Applied Phycology

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tapy20

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To cite this article: Virginia Martin Torrejon, Sara Fernando, Uttam K. Roy, Uche Onwukwe & Lorna Anguilano (2025) Transforming seaweed into bioplastics: a review of cultivation, harvesting and processing methods, Applied Phycology, 6:1, 52-73, DOI: 10.1080/26388081.2024.2435035

To link to this article: https://doi.org/10.1080/26388081.2024.2435035

Published online: 19 Feb 2025.

APPLIED PHYCOLOGY
2025, VOL. 6, NO. 1, 52–73
https://doi.org/10.1080/26388081.2024.2435035

British Phycological Society
Understanding and using algae
Taylor & Francis
Taylor & Francis Group

Transforming seaweed into bioplastics: a review of cultivation, harvesting and processing methods

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ABSTRACT
Seaweed, once overlooked as a low-value resource, is emerging as a promising feedstock for bioplastic production. This review examines in seaweed cultivation, harvesting and processing techniques, highlighting innovative approaches to overcoming current challenges and emphasizing the seaweed's potential to revolutionize the bioplastics industry. Seaweed offers numerous advantages over traditional bioplastic sources, including rapid growth in marine environments, no competition for arable land or freshwater and the ability to sequester carbon dioxide and absorb excess nutrients, contributing to climate change mitigation. The unique biochemical composition of seaweed, rich in hydrocolloids such as agar, carrageenan alginate and other biopolymers like ulvan and starch, enhances its suitability for bioplastic production. However, despite these benefits, seaweed-based bioplastics are still in their infancy, constrained by economic and logistical challenges, such as high production costs, technological limitations and supply chain integration issues. The findings underscore the significant potential of seaweed to contribute to sustainable development, emphasizing the need for continued innovation, collaborative efforts and investment to realize this potential fully.

ARTICLE HISTORY
Received 4 September 2024
Accepted 23 November 2024

KEYWORDS
Biopolymers; bioplastic sources; carbon sequestration; feedstock; hydrocolloids; sustainable development

Introduction

Seaweed has been an overlooked marine resource for centuries, often dismissed as a nuisance. However, as we face unprecedented environmental challenges (Abbass et al., 2022; Mamun et al., 2023; Mikhaylov et al., 2020; Myers et al., 2021), this marine organism is emerging as an unexpected ally in the quest for more sustainable materials (Thiruchelvi et al., 2020). With its rapid growth, minimal resource requirements and remarkable biochemical properties, seaweed is proving to be a valuable resource with the potential to address one of our most pressing global issues: plastic pollution (Hahladakis & Iacovidou, 2019; Roland et al., 2022).

Plastics have revolutionized many industries, improved our quality of life and enabled technological advancements (Andrady & Neal, 2009; North & Halden, 2013). Their versatility, durability and cost-effectiveness make them indispensable in various applications, from healthcare to aerospace. However, the problem lies not in the material itself but in our unsustainable use and poor post-consumption management. The slow degradation of plastics, combined with their widespread use in single-use products, has resulted in a significant accumulation of plastic waste in marine and terrestrial ecosystems (Blair & Mataraarachchi, 2021; Vadera & Khan, 2021). This waste, which includes both macroplastics (> 5 mm) and microplastics (< 5 mm) (Moore, 2008), contaminates our ecosystems, harms wildlife and introduces toxic pollutants into the food chain, ultimately threatening human health (Moore, 2008; Vadera & Khan, 2021).

The environmental damage caused by conventional plastics has sparked a global search for more sustainable alternatives, and bioplastics have been proposed as a potential solution (Rosenboom et al., 2022). However, many bioplastics are derived from edible sources, such as corn, sugarcane and potatoes, which compete with food production and require substantial land and water resources (Cruz et al., 2022; Jin et al., 2023). In contrast, seaweed is a promising alternative as it can grow rapidly in different marine environments without competing for arable land or freshwater. Additionally, seaweed cultivation does not require fertilizers or pesticides and absorbs carbon dioxide and excess nutrients from the water, thereby helping to mitigate climate change (Bullen et al., 2024; Duarte

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et al., 2017). These environmental benefits make seaweed an attractive feedstock for bioplastics production, addressing many of the limitations associated with land-derived materials.

Seaweed's biochemical composition, high in hydrocolloids like agar, carrageenan and alginate, makes it suitable for bioplastics production due to its gelling and film-forming properties (Schmidtchen et al., 2022). In addition to these hydrocolloids, seaweed also contains other biopolymers such as cellulose and starch, which also have the potential as a raw material for bioplastic production. Unlike terrestrial crops, seaweed lacks lignin, a complex polymer that requires intensive chemical treatment, allowing for more efficient processing with lower environmental impact (Romero-Vargas et al., 2023).

The global bioplastic market, valued at $11.5 billion, is driven by increasing demand for sustainable materials and significant investments in research and development (The World Bank, 2023). However, seaweed-based bioplastics development is still in its infancy, limited by challenges such as supply consistency, high production costs and integration into existing plastic supply chains (The World Bank, 2023).

This review examines transforming seaweed into bioplastics, from cultivation and harvesting to biopolymer extraction and final product manufacturing (see Fig. 1 for an overview of the production pathway). It highlights recent advancements in bioplastic production, focusing on processing techniques and the integration of seaweed into the circular economy.

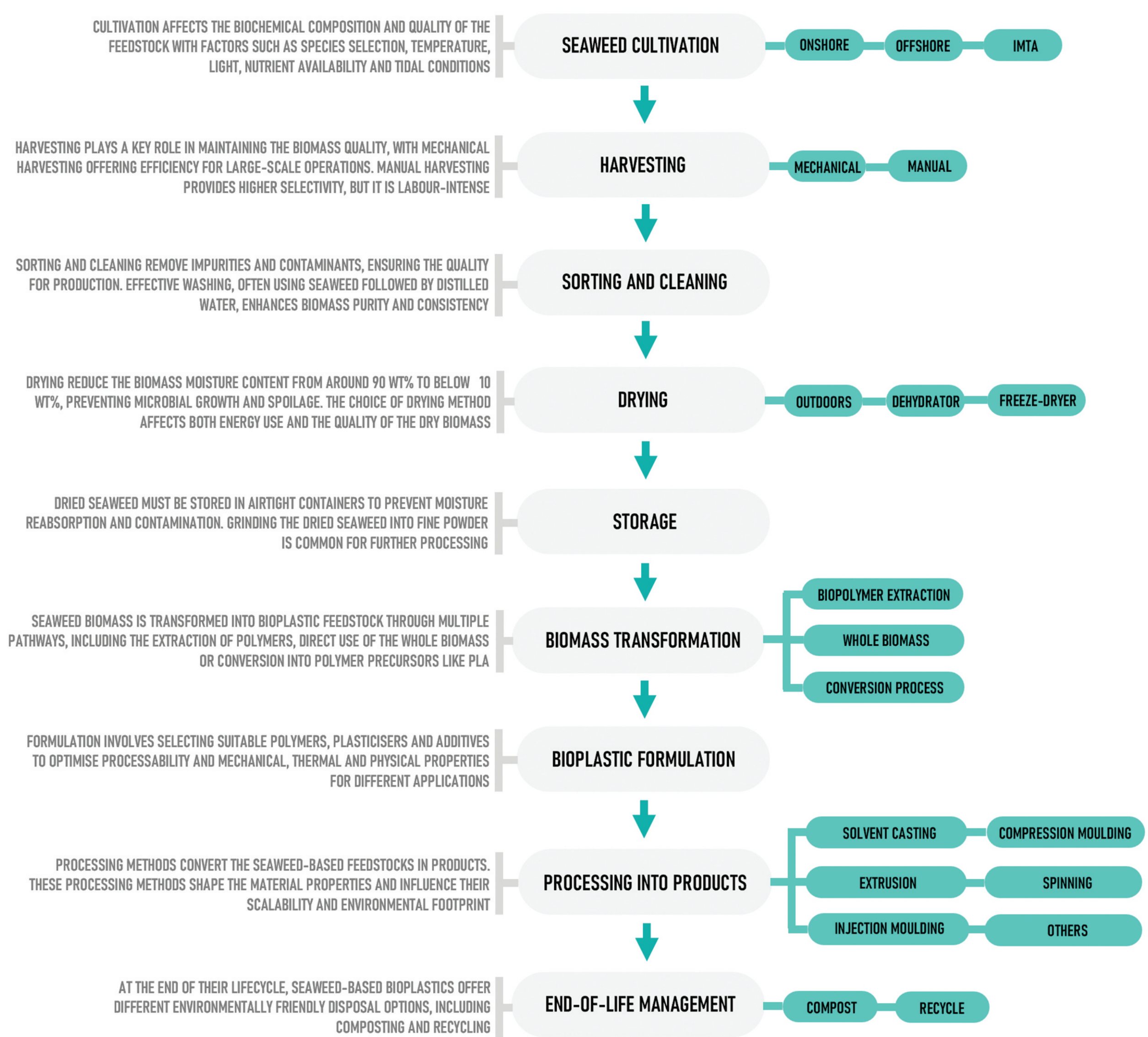

Fig. 1. Process diagram illustrating the main stages of seaweed transformation for bioplastic production, from cultivation to end-of-life management.

It is important to recognize that seaweed's success as a feedstock for bioplastics processing is not guaranteed by itself alone. Developing seaweed-based bioplastics requires coordinated efforts in research and development and stakeholder collaboration to address the challenges of cost, scalability and supply chain integration. Only through these efforts can seaweed become a viable alternative to conventional plastics, contributing to the global transition towards more sustainable materials. Ultimately, the idea that a resource, once dismissed as insignificant, could help shaping a more sustainable future is a powerful reminder of the untapped opportunities around and within us.

Seaweed cultivation and harvesting

Ensuring a reliable and consistent supply of high-quality seaweed biomass is essential to the success of seaweed-based bioplastics implementation. Seaweed farming has the potential to revolutionize the bioplastics sector, offering a sustainable and scalable alternative to fossil-fuel materials (Nagarajan et al., 2024; Zhang et al., 2024) and understanding cultivation methods and species selection is essential for maximizing biomass yield and quality and aligning seaweed farming with sustainability goals, paving the way for its broader adoption. Additionally, seaweed cultivation offers ecological benefits, such as the absorption of excess nutrients from marine environments and the potential to enhance local diversity (Bullen et al., 2024; Jagtap & Meena, 2022). From a social perspective, seaweed farming can provide economic opportunities for coastal communities (Jagtap & Meena, 2022).

Species selection and cultivation

Seaweeds are categorized into three primary groups based on their pigmentation and biochemical composition: green (Chlorophytes), brown (Phaeophyceae) and red (Rhodophyta) seaweeds (Schmidtchen et al., 2022). Each group is characterized by distinct biochemical components (see Fig. 2) contributing to their unique properties and potential applications. Green seaweeds are rich in starch and ulvan (Ghosh et al., 2019, 2021). Brown seaweeds contain high levels of alginate, a valuable polysaccharide widely used in food, pharmaceutical and biomedical industries (Berglund et al., 2020) and red seaweeds are known for their high content of carrageenan and agar, which are extensively utilized in food processing, biotechnology and other fields (Schmidtchen et al., 2022).

The selection of seaweed species is a strategic decision in cultivation as it influences the type and quality of bioplastics that can be produced. Selecting the appropriate species for cultivation involves considering several factors, including growth rates, biochemical composition and adaptability to different environmental conditions (Majeed, 2023). Seaweed species across various genera have been investigated for their potential applications in bioplastic development, with each species offering unique properties suited to different uses. Within the Chlorophyta (green seaweeds), *Ulva* sp. has been studied for its role in biomass conversion to polyhydroxyalkanoates (PHA) (Ghosh et al., 2019, 2021); *Ulva lactuca* has been explored for biomedical applications (Guzman-Puyol et al., 2017) and the creation of reusable bags (Kadell & Callychurn, 2023), while *Ulva ohnoi* has been used as a source of starch (Prabhu et al., 2019). The use of seaweed for the production of films is relatively widespread in *Ulva* spp (Manikandan & Lens, 2023), as well as other species such as *Ulva reticulata* and *Ulva armoricana* (Barghini et al., 2010; Bordeos et al., 2024).

In the Phaeophyceae (brown seaweeds) category, film production is again a widespread application: *Sargassum natans* (Mohammed et al., 2023), *Sargassum* sp (Kanagesan et al., 2022), *Saccharina latissima* (Ayala et al., 2024), *Padina pavonica Rugulopteryx okamurae*, *Laminaria digitata* and *Jolinay laminaioides* have all been researched for use in packaging films. In addition, *Sargassum plagiophyllum* has been studied for rigid packaging (Kachaanun et al., 2022); *Saccharina latissima* has been investigated for its potential in biomedical products (Guzman-Puyol et al., 2017); *Padina pavonica* and *Rugulopteryx okamurae* have been examined for food packaging, with the latter also being used in controlled-release applications (Barcellos et al., 2023; Dalal et al., 2023; Santana et al., 2022), while *Laminaria digitata* and *Jolinay laminaioides* have been explored for their potential in hydrogels and biomedical devices (Berglund et al., 2020; Rasheed et al., 2023).

Among the Rhodophyta (red seaweeds), several species, like *Gracilaria salicornia*, *Gracilaria verucosa*, *Kappaphycus* sp., *Kappaphycus alvarezii*, *Eucheuma spinosum*, and *Eucheuma cottonii* have all been investigated for their applications in producing films for bioplastics, with studies highlighting their mechanical strength, biodegradability and potential use in packaging and reusable bags (Bhatia et al., 2023; Burhani et al., 2023; Darni et al., 2019; Ghobashy et al., 2023; Hanry, 2023; Hanry & Surugau, 2024; Kadell & Callychurn, 2023; Leong et al., 2024; Rizal et al., 2021; Romero-Vargas et al., 2023; Siew Ling et al., 2016; Wan Yahaya et al., 2023). Beyond their applications in film

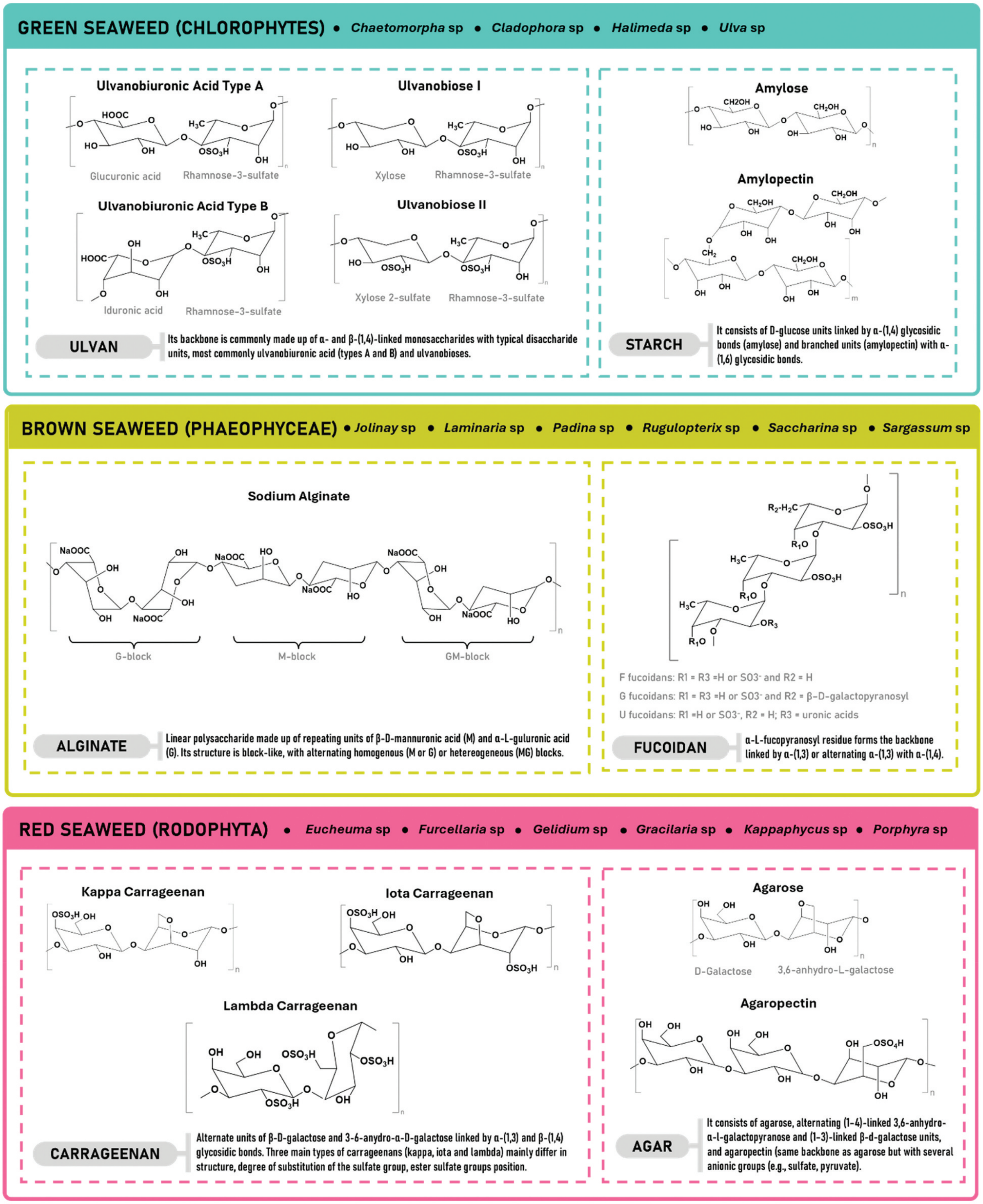

Fig. 2. Main polysaccharides and key seaweed species in green, brown and read seaweed for bioplastics production.

production, several red seaweed species have demonstrated potential in other bioplastic-related areas. *Gracilaria corticata*, for instance, has been highlighted for its role in lactic acid production through fermentation, essential in producing polylactic acid (PLA) bioplastics (Sudhakar & Dharani, 2022). Meanwhile, *Gelidium corneum* and *Gelidium elegans* have been explored for their use in reinforcing biocomposites, offering enhanced mechanical properties when used as fibres (Mouga & Fernandes, 2022; Pranoto et al., 2007).

Additionally, *Porphyra yezoensis* has shown promise in biomedical applications due to its biochemical composition, and *Furcellaria lumbricalis* has been studied for its potential to create eco-friendly utensils such as spoons and cups, as well as rigid packaging materials (Zaimis et al., 2021).

Cultivation methods vary based on the species and environmental conditions. Fig. 3 compares onshore, offshore and Integration Multi Trophic Aquaculture (IMTA) cultivation methods. The choice of cultivation method directly impacts the biomass yield, composition and quality and the production process's sustainability, which aligns with broader environmental goals such as reducing the carbon footprint (Steinhagen et al., 2022).

Onshore cultivation consists of growing seaweed in controlled environments such as tanks and ponds, which allows for precise management of nutrients, light and CO_2 levels (Prasad Behera et al., 2022). This method is particularly effective for high-value species or when environmental conditions in open waters are unsuitable. However, onshore methods require significant infrastructure and operational costs due to land

	ONSHORE CULTIVATION	OFFSHORE CULTIVATION	IMTA
TECHNOLOGIES	Photobioreactors, controlled tank systems, LED lighthing for optimised growth	Rope and line systems, floating farms, use of buoys for stability	Integrated systems combining seaweed with fish or shellfish farming, nutrient recycling technologies
SCALABILITY POTENTIAL	Medium; requires infrastructure for controlled environments	High; scalable for large ocean-based operations	High; integrates with other aquaculture enhancing scalability
COSTS	High initial and operational costs due to infrastructure	Medium; lower initial costs, ongoing maintenance required	Medium; shared costs with other aquaculture activities
IMPACT ON QUALITY AND YIELD	High; controlled environments ensure consistent quality and optimised biopolymer content	Variable; dependent on environmental conditions that may affect biochemical composition consistency	High; nutrient-rich environment enhances quality
ENVIRONMENTAL IMPACT	Medium to high; energy-intensive, but low water contamination	Low; integrates with natural ecosystems	Positive; reduces environmental impact of other aquaculture activities
CARBON SEQUESTRATION POTENTIAL	Moderate, depends on species and growth rate	High; significant potential, especial for kelp species	High; enhances carbon sequestration through nutrient recycling
BIODIVERSITY IMPACT	Low; limited to controlled environments, minimal impact on local diversity	Moderate; can enhance local marine biodiversity but may disrupt ecosystems if not managed properly	High; promotes diversity by integrating multiple species and trophic levels
REGULATORY CHALLENGES	High; stringent controls required for water use, waste management and species protection	Moderate; subject to maritime laws and environmental regulations	High; must comply with regulations for both aquaculture and environmental protection
SUITABILITY FOR BIOPLASTICS PRODUCTION	Best for specialised, high-quality bioplastics	Suitable for mass production of feedstocks for bioplastics	Diverse outputs can support various bioplastic applications

Fig. 3. Comparison of IMTA, onshore and offshore cultivation.

acquisition, infrastructure costs and maintenance (García-Poza et al., 2020). Offshore cultivation utilizes natural sea conditions, often employing rope or line systems where seaweed is suspended in the water column to maximize exposure to sunlight and nutrients. This method is less labour-intensive and can be scaled up more easily, but it is subject to environmental variables such as storms, temperature fluctuations and biofouling, which can affect yield and quality (García-Poza et al., 2020).

IMTA is another innovative approach that combines seaweed cultivation with other forms of aquaculture, such as fish or shellfish farming (Chopin, 2013; García-Poza et al., 2020; Prasad Behera et al., 2022). In IMTA systems, seaweed absorbs excess nutrients from the water, enhancing its growth and reducing the environmental impact of other aquaculture operations (Correia et al., 2020). This method increases biomass yield and contributes to the sustainability of the entire aquaculture system.

Harvesting

Harvesting is a critical phase in the cultivation process, as it directly influences the quality and economic viability of the seaweed used for bioplastic production (Santana et al., 2024). Mechanical harvesting is often employed on large-scale farms, using specialized equipment such as boats equipped with cutting mechanisms to efficiently collect seaweed (Majeed, 2023; SAMS Research Services Ltd, 2019). While this method is cost-effective, it can sometimes cause damage to the seaweed, potentially affecting its quality. Manual harvesting remains prevalent in smaller-scale operations or for high-value species (SAMS Research Services Ltd, 2019). This method allows for selective harvesting, ensuring that only the highest quality seaweed is collected. However, it is labour-intensive and less scalable, which can be a limitation in meeting large-scale production demands. Fig. 4 compares the mechanical and manual harvesting methods, highlighting their key differences.

Regulatory considerations

Expanding seaweed cultivation for bioplastic production is subject to various regulatory frameworks that aim to protect marine ecosystems and ensure sustainable practices. For example, in the UK, seaweed farming is regulated by the Department for Environment, Food & Rural Affairs (DEFRA) Department for Environment, (2015). Additionally, the UK's sanitary and phytosanitary controls mandate that a Phytosanitary Certificate accompanies any imported or exported seaweed to prevent the spread of pests and diseases (Department for Environment, 2023). While necessary for environmental protection, these regulatory requirements present challenges for scaling up seaweed cultivation. Producers must navigate these regulations carefully to avoid delays and additional costs, making it essential for successful large-scale operations.

Post-harvesting activities: feedstock preparation for processing

Post-harvesting activities ensure that the biochemical properties and the quality of the seaweed are preserved and optimized, which is essential for producing high-performance bioplastics. From sorting and cleaning to drying and storage, each step in the post-harvesting process must be meticulously managed to maintain the integrity of the biomass and ensure its suitability for conversion into bioplastic materials.

Sorting and cleaning

The first post-harvesting activities involve sorting and cleaning the harvested seaweed. Effective sorting and cleaning not only enhance the purity of the biomass but also contribute to the consistency of the bioplastic's mechanical and physical properties, which are critical for meeting production standards. During sorting, the biomass is inspected and separated based on quality, removing impurities, unhealthy tissues and fouling organisms that could compromise the final bioplastic product (Good et al., 2021). Cleaning follows, where the seaweed is thoroughly washed to remove sand, debris and any attached epiphytes or contaminants (El-Sheekh et al., 2024; Sudhakar et al., 2021). This step is crucial for ensuring that the seaweed's surface is free from any materials that could interfere with subsequent processing stages or diminish the quality of the bioplastic. This process is akin to selecting the finest ingredients for a recipe; just as the quality of ingredients determines the outcomes of a dish, the thoroughness of sorting and cleaning influences the quality of the bioplastics produced.

Seawater is commonly used immediately after harvesting to perform a preliminary rinse, which helps remove surface debris and organic matter. After this, a second wash is typically conducted in the laboratory, using either tap (Dalal et al., 2023; Hanry, 2023; Kadell & Callychurn, 2023) or distilled water (Asif et al., 2021; Leong et al., 2024; Tarangini et al., 2023) to eliminate remaining salts and minerals that could interfere with the biopolymer composition, ensuring greater purity.

	MECHANICAL HARVESTING	MANUAL HARVESTING
TECHNOLOGIES/ TECHNIQUES	Mechanical cutters, automated harvesters with quality sensors	Hand-picking
SCALABILITY	High; ideal for large-scale bioplastics feedstock	Low; best for niche or high-value bioplastics
COSTS	High initial investment, low labour costs, suited for bulk bioplastic production	Low initial cost, high ongoing labour, suitable for high-value bioplastics
IMPACT ON QUALITY AND YIELD	Medium; potential damage could affect biopolymer yield and extraction quality	High; careful selection preserves quality
ENERGY CONSUMPTION	High; necessary for large-scale operations	Low; minimal energy usage, labour intensive
EXTRACTION EFFICIENCY	Medium, risk of contamination or damage during harvesting could lower efficiency	High; selective harvesting ensures high-quality inputs for extraction
SUITABILITY FOR BIOPLASTICS PRODUCTION	Best for mass production where quantity is prioritised	Suitable for high quality, high-value bioplastics

Fig. 4. Comparison of mechanical and manual harvesting.

Washing with distilled water until the water's pH reaches neutrality minimizes the presence of residual salts or minerals in the seaweed and improves reproducibility (Nilsson et al., 2022).

Moreover, the washing process must be carefully controlled in terms of time and temperature. Prolonged washing or high temperatures may result in the undesirable extraction of biopolymers at this stage.

Drying techniques

Drying is one of the most critical steps in feedstock preparation as it preserves the seaweed biomass by reducing its moisture content from around 90% to below 10%, where 10 kg of fresh seaweed typically produces 1 kg of dried biomass (Sudhakar et al., 2018). The selected drying method can significantly affect the quality of the seaweed and the properties of the bioplastic produced, requiring a balance between energy consumption and the preservation of biochemical properties. This balance is crucial for ensuring the feedstock's suitability for further processing and its contribution to the overall sustainability of the bioplastic lifecycle. Several drying techniques are employed, each with its advantages and limitations:

- Sun-drying and shade-drying. These traditional methods are cost-effective and involve spreading the seaweed under direct sunlight or in shaded areas until fully dried. While sun-drying is energy-efficient, it may lead to uneven drying and contamination from environmental factors like dust or soil (Suherman et al., 2018). Shade drying, on the other hand, can take longer, typically 3-4 days, as Asif et al. (2021) observed, offering more protection but less practical for large-scale operations.

- Commercial dehydrators and ovens. These methods provide controlled environments for drying, ensuring uniform moisture removal. For example, drying at 60°C for 12-24 hr can be effective, as Hanry and Surugau (2024) demonstrated. However, the energy intensity of these methods requires careful consideration, particularly when scaling up production. Combining sun-drying and oven-drying is also common to semi-dry seaweed after harvesting and before transportation (Hanry & Surugau, 2024; Kanagesan et al., 2022).
- Freeze-drying. Although more energy-intensive, freeze-drying preserves the seaweed's biochemical and structural integrity by sublimating moisture without passing through the liquid phase (Badmus et al., 2019). This method is particularly useful for high-value applications where maintaining the highest quality is paramount.

Storage and handling

Once dried, seaweed must be properly stored to prevent reabsorption of moisture and contamination, which could degrade the quality of the feedstock and affect the bioplastic production process. Typically, dried seaweed is stored in airtight containers or bags that protect it from humidity and other environmental factors. Proper storage extends the shelf life of the feedstock and ensures that it retains its desirable properties until it is ready for processing.

Additionally, the dried seaweed is often ground into a fine powder before further processing (Hanry & Surugau, 2020, 2023; Kachaanun et al., 2022; Kanagesan et al., 2022) to facilitate the extraction of biopolymers and mixing. The particle size of the ground seaweed can significantly impact the properties of the resulting bioplastics and their processability. While smaller particles generally provide a higher surface area, enhancing interactions between the additives and the polymer matrix, dispersion and extraction of certain seaweed components (Bahari et al., 2021; Prasedya et al., 2021), there are instances where the reduction in particle size may not lead to the expected improvement in processability. For example, as observed in the milling of *Laminaria digitata* (Manns et al., 2016), while particle size reduction typically enhances enzyme access by increasing surface area, the two-dimensional nature of the milling process, in this case, limited such benefits. Nevertheless, milling may still be advisable to ensure a homogeneous process, as uniform particle size can contribute to more consistent processing conditions and overall quality control during bioplastic production.

Quality control

Quality control is a vital aspect of feedstock preparation, ensuring that the processed seaweed meets the necessary standards for bioplastic production. A comprehensive specification of the feedstock prior to processing is essential for maintaining consistency and optimizing downstream processes. This involves detailed biochemical analysis to determine the basic composition of the seaweed. The key components are moisture, ash (minerals), protein, fat and carbohydrates. For moisture content, an oven drying method is typically employed, where the seaweed is dried at a controlled temperature until a constant weight is achieved. Ash content is determined by incinerating the sample in a furnace at high temperatures until only the mineral content remains. The protein content is usually measured using the Kjeldahl method, which calculates the total nitrogen in the sample and the fat content is typically analysed using Soxhlet extraction (AOAC, 2019). Carbohydrates are calculated indirectly by subtracting the total of the other components from 100%.

To ensure the safety of the feedstock, especially for applications in food packaging and biomedical materials, testing for heavy metals using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is crucial (Ródenas de la Rocha et al., 2009). Microbiological testing may also be required to guarantee that the seaweed is free from harmful pathogens.

Biopolymer extraction, conversion and biomass utilization

The next phase in the production of seaweed-based bioplastics involves the transformation of harvested biomass into usable materials. This transformation encompasses several pathways, including the extraction of specific biopolymers (such as alginate, carrageenan and agar), the direct utilization of whole biomass without isolating individual components or the conversion of biomass into polymer precursors, which are then synthesized into bioplastics like polylactic acid (PLA) and polyhydroxyalkanoates (PHA). Each approach offers unique advantages and challenges, contributing to the overall versatility of seaweed as feedstock for bioplastics.

Extraction of biopolymers

The extraction of biopolymers from seaweed is a cornerstone of seaweed-based bioplastic production. Alginate, derived primarily from brown seaweeds

(Bouzenad et al., 2024; Dalal et al., 2023; Kanagesan et al., 2022; Mohammed et al., 2023; Santana et al., 2024), and carrageenan (Adam et al., 2022; Sari et al., 2021; Suryanto et al., 2019) and agar (Agusman et al., 2022; Hii et al., 2016; Irianto & G, 2024) extracted both from red seaweeds, provide a versatile matrix for bioplastics due to its film-forming capabilities, ability to form gels, biocompatibility, availability and encapsulation efficiency (Abdul Khalil, Tye, et al., 2017; Beaumont et al., 2021; Bukhari et al., 2023; Nagarajan et al., 2024). The extraction processes for these biopolymers typically involve alkaline and acidic treatments and refinement techniques (e.g. filtration, precipitation, dialysis and drying), all aimed at isolating the polymers (Sacramento et al., 2022). However, these methods often involve harsh processing conditions, significant energy consumption and large amounts of solvents, leading to environmental concerns (Lomartire & Gonçalves, 2022). In response to these challenges, green extraction methods have recently gained considerable attention (Lim et al., 2021; Saji et al., 2022). Techniques such as ultrasound-assisted extraction (Flórez-Fernández et al., 2019; Gómez Barrio et al., 2022; Martín-Del-Campo et al., 2021; Martínez-Sanz et al., 2019; Youssouf et al., 2017), microwave-assisted extraction (Álvarez-Viñas et al., 2023; Maleki et al., 2023; Nesic et al., 2023; Rudke et al., 2022), supercritical fluid extraction (Ospina et al., 2017) and enzyme-assisted extraction (Tarman et al., 2020; Xiao et al., 2019) have been optimized to minimize environmental impact (Li et al., 2021; Matos et al., 2021). These methods aim to minimize environmental impacts while improving the efficiency of biopolymer recovery by reducing energy use, solvent consumption and processing time. Such advancements are crucial for producing seaweed-based bioplastics more sustainably and economically viable (Junior & Turan, 2022; Matos et al., 2021).

Whole biomass utilisation

In contrast to extraction-focused methods, the direct utilization of whole seaweed biomass offers a more holistic approach to bioplastic production. This method involves the mechanical and thermal processing of the entire biomass to form bioplastics directly, bypassing the need for polymer isolation (Hanry & Surugau, 2024; Kachaanun et al., 2022; Santana et al., 2022; Sudhakar et al., 2021). The biomass used in this approach can also originate from repurposing waste from residual materials left after the extraction of specific polymers within a biorefinery approach.

This approach reduces processing steps and minimizes waste, making it an attractive option for producing bioplastics with a lower environmental footprint. For example, seaweed biomass can be processed into films by grinding the dried seaweed, mixing it with plasticizers, and casting it into moulds. This method exemplifies how whole biomass utilization can streamline production while yielding materials suitable for various applications.

The integration of whole biomass utilization into the bioplastic production process highlights the innovative nature of this approach. It positions seaweed as not just a resource for extraction but as a versatile material that can be fully harnessed, contributing to the overall sustainability of the bioplastics industry.

Conversion processes

Conversion processes represent an innovative approach in seaweed-based bioplastics (Bhatia et al., 2023). These processes involve breaking down seaweed polysaccharides into their monomeric units, which are then used in microbial fermentation or chemical synthesis to produce bioplastics. For instance, seaweed-derived sugars can be fermented into lactic acid (Deng & Zhang, 2020; Nagarajan et al., 2022), the precursor for polylactic acid (PLA) or polyhydroxyalkanoates (PHA) can be synthesized through microbial fermentation (Kargupta et al., 2023; Romero-Vargas et al., 2024).

These conversion processes are often integrated within a biorefinery framework, which seeks to maximize the utilization of all components of the seaweed biomass (Romero-Vargas et al., 2023). By valorizing the entire biomass, including industrial residues, the biorefinery approach enhances the economic viability of bioplastic production and aligns with circular economy principles, reducing waste and improving resource efficiency.

Seaweed-based bioplastics formulation

The formulation of seaweed-based bioplastics is critical for their performance and processability. Formulation development involves the selection of polymers, plasticizers and other additives which influence the material's mechanical, thermal and physical properties (Fig. 5 and 6). A well-engineered formulation ensures that the bioplastics meet their application's functional requirements and are compatible with the specific production process.

Polymer blends and composites

Polymer blends and composites are two effective strategies for modifying seaweed-based bioplastics properties (Krishnan et al., 2024).

Category	Test	Description	Key Properties	Key Standard Methods
Mechanical Properties	Tensile Testing	Evaluates the material's behaviour under tension to determine its ability to withstand pulling forces (strength), its stiffness (Young's modulus) and stretchability (elongation). Essential for films and rigid structural materials where mechanical integrity is important	Tensile strength (Pa), Elongation at break (%), Young's modulus (Pa), Poisson ratio (dimensionless)	ASTM D638-22 (ASTM International, 2022e), ASTM D882-18 (ASTM International, 2018d), ISO 527-1:2019 (International Organisation for Standardisation, 2019b), ISO 527-3:2018 (International Organisation for Standardisation, 2018)
	Flexural Testing	Measures how a material responds to bending forces. It evaluates the material's ability to resist deformation or failure under load (flexural strength) and its stiffness during bending (flexural modulus). Significant for rigid structural and load-bearing components like trays and panels	Flexural strength (Pa), flexural modulus (Pa)	ASTM D790-17 (ASTM International, 2017f) ISO 178:2019 (International Organisation for Standardisation, 2019a)
	Impact Testing	Assesses the material's toughness and ability to absorb and dissipate energy during sudden impacts. Key for applications requiring durability under dynamic forces, such as packaging, protective gear and automotive components	Impact energy (J), impact strength (J/m)	ASTM D256-23e1 (ASTM International, 2023b) ASTM D4812-19e1 (ASTM International, 2022c) ISO 179-1:2023 (International Organisation for Standardisation, 2023)
	Hardness Testing	Evaluates resistance to surface indentation, critical for determining durability in applications like coatings and protective covers	Shore hardness (Dimensionless, shore A for soft materials or D for harder materials)	ASTM D2240-15 (ASTM International, 2021d) ISO 868:2003 (International Organisation for Standardisation, 2003)
	Tear Resistance	Measures how well the material resists tearing after a cut or defect. Important for films, bags and membranes that must maintain structural integrity under stress	Tear strength (N/mm)	ASTM D624-00 (ASTM International, 2020a) ISO 34-1:2022 (International Organisation for Standardisation, 2022)
	Compression Testing	Examines how a material withstands forces that try to reduce its volume, including resistance to crushing and stiffness under compression. Relevant to foams, cushions and packaging supports	Compressive strength (Pa), compressive modulus (Pa)	ASTM D695-23 (ASTM International, 2023c) ASTM D3574 (ASTM International, 2017b) ASTM D1621-16 (ASTM International, 2023d)
	Creep Testing	Tests how a material deforms over time under a constant load. Key for applications like seals, supports and components subjected to prolonged stress	Creep strain (%), creep modulus (Pa), time to failure (hours/days)	ASTM D2990-17 (ASTM International, 2017b)
Thermal Properties	Thermo Gravimetric Analysis (TGA)	Monitor weight changes as a function of temperature or time to evaluate thermal stability, compositional analysis and decomposition characteristics	Decomposition temperature (°C), weight loss (%), composition (e.g., ash content)	ASTM E1131-20 (ASTM International, 2020e) ISO 11358-1:2022 (International Organisation for Standardisation, 2022b)
	Differential Scanning Calorimetry (DSC)	Identifies thermal transitions like melting, crystallization and glass transition by measuring heat flow during controlled heating or cooling	Melting temperature (°C), crystallisation temperature (°C), glass transition temperature (°C)	ASTM D3418-21 (ASTM International, 2021e) ASTM E1356-23 (ASTM, International, 2023e)
	Thermal Conductivity	Measures the ability of a material to conduct heat. Important for evaluating insulation performance and heat dissipation in electronic and thermal applications	Thermal conductivity (W/m·K)	ASTM C177-19 (ASTM International, 2023a) ISO 8302: 1991 (International Organisation for Standardisation, 1991)
	Brittleness Temperature	Determines the lowest temperature at which a material can withstand impact or stress without cracking. Essential for low-temperature applications	Brittleness temperature (°C)	ASTM D746-20 (ASTM International, 2024a)
	Coefficient of Linear Thermal Expansion (CLTE)	Evaluates the rate at which a material expands or contracts when exposed to temperature changes. Critical for applications requiring dimensional precision	Expansion rate (µm/m·°C)	ASTM E831-19 (ASTM International, 2024b) ISO 11359-2:2021 (International Organisation for Standardisation, 2021)
	Vicat Softening Temperature (VST)	Measures the temperature at which a material begins to soften under a standard load. Used for determining thermal stability and softening behaviour	Softening temperature (°C)	ASTM D1525-17e1 (ASTM International, 2017a)
	Heat Deflection Temperature (HDT)	Measures the temperature at which a material deforms under a specified load. Indicates the heat resistance of the material under mechanical stress	Deflection temperature (°C)	ASTM D648-18 (ASTM International, 2018b)

Fig. 5. Key bioplastics properties and testing methods.

A polymer blend is a homogeneous combination of two or more polymers (Paul & Barlow, 1980). Carrageenan, agar and alginate are frequently blended with other biopolymers, such as starch (Sofiante et al., 2022; Suryanto et al., 2019), gelatine (Dzeikala et al., 2023) or chitosan (Muryeti et al., 2024). For instance,

Category	Test	Description	Key Properties	Key Standard Methods
Dimensional Properties	Density	Measures the mass per unit volume of a material. It helps determine material consistency, identify polymers and evaluate cost	Density (kg/m^3)	ASTM D792-20 (ASTM International, 2020b) ASTM D1622-20 (ASTM International, 2020c) ISO 1183-1:2019 (International Organisation of Standardisation, 2019)
	Specific Gravity	Compares the material's density to that of water (dimensionless). Used for identifying materials and controlling quality during production	Specific gravity (dimensionless)	ASTM D792-20 (ASTM International, 2020b)
	Shrinkage	Evaluates the dimensional change of the material as it cools, typically after moulding or drying. Critical for tool design and ensuring dimensional accuracy	Shrinkage (%)	ASTM D955-21 (ASTM International, 2021b) ISO 294-4:2018 (International Organisation of Standardisation, 2018)
Moisture-Related Properties	Water Absorption	Measures the amount of water a material absorbs over a specified time under controlled conditions. Important for materials in humid or wet environments	Water absorption (%)	ASTM D570-22 (ASTM International, 2022) ISO 62:2008 (International Organisation for Standardisation, 2008)
	Permeability	Assesses the rate at which gases, vapours or liquids pass through a material. Crucial for barrier applications, such as food or medical packaging	Water Transmission rate (WVTR, g/m^2·day), gas permeability (cm^3/m^2·day·atm)	ASTM E96-00 (ASTM International, 2017e) ASTM D3985-02 (ASTM International, 2017d) ISO 15105-1:2005 (International Organisation for Standardisation, 2005)
	Hygroscopicity	Evaluates the material's tendency to attract and retain moisture form the environment. Impacts processing, storage and performance in humid conditions	Equilibrium moisture content (%)	ASTM D5229/D5229M-20 (ASTM International, 2020d)
Optical Properties	Refractive Index	Measures how light bends when passing through the material. Important for optical clarity in lenses, films and transparent products	Refractive Index (dimensionless)	ASTM D542-22 (ASTM International, 2022a)
	Transparency and Haze	Evaluates the material's optical clarity and the scattering of light. Critical for aesthetic and functional applications, such as packaging and displays	Transparency (%), haze (%)	ASTM D1003-21 (ASTM International, 2021c)
	Gloss	Assesses the surface reflectivity of a material. Used for aesthetic evaluation in applications like automotive parts, packaging and consumer goods	Gloss units (GU)	ASTM D523-14 (ASTM International, 2018a)
Other Properties	Biodegradability	Determines the material's ability to break down in natural environments or controlled composting conditions. Bioplastics must be tested to determine their ability to degrade in specific environments, such as soil, compost or marine ecosystems	Biodegration rate (%), disintegration, CO_2 evolution	ASTM D6400-21 (ASTM International,2022d), ASTM D5988-12 (ASTM International, 2018c), ASTM D6691-17 (ASTM International, 2017, ISO 14855-2:2018 (International Standardisation Organisation, 2018), EN 13432:2000 (European Commission, 2000)
	Chemical Resistance	Tests the material's ability to withstand exposure to chemicals such as acids, bases or solvents. Essential for packaging, industrial or medical applications	Weight change (%), appearance	ASTM D543-21 (ASTM International, 2021a)
	Flammability	Evaluates how easily the material ignites, burns or self-extinguishes when exposed to a flame. Important for safety in construction, automotive and electronics	Burn rate (mm/min), ignition time (s)	ASTM D635-22 (ASTM International, 2022b)

Fig. 6. Key dimensional, moisture-related, optical and other properties along with selected testing methods for bioplastics.

in the literature, blends with starch have been reported to increase and decrease the bioplastic's mechanical properties and degradation rate. Some studies indicate that starch blends can increase the glass transition temperature of the blend (Dzeikala et al., 2023), enhance the mechanical strength (Sofiante et al., 2022) and increase the degradation rate (Faradina et al., 2024), while other studies report decreases in these properties (Suryanto et al., 2019). This variability in the literature can be attributed to several factors, such as differences in starch concentration, processing conditions, the chemical properties of the starch (e.g. degree of crystallinity or starch type) and the use of different additives within the polymer blend.

When seaweed-based polysaccharides are blended with other biopolymers, intermolecular forces like hydrogen bonding, electrostatic, hydrophobic and van der Waals interactions play a key role (Dickinson, 1998). These interactions help achieve a homogeneous blend structure, translating into enhanced mechanical properties (Krishnan et al., 2024). However, a significant challenge is achieving blending compatibility to avoid phase separation, which leads to inconsistent properties. The optimization of polymer ratios, processing conditions and compatibility is key in ensuring homogeneous mixtures and preventing phase separation during processing.

A composite, in contrast, combines a polymer matrix with a reinforcing phase, as fibres, particles or fillers (Dickinson, 1998). This reinforcing phase can enhance certain properties, like stiffness or water resistance, without fully blending at the molecular level (Clyne & Hull, 2019). Nanocomposites, incorporating materials like nanoclays, nanocellulose or silver particles, leverage the high surface area of the nanofillers to create interfacial bonding with the polymer matrix (Bulota & Budtova, 2016; Njuguna et al., 2008). They can significantly improve tensile strength, modulus and thermal stability, among other properties (George et al., 2021). For example, combining seaweed polysaccharides with cellulose can enhance the tensile and flexural properties, improve moisture resistance (Jumaidin et al., 2017) and extend the bioplastic shelf life (Abdul Khalil, Tye, et al., 2017), while Rhim et al. (2011) showed that the properties of agar/clay nanocomposite films can be improved or modified when the proper type of clay is used. A challenge in formulating nanocomposites is achieving uniform nanoparticle dispersion within the polymer matrix. Poor dispersion due to agglomeration can cause inconsistent properties. Techniques such as surface functionalisation of nanoparticles or solvent-assisted dispersion can help to achieve even particle distribution, ensuring consistent properties (Alves et al., 2019; Dhali et al., 2022).

Plasticisers

Plasticizers interact with seaweed-based biopolymers by disrupting intermolecular forces, which provide rigidity in the biopolymer structure. Plasticizers reduce the biopolymer matrix's glass transition temperature (Tg) and enhance the mobility of polymer chains, thereby increasing flexibility (Fransiska et al., 2024). Among the most commonly employed plasticizers in seaweed-based bioplastics are glycerol (Darni et al., 2019; Rasheed et al., 2023; Santana et al., 2022), sorbitol (Alvarado et al., n.d.; Asif et al., 2021) and polyethylene glycol (PEG) (Razavi et al., 2015; Sudhakar et al., 2021).

Including plasticizers in the bioplastic, formulation allows for enhanced processability in production methods such as solution casting, extrusion or injection moulding. These additives improve the flow properties of the polymer melt, facilitating better material distribution during moulding. The elongation at break tends to increase after the addition of the plasticizer, while tensile strength decreases as reviewed by Budiman et al. (2022).

However, plasticizers also present certain limitations. Their incorporation can increase the permeability of the bioplastic to moisture and gases (Fransiska et al., 2024), which can negatively affect the barrier properties essential for applications such as food packaging.

Bioplastic production methods

The success of bioplastic production methods is intricately linked to the formulation development process and the high-quality feedstocks prepared in the previous stages. These methods not only determine the physical and mechanical properties of the bioplastics but also influence their environmental footprint and economic viability. Notably, some of these production methods (such as solution casting, compression moulding, extrusion and injection moulding) are commonly used in the production of conventional plastics as well, making it feasible to integrate seaweed-based bioplastics into existing manufacturing systems.

This section explores various methods used to produce seaweed-based bioplastics, while Fig. 7 provides a detailed overview of the key steps involved in transforming seaweed feedstock into bioplastics through these processes.

Solution casting

Solution casting is one of the most widely used techniques for producing seaweed-derived bioplastics films (Dalal et al., 2023; Darni et al., 2019; El-Sheekh et al., 2024; Kanagesan et al., 2022; Mohammed et al., 2023; Rasheed et al., 2023; Rizal et al., 2021). This method involves dissolving the polysaccharide-rich seaweed biomass or polysaccharides extracted from the seaweed in a solvent, often water, to create a viscous solution that is then cast into thin films. The solution is typically heated to enhance solubility (Lu & Murray, 2019; Xie et al., 2024) and mixed with additives, such as plasticizers, to improve flexibility. Once cast, the films are dried at

SEAWEED	ADDITIVES USED	PRODUCTION METHOD	APPLICATION	REFERENCE
Kappaphycus alvarezii	Extracted polymers (starch, carrageenan, chitin), glycerol, acetic acid, HCl, NaOH, potassium permanganate, oxalic acid, ethanol	**(1)** Extraction of carrageenan. 10 g of dried seaweed boiled in 1 L distilled water for 30 min, filtered, precipitated with 1 L of 90% cold ethanol, stirred for 30 min, collected, and dried at 50 °C. **(2)** Extraction of starch. 2 g/mL of dried seaweed soaked in distilled water for 2 h, supernatant separated and filtered, treated with 10 mL of 1% HCl, heated for 10 min, clumps filtered, solution dried to yield starch powder. **(3)** Extraction of chitin from ramshorn snail **(4)** Solution casting. Mix at 65 °C, stirred until dissolved and cool.	Films	(Ling Leong et al., 2024)
Kappaphycus sp.	Natural dyes, glycerol, magnesium nitrate hexahydrate, silica gel, agar	**(1)** Seaweed oven-dried at 60 °C for 24 h and ground into powder. **(2)** Seaweed powder dissolved in distilled water, heated to 60 °C with continuous stirring for 30 minutes. **(3)** Glycerol added, heated to 80 °C and stirred. **(4)** Solvent cast and dried at 50 °C for 24 h. **(5)** Dyed extract added.	Films	(Hanry & Surugau, 2024)
Kappaphycus alvarezii	PEG-3000, nanoparticles (ZnONPs and SiO_2NPs, CuONPs)	**(1)** Seaweed washed with seawater and freshwater; shade dried for 3 days. **(2)** Small pieces of dry biomass autoclaved at 121 °C for 15 min. Then, the autoclaved seaweed made into a slurry using a mixer. **(3)** Mixing of seaweed slurry, nanoparticles suspension and PEG-3000 and then warm in a microwave oven at 70 °C. **(4)** Solvent cast and dry overnight. Then films were peeled and dried in an oven for 3 hours at 50 °C.	Films	(Sudhakar et al., 2022)
Kappaphycus alvarezii	Glycerol, sulfuric acid, diethyl ether, cyclohexane, ethanol	**(1)** Isolation and purification of lignin. **(2)** Preparation of lignin nanoparticles (LNPs). **(3)** Fabrication of composite films (a) soak macroalgae in water and cut into small pieces, (b) oven-dry macroalgae 40 °C for 72 hours, (c) Dissolve macroalgae in water and glycerol, (d) Add LNPs and heat solution to 90 °C for 60 min with continuous stirring, (e) Cast solution and dry in oven at 40 °C, 50% RH for 24 h.	Films	(Rizal et al., 2021)
Kappaphycus sp.	Sodium alginate, glycerol, magnesium nitrate hexahydrate, silica gel	**(1)** Pre-treatment. (a) Wash seaweed and sun dry for 2 days (40-50% moisture content), (b) oven dry at 60 °C for 24 h (15%-17% moisture content), (c) grind to powder form. **(2)** Bioplastic Development. (a) Dissolve seaweed biomass powder in water (1:60 biomass:water ratio) (b) add glycerol, (c) heat the mixture to 80 °C and maintain 1 minute, then slowly mix with a glass rod to eliminate any bubbles, (d) casting and (e) dry at 50 °C for 24 hours in a ventilated dryer.	Sheets	(Hanry & Surugau, 2023)
Kappaphycus sp.	Glycerol	**(1)** Pre-treatment. (a) Wash the seaweed, (b) Dry at 60 °C overnight, (c) Blend into powder form. **(2)** Film preparation. (a) Heat and stir biomass in water at 60 °C and leave to settle at room temperature for 30 minutes , (b) add glycerol, (c) heat the mixture to 80 °C and maintain, (d) casting and (e) dry at 50 °C overnight in a ventilated dryer.	Films	(Hanry & Surugau, 2020)
Sargassum sp.	Extracted biopolymer (alginate), inverted sugar	**(1)** Extraction of alginate. Dried seaweed ground into fine powder, alginate extracted following Mazumder et al. (2016) with modifications. **(2)** Preparation of inverted sugar. Prepared as per Bratu and Al Dumitru (2015) with modifications. **(3)** Solution casting. Mixed alginate with varying concentrations (2%, 6%) and IS (plasticiser). Heat mixture, stirred until dissolved, **(4)** cast into films and dry.	Films	(Kanagesan et al., 2022)
Sargassum natans	Extracted biopolymer (alginate), Manugel DMB (commercial sodium alginate)	**(1)** Extraction of alginate. (a) Initial extraction 3.75% (w/v) Na2CO3, 6 hours at 80°C, Centrifuged at 8000 rpm for 10 minutes (b) Second extraction (c) bleaching, 1:80 (v/v) of 15% NaClO for 20 minutes (d) Precipitation, centrifuged at 8000 rpm for 10 minutes at 25°C and pH 2 adjustment; (e) alcohol treatment, 50% (v/v) reagent alcohol 1:15 (v/v) for 2 hours under constant stirring; Adjusted pH to 10, centrifuged (f) drying, Stored in freezer at -17 °C for 24 hours, freeze-dried at -41 °C for 24 hours. **(2)** Solutions were thermo-mixed at 65 °C for 2 hours and casted using an automatic film applicator, immersed into calcium chloride bath and then dried in an oven at 30 °C for 24 hours.	Composite bioplastic	(Mohammed et al., 2023)
Sargassum plagiophyllum	Glycerol	**(1)** Pre-treatment. (a) Wash seaweed, (b) dry in a hot air oven at 80 °C for 24 h, (c) Grind in a planetary ball mill at 400 rpm for 1 hour to obtain algae powder. **(2)** Preparation of WG biocomposites. (a) Mix the algae powder with glycerol in PE bags, (b) Mix the formulation in a two-roll mill at room temperature for 3 min, (c) Compression moulding. Preheat mould to 140 °C for 4 min and sheets compressed at 350 kg/cm^2 for 7 minutes.	Sheets	(Kachaanun et al., 2021)
Gracilaria corticata	Extracted biopolymer (agar) glycerol and sorbitol	**(1)** Extraction of agar. 1:5 (w/v) seaweed to water ratio, boiling for 2-3 hours, repeated sieving, freezing, thawing, oven drying at 70 °C, and grinding into powder. **(2)** Film casting. (a) Stirring agar and plasticiser in a water bath at 90 °C for 30 minutes (b) cast the solution into moulds, (c) dry in oven for 24 hours at 50 °C.	Films	(Asif et al., 2021)
Gracilaria salicornia, Ulva lactuca	Extracted biopolymers (agar and starch), sodium hydroxide, glycerol, acetic acid	**(1)** Wash seaweed with tap water to remove impurities and dry. **(2)** Bleach the dry seaweed with 20% NaOH aqueous solution and spread on a plastic board for sun drying. Repeat the process until completely bleached. This process cause delignification and increase gel strength. **(3)** Grind and sieve the bleached dry seaweed, **(4)** Heat seaweed powder in water bath for at least 15 minutes to extract agar **(5)** Mix extracted agar and cassava starch with glycerol and acetic acid, **(6)** Solvent casting and dry.	Films to produce bags	(Kadell & Callychurn, 2023)
Kappaphycus alvarezii	Cellulose nanofibre, glycerol, hydrochloric acid, potassium chloride, potassium oxide	**(1)** Refined and semi-refined carrageenan extraction. **(2)** Mix the seaweed powder in water and heat to 80 °C, **(3)** add glycerol and heat to 90 °C for 1 minute **(4)** add the cellulose suspension **(6)** Solvent casting and dry for 1 day at approximately 40 °C.	Films	(Yahaya et al., 2023)
Gracilaria edulis	Starch, glycerol, acetic acid, and chitosan	**(1)** Pretreatment. (a) Wash biomass with water, (b) soak biomass in water for 24 hours with a lemon slice to remove odour, (c) store swelled at 4 °C. **(2)** Film preparation. (a) sonicate swelled biomass in water at 70 °C for 45 min, (b) autoclave at 121 °C for 15 min, (c) homogenise autoclaved biomass and filter through muslin cloth, (d) add starch and boil the suspension at 95 °C until homogeneous, (e) add glycerol, acetic acid, chitosan and mix. (f) Cast the dispersion and dry at ambient conditions for 48 hours.	Films	(Tarangini et al., 2023)
Padina pavonica	Extracted biopolymer (alginate), glycerol, sunflower oil, water and $CaCO_3$	**(1)** Extraction of sodium alginate. (a) 20 g of mashed biomass boiled with 300 mL of water for 30 minutes, (b) boiling with 300 mL of 0.5% (w/v) $CaCl_2$ solution for 30 min., (c) boiling with 300 mL of 0.5% (w/v) NaCl solution for 30 min., (d) boiling with 100 mL of 5% (w/v) Na_2CO_3 solution for 30 min. **(2)** (a) Alginate mixed with water and mixed using a hand blender, (b) glycerol, sunflower oil and calcium carbonate added and mix for 1 hour Mixing, (c) casting and (d) drying.	Films	(Dalal et al., 2023)

Fig. 7. Seaweed used for the production of bioplastics.

SEAWEED	ADDITIVES USED	PRODUCTION METHOD	APPLICATION	REFERENCE
Eucheuma Cottonii	Extracted biopolymer (carrageenan), sodium hydroxide, sorbitol, glycerine, starch	**(1)** Extraction of carrageenan. Heat on a hot plate at 90 °C for 3.5 hours. **(2)** Solvent casting (a) Mix the carrageenan, starch, water and plasticisers for 5 minutes, (b) oven-dry the paste at 65 °C for 3 hours in a cylindrical mould.	Drinking straws	(Alvarado et al., 2023)
Eucheuma spinosum	Extracted biopolymers (fibre), starch, sorghum stalk as fibre, glycerol	**(1)** Extraction. treated with 40% NaOH at 100 °C for 3 hours, washed to pH 11, treated with 6% H_2O_2 at room temperature, washed to pH 7, dried at 105 °C, milled and sieved to 63 microns. **(2)** Solvent casting. Mix and heat at 200 °C, stirred for 35 minutes at 375 rpm, poured into molds, oven-dried at 50 °C for 8 hours, stored in a desiccator for 24 hours.	Films	(Darni et al., 2019)
Jolyna laminarioides	Extracted biopolymer (alginate and starch) glycerol and sorbitol	**(1)** Sodium alginate extraction. (a) soaking solution 4% Na_2CO_3 for 12 hours, (b) Precipitation, 2% H_2SO_4, (c) drying at 60 °C. **(2)** Solvent casting. (a) Sodium alginate, starch and plasticiser mixed and heated with water, (b) cast, (c) dry	Films	(Rasheed et al., 2023)
Rugulopteryx okamurae	Glycerol	**(1)** Freeze-dried seaweed ground into flour (10 to 100 µm particles). **(2)** Seaweed flour mixed with glycerol in a two-blade counter-rotating batch mixer at room temperature and 50 rpm until homogeneous. **(3)** Injected into mould using Injection Molding System at 60 °C cylinder temperature and mould temperature at 90, 120, or 150 °C. Injection pressure of 500 bar for 20 s and post-injection pressure of 200 bar for 150 s.	Probes	(Santana et al., 2022)
Halimeda opuntia	Glycerol and PVA (85000–124,000 Mw)	**(1)** Seaweed was washed with freshwater to remove impurities and shade-dry for three days at room temperature. **(2)** Grind dried seaweed into fine powder, **(3)** Immerse seaweed powder in water and sonicate at 50/60 Hz for 30 min at 25 °C. Filter the mixture with Whatman no. 2 filter paper. **(4)** Add glycerol to the seaweed solution and heat for 120 minutes. Dissolve PVA in water and heat separately. **(5)** Add plasticised seaweed to melted PVA, mix at 60 °C for 1 h, **(6)** Cast the film into glass plates and dry at 40 °C.	Films	(El-Sheekh et al., 2024)
Rugulopteryx okamurae	Glycerol	**(1)** Freeze-dried seaweed ground into flour (10 to 100 µm particles). **(2)** Seaweed flour mixed with glycerol in a two-blade counter-rotating batch mixer at room temperature and 50 rpm for 10 minutes. **(3)** Injected into mould using Injection Molding System at 60 °C cylinder temperature at a pressure of 500 bar for 20 seconds. Injected samples were kept in the mould at 140 °C and 200 bars for 150 seconds.	Probes	(Santana et al., 2024)

Fig.7. (Continued).

controlled temperatures to solidify the material, producing bioplastic sheets.

It is a relatively simple and accessible process that does not require complex equipment, making it appealing for various applications, including food packaging and biomedical films. However, the method also presents challenges, such as the potential for film shrinkage during drying and the energy-intensive nature of the process for both dissolving the biomass and drying the cast films (Schmidtchen et al., 2022). These factors may limit the scalability of solution casting in large-scale bioplastic production (Xie et al., 2024). Innovations in solution casting, including eco-friendly solvents and improved drying techniques, are essential for enhancing the sustainability and scalability of this method, aligning it with broader environmental goals.

Compression moulding

Compression moulding is another method commonly used to produce seaweed-based bioplastics, particularly for creating rigid or semi-rigid products like containers and trays. This technique involves placing the seaweed biomass, often mixed with plasticizers and other additives, into a mould which is subjected to high pressure and heat (Santana et al., 2022). The heat softens the materials, allowing them to flow and take the shape of the mould. This method is highly effective for producing durable bioplastic products with complex shapes, making it suitable for packaging and consumer goods applications. However, the process requires precise temperature and pressure control to ensure uniformity and prevent defects in the final product.

The temperature, pressure and time parameters vary significantly. The reported temperatures used range from 130 to 160°C, compression pressures range from 20 kPA to 10 MPa, while the moulding time ranges from 3 to 20 minutes. Before the moulding process, the mixtures need to be uniformly mixed. Some publications employ heating during this step.

Extrusion

Extrusion is a versatile and widely used method for producing bioplastics, particularly in films, fibres and sheets (Faradina et al., 2024; Suryanto et al., 2019). In this process, the seaweed biomass is fed into an extruder, subjected to high temperatures and shear forces, causing it to melt and flow through a shaped die. As the material exits the die, it is cooled and solidified into a continuous product.

Extrusion offers several advantages, including high throughput, the ability to produce complex shapes and the potential for integrating other materials or additives to modify the properties of the bioplastic. However, the process requires careful management of temperature and shared conditions to prevent degradation of the seaweed's biopolymers, which could compromise the material's strength and mechanical properties.

Injection moulding

Injection moulding is particularly suited for producing complex, high-precision plastic parts, such as those used in automotive or electronic applications. In this method, the seaweed-based biomass is melted and injected into a mould cavity under high pressure. The material is then cooled and solidified, creating a bioplastic part with fine details and high dimensional accuracy.

One of the main advantages of injection moulding is its ability to produce large volumes of consistent, high-quality parts at a relatively low cost. However, the process can be energy-intensive, and the high temperatures required may lead to the degradation of certain biopolymers, which could affect the mechanical properties of the final product. Research into optimizing injection moulding conditions for seaweed-based bioplastics is ongoing, focusing on improving material performance while minimizing energy use.

Other processing methods

In addition to traditional bioplastic production methods, several alternative processing techniques have emerged, particularly suited for biomedical and specialized applications. Inotropic gelation is highly effective for producing micro- and nanoparticles for drug delivery systems. For instance, Fujiwara et al. (2013) developed alginate-starch-chitosan microparticles through a one-stage ionotropic gelation process. In this method, an alginate solution, incorporating chitosan and starch, is dispersed in a calcium chloride gelling bath, where cross-linking occurs, forming microparticles.

Electrospinning can be employed to produce fibres for wound dressings and tissue engineering applications (Xie et al., 2024). Through electrostatic forces, fine biopolymer fibres are drawn out, allowing precise control over fibre morphology and porosity, which are essential for cell proliferation and nutrient transport.

3D printing technologies have enabled the fabrication of structures from seaweed-based biomass. This method is used in biomedical applications where 3D-printed bioplastics can serve as implants, scaffolds or drug delivery systems (Xie et al., 2024).

Innovation and future directions

As we look towards the future, the continuous transformation of seaweed from a raw, natural resource into sophisticated bioplastic products underscores the innovative spirit driving this field. While each production method offers unique advantages, there is significant potential for further innovation in seaweed-based bioplastics. For instance, active research includes developing new biopolymer blends, using advanced processing techniques like 3D printing, and integrating smart materials that respond to environmental stimuli. Moreover, optimizing these production methods to reduce energy consumption and enhance the environmental benefits of seaweed-based bioplastics is crucial for their widespread adoption. These innovations push the boundaries of what is possible with seaweed and reinforce the broader environmental and economic goals of reducing plastic pollution and fostering sustainable development.

Conclusion

This review highlights the transformative potential of seaweed as a sustainable feedstock for bioplastic production, with each stage of the production process offering unique opportunities and challenges. Starting with cultivation, seaweed's rapid growth and minimal resource requirements position it as an ideal candidate for large-scale bioplastic production. Cultivating seaweed in marine environments without competing for arable land or freshwater further underscores its sustainability. However, scaling up cultivation to meet global demand requires advancements in both onshore and offshore farming techniques and innovative approaches like Integrated Multi-Trophic Aquaculture (IMTA) that enhance environmental sustainability and yield.

The harvesting stage is equally critical, as it directly impacts the quality and economic viability of the seaweed biomass. While mechanical harvesting methods offer efficiency for large-scale operations, they must be refined to minimize damage to the biomass and maintain quality. Conversely, manual harvesting, though labour-intensive, remains essential for high-value species and small-scale operations. Post-harvest handling, including drying and storage, is crucial for preserving the biochemical integrity of the seaweed, which directly influences the quality of the final bioplastic products. Quality control processes, including rigorous testing for contaminants and consistent polysaccharide content, ensure that the biomass meets the standards required for high-performance bioplastics.

Finally, transforming seaweed into bioplastics through methods like extracting hydrocolloids, whole biomass utilization and conversion processes presents the most significant technological challenges and opportunities. Each method has its advantages, from reducing processing steps to maximizing the use of all biomass components. Future research must focus on optimizing these processes integrating advanced technologies to enhance efficiency, scalability, and sustainability.

In conclusion, the success of seaweed-based bioplastics hinges on innovations and improvements across all stages of production, from cultivation and harvesting to processing and final product development. By addressing the challenges at each stage, collaborative efforts between stakeholders and continued investment in research and technology, seaweed has the potential to represent a key role in the sustainable materials industry, contributing significantly to the global effort to reduce plastic pollution and contribute to a circular economy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by the Guarantee funding for Horizon European MSCA for the project 'Development of compostable and renewable foams from macroalgae-based sources and identification of strategies for their successful implementation in the waste management system (CORAL), [grant EP/Y027701/1].

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