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Production and Evaluation of a Seaweed-Based Bioplastic Sheet for Food Packaging

Janani, Sathiamurthy [a], Geetha, R.V. [b] and Rajesh Kanna Gopal [b*]

[a] Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India.
[b] Department of Microbiology, Saveetha Dental College and Hospitals, Saveetha Institute of Medical and Technical Sciences, Saveetha University, Chennai, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

In 2020, global plastic waste production reached 367 million metric tons, a figure anticipated to escalate in the future. India, ranking fifth worldwide in plastic waste output, confronts significant challenges due to plastic pollution, a pressing environmental issue. Addressing this problem requires a departure from petroleum-based plastics. Seaweed-based bioplastics have emerged as a sustainable alternative, gaining attention for their versatility, particularly in food packaging applications. Approximately 1 kg of wet *Kappaphycus alvarezii*, a red seaweed, was boiled in 1L of distilled water for 15 minutes and then filtered, yielding roughly 98% crude jelly polysaccharides. The resulting mixture was air-dried, yielding about 5% (50 g dry weight from 1 kg wet weight) of dry crude polysaccharide. To produce bioplastic, 6 g of dry crude polysaccharide was combined with 3 mL of glycerol and 3 mL of vinegar, then mixed in 100 mL of distilled water. The mixture was

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**Corresponding author: Email: rajeshkannag.sdc@saveetha.com;*

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heated in a water bath at 100°C for 7 to 10 minutes, cast into a sheet, and left to cool for 2 days. Various mechanical properties were evaluated, including a maximum force of 5.85N, tensile stress of 3.65 MPa, tensile strain at the break of 10.38%, and tensile stress at the break of 2.54 MPa, which are critical for assessing materials in food packaging. These parameters provide insights into strength, flexibility, and ultimate stress under tension. Additionally, the identification of functional groups through frequencies and wavelengths, such as OH stretch, C-C stretch, and C-O stretch, offers valuable information on moisture interactions and structural integrity, enhancing the material's suitability for food packaging. Seaweed-derived bioplastics, especially those containing crude carrageenan, offer a sustainable and eco-friendly alternative to traditional plastics. They are biodegradable and renewable, naturally decomposing through microbial and marine organism activity, thereby reducing their environmental impact. Unlike fossil fuel-based plastics, carrageenan-based bioplastics degrade naturally over time. Seaweed-derived carrageenan is deemed safe and compatible with animal consumption. Unlike conventional plastic packaging, seaweed-based plastic does not pose a risk of clogging in the digestive systems of terrestrial or marine animals. This highlights their potential to significantly diminish the ecological footprint associated with plastic waste.

Keywords: Biodegradable plastic; seaweed; food packaging; polysaccharide; Kappaphycus alvarezii; carrageenan.

1. INTRODUCTION

The global production of plastic, primarily sourced from natural gas and crude oil for various applications, has resulted in an estimated cumulative weight of 8.3 billion tonnes. Between 1950 and 2015, a total of 6.3 billion tonnes of plastic waste, including both primary and secondary (recycled) sources, was generated. However, only about 9% of this waste was recycled, with 12% incinerated, and the remaining 79% either landfilled or released into the environment. In 2015, the world produced 407 million tonnes of plastic, with 164 million tonnes designated for packaging, representing 36% of total production. Packaging accounts for approximately one-third of plastic usage, with around 40% ending up in landfills and 32% escaping proper collection systems [1].

The presence of fragmented or minute plastic materials in the form of micro or nanoplastics has raised persistent environmental concerns. The disruption of organismal physiology and behavior due to micro and nanoplastics has been extensively documented in marine invertebrates, and similar effects have been observed in larger marine creatures like fish. More recently, there have been reports of potential impacts of micro- and nanoplastics on the gut microbiota of mammals, as well as cellular and metabolic toxicity in mouse models. Human exposure to micro- and nanoplastics primarily occurs through ingestion, as these particles are found in food or originate from food packaging [2]. Each day, the food industry generates substantial quantities of food, from production and processing to transportation and consumption, with direct consequences for both our health and the environment.

The present food system is increasingly burdening the Earth's natural resources, underscoring the urgency of adopting sustainable food production practices. Environmental concerns within the food industry primarily revolve around food processing losses, food waste, and packaging; energy conservation; food transportation; water usage; and waste disposal [3]. Food contact materials (FCMs) refer to substances that interact with food items, including food packaging, and have a crucial impact on food quality and safety. Food packaging plays a pivotal role in the contemporary food industry, serving as a primary method for preserving the quality of food products throughout their journey from production to consumption [4].

With the expansion of the food industry, there is a growing need for packaging materials. However, traditional petroleum-based plastics, being non-degradable, have posed significant ecological challenges, including threats to aquatic life and air quality degradation. In response to these issues, biodegradable polymers or biopolymers have emerged as an alternative solution for various industrial applications to mitigate the environmental risks associated with non-biodegradable plastics. These biopolymers can be categorized based on their source material, which includes polymers derived from biomass, synthesized from monomers, and produced through microorganisms [5]. Natural edible polymers refer to materials derived from edible sources that pose no health risk when consumed by humans or animals. They are directly consumed with food, leaving no waste for disposal. These materials, categorized as polysaccharides, lipids, and proteins, are utilized for creating coatings and edible films that envelop the surfaces of food products [6]. The utilization of biodegradable polymers is instrumental in advancing environmental sustainability, presenting promising attributes and capabilities for diverse applications across various sectors. There has been significant research focus on seaweed-derived polysaccharide-based composites, owing to their renewable and sustainable nature, particularly in industries like food packaging and medical fields such as tissue engineering and drug delivery.

Seaweed derivatives like alginate, carrageenan, and agar are popular choices for these applications due to their abundance, and gel-forming properties. Although seaweed exhibits unique film-forming characteristics, it tends to have limited mechanical strength and water vapor barrier properties [7]. Carrageenan, a polysaccharide derived from red algae, presents significant economic opportunities across diverse industries, including pharmaceuticals, food, cosmetics, printing, and textiles. Its primary production involves aquaculture-based seaweed cultivation, with Eucheuma and Kappaphycus species contributing to over 90% of the global output. Red algae offer three major types of carrageenan: kappa (κ), iota (ι), and lambda (λ). *Kappaphycus alvarezii*, primarily cultivated in Asian nations like Indonesia, the Philippines, Vietnam, and Malaysia, is a major source of kappa-carrageenan. Recently, carrageenan extracted from *K. alvarezii* has gained significant attention due to its economic potential in a wide array of applications [8].

Addressing the growing environmental challenges associated with plastic-based packaging, there is a notable surge of interest in the utilization of carrageenan-based films for food packaging. These films are gaining traction due to their cost-effectiveness, biodegradability, compatibility, and film-forming characteristics. To overcome the inherent limitations of pure carrageenan films, enhancements in their physical and chemical properties are achieved through the incorporation of other compounds. As a result, carrageenan-based films find versatile applications in prolonging food shelf life and monitoring freshness by suppressing microbial growth, minimizing moisture loss, and reducing respiration in food products [9-12].

Hence, current research efforts are primarily directed toward the utilization of bio-based materials in the field of food packaging. Biodegradable polymers, designed to be food-safe, are employed in the creation of edible packaging materials. These materials are meant to be consumed along with the food, offering consumers extra health advantages. Recent research has now turned its attention to the development of food packaging using multilayer coatings and films, with the aim of introducing unique additional properties to the packaging material [13]. The aim of this study is to develop biodegradable plastic from seaweed for sustainable food packaging.

2. MATERIALS AND METHODS

Approximately 1 kg of wet *K. alvarezii* seaweed is taken. 1 liter of water is added to the seaweed, and the mixture is thoroughly mixed to extract the polysaccharides. The mixture is then filtered through a nylon mesh to separate the seaweed from the extract. The resulting product is expected to contain approximately 98% crude polysaccharides (Crude extract = Extract yield / Total biomass in g). The crude polysaccharides are then shade-dried to remove excess moisture.

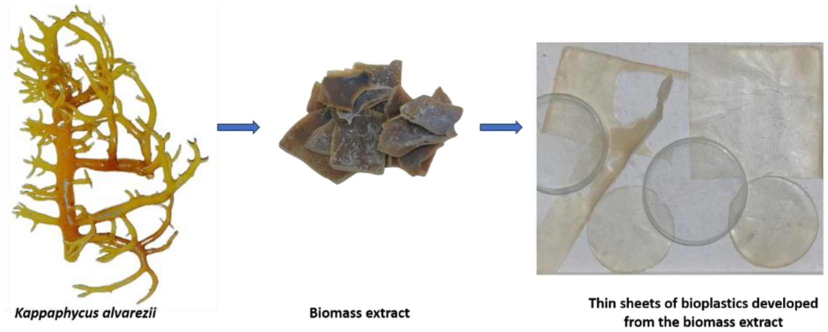

Fig. 1. The illustration of a marine red seaweed *Kappaphycus alvarezii* was extracted with its dry biomass and involved in the development of thin bioplastic sheets

6g of the shade-dried crude polysaccharide is taken. To this, 3 ml of glycerol and 3 ml of vinegar are added in a beaker. 100 ml of distilled water is also added to the beaker to create the polysaccharide solution. The beaker containing the polysaccharide solution is placed in a hot water bath at 100°C. The solution is heated until it becomes viscous and gel-like. Once the desired consistency is achieved, the casting mold is used to shape the solution into the desired form. The casting mold with the shaped polysaccharide product is allowed to cool down. Subsequently, the product is removed from the mold and shade-dried for a period of 2 days, allowing it to solidify and achieve the desired properties (Fig. 1). Tensile strength at stress and FT-IR analysis of the bioplastic sheets were also recorded and appended.

3. RESULTS

The results reveal important mechanical properties for assessing the suitability of materials in food packaging. The maximum force of 5.85N indicates the strength a material can withstand under tension. The tensile stress, measuring 3.65 MPa, signifies the material's ability to endure stress before reaching its maximum strength. The tensile strain at the break, at 10.38%, provides insight into the material's flexibility and deformation characteristics during the testing process. The tensile stress at the break, measuring 2.54 MPa, offers information about the material's ultimate strength at the point of fracture (Fig. 2 and Table 1). These parameters collectively contribute valuable data for evaluating and selecting materials suitable for food packaging applications, considering factors such as strength, flexibility, and ultimate stress under tension.

The recorded frequencies and wavelengths associated with functional groups in the material offer insights relevant to food packaging. Notably, the OH stretch at 3278 and 2928 indicates the presence of hydroxyl groups, potentially contributing to the material's interactions with moisture, a critical factor in food packaging. The C-C stretch in the ring at 1648 and 1421 suggests the presence of aromatic compounds, contributing to the material's structural properties. The C-O stretch at 1229 and 1029 signifies the presence of carbonyl groups, which influence the material's barrier properties. Additionally, the C-H bends and rocks at various frequencies suggest the presence of aliphatic hydrocarbons, contributing to the overall composition and mechanical properties of the material. The observed functional groups and their associated frequencies provide valuable information for understanding the material's suitability for food packaging, particularly regarding moisture interactions, structural integrity, and barrier properties (Fig. 3 and Table 2).

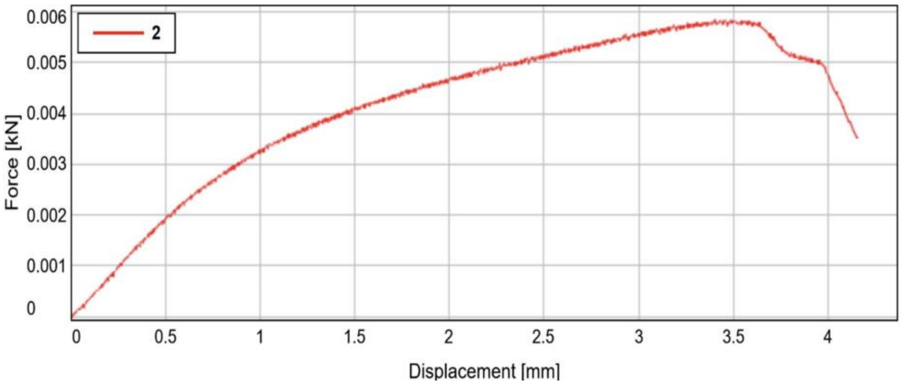

Fig. 2. The graph showing the displacement upon force describes the tensile strength of the material

Table 1. The table shows the tensile strength and stress of the bioplastic material

Maximum Force [N]	Tensile Stress at Tensile Strength [MPa]	Tensile Strain (Displacement) at Break (Standard) [%]	Tensile Stress at Break (Standard) [MPa]
5.85	3.65	10.38	2.54

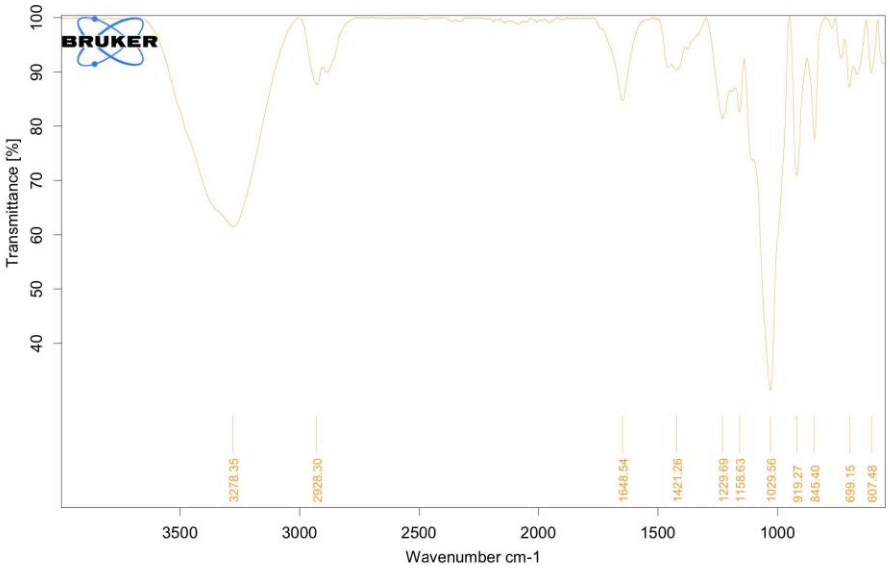

Fig. 3. The FT-IR spectrum of the bioplastic material developed from *K. alvarezii*

Table 2. The FT-IR table shows the functional group of the bioplastic material

Frequency Wavelength	Functional Group
3278	OH stretch
2928	OH stretch
1648	C-C stretch (in ring)
1421	C-C stretch (in ring)
1229	C-O stretch
1158	C-H wag (-CHX2)
1029	C-O stretch
919	C-H “loop”
845	C-H rock
699	C- H bend
607	C- H bend

4. DISCUSSION

In the realm of seaweed-based bioplastics, carrageenan derived from *K. alvarezii* offers distinct advantages over polysaccharides from other seaweed species like *Gelidium, Gracilaria*, or *Ulva*, such as agar or alginate. Its desirable properties and bioavailability make carrageenan stand out in bioplastic production. While studies may explore alternatives, comparing the properties and availability of different seaweed species and their polysaccharides is crucial for understanding their suitability in bioplastic applications. Alginate from brown seaweed is also a wonderful source for the production of bioplastics [14]. Research on seaweed-based bioplastics often concentrates on specific applications like food packaging, agricultural films, or personal care products [15]. A comparative analysis of seaweed-based bioplastics with commonly used materials in food packaging, such as petroleum-based plastics or biodegradable alternatives, can shed light on their advantages and areas for potential improvement [16]. These films serve as sustainable, readily biodegradable biomaterials, offering potential replacements for petroleum-based plastics across various applications, notably in packaging [17]. A review explores the potential of enhancing the functional properties of rice starch for industrial applications through physical mixing with natural or synthetic polymers and plasticizers. The focus is on modifying rice starch to create functional blends or composites, particularly for the development of sustainable packaging materials, pharmaceuticals, and nutraceutical products [18].

Packaging films were created using the solvent casting technique, combining natural red seaweed (*K. alvarezii*) and coffee waste. SEM analysis confirmed even dispersion of coffee filler, enhancing structural properties. FT-IR results indicated successful incorporation of coffee waste with the presence of a N-H bond. Optimal tensile strength (35.47 MPa) was achieved at 4 wt% coffee powder, improving the biopolymer film's functional properties [19]. Microbial gums, recognized as safe by the FDA, possess diverse physicochemical properties suitable for pharmacy, medicine, and food applications. With microbiological stability, adhesion, cohesion, wettability, solubility and transparency these gums find applications as edible films or coatings. They can be combined with bioactive compounds to extend the shelf life of perishable products [20]. A food-safe cellulose nanofiber (SCNF) extracted from common seaweed in an energy-efficient process under mild conditions serves as the basis for a robust structural material (SCNSM). By densely assembling SCNF, the resulting SCNSM exhibits high strength (283 MPa) and excellent thermal stability (>160°C). This material also demonstrates good machinability, allowing for the production of tableware, such as knives and forks, with varied shapes. The overall performance of SCNSM-based tableware surpasses that of commercial plastic, wood-based, and poly (lactic acid) alternatives, showcasing its significant potential in the tableware industry [21]. *Ulva intestinalis* seaweed's sulfated polysaccharides exhibit diverse biological activities. Films made from these polysaccharides using glycerol and polyethylene glycol (PEG) as plasticizers were studied for mechanical, physicochemical, barrier, and surface properties. Successful preparation of *Ulva intestinalis* sulfated polysaccharide films (USP films) was achieved with varying plasticizer concentrations (30%, 40%, and 50%). Increasing plasticizer concentration led to increased thickness, moisture content, solubility, and elongation at break, while reducing tensile strength, young's modulus, transparency, and barrier properties of the films [22].

Cinnamon nanoparticles were integrated into red seaweed (*K. alvarezii*) biopolymer films via a solvent casting method. Different concentrations of cinnamon (1%, 3%, 5%, and 7% w/w) were employed to enhance film properties. The hydrophobicity increased with higher cinnamon concentrations, while tensile and thermal properties notably improved. At 7% cinnamon, the biopolymer films demonstrated effective antimicrobial activity against *Escherichia coli* (*E. coli*), Staphylococcus aureus (*S. aureus*), and Salmonella bacteria, indicating their potential in inhibiting microbial growth [23]. Algal derivatives, encompassing microalgae starch, cyanobacteria-derived polyhydroxyalkanoates (PHAs), and polysaccharides from macroalgae, are recognized as renewable biomass for bioplastic production. These derivatives can serve as primary ingredients, like starch and PHAs, or additives such as sulfated polysaccharides in bioplastic formulations. The unique functional groups in algae, including carboxyl, hydroxyl, and sulfate, can be tailored to enhance bioplastic qualities, especially for applications in food, pharmaceuticals, and medical packaging. Implementing standardized cultivation, harvesting, and extraction processes in an eco-friendly manner holds promise for both pollution control and sustainable bioplastic production [24].

5. CONCLUSION

This research emphasizes the potential of carrageenan-based bioplastics to enhance food product quality and safety while contributing to a more sustainable and eco-friendly packaging solution.

6. SCOPE OF FUTURE RESEARCH

- Modification of polysaccharides to enhance their mechanical, thermal, and barrier properties, thereby improving their suitability for specific packaging applications.
- Combining seaweed polysaccharides with other biopolymers, such as starch or chitosan.
- Investigating market viability, economic feasibility, and consumer acceptance of seaweed-based bioplastics will be crucial for their successful commercialization
- Evaluating the safety and regulatory aspects of edible and biodegradable packaging to ensure they meet food safety standards.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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