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Sargassum-Derived Bioplastic for Sustainable Packaging: Evaluation of Mechanical, Thermal, and Barrier Properties

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ABSTRACT

Plastic pollution remains a critical environmental issue due to the persistence of petroleum-based plastics in natural ecosystems. This study evaluates *Sargassum* seaweed, an abundant coastal biomass in Malaysia, as a renewable feedstock for biodegradable bioplastic production. To overcome the inherent limitations of alginate-based bioplastics, glycerol 12.6% (w/w, relative to polymer mass) has been incorporated as a plasticizer, with calcium chloride (2% w/v) as a cross-linking agent. Bioplastic films were produced via alginate extraction, film casting, and drying, and characterized through tensile testing, differential scanning calorimetry (DSC), water absorption, grease absorption, and biodegradability analyses. The modified *Sargassum*-based bioplastics exhibited enhanced tensile strength (maximum force up to 6.67 N), improved elongation at break (up to 31.33%), and increased thermal stability, with a melting temperature of 160°C and degradation onset at 190°C. Swelling, biodegradation, and oil uptake behaviors were governed by the interplay between hydrophilic diffusion and calcium-mediated cross-link stabilization. Complete biodegradation was observed within 30 days in soil. These findings demonstrate that formulation optimization allows *Sargassum*-derived bioplastics to achieve balanced mechanical performance, barrier properties, and environmental degradability. This will enhance their potential for sustainable single-use packaging applications.

HIGHLIGHTS

- Valorization of abundant Sargassum seaweed for bioplastic production.
- Enhanced strength and thermal stability via glycerol and $CaCl_2$ modification.
- Complete biodegradation of films achieved within 30 days of testing.
- Promising eco-friendly alternative for single-use packaging materials.

1. INTRODUCTION

Plastic pollution has emerged as a critical environmental concern, due to the extensive use of non-biodegradable petroleum-based plastics, which can persist in ecosystems for centuries. A major consequence of their persistence is the formation of microplastics, tiny plastic fragments that accumulate in marine and terrestrial environments, posing risks to aquatic life, food safety, and even human health (Khan and Setu, 2022; Putri et al., 2023). These conventional plastics not only contribute to marine pollution and habitat destruction, but also release greenhouse gases during both production and degradation (Gross and Enck, 2021). In response, bioplastics made from renewable resources have gained attention as a sustainable alternative capable of reducing environmental harm (Nagarajan et al., 2024). In Malaysian coastal regions such as Port Dickson, seasonal *Sargassum* blooms are frequently observed during warmer periods (Chin et al., 2023). While excessive accumulations may lead to beach fouling and temporary disruptions to tourism and fisheries, these biomasses present valuable opportunities for sustainable resource utilization. Recent studies

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highlight the potential of converting *Sargassum* into biodegradable plastics as a practical strategy to reduce dependence on conventional petroleum-based plastics while supporting circular economy principles in local industries (Farghali et al., 2023).

Sargassum contains alginate, a naturally biodegradable polymer suitable for bioplastic production. However, existing research shows that *Sargassum*-based bioplastics often exhibit insufficient mechanical strength and thermal stability, limiting their practical applications (Bullen et al., 2024; Liu et al., 2023). Enhancing these properties through optimized formulations and processing techniques could significantly improve their usability. Research indicates that blending *Sargassum* alginate with biodegradable polyesters like polylactic acid (PLA) or polyhydroxyalkanoates (PHA) yields superior tensile properties while mitigating inherent brittleness (Santana et al., 2024). Glycerol was selected as the plasticizer in this study due to its proven compatibility with polysaccharide-based biopolymers, particularly alginate, and its widespread use in biodegradable film formulations (Hanry and Surugau, 2024). As a low-molecular-weight, hydrophilic plasticizer, glycerol effectively improves polymer chain mobility through hydrogen bonding interactions, thereby enhancing film flexibility and processability (Ben et al., 2022). In addition, glycerol is non-toxic, biodegradable, inexpensive, and readily available, making it suitable for sustainable packaging applications. Compared to alternative plasticizers such as sorbitol or polyethylene glycol, glycerol has been shown to provide a favourable balance between flexibility and mechanical integrity when used at controlled concentrations, while avoiding excessive stiffness or brittleness in alginate-based films (Langit et al., 2019). Cross-linking modifications using calcium chloride ($CaCl_2$) are particularly effective in enhancing structural rigidity and moisture resistance via ionic-bridge formation between alginate polymer chains (Asmadi et al., 2025). Composite formulations combining *Sargassum* alginate with PLA demonstrate enhanced thermal resistance, with decomposition onset temperatures exceeding 200°C in optimized compositions (Dungani et al., 2021), while cellulose nanofiber reinforcement enhances stability up to 200°C. However, plasticizers like glycerol (20%) can lower thermal resistance to around 140°C (Santana et al., 2024). Cross-linking with $CaCl_2$ improves thermal (190°C) and mechanical properties compared to non-crosslinked counterparts (Asmadi et al., 2025).

Previous studies have reported a wide range of mechanical performance for bio-based plastics derived from seaweed and alginate composites. For example, *Sargassum*-based alginate films typically show tensile strengths between 2-8 MPa and elongation at break values of 10-40% depending on the type and concentration of plasticizer used (Mohammed et al., 2023). Reinforcement with cellulose nanofibers or PLA has been shown to increase tensile strength up to 15 MPa, while glycerol-rich formulations may reduce strength to below 5 MPa but improve flexibility (Dungani et al., 2021). Calcium chloride cross-linked alginate films often demonstrate improved rigidity with tensile strength values reaching 10-12 MPa and reduced elongation compared to non-cross-linked films (Asmadi et al., 2025). These studies highlight that balancing cross-linking and plasticizer content is essential to achieving both strength and flexibility in bioplastics.

This research aimed to develop improved *Sargassum*-based bioplastics by incorporating glycerol as a plasticizer and calcium chloride as a cross-linking agent to boost mechanical and thermal performance. This study also compared the enhanced bioplastics with conventional packaging plastics and assessed their biodegradability, supporting the development of functional, eco-friendly materials. By addressing the current limitations of *Sargassum* bioplastics, this work contributes to sustainable solutions for plastic pollution. The findings highlight the potential of utilizing Malaysia's natural *Sargassum* resources while advancing environmentally responsible alternatives to traditional plastics.

2. METHODOLOGY

2.1 Sample location

Sargassum seaweed samples were collected from the primary sampling site of Avillion Beach, Port Dickson, Malaysia. Species identification was carried out based on morphological characteristics, including thallus structure, blade shape, presence of air vesicles, branching pattern, texture, and pigmentation. Visual comparisons with established taxonomic descriptions and published identification keys were supported by high-resolution reference images from peer-reviewed literature and authoritative online algal databases. Based on these criteria, the dominant species identified at the sampling site included *Sargassum muticum*, *Padina tetrastromatica*, and *Chondrus crispus*. Among these, *Sargassum muticum* was selected for bioplastic production, due to its

abundance and reported suitability for alginate extraction. Figure 1 presents an overview of the seaweed types identified at Avillion Beach, Port Dickson, including *Sargassum muticum*, *Padina tetrastromatica*, and *Chondrus crispus*.

Figure 1. Seaweed types found at Avillion Beach, Port Dickson. a), Location of sample collection. b), Seaweed collection at the shoreline of the beach. c), *Sargassum muticum* (used in this study), d), *Padina tetrastromatica* also known as mermaid's fan seaweed (Palaniveloo et al., 2021). e), *Chondrus crispus* commonly called as Irish Moss (Wilkes, 2022)

2.2 Pre-processing and drying

Sargassum samples were processed according to the previously described method (Alallam et al., 2025) with slight modifications. Each sample was chopped into smaller pieces and dried in an oven at 60°C. After drying, the samples were ground into fine powder using a mechanical grinder to increase surface area for alginate extraction. The resulting powder was passed through a 60 mesh sieve, yielding particles of approximately ~250 µm. The sieved powder was then stored in airtight containers to prevent moisture absorption until further processing.

2.3 Alginate extraction and liquefaction

The alginate extraction was performed as previously described method with slight modification (Alallam et al., 2025). Modifications included reducing extraction temperature to 50°C to prevent polymer degradation, fixing sodium carbonate concentration at 2% (w/v), and limiting stirring duration to 2 h to maintain polymer integrity. Subsequently, the solution was filtered under vacuum to remove solid residues. The liquid collected contains the extracted alginate. To precipitate the alginate, 150 mL of 2% (v/v) calcium chloride was added to the solution and stirred for 30 minutes until a gel-like precipitate formed.

2.4 Formulation, film casting and drying of bioplastic

The alginate gel-like structure was enhanced by the addition of 12.6% (w/w, relative to polymer mass) of glycerol as a plasticizer, stirred for 30 min at 50°C. The sample was then allowed to cool down for 10 minutes before casting. The *Sargassum* bioplastics mixture was poured into a mold (200 mm × 28 mm) to form a thin and uniform film with an approximate thickness of 0.2 mm. The cross-linking was achieved by spraying 5 ml of 2% diluted calcium chloride solution onto the cast film (Mohammed et al., 2023). Then, the sample was left to air dry for three days, carefully removed from the mold, and stored at room temperature for 48 h under controlled conditions for further testing. This method of film plasticization and cross-linking has been supported in previous studies for improving the structural integrity and moisture

resistance of alginate-based bioplastics (Bouzenad et al., 2024; Elkaliny et al., 2024). The flow process of the glycerol plasticization, film casting and calcium chloride cross-linking process is depicted in Figure 2.

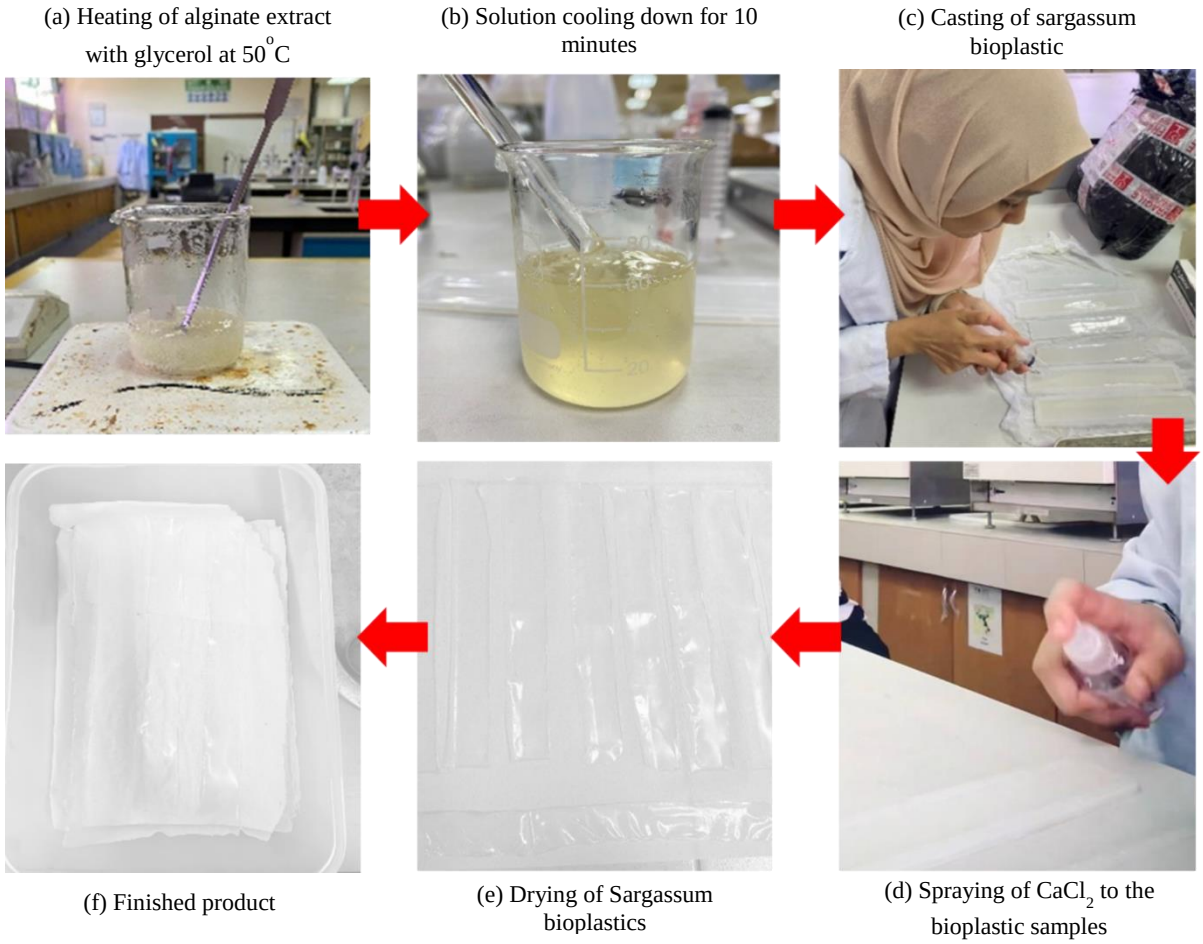

Figure 2. Fabrication process of *Sargassum*-based bioplastic films: (a) heating alginate extract with glycerol at 50°C, (b) cooling for 10 min, (c) film casting, (d) $CaCl_2$ spraying for cross-linking, (e) air-drying, and (f) final dried bioplastic film

2.5 Mechanical testing

The tensile properties of *Sargassum* bioplastics were evaluated using a textile tensile machine (UTS-Tex-Plus, UTS International, China), following the ASTM D882 standard. The method was adapted from a previous study (Kumari et al., 2024), by adjusting clamp speed to 1 mm min^{-1} and using duplicate samples due to material availability constraints. Mechanical testing was done in duplicates for both *Sargassum* bioplastic (SB) and conventional plastic (CP). Dumbbell-shape bioplastic samples were clamped into the machine's grips and pulled at a constant rate until fracturing. The machine was set at a clamp speed of 1 mm/min with the sample length 45 mm. A load cell of ID/FS (5/500) was used. Mechanical testing was conducted in duplicate due to material preparation constraints; therefore, tensile data are interpreted as comparative trends rather than statistically validated differences. This method measured the tensile strength and elongation at break, providing insight into the flexibility and mechanical durability of the films. These properties are especially critical for assessing the bioplastics' feasibility in packaging applications, in which strength and stretchability are essential (Kumari et al., 2024).

2.6 Thermal testing

The thermal behavior of the *Sargassum* bioplastics was assessed using Differential Scanning Calorimetry (DSC 1, METTLER TOLEDO, Switzerland), aligned with ASTM. The experimental procedure was adapted from a previous study (Bauta et al., 2024), with modifications including a heating range of 25-350°C and nitrogen flow rate of 50 mL min^{-1} to ensure uniform thermal analysis conditions. Firstly, a section of the bioplastic film was cut and trimmed to precise masses within the 5-10 mg range, and the exact mass of each sample (5.4-5.6 mg) was

recorded prior to analysis and is reported in Table 2. The sample was sealed in a 40 µL aluminium crucible and excess moisture was removed. The DSC system was calibrated using indium as a reference material. Thermal testing was performed in triplicate for the *Sargassum* bioplastic (SB) samples. Both the sample and an empty reference crucible were placed into the DSC chamber. Testing was performed from 25°C to 350°C at a heating rate of 10°C/min under a nitrogen flow rate of 50 mL/min. The DSC curve was used to identify the glass transition temperature (T_g), melting temperature (T_m), and thermal degradation point. After testing, samples were visually inspected for any physical changes, including melting or charring, to assess thermal endurance. Thermogravimetric Analysis (TGA) was not conducted in this study due to equipment limitations; however, the Differential Scanning Calorimetry (DSC) data provided sufficient insight into the bioplastic's thermal transition and stability behavior. Future work could include TGA testing to further quantify the decomposition stages and thermal degradation profile of *Sargassum*-derived bioplastics.

2.7 Water absorption test

The bioplastics underwent a water absorption test following the ASTM D570-98 standard (ASTM, 1999). The method applied was based on previous study (Farhoud et al., 2024), with slight modifications involved extending observation duration to 35 days. Measurements were recorded at 2-5 day intervals to capture long-term absorption behaviour. The *Sargassum* bioplastic (SB) samples were tested in triplicate. They were initially weighed and then fully immersed in 600 mL of distilled water at room temperature (25±1°C). At regular intervals of 2-5 days, the samples were removed, gently patted dry, and reweighed to monitor the rate and extent of water absorption. This test is crucial for understanding the behavior of the *Sargassum*-based bioplastics under humid or wet conditions, a critical factor in applications such as food packaging or agricultural films.

2.8 Biodegradability test

Environmental compatibility was assessed using the soil burial method in accordance with ASTM D5988 with methodological adaptation (Synani et al., 2024). Triplicates samples of the *Sargassum* bioplastics (SB) were first weighed and then buried approximately 2 cm deep into organic-rich garden soil (Tarangini et al., 2023). Every week, the samples were removed, cleaned with distilled water, dried at room temperature for 24 h, and reweighed. The percentage of weight loss was calculated to determine the rate of degradation (Equation 1). This method simulates natural environmental conditions and helps to evaluate the biodegradability of the material over time.

$$\text{Biodegradation (\%)} = \left(\frac{\text{Initial Weight} - \text{Final Weight}}{\text{Initial Weight}}\right) \times 100 \quad (1)$$

2.9 Grease absorption test

A grease absorption test was carried out to assess resistance to oil penetration. This was based on procedures aligned with ASTM F119-82 (ASTM, 2022), with slight modifications based on the method used by Mohammed et al. (2023). Vegetable oil was heated to four different temperatures (20°C, 40°C, 60°C, 80°C), and 10 mL of the hot oil was poured onto each sample. The bioplastics were allowed to rest for 30 min to permit oil absorption. The samples were weighed before and after oil exposure to calculate the amount of oil absorbed. This test indicates how well the bioplastics can resist grease, which is essential for food-contact applications, especially in packaging.

3. RESULTS AND DISCUSSION

3.1 Mechanical testing

Mechanical testing was conducted to assess the tensile strength and flexibility of the *Sargassum*-based bioplastics. These properties are essential to real-world applications, such as biodegradable packaging and disposable consumer products. In this testing, the conventional plastic (CP) used as control was commercial low-density polyethylene (LDPE) film. Figure 3 presents the tensile test conditions of *Sargassum* bioplastics (SB) and conventional plastics (CP), showing both materials before and after maximum elongation. The results demonstrated that the addition of glycerol as a plasticizer and calcium chloride as a cross-linking agent significantly enhanced the mechanical performance of the samples (Bouzenad et al., 2024; Mohammed et al., 2023).

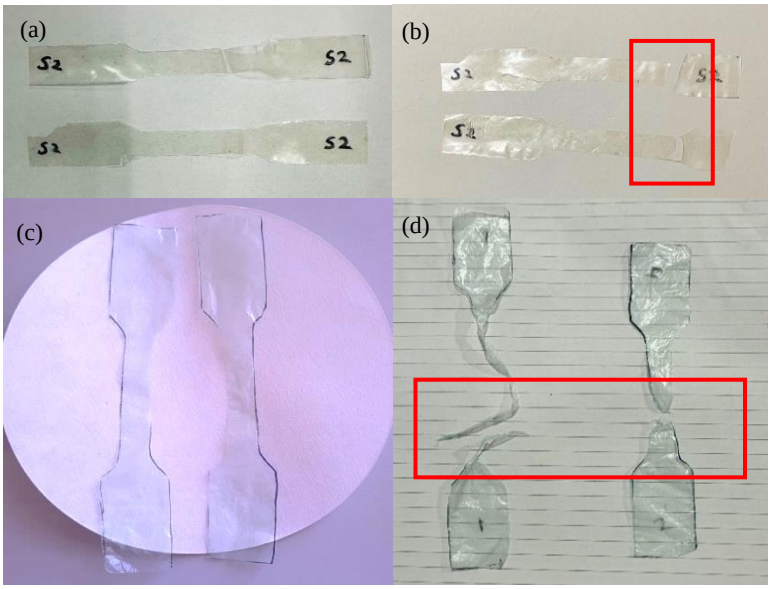

Figure 3. Mechanical tensile test comparison of *Sargassum* bioplastics (SB) and conventional plastic (CP). (a), SB samples before tensile testing. (b), SB after maximum elongation. (c), CP samples before tensile testing. (d), CP after maximum elongation. Red boxes indicate the regions of maximum deformation and fracture, highlighting elongation behaviour and failure points of the tested specimens

Table 1 summarizes the tensile properties of the *Sargassum*-based bioplastic (SB, n=2) compared with the conventional plastic reference (CP, n=2). The *Sargassum* bioplastic exhibited a mean maximum force of 5.74±1.31 N, elongation at break of 29.00±3.30%, and time-to-failure of 783±89 s. In contrast, the conventional plastic demonstrated lower tensile resistance (1.86±0.00 N), reduced elongation (9.67±2.36%), and shorter failure time (261±63.64 s). Under the tested conditions, the *Sargassum*-based film therefore showed greater extensibility and resistance to fracture than the LDPE reference.

Table 1. Tensile properties of *Sargassum*-based bioplastic films compared with the reference conventional plastic control (Low-Density Polyethylene, LDPE)

Sample	Description	Maximum force (N)	Maximum elongation (%)	Time (s)
SB (n=2)	*Sargassum* + Glycerol + $CaCl_2$ (0.2 M)	5.74±1.31	29.00±3.30	783±89
CP (n=2)	Conventional plastic	1.86±0.00	9.67±2.36	261±63.64

The enhanced mechanical performance may be attributed to the complementary roles of glycerol and calcium chloride within the alginate-based matrix (Asmadi et al., 2025; Bojorges et al., 2023; Mohammed et al., 2023; Santana et al., 2024). Glycerol functions as a plasticizer by forming hydrogen bonds with hydroxyl and carboxyl groups along the polymer chains, thereby increasing chain mobility and reducing intermolecular rigidity (Langit et al., 2019). This contributes to improved flexibility and elongation capacity. Meanwhile, calcium ions from $CaCl_2$ act as ionic cross-linkers, forming electrostatic bridges between alginate carboxylate groups and generating a three-dimensional network structure (Barman et al., 2025). This cross-linked network both limits excessive chain slippage and enhances tensile integrity and structural stability (Mohammed et al., 2023). A combination of plasticization and ionic cross-linking results in a balanced polymer system capable of exhibiting both moderate strength and improved extensibility (Barman et al., 2025).

Mechanical testing was conducted twice. Therefore, the reported values represent comparative trends rather than statistically validated differences. Additional replications would be required to confirm statistical significance. Nonetheless, the results indicate that incorporation of glycerol and calcium chloride can enhance the mechanical performance of *Sargassum*-derived bioplastics through synergistic molecular interactions. The mechanical behaviour observed supports the potential of this material for

low-load and short-term packaging applications in which moderate strength and flexibility are required.

3.2 Analysis of thermal testing using DSC

Figure 4 presents the DSC thermograms of the *Sargassum*-based bioplastic samples (SB1-SB3) and the conventional plastic control (CP). It should be noted that SB1-SB3 represent triplicate specimens of the same formulation tested to assess experimental reproducibility. The curves reveal distinct thermal transitions which correspond to the glass transition temperature (T_g), melting temperature (T_m), and onset of thermal degradation, respectively.

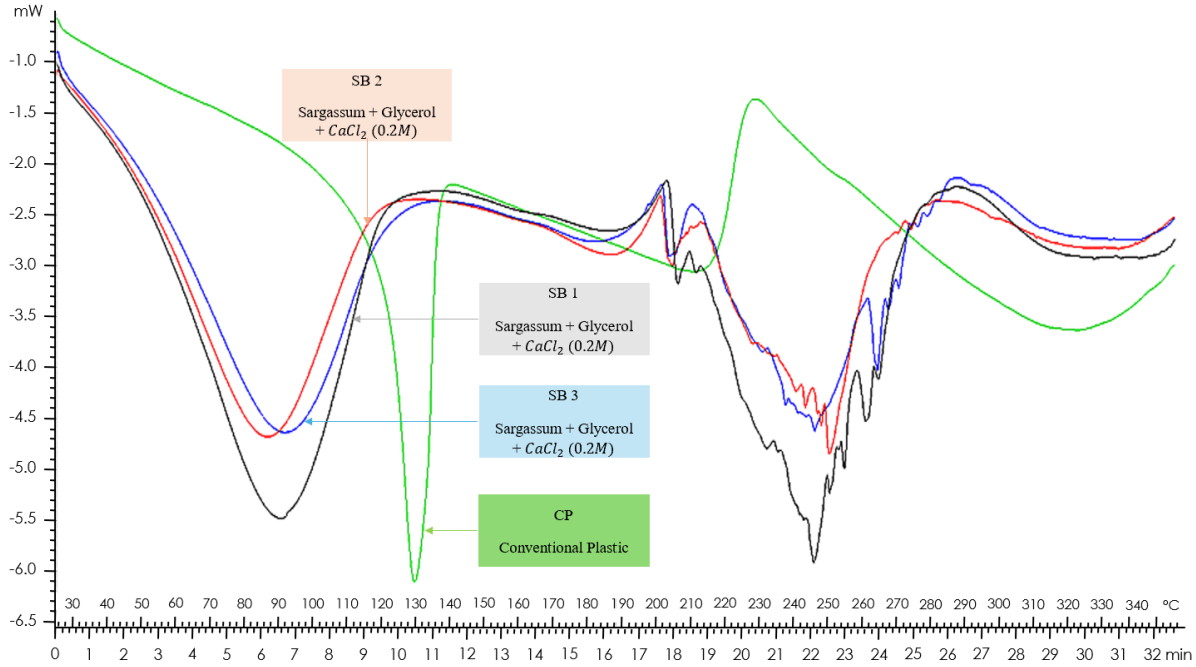

Figure 4. Differential Scanning Calorimetry (DSC) thermograms of *Sargassum*-based bioplastic films compared with the conventional plastic control. SB1-SB3 correspond to triplicate specimens of the same *Sargassum* bioplastic formulation (*Sargassum* + glycerol + $CaCl_2$, 0.2 M), while CP represents the conventional plastic reference. The curves show characteristic thermal transitions including glass transition (T_g), melting temperature (T_m), and thermal degradation onset. Small differences among SB thermograms are attributed to experimental variability among replicates.

The first transition observed in the SB samples occurred around 52-55°C and corresponded to the glass transition temperature (T_g), marking the shift from a rigid, glassy state to a more flexible, rubbery state. The relatively moderate T_g values indicate that glycerol acts as a plasticizer, increasing polymer chain mobility by reducing intermolecular hydrogen bonding between alginate chains. Minor variations among SB1-SB3 may be attributed to sample heterogeneity and thermal measurement sensitivity rather than formulation differences.

A second endothermic peak can be observed between 148-160°C, corresponding to the melting temperature (T_m), which reflects disruption of ordered domains within the calcium-cross-linked alginate network. The small variation in Tm among replicates likely reflects differences in local cross-link density and film thickness. These results confirm that ionic cross-linking contributes to structural stabilization and moderate thermal resistance.

The onset of degradation for the SB samples occurred between 180-190°C, representing breakdown of the polymer backbone and weakening of the cross-linked network. Slight shifts in degradation onset among replicates are considered within expected experimental variation. In comparison, the conventional plastic exhibited higher T_g and T_m values, consistent with its greater crystallinity and synthetic polymer structure. Nevertheless, the thermal performance of the *Sargassum*-based bioplastic would be adequate for low-temperature packaging applications.

Previous studies have similarly reported enhanced thermal resistance in $CaCl_2$-cross-linked alginate films due to ionic bridging effects (Abu Ubaidah et al., 2024; Barman et al., 2025; Chakraborty et al., 2022). Although Differential Scanning

Calorimetry (DSC) provides insight into thermal transitions, thermogravimetric analysis (TGA) would further complement these findings by providing quantitative mass loss profiles and degradation kinetics. Comprehensive thermal characterization is thus recommended for studies incorporating TGA.

Table 2. Differential scanning calorimetry test of *Sargassum* bioplastics

Sample	Description	Glass transition temperature, T_g (°C)	Melting point, T_m (°C)	Onset degradation temperature, (°C)	Enthalpy, $\Delta H_{cc}(\frac{J}{g})$	Observation
SB1 (Rep1)	*Sargassum* + Glycerol + $CaCl_2$ (0.2 M) Black line, 5.5 mg	55	150	185	Moderate	Moderate thermal profile, relatively stable
SB2 (Rep2)	*Sargassum* + Glycerol + $CaCl_2$ (0.2 M) Red line, 5.6 mg	52	148	180	Slightly lower	More flexible; lower degradation resistance
SB3 (Rep3)	*Sargassum* + Glycerol + $CaCl_2$ (0.2 M) Blue line, 5.5 mg	54	160	190	Higher	Highest thermal stability among bio-based samples
CP	Conventional Plastic Green line, 5.4 mg	75	180	210	High	Sharp thermal transitions; most stable

3.3 Water absorption test

The water absorption characteristics of *Sargassum*-based bioplastics show a consistent absorption-degradation pattern over 35 days of testing, demonstrating their hydrophilic nature and biodegradability. Figure 5 illustrates the water absorption characteristics of *Sargassum* bioplastics over time, indicating their initial shape and changes after 5, 10, 20 and 35 days, respectively.

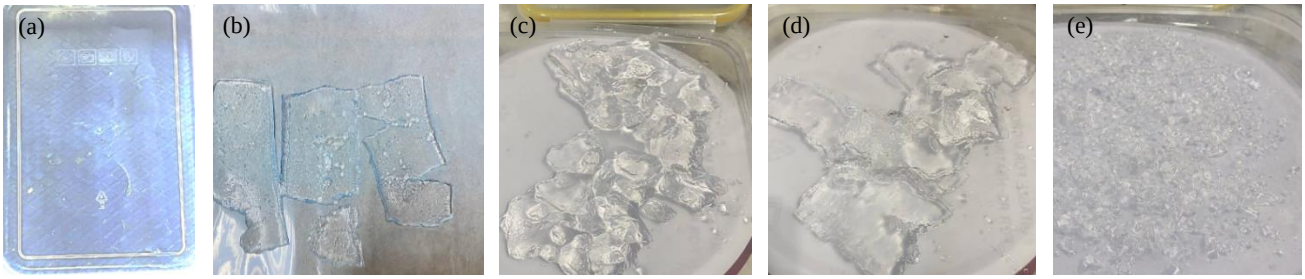

Figure 5. Water absorption characteristics (a) initial shape of *Sargassum* bioplastics; (b) SB after 5 days; (c) SB after 10 days; (d) SB after 20 days; (e) SB at 35 days

Figure 6 presents the water absorption behaviour of the *Sargassum*-based bioplastic, expressed as mean±standard deviation from triplicate measurements. The samples exhibited rapid water uptake within the first 48 h, followed by a gradual decline in measurable mass over time. The initial dry weights ranged from 0.70 g to 0.88 g across replicates. This increased sharply by Day 2, reaching a mean value of approximately 37.8 g. The relatively large standard deviation observed at this early stage reflects variability in swelling behaviour among replicates, likely due to minor differences in film thickness, porosity, and cross-link density. The pronounced hydrophilicity is consistent with previous findings on glycerol-plasticized alginate films, as abundant hydroxyl and carboxyl functional groups promote hydrogen bonding with water molecules (Mohammed et al., 2023; Tarangini et al., 2023). Following the initial swelling phase, a gradual reduction in measurable mass was observed from Day 5 onward. This decline is attributed to both the progressive structural weakening of the hydrated polymer network and the partial hydrolytic breakdown of ionic cross-links.

The decrease in mass between Day 10 and Day 30 indicates destabilization of the cross-linked alginate matrix. This is consistent with literature reporting that prolonged immersion weakens calcium-mediated ionic bridges, leading to fragmentation and

erosion of the polymer network (Vandanjon et al., 2023; Jo et al., 2024). Although ionic cross-linking enhances structural stability during early immersion, sustained hydration promotes network loosening and eventual disintegration. By Day 35, the bioplastic samples had undergone complete structural disintegration, leading fragmented gel-like residues to disperse in the surrounding water. Consequently, quantitative mass measurement was not possible, because no intact polymer matrix could be recovered for weighing. The visual evidence of fragmentation supports previously reported aqueous degradation behaviour of alginate-based marine biopolymers (Gross and Enck, 2021).

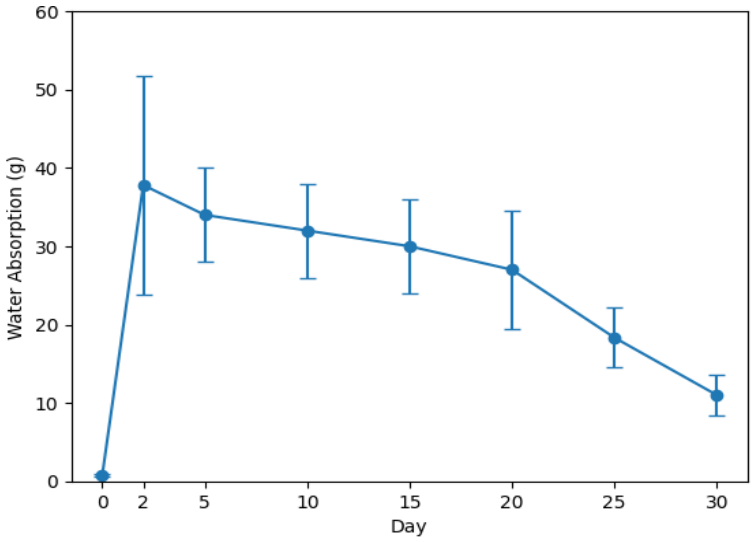

Figure 6. Water absorption of *Sargassum* bioplastic (mean±SD) over time

The biodegradability of the *Sargassum*-based bioplastic was evaluated over 30 days under soil burial conditions, with results expressed as mean±standard deviation from triplicate measurements (Figure 7). A progressive reduction in remaining mass was observed throughout the testing period, confirming the biodegradable nature of the material. The initial average mass of approximately 1.03 g decreased markedly within the first 7 days to around 0.53 g, indicating rapid early-stage degradation. The relatively large standard deviation at Day 7 reflects variability in microbial activity and moisture exposure among replicates, which is typical in soil burial environments. By Day 14, the remaining mass had declined to near-zero values, suggesting the substantial structural breakdown of the polymer matrix.

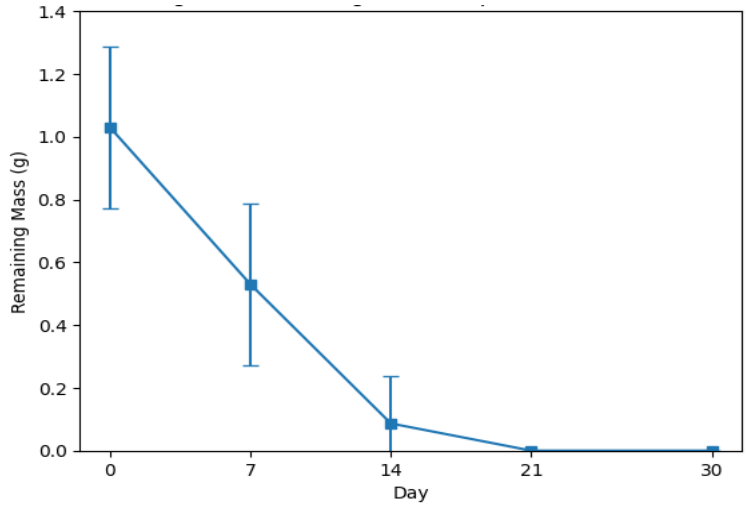

Figure 7. Biodegradation of *Sargassum* bioplastic (mean±SD) over time

Complete degradation was observed between Day 21 and Day 30, with no recoverable material remaining by the end of the experiment. The rapid mass loss is attributed to the high content of biodegradable polysaccharides, particularly alginate and cellulose, which are susceptible to enzymatic and microbial degradation under moist soil conditions (Mohammed et al., 2023; Zdiri et al., 2022). Initial water uptake likely enhanced microbial accessibility by increasing both polymer chain mobility and surface exposure. The degradation profile observed in this study aligns with previously reported 21-40 day decomposition windows for seaweed-derived bioplastics under aerobic conditions (Abu Ubaidah et al., 2024; Akbar and Mustari, 2024; Elkaliny et al., 2024). These findings support the environmental compatibility of *Sargassum*-based bioplastics and highlight their suitability for short-term and compostable packaging applications, in which controlled and timely degradation is required.

3.4 Grease absorption test

The grease absorption test was conducted to evaluate the oil resistance of the *Sargassum*-based bioplastic under elevated temperature conditions relevant to food packaging applications. The results have been presented as mean±standard deviation from quadruplicate measurements (Figure 8).

A gradual increase in oil uptake was observed as temperature increased from 20°C to 80°C. The mean weight rose slightly from approximately 0.20 g at 20°C to around 0.21-0.22 g at higher temperatures. This trend indicates temperature-dependent diffusion behaviour, as an elevated temperature reduces oil viscosity and enhances polymer chain mobility, facilitating greater oil penetration into the biopolymer matrix.

The relatively wide-ranging standard deviations observed at higher temperatures suggest variability in oil diffusion among replicates, likely influenced by minor differences in film thickness, surface morphology, and cross-link density. Despite the observed increase, the overall magnitude of oil uptake remained moderate, indicating that the calcium-cross-linked alginate network provides partial resistance to non-polar diffusion.

These findings are consistent with previous reports on alginate- and cellulose-based films, which have demonstrated moderate oil barrier properties with increased permeability at elevated temperatures (Mohammed et al., 2023; Tarangini et al., 2023). Although grease resistance is not absolute, the performance observed suggests suitability for short-term packaging of warm or moderately oily foods. Further optimization, such as surface coating or multilayer barrier integration, may enhance oil resistance for use in demanding applications.

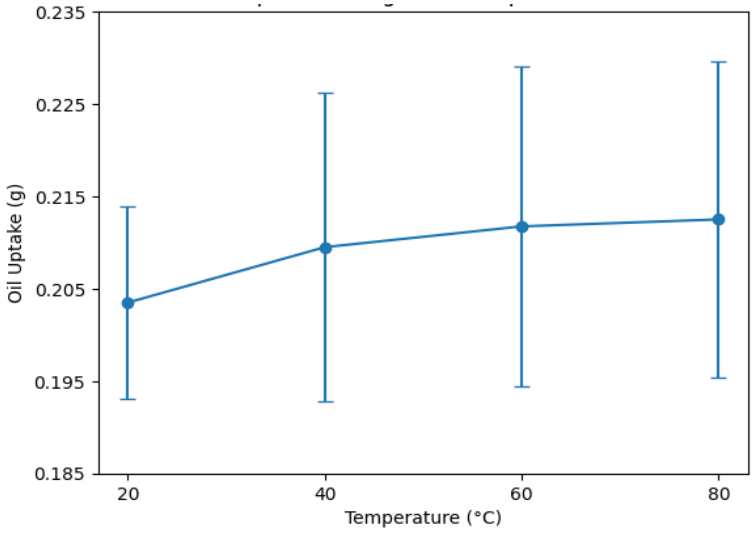

Figure 8. Grease absorption test

4. CONCLUSION

This study evaluated the feasibility of utilizing *Sargassum* seaweed as a renewable feedstock for biodegradable bioplastic production, with specific emphasis on packaging applications. The incorporation of glycerol as a plasticizer and calcium chloride as an ionic cross-linker contributed to the

improvement of mechanical performance, yielding films with enhanced tensile strength and flexibility compared to the conventional plastic reference. These results indicate suitability for low-load, short-term packaging applications.

Thermal analysis revealed a glass transition temperature of approximately 54°C, a melting temperature near 160°C, and a degradation onset around 190°C, confirming moderate thermal stability appropriate for handling and typical environmental exposure conditions. Water absorption tests demonstrated rapid initial swelling followed by progressive structural weakening under prolonged immersion, reflecting the hydrophilic nature of the alginate-based matrix. Grease absorption further exhibited a modest temperature-dependent increase, with overall oil uptake remaining moderate even at elevated temperatures. These behaviours together suggest that while the material may not be fully impermeable to moisture or oils, it maintains acceptable barrier performance for short-term contact with dry or moderately greasy foods. Biodegradation analysis confirmed substantial mass reduction within the first two weeks, with complete structural disintegration within 21-30 days under soil burial conditions. Such a controlled and timely degradation highlights the environmental compatibility of the material and its advantage over persistent petroleum-based plastics.

In conclusion, the functional performance of the *Sargassum*-based bioplastic is governed by a balance between hydrophilic diffusion mechanisms and calcium-mediated ionic network stabilization. *Sargassum*-derived bioplastics show strong potential as sustainable alternatives for compostable and single-use packaging applications.

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AUTHOR CONTRIBUTIONS

Conceptualization, Dzulaikha Khairuddin; Methodology, Nur Syazwina Kamarozaman and Nasaei Zainuddin; Validation, Dzulaikha Khairuddin and Nur Syazwina Kamarozaman; Formal Analysis, Dzulaikha Khairuddin; Investigation, Nur Syazwina Kamarozaman; Resources, Dzulaikha Khairuddin and Nasaei Zainuddin; Data Curation, Nur Syazwina Kamarozaman; Writing-Original Draft Preparation, Nur Syazwina Kamarozaman; Writing-Review and Editing, Dzulaikha Khairuddin; Visualization, Nur Syazwina Kamarozaman; Supervision, Dzulaikha Khairuddin; Project Administration, Dzulaikha Khairuddin; Funding Acquisition, Dzulaikha Khairuddin.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that there are no competing interests to disclose

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