however, they are frequently blended with other polymers to improve durability (Pooja et al., 2023).

Recent studies highlight that marine-derived biopolymers can be processed into bioplastics with competitive mechanical properties and biodegradability, offering potential for sustainable packaging, biomedical, and agricultural applications (Tennakoon et al., 2023). Marine-derived biopolymers, synthesized from marine algae, fish waste, and microorganisms, offer eco-friendly solutions to reduce reliance on fossil fuels and mitigate pollution, and are a great leap toward green materials. Biodegradability and reduced dependence on fossil fuels are two advantages of bioplastics based on algae, especially those using polyhydroxyalkanoates (PHA) and polyhydroxybutyrate (PHB) derived from Chlorella and Spirulina (Tennakoon et al., 2023). Recent innovations in processing have shifted towards utilizing whole algal biomass rather than isolated extracts, optimizing production efficiency while retaining the full nutrient and fiber profile of the raw material (El Semary et al., 2022). By extracting chitin and chitosan from crustacean shells and collagen and gelatin from fish skin, biodegradable packaging and medical films can be created, reducing the demand for petroleum-based plastics (Nazar et al., 2025). Bioplastics derived from sea microbes, including genetically modified strains, offer a suitable replacement to combat plastic pollution. These microorganisms, such as bacteria, produce biodegradable polymers that can decompose in marine environments, thereby reducing plastic waste (Samadhiya et al., 2022). The development and deployment of marine bioplastics require careful life cycle assessments and environmental impact studies to ensure that these materials deliver genuine sustainability benefits (Piao et al., 2024). Furthermore, their mechanical and physical characteristics, including tensile strength and elasticity, can be customized by blending with other polymers or plasticizers, enabling their use in diverse applications such as packaging and biomedical products. Some marine bioplastics require additives (e.g., phthalates) that leach toxins in seawater (Boldrini et al., 2024), and degradation rates vary with environmental conditions. Despite these limitations, marine-derived bioplastics offer a path toward circularity by converting fishery waste and invasive algae into valuable materials. To mitigate plastic pollution effectively, innovations in material design must pair with global waste management reforms. This has been achieved without using fresh water or fertile soil. Despite progress, issues remain, including the scalability of waste-to-bioplastic technologies and non-uniform marine degradation kinetics, which necessitate further convergence of bioengineering and the principles of the circular economy (Phosri et al., 2022; Samadhiya et al., 2022).

This review emphasizes the role marine algae, fishery by-products, and marine microbes in developing bioplastics that reduce dependence on fossil fuels and address plastic pollution. The objectives of this study are to highlight the potential of these renewable materials for sustainable bioplastic production, evaluate their biodegradability and functional applications in sectors like packaging and biomedicine, and assess environmental and economic benefits through life cycle perspectives. It also aims to outline existing challenges, including scalability and variability in degradation, while pointing to future directions that integrate bioengineering innovations with circular economy principles.

2. GLOBAL PLASTIC POLLUTION CRISIS

According to data from the Organisation for Economic Co-operation and Development (OECD), global annual plastic production in 2023 was approximately 500 mmt. In 2024, estimates indicate a 4–5% annual increase. By 2025, projections suggest that annual production could reach between 600 and 650 mmt, emphasizing the growing scale of plastic manufacturing worldwide, and according to researchers, this amount could double by 2050. Most plastics made from fossil fuels take hundreds of years to decompose (Pilapitiya et al., 2024). Sadly, 79% of plastic waste is never recycled, posing serious environmental problems (Narancic et al., 2020). The EPA (Environmental Protection Agency) reveals that nearly all plastics created still exist, taking 500-1000 years to degrade. Even then, they break down into harmful microplastics. Plastic pollution badly impacts both terrestrial and aquatic ecosystems. Shockingly, 50–75 trillion plastic and microplastic pieces now pollute our oceans, endangering marine life (UNESCO). An estimated 8–12 mt of plastic reach the oceans each year, seriously jeopardizing marine life through ingestion and entanglement (Kumar et al., 2024). Transboundary plastic waste exacerbates environmental and social injustices, as wealthier nations export their waste to developing countries, burdening local communities and ecosystems (Fiore de Miguel, 2022). Over 1 million marine animals die annually from plastic ingestion or entanglement. Fishing gear (nets, lines) accounts for 20% of ocean plastic. "Ghost gear" entraps marine life and devastates coral reefs and deep-sea ecosystems. Shipping and aquaculture also add to the burden. Whales consume up to 10 million microplastic particles daily. Microplastics, small pieces of plastic that are less than 5 mm, are now present in food chains, prompting worries that they could negatively impact human health through oxidative stress and the promotion of chronic disease (Mastrolia et al., 2022).

3. IMPACT OF BIOPLASTICS ON PLASTIC POLLUTION

Bioplastics can play an important role in tackling marine plastic pollution, but they come with challenges. They reduce our dependence on fossil fuels and lower greenhouse gas emissions, especially when they're made from renewable sources like algae or livestock waste (Atiwesh et al., 2021). Plus, they steer clear of nasty additives like bisphenol A (BPA), which helps protect marine life from health risks. Yet, how these bioplastics impact the environment depends on how they're made and the conditions under which they degrade. Many of them need industrial composting, which doesn't happen in the ocean, so they end up sticking around much like regular plastics do. This means they can break down into microplastic fragments that can seep into the food chain (Chia et al., 2020). On top of that, making bioplastics often involves growing crops. This increases the use of fertilizers that can run off into water bodies, leading to problems like algal blooms, oxygen depletion, and sprawling dead zones in our waters (Atiwesh et al., 2021). Fertilizers also contribute to nitrous oxide emissions, which are harmful to the ozone layer and can acidify ecosystems. While bioplastics have the potential to help, we need to think carefully about their side effects in marine environments (Samer et al., 2022). Bioplastics derived from ocean as broadly classified into three groups. Figure 1 illustrates the categorization of bioplastics sourced from marine environments.

4. BIOPLASTICS DERIVED FROM MARINE ALGAE

Marine algae, both macroalgae (seaweeds) and microalgae, can be used for bioplastic synthesis. Microalgae like Chlorella and Spirulina and macroalgae like Ulva and Laminaria are increasingly recognized as great bioplastic sources (Semary et al., 2022). They produce

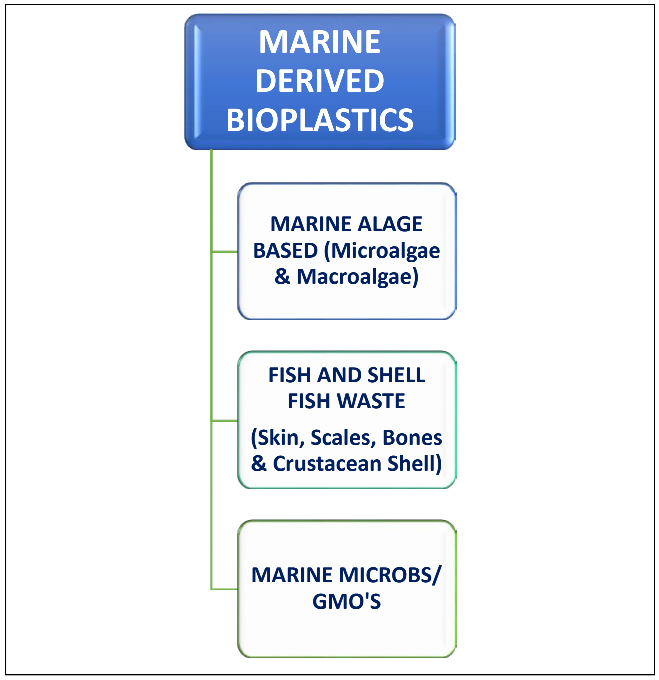
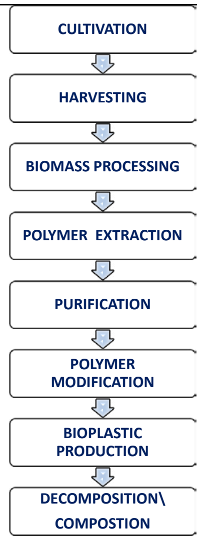


Figure 1: Types of marine-derived bioplastics

biopolymers that are precursors to biodegradable plastics (Adetunji et al., 2024), such as polyhydroxyalkanoates (PHAs), alginate, carrageenan, agar, and starch (Sudhakar et al., 2024). Algae, compared to terrestrial crops, do not compete with food production, need little freshwater, and may grow in various environments, including wastewater (Costa et al., 2023). So, it is considered one of the reliable sources of plastic to meet the global need.

4.1. Bioplastic production from marine algae

Macroalgae are grown in open seawater systems or along coastal farms, while microalgae typically thrive in open ponds or specialized photobioreactors. When it's time to harvest the cultivated biomass, different methods are employed. Mechanical scrapers or nets are used for harvesting macroalgae, while processes like centrifugation, filtration, or flocculation using agents like chitosan or alum are used for harvesting microalgae (Adetunji et al., 2024). To get rid of water, the biomass is dried using techniques such as sun-drying or spray-drying before being processed to break down its molecular structure. This can be done by milling, enzymatic hydrolysis, or acid/alkali hydrolysis for polymer extraction (Semary et al., 2022). Once the polymers are extracted, recovery methods vary. The process of bioplastics synthesis from Marine algae is depicted in Flow chart 1. For example, alginate from brown seaweed is obtained by alkalizing it with sodium carbonate and then precipitating it with calcium chloride. PHAs from microalgae are collected through solvent extraction, like using chloroform, and dialysis to purify them by removing proteins and pigments. After extraction, the polymer is often



Flow Chart 1: Process of bioplastic synthesis from marine algae

modified by adding substances like glycerol or polyethylene glycol (PEG) to make it more flexible and stable when heated. For instance, blends of Ulva and PEG show about 40% biodegradation in soil after three months (Semary et al., 2022). Finally, the modified polymers are shaped into films by pouring them into molds or creating products through methods like extrusion, injection molding, or even 3D shaping (Costa et al., 2023; Onen et al., 2020).

4.2. Important biopolymers from marine algae

Microalgae like cyanobacteria produce polyhydroxyalkanoates (PHAs) intracellularly. These are entirely biodegradable and have characteristics similar to those of traditional plastics, such as flexibility and durability (Sharma et al., 2024). For example, in nitrogen-limited environments, cyanobacteria like Synechocystis sp. can accumulate up to 80% PHB (a type of PHA) (Mogany et al., 2024). A macroalgae alginate, which is used to make hydrogels for films and coatings, is extracted from brown algae (Laminaria) (Onen et al., 2020). Green algae, such as Ulva sp. and Chlorella sorokiniana, contain starch. Glycerol and other additives enhance starch-based bioplastics (Dino and Kishore, 2024). Blending Ulvan, a sulfated polysaccharide derived from green algae (Ulva sp.), with natural plasticizers such as Plantago ovata seeds results in composites with exceptional tensile strength (Semary et al., 2022). A brief review on different types of biopolymers synthesised from marine algae, their source, extraction method, properties, and Applications of each biopolymer is presented in Table 1.

4.3. Application of bioplastics derived from marine algae

Seaweed-based bioplastics, made from sources like Ulva sp., Sargassum, and spirulina, are used in the making of disposable food containers, trays, and films in food packaging, which dissolve in water or break down quickly in soil, usually within about 4 to 6 weeks. Active packaging materials made with seaweed polysaccharides like carrageenan or alginate that help to improve UV resistance and fight off bacteria can help keep perishable goods fresh for longer (Elkaliny et al., 2024). In agriculture, algal bioplastics are being used in things like biodegradable mulch films, where Ulva sp. is blended with Plantago ovata to release nutrients into the soil, cutting down on the need for synthetic fertilizers (Semary et al., 2022). Microalgae-derived PHAs can even wrap seeds or agrochemicals for controlled release, which helps minimize contamination (Sharma et al., 2024). In the medical field, PHAs and PHB from microalgae such as Chlorella and Spirulina are biocompatible, making them excellent choices for surgical sutures, implants, and drug delivery systems (Anli and Kishore, 2024; Sharma et al., 2024). Textiles and consumer products are also getting a green upgrade, with algal cellulose and starch fibers used to create eco-friendly fabrics that help reduce microplastic pollution (Elkaliny et al., 2024). Algal bioplastics have a role in electronics and 3D printing, which are used in things like circuit boards and biodegradable components (Mogany et al., 2024). There are also exciting developments in fire-resistant materials like spirulina-based plastics that self-extinguish when exposed to flames, making them great for heat-resistant applications. These innovations come with plenty of environmental perks, like carbon capture during algae cultivation, which helps offset emissions. Of course, there are challenges to overcome, such as quick degradation in water and brittleness, but additives like glycerol or cross-linking agents can help with that (Thirumalai et al., 2023). Enhancing scalability is key, and that's where genetic engineering and using cost-effective wastewater nutrients come in, paving the way for wider use of algal bioplastics (Mogany et al., 2024).

5. BIOPLASTICS DERIVED FROM MARINE FISH WASTE

Marine skins and scales, abundant in collagen and gelatin, exhibit remarkable film-forming properties. These natural components serve as excellent materials for sustainable packaging and coatings and are extracted via hydrolysis, used for UV-blocking films (Lionetto and Esposito, 2021). Fish bones are a rich source of hydroxyapatite, a mineral vital for biomedical applications such as bone grafts and dental implants. Additionally, the proteins derived from fish bones hold significant potential in medicine and materials science. Offal, an underutilized resource, contains oils and proteins that can be transformed into biofuels, cosmetics, and nutraceuticals (Lionetto and Esposito, 2021). By repurposing these substances, industries can unlock new avenues for sustainability and efficient resource management. Collagen and gelatin, extracted

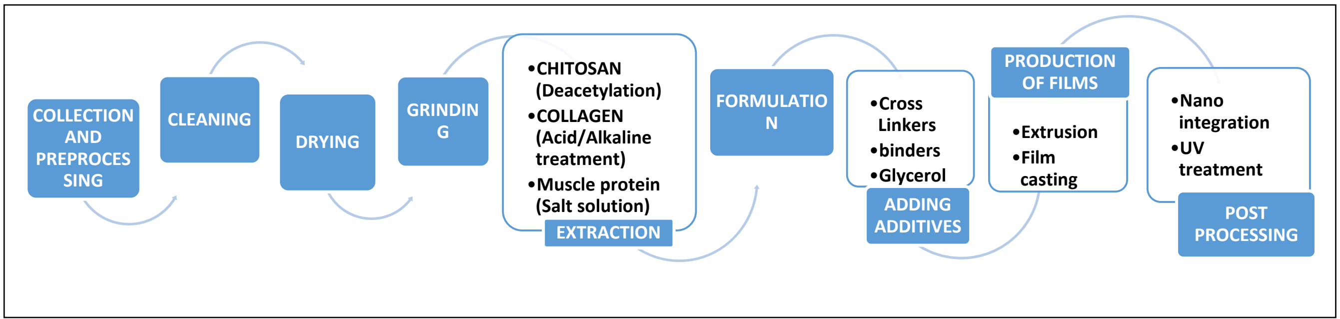
Table 1: Key Polymers derived from Marine Algae

Biopolymer	Source	Extraction Method	Key Properties	Applications	References
Alginate	Brown algae (e.g., Ascophyllum, Fucus)	Alkaline extraction ($NaOH/Na_2CO_3$), followed by precipitation with calcium ions	Flexible films, water-resistant, biodegradable, and biocompatible	Food packaging, hydrogel-based materials, coatings	(Carvalho et al., 2024)
Carrageenan	Red algae (e.g., Gracilaria, *Chondrus crispus*)	Hot water extraction and purification via KCl precipitation	Thermally stable, gelling, transparent films	Edible films, biodegradable coatings, and food packaging	(Carvalho et al., 2024; Bose et al., 2023)
Agar	Red algae (e.g., Gelidium, Gracilaria)	Boiling in water, gelation, and freeze-thaw cycles	High gel strength, thermally reversible, water-soluble	Rigid films, encapsulation matrices, microbial culture media	(Bose et al., 2023)
Ulvan	Green algae (e.g., Ulva, Enteromorpha)	Hot water or acid extraction, dialysis, and lyophilization	Sulfated polysaccharide, antioxidant, antimicrobial, enhances biodegradability	Blended composites, compostable plastics, and drug delivery	(Carvalho et al., 2024; Arora et al., 2023)
Fucoidan	Brown algae (e.g., Fucus, Sargassum)	Acid extraction (HCl), ethanol precipitation	Sulfated polysaccharide, anti-inflammatory, antioxidant	Bioactive packaging, wound healing, and pharmaceuticals	(Carvalho et al., 2024; Tennakoon et al., 2023)
Cellulose	Microalgae (e.g., Chlorella)	Mechanical disruption, alkaline treatment, and bleaching	High crystallinity, tensile strength, and biodegradable	Reinforcing agent in composites, 3D-printed materials	(Onen et al., 2020; Dianursanti, 2018)
PHAs	Cyanobacteria (e.g., Synechocystis)	Solvent extraction (chloroform), intracellular accumulation under nutrient stress	Thermoplastic, fully biodegradable, biocompatible	Packaging, medical devices, and agricultural films	(Tennakoon et al., 2023; onen et al., 2020)
Starch	Microalgae (e.g., Chlamydomonas)	Enzymatic hydrolysis, thermal gelatinization	High amylose content requires plasticizers (e.g., glycerol)	Blends with PLA, biodegradable packaging	(Onen et al., 2020)
Proteins	Microalgae (e.g., Spirulina, Chlorella)	Alkaline or enzymatic extraction, isoelectric precipitation	Film-forming, gas barrier properties, high tensile strength	Edible films, bioactive coatings, food wraps	(Mahmud et al., 2021)
Laminarin	Brown algae (e.g., Laminaria)	Hot water extraction, ethanol precipitation	β-1,3-glucan, antioxidant, low molecular weight	Filler in composites, bioactive packaging	(Carvalho et al., 2024; Tennakoon et al., 2023)

from marine resources through hydrolysis, are versatile biopolymers widely used in the creation of UV-blocking films. These films offer enhanced durability and protection against ultraviolet rays. Chitosan, another biopolymer derived from crustacean shells and potentially fish scales, stands out for its applications in water purification, bioplastics, and even agriculture (Surya et al., 2023). Among additives, plasticizers, such as glycerol, play a crucial role in enhancing the flexibility of materials like films and adhesives (Lionetto and Esposito, 2021). Natural binders, including those sourced from red algae, provide structural integrity to various formulations, promoting environmentally conscious alternatives in manufacturing processes.

5.1. *Bioplastic production from fish waste*

The production of biopolymers from fish waste entails several systematic procedures, starting with the collection and pre-processing of raw materials such as skins, scales, bones, offal, and muscle tissues, which account for 50–75% of fish processing waste (Rudovica et al., 2021). Pre-processing involves cleaning to eliminate impurities with water or mild solvents, drying (through oven-drying or freeze-drying) to minimize moisture, and grinding into fine particles to enable efficient extraction (Vijayakumar et al., 2024). Extraction of biopolymers follows, where collagen and gelatin are recovered through hydrolysis with acid/alkali treatments (e.g., acetic acid or NaOH) or enzymatic treatments (e.g., proteases such as pepsin) for green processing (Lionetto and Esposito, 2021), producing gelatin at 58.25% efficiency from fish skin or bones. Muscle proteins, e.g., myofibrillar and sarcoplasmic proteins, are recovered with high-salt solutions for bioplastic film-making (Lionetto and Esposito, 2021), and chitosan from crustacean shells by the deacetylation of chitin (Rudovica et al., 2021). In the formulation phase, additives like glycerol (40–60%) are incorporated to limit brittleness and enhance flexibility, binders like red algae (MarinaTex) to offer structural integrity, and sericin from silk cocoons to increase tensile strength. Cross-linkers like electron beam treatments are used to enhance water resistance. Processing methods involve film casting, in which biopolymer solutions are cast into molds and dried at temperatures less than 100°C, and extrusion or compression molding for thicker sheets or three-dimensional structures, followed by post-processing operations such as UV treatment or nanocomposite integration to increase durability and functionality (Tennakoon et al., 2023). The flow chart for the synthesis of bioplastics from fish waste is given in Flow Chart 2.



Flow Chart 2: Process of bioplastic synthesis from fish waste

5.2. *Important biopolymers from marine fish waste*

Biopolymers synthesised from marine fish waste have a vast application in different fields. A brief picture of types of biopolymers produced from marine fish waste, their source, Extraction method, key properties of biopolymers and their applications are presented in Table 2.

Collagen and Gelatin, primarily sourced from fish skins, scales, and bones, exhibit exceptional properties and a wide range of applications. Collagen has high film-forming ability, UV-blocking properties, and biocompatibility, making it an ideal material for sustainable innovations (Lionetto and Esposito, 2021). Gelatin, derived from collagen through hydrolysis, is particularly valued for its capacity to form flexible films (Mahmud et al., 2021) and coatings with notable oxygen-barrier properties (Vijayakumar et al., 2024). These biomaterials find extensive use in food packaging, such as wraps for meat and seafood, and are often combined with additives like starch or algae to create advanced bioplastics, like MarinaTex, a bioplastic which have a tensile strength surpassing that of LDPE.

Fish muscle proteins, including myofibrillar and sarcoplasmic proteins, offer unique properties with significant potential for packaging innovations. These proteins demonstrate excellent gas barrier properties against oxygen and carbon dioxide, UV resistance, and the capability for active packaging applications, such as antimicrobial films (Lionetto and Esposito, 2021). However, their high hydrophilicity poses challenges to water resistance, necessitating cross-linking to enhance functionality (Mahmud et al., 2021). Applications of these proteins include edible films designed for preserving perishable foods and blends with plant-based polymers, such as corn starch, to improve mechanical strength and broaden their usability.

Chitosan, derived from crustacean shells or fish scales, is a biodegradable substance and has film-forming properties. It plays a vital role in active food packaging by preventing microbial growth, thus extending shelf life. Additionally, chitosan is blended with gelatin or alginate to produce durable composite films, expanding its applications in sustainable packaging solutions (Mahmud et al., 2021;

Table 2: Key polymers derived from fish waste

Biopolymer	Source	Extraction method	Key properties	Applications	References
Collagen	Fish skins, scales, bones	Acid/alkali treatment or enzymatic hydrolysis	High film-forming ability, UV-blocking, and biocompatibility	Sustainable packaging, biomedical films	(Lionetto and Esposito, 2021)
Gelatin	Collagen hydrolysis	Thermal or enzymatic hydrolysis	Flexible films, oxygen-barrier properties	Food wraps, bioplastics (e.g., MarinaTex)	(Mahmud et al., 2021); (Vijayakumar et al., 2024)
Fish muscle proteins	Fish muscle tissues	High-salt solution extraction	Gas barrier (O_2/CO_2), UV resistance, antimicrobial activity	Edible films, blends with plant polymers (e.g., corn starch)	(Lionetto and Esposito, 2021); (Mahmud et al., 2021)
Chitosan	Crustacean shells, fish scales	Deacetylation of chitin	Biodegradable, antimicrobial, film-forming	Active packaging, composite films (with gelatin/alginate)	Mahmud et al., 2021); (Rudovica et al., 2021)
Fish DNA-based	Salmon milt (DNA-rich waste)	Cross-linking with formaldehyde	Water stability, thermal resistance, and enzymatic biodegradability	Niche biodegradable films, functional materials	Yamada et al., 2022)
Hybrid biopolymers	Fish waste+ algae/plant additives	Blending with additives (e.g., red algae)	Mechanical strength, rapid biodegradability (4–6 weeks)	MarinaTex packaging, sericin-gelatin blends	(Vijayakumar et al., 2024)

Lionetto and Esposito, 2021).

Fish DNA-based bioplastics, sourced from DNA-rich waste like salmon milt, are water-stable and thermally resistant when cross-linked with formaldehyde. They are biodegradable by enzymatic nucleases, they can also bind DNA agents like ethidium bromide, making them ideal for niche uses in biodegradable films and functional materials (Yamada et al., 2022).

Hybrid biopolymers, which combine fish waste with algae or plant-based additives, are sustainable materials with diverse uses. MarinaTex uses fish scales and red algae to create biodegradable packaging that degrades within 4–6 weeks. Similarly, fish gelatin blended with sericin (silkworm protein) enhances mechanical properties and biodegrades by 85% in 14 days (Vijayakumar et al., 2024). These innovations reduce reliance on crops like corn starch, repurpose marine waste, and support circular economies.

5.3. Applications of bioplastics derived from fish waste

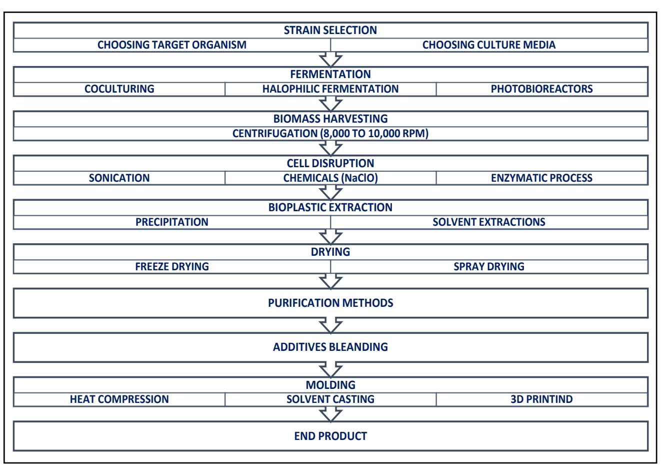
The EU's initiative "Blue Growth," which encourages the sustainable use of marine resources, discarded fish species, or by-catch, is converted into bioplastics, thus lessening ocean pollution and aiding innovation in our circular economy (Lionetto and Esposito, 2021). Waste-derived biopolymers for food packaging are muscle proteins, collagen, gelatin, and chitosan recycled from fish skin, scales, and viscera Plastics produced from fish myofibrillar proteins demonstrated excellent barrier properties to gaseous substances (such as oxygen) and UV light, indeed having better oxygen permeability compared to synthetic polymers (PVC), while films produced from collagen and gelatin showed excellent barrier properties to water vapour, especially in blends with additives such as glycerol and/or starch (Neves et al., 2019). In Active and intelligent packaging systems, incorporation of bioactive compounds such as antioxidants and antimicrobials, enhance quality, namely incorporation of ascorbic acid into fish protein films, resulting in reduced oxidation and microbial growth, and the use of fish gelatin mixed with myofibrillar proteins to improve mechanical strength and flexibility to wrap perishables (Neves et al., 2019; Vijayakumar et al., 2024). Fish Collagen, which has a very similar structure to human collagen, is used in tissue engineering and wound dressing especially because of the combined properties of biocompatibility and biodegradability (Lionetto and Esposito, 2021), while chitosan derived from fish scales is formed into hydrogels for controlled drug release (Rajput et al., 2024). As for single-use products, there are various options such as MarinaTex a bioplastic made from fish scales and red algae, which is completely biodegradable within 4–6 weeks and can be used for bags and packaging and composite materials of fish gelatin and plant-based polymers like starch molded into compostable cutlery that will disappear in soil within weeks (Vijayakumar et al., 2024). Nanocellulose crystals improve tensile strength and thermal stability in composite materials like fish gelatin (Vijayakumar et al., 2024), and protein-starch composites offer rigid yet biodegradable bioplastics for packaging or agricultural films (Neves et al., 2019).

6. BIOPLASTICS DERIVED FROM MARINE/ HALOPHILIC MICRO-ORGANISMS

Marine microbes include Pseudomonas, Bacillus, Arthrospira, *Nostoc muscorum*, Synechocystis PCC6803, and Synechococcus sp. MA19, which has been extensively studied for its ability to produce PHAs (Pinnell et al., 2022), and Chlorella vulgaris for the production of a maximum concentration (80%) of PHB, a biopolymer suitable for making bioplastics (Arora et al., 2023). Marine environments host diverse microorganisms that synthesize biopolymers such as polyhydroxyalkanoates (PHAs), including polyhydroxybutyrate (PHB) and its copolymer poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), as well as polylactic acid (PLA) and polybutylene succinate (PBS) (Phosri et al., 2022). These polymers are synthesized intracellularly by bacteria as energy storage molecules under nutrient-limiting conditions. These biopolymers represent a highly promising source of bioplastics, offering a sustainable alternative to conventional packaging materials that are detrimental to the environment.

6.1. Bioplastic production from marine microorganisms/ halophilic bacteria

The production of bioplastics begins with the selection and cultivation of specific strains of microorganisms (Flow chart 3). These include PHA and PHB producers such as *Halomonas halophila*, Synechocystis sp. PCC 6803, and *Erythrobacter aquimaris* (Mostafa et al., 2020); (Ahuja et al., 2024), as well as PHA degraders like Alteromonadaceae and Pseudomonas spp (Mostafa et al., 2020). In addition, PET-degrading enzymes engineered into *Vibrio natriegens* are used (de Souza et al., 2024). These microorganisms are grown in saline media, simulating marine environments (2–4% NaCl, pH 7.5–8.0), utilizing carbon sources such as glucose, glycerol, or date syrup. Stress induction by nitrogen or phosphorus starvation stimulates biopolymer production, exemplified by the 81% PHB yield from nitrogen starvation in Synechocystis (Ameen et al., 2024).



Flow Chart 3: Process of bioplastic synthesis from marine microorganisms/halophilic bacteria

After microbial cultivation, fermentation techniques tailored to microbial species and target products are employed. Fed-batch or batch fermentation methods are commonly applied, including halophilic fermentation using salt-resistant microbes like Halomonas halophila, which can thrive in 2% NaCl at 35°C (Varghese et al., 2022), producing biopolymers in saline environments. Photosynthetic organisms such as Synechocystis are genetically engineered ones that are used in photobioreactors under light/dark conditions to produce bioplastic precursors while utilizing nutrients from saltwater or wastewater (Samadhiya et al., 2022). Co-culturing combines degraders like *Vibrio natriegens* with producer microbes, converting plastic waste into bioplastic precursors through synergistic degradation and synthesis processes.

Once sufficient biomass is produced, harvesting is performed using centrifugation at 8,000 to 10,000 rpm to separate the biomass after a growth cycle of 7 to 10 days (Mostafa et al., 2020). Cell disruption techniques release biopolymers trapped within cells using mechanical methods like sonication or bead-beating (Ahuja et al., 2024), chemical treatments such as sodium hypochlorite, or enzyme treatments like lysozyme, particularly suited for Gram-negative bacteria requiring gentle processing. Extraction and purification of bioplastics are then conducted using solvent extraction methods, traditionally involving chloroform but increasingly employing eco-friendly alternatives like ethyl acetate. Followed by purification, typically involving cold methanol or ethanol precipitation, achieving more than 90% purity (Mostafa et al., 2020), drying methods like freeze-drying or spray-drying are employed to preserve the bioplastics (Ahuja et al., 2024).

The final stage involves material processing and application. Biopolymers are compounded with additives to improve their physical properties, such as blending with starch or chitosan for enhanced flexibility and toughness or alginate-based blends for biodegradable food packaging (Tennakoon et al., 2023). Molding techniques such as heat compression at 160–180°C or solvent casting are utilized to produce diverse products, including films, pellets, and 3D-printed structures. The flow of production of bioplastics from marine/ halophilic bacteria can be seen in Flow Chart 3.

6.2. Important bioplastic-producing marine microorganisms/ halophilic bacteria and their biopolymer

Several types of microorganisms can produce polyhydroxyalkanoates (PHAs) when they're in just the right conditions. For instance, *Cupriavidus necator* can make short-chain-length PHA (like PHB) when nutrients are limited, such as nitrogen or phosphorus, and does this using glucose or vegetable oil as a source of carbon. It can achieve productivity levels of up to 80% of cell dry weight (CDW) (Vicente et al., 2023). Likewise, *Pseudomonas putida* KT2440 can produce medium-chain-length PHA (mcl-PHA) under similar nitrogen-limiting conditions, using fatty acids or glucose as its feedstock, reaching as much as 75% CDW (Dalton et al., 2022). Then there's *Burkholderia sacchari*, which generates poly (3-hydroxybutyrate) [P(3HB)] from lignocellulosic waste, like by-products from sugarcane, also under limited nitrogen conditions, yielding as much as 80% CDW (Dalton et al., 2022). Cyanobacteria such as *Synechocystis* sp. PCC 6803 can accumulate PHB (81% CDW) when facing nitrogen limitation, whether in saltwater or wastewater (Dalton et al., 2022; Vicente et al., 2022). Halophiles like *Halomonas halophila* produce PHB (4.41 g l^{-1}) at a pH of 8.0, 35°C, and with 2% NaCl (Mostafa et al., 2020). Meanwhile, *Pseudodonghicola xiamenensis* can achieve higher yields of PHB (15.54 g l^{-1}) under a slightly lower pH of 7.5, 35°C, and with 4% NaCl and some date syrup added (Mostafa et al., 2020). *Haloferax mediterranei* can produce PHBV (70–90% CDW) in highly saline environments (15% NaCl) using glucose as a carbon source (Obruca et al., 2022). *Halomonas daqingensis* makes use of algal biodiesel waste to synthesize PHB (0.236 g g^{-1} CDW) at a salt concentration of 5% and a temperature of 35°C (Dubey et al., 2021). Finally, *Erythrobacter aquimari*s forms structurally pure PHB when using glucose and peptone at a pH of 8.0, as confirmed by FTIR analysis (Mostafa et al., 2020). Table 3 provides a note on the different microorganisms used in the synthesis of biopolymer, the type of polymer/ PHA produced, the Conditions for the culture of the microbe, and its productivity.

6.3. Applications of bioplastics derived from marine microorganisms

Bioplastics from marine and halophilic microorganism strains have diverse applications. Marine microorganisms, especially Halophilic archaea, exhibit high production of polyhydroxyalkanoates (PHAs), including polyhydroxybutyrate (PHB) and polyhydroxyvalerate (PHV), which are biocompatible and biodegradable and exhibit excellent applications in biomedical applications (Obruca et al., 2022). Their excellent biocompatibility and biodegradation make them fit for biomedical applications. For example, PHB and PHV copolymers find application in tissue engineering scaffolds, sutures, and drug delivery systems because they can be degraded safely in vivo without causing toxic by-products (Simo-Cabrera et al., 2021). Halophilic archaea, including Halomonas spp., possess

Table 3: Key Polymers derived from microorganisms

Organism	PHA/ biopolymer type	Optimal conditions for culture	Productivity	Reference
Cupriavidus necator	PHB (scl-PHA)	Nutrient stress (nitrogen/ phosphorus limitation), glucose/ vegetable oil as a carbon source	Up to 80% of cell dry weight (CDW)	(Vicente et al., 2023)
Pseudomonas putida KT2440	mcl-PHA	Nitrogen limitation, fatty acids, or glucose as a carbon source	Up to 75% CDW	(Dalton et al., 2022)
Burkholderia sacchari	P(3HB)	Lignocellulosic waste (e.g., sugarcane byproducts), nitrogen limitation	Up to 80% CDW	(Dalton et al., 2022)
Synechocystis sp. PCC 6803	PHB	Nitrogen limitation in saltwater or wastewater	81% CDW	(Dalton et al., 2022); (Vicente et al., 2022)
Halomonas halophila	PHB	pH 8.0, 35°C, 2% NaCl	4.41 g l^{-1} PHB	(Mostafa et al., 2020)
Pseudodonghicola xiamenensis	PHB	pH 7.5, 35°C, 4% NaCl+date syrup	15.54 g l^{-1} PHB	(Mostafa et al., 2020)
Haloferax mediterranei	PHBV	15% NaCl, glucose	70–90% CDW as PHBV	(Obruca et al., 2022)
Halomonas daqingensis	PHB	5% NaCl, 35°C, algal biodiesel waste	0.236 g PHB/g CDW	(Dubey et al., 2021)
Erythrobacter aquimaris	PHB	pH 8.0, glucose+peptone	High structural purity (FTIR)	(Mostafa et al., 2020)

distinct advantages in the industrial production of PHAs, as their high salt tolerance reduces contamination hazards, lowers the cost of sterilization, and streamlines downstream processing through hypo-osmotic cell lysis (Stanley et al., 2021). Genetically modified organisms (GMOs) also increase bioplastic use. For example, engineered Vibrio natriegens express PETase enzymes to degrade polyethylene terephthalate (PET) in marine environments, addressing microplastic pollution (Serrano et al., 2025). While marine-sourced PHAs are also tested in “smart packaging” with pH-sensitive additives to monitor food freshness (Tennakoon et al., 2023). Environmental remediation is improved by halophiles such as *Halomonas boliviensis* that produce PHAs from agro-industrial waste to facilitate circular economy approaches (Stanley et al., 2021). At the same time, GMOs such as methanotrophic bacteria produce PHAs from waste methane, connecting emissions reduction with bioplastic manufacture (de Souza et al., 2024). These micro-innovations highlight the efficacy of bioplastics to eliminate petroleum-based plastic use in health, agriculture, and environmental preservation approaches (Stanley et al., 2021; De Souza et al., 2024; Simó-Cabrera et al., 2021).

7. BENEFITS OF MARINE BIOPLASTICS

Marine biomass, specifically macroalgae such as seaweed, grows very quickly without the need for freshwater, fertilizers, or arable land, thus competing less with food crops. Macroalgae produce 20 times more biomass unit area^{-1} than land plants, which makes them a very scalable resource (Elkaliny et al., 2024). Most bioplastics from the marine environment, for example, polyhydroxyalkanoates (PHAs) and chitosan, are also biodegradable in natural environments, decomposing into water, CO_2, or methane without producing harmful residues, albeit in stark contrast to traditional plastics that last for centuries in environments (Nanda et al., 2022). Macroalgae sequester CO_2 while growing, serving as efficient carbon sinks and contributing to greenhouse gas reduction efforts while supporting circular economy principles (Elkaliny et al., 2024). Moreover, marine biopolymers such as alginate and carrageenan have unusual characteristics, with high mechanical resistance, UV tolerance, and heat stability, hence appropriate for versatile applications such as packaging, medical devices, and fabrics. Algae-based films, in some instances, have antimicrobial properties, leading to increased shelf life of foods (Nanda et al., 2022). Through extraction from renewable biomass, marine bioplastics are also less dependent on petroleum, as well as sharply decreasing lifecycle carbon emissions relative to traditional plastics (Atiwesh et al., 2021).

8. CHALLENGES ASSOCIATED WITH MARINE BIOPLASTICS

Marine-derived bioplastics, despite their potential, are hindered by multiple obstacles that dampen their widespread implementation. Their high production costs and scalability problems stem from energy-demanding extraction techniques, including solvent processing, and sparse industrial infrastructure, thus challenging scalable production at quality levels (Tennakoon et al., 2023). Even though biodegradable, these bioplastics typically require specific conditions, such as industrial composting, to break down fully. In the ocean, this process can take years, with some formulations of them breaking down into microplastics or releasing toxic additives (Censi et al., 2022). Some bioplastics also have chemical additives like plasticizers that can damage marine ecosystems; for example, cornstarch-based bioplastics have been found to deplete oxygen in sediment, destroying local habitats (Elkaliny et al., 2024). In addition, the absence of uniform definitions and regulations for “biodegradable” and “bio-based” creates consumer uncertainty and the need for reforming new standards in labeling and waste management (Rosenboom et al., 2022; Atiwesh et al., 2021).

9. CONCLUSION

Marine-derived bioplastics offer sustainable alternatives to petroleum-based plastics by reducing fossil fuel dependence, enhancing biodegradability, and supporting circular economy practices. Their potential in packaging, biomedical, and agricultural sectors demonstrates practical value, though issues of scalability, degradation variability, and environmental impact remain. Progress in bioengineering and standardized life cycle assessments will be critical to overcoming these barriers. In this way, the discussion aligns with the objectives of this review by emphasizing both the opportunities and challenges in advancing marine bioplastics.

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