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Sustainable Fruit Preservation Using Algae-Based Bioactive Coatings on Textile Packaging

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Abstract: This study explores the potential of using natural textile packaging infused with algae-based coatings as an eco-friendly alternative to traditional plastic packaging for extending fruit shelf life. Traditional plastic packaging is known to release harmful chemicals into both food and the environment, which underscores the need for safer, more sustainable alternatives. This study investigates algae from three distinct groups—green, red, and brown algae—renowned for their rich bioactive compounds that exhibit natural preservative properties. Algae powders were prepared via immersion in purified water, boiling, and mixing with gum arabic to form a gelatinous coating solution. The algae coating was applied to knitted fabric, which was then crafted into bags for storing fruits such as tomatoes and apples. Over 21 days, the texture, weight loss, and juice content of the fruits stored in algae-coated bags were monitored and compared to those stored in uncoated packaging. The results showed that fruits in algae-coated packaging demonstrated significantly less weight loss and retained better texture. In terms of weight, the combination of red, green, and brown algae-coated packaging demonstrated the lowest reduction in weight for tomatoes (4.2%) and apples (3.8%) after 21 days, outperforming uncoated packaging, which exhibited reductions of 11.2% and 10.8%, respectively. These findings support the potential of algae-coated textile packaging to reduce reliance on conventional plastics while maintaining fruit quality during storage.

Keywords: red algae; green algae; brown algae; food packaging; shelf life

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1. Introduction

Inadequate storage conditions significantly reduce the shelf life of both climacteric and non-climacteric fruits, leading to increased waste and economic loss. The widespread use of low-quality plastic packaging in the fruit industry exacerbates these issues, posing serious risks to environmental sustainability and human health. Conventional plastic materials can leach toxic chemicals into produce, raising potential health hazards [1]. Furthermore, these plastics have minimal biodegradability, persisting in ecosystems for centuries and causing long-lasting ecological damage. The production of plastic packaging relies heavily on fossil fuels, contributing to greenhouse gas emissions, marine pollution, and climate change. The escalating environmental impact of plastic pollution has intensified the need for sustainable food packaging alternatives. The European Union's target to eliminate plastic food packaging by 2030 highlights the urgency of this challenge [2]. Food deterioration, driven by oxidative, microbial, and metabolic processes, is heavily influenced by environmental conditions such as temperature, humidity, and microbial contamination [3]. Effective packaging is essential to preserve food quality, ensure safety, and extend shelf life. Biopolymers like chitosan and alginate show great promise as replacements for traditional plastics due to their abundance, non-toxicity, and biodegradability [4]. When incorporated into nanocomposites, these biopolymers offer the potential to create eco-friendly packaging materials with enhanced mechanical, barrier, and antimicrobial properties, fueling growing interest and demand for sustainable packaging solutions [5].

Bioactive coatings are designed to biologically interact with living cells and integrate active elements, such as antimicrobials, antioxidants, and enzymes, which can interact with packaged food, extend its shelf life, and enhance its quality and safety. Recent studies have highlighted the use of various bioactive materials for food packaging, demonstrating their potential to improve preservation and functionality. For instance, gelatin-based films have been shown to provide excellent oxygen barrier properties and biocompatibility [6,7], while polylactic acid (PLA) has gained attention for its biodegradability and ability to form composite films with antimicrobial agents [8]. Carrageenan, a natural polysaccharide, has been used to develop edible coatings with moisture barrier properties [9]. Cellulose nanocrystals have been incorporated to improve the mechanical and thermal properties of bioactive films, and whey protein has been studied for its ability to form transparent, flexible coatings with antimicrobial activity [10] and whey protein [11]. Algae are a rich source of bioactive compounds with promising applications in extending food shelf life. Polysaccharides, peptides, and pigments derived from algae demonstrate a range of bioactivities, including antioxidant, anti-inflammatory, antibacterial, antiviral, and antifungal properties. These bioactive components not only offer natural preservation benefits but also contribute to safer, more sustainable packaging solutions, making algae an attractive alternative in the development of eco-friendly, functional food packaging [12–14]. These compounds offer promising opportunities for the development of functional coatings. Additionally, algal chitosan, a cell wall component, possesses antimicrobial characteristics and has applications in algae harvesting through flocculation [15].

Green algae, belonging to the division Chlorophyta, are a large and diverse group distinguished by their green chlorophyll pigments, which enable efficient photosynthesis and energy capture from sunlight. Found across freshwater, marine, and terrestrial environments, these algae serve as primary producers and are essential to numerous food chains. Green algae species vary from unicellular to complex multicellular forms and have versatile applications, including in human and animal nutrition, biofuel production, and bioplastic manufacturing. Their capacity to absorb carbon dioxide further enhances their appeal as a potential resource for climate change mitigation, making them valuable in both ecological and industrial contexts [16,17]. Rhodophyta, or red algae, are a diverse group distinguished by the red pigment phycoerythrin, which allows them to efficiently absorb light in deeper waters, particularly in marine environments. Red algae hold significant commercial value, especially as a source of carrageenan, widely used as a natural thickening and stabilizing agent in food and pharmaceuticals. Additionally, red algae are of scientific interest for their unique bioactive compounds, which exhibit potential antibacterial and medicinal properties, making them promising candidates for various health and therapeutic applications [18]. Red algae are increasingly being explored as an alternative to conventional packaging materials thanks to their abundance, biodegradability, and low environmental impact [19]. Research in the packaging industry focuses on the versatility of red algae, from the extraction of biopolymers to the development of bio-based coatings. One of the most fascinating aspects of red algae is their distinctive cell structure, which contains pigments like phycocyanins and phycoerythrins that optimize light absorption for photosynthesis [20]. Brown algae, or Phaeophyceae, are a diverse group of large, multicellular algae predominantly found in aquatic environments. Named for their characteristic brown pigments, including fucoxanthin, they are capable of photosynthesis, allowing them to convert sunlight into energy. These algae thrive in various habitats, such as rocky shores and deeper waters. Brown algae are of particular interest due to the unique compounds they contain, which hold potential for therapeutic and biotechnological applications [21].

The use of algae as a coating material for packaging is still an emerging area of study. Notably, there is limited research exploring the comparative use of red, brown, and green algae blends in fruit packaging. This study addresses this gap by evaluating their potential applications, thus contributing to the body of knowledge on sustainable packaging solutions. This study aims to evaluate the effects of individual algae species as well as the synergistic combination of red, brown, and green algae on enhancing the shelf life of fruit packaging materials. The goal of this research is to develop an eco-friendly packaging material using algae-coated natural textiles to extend the shelf life of climacteric fruits (tomatoes, apples). Algal-based packaging works by absorbing carbon dioxide and incorporating antimicrobial compounds to mitigate quality deterioration, including weight loss, texture changes, and microbial spoilage.

2. Materials and Methods

2.1. Materials

Brown, red, and green algae powder collections of different species of algae were acquired from online stores. Knitted jersey fabric was specifically made with 100% cotton white in color, and the specifications of the fabric were as follows: 35 wales per inch, 45 cpi, a 2.30 stitch length, and a fabric gsm of 104.6. It was obtained from the Department of Textile and Apparel Science. For graphing and data analysis, we used Origin 9 Pro software, which provided accurate plotting and statistical analysis to support the findings.

2.2. Methods

2.2.1. Application of Red and Green Algae

Red and green algae powders (2 g) were dispersed in 100 mL distilled water separately and subjected to a 24 h hydration period to enhance viscosity and consistency. Subsequently, the suspensions were heated to 80 °C for 30 min under magnetic stirring at 80 rpm. Following a cooling and filtration step, 2 g of gum arabic was incorporated, and the mixture was boiled at 80 °C for 30 min. The resulting algal solution was then applied to 7 g knitted fabric specimens (with a pore size of 0.2) using a padder machine before undergoing oven drying. All experimental parameters adhered to the protocol outlined in Table 1.

Table 1. The recipe used for the development of samples.

	Uncoated (Control)	Sample 1	Sample 2	Sample 3	Sample 4
Red algae	---	2.5 g			2.5 g
Green algae	---		2.5 g		2.5 g
Brown algae	---			2.5 g	2.5 g
Gum arabic	---	2.0 g	2.0 g	2.0 g	2.0 g

2.2.2. Extraction and Application of Brown Algae

To extract alginate from brown algae (Figure 1), a two-step process was employed. Brown algae, rich in alginate and other polysaccharides, underwent initial treatment with a sodium carbonate solution (4 g in 100 mL distilled water) for 24 h to enhance alginate solubility. The resulting mixture was filtered, and the residue was washed thrice with distilled water to remove excess salts. Subsequently, mineral removal was achieved by immersing the alginate residue in a dilute hydrochloric acid solution (3 mL HCl in 100 mL water) for 24 h. The acid-treated residue was then washed extensively with distilled water until a neutral pH was attained. To regenerate alginate, the purified residue was combined with a sodium carbonate solution (4 g in 100 mL distilled water) and heated under magnetic stirring for 30 min. Gum arabic (3 g) was added to the alginate solution and stirred for an hour at 70 °C. The final mixture was applied to a 7 g (0.2 pore size) knitted fabric using a padder machine and dried in an oven.

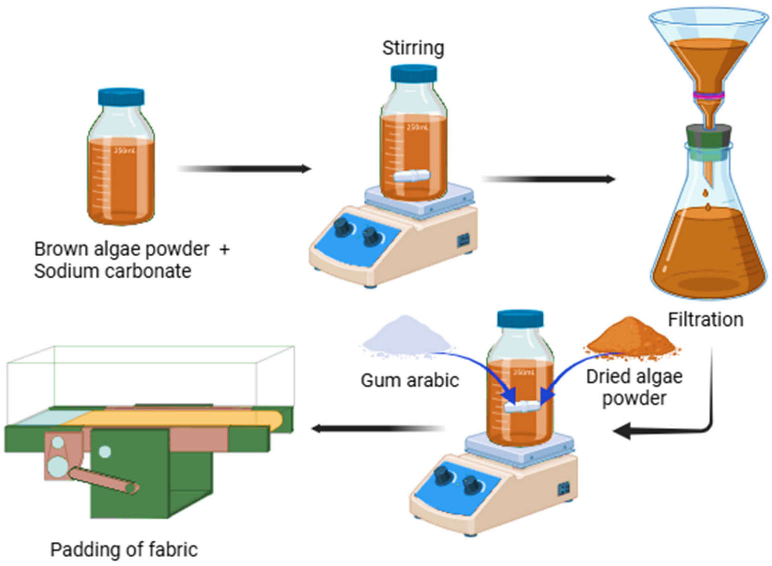

Figure 1. Scheme for packaging coated with brown algae.

2.2.3. Application of Red, Green, and Brown Algae

As illustrated in Figure 2, individual suspensions of red, green, and brown algae powders (2 g each) were prepared via dispersion in 30 mL of distilled water, allowing them to hydrate for 24 h. The resulting mixtures were filtered and subjected to heat treatment at 80 °C for 30 min under magnetic stirring. Subsequently, the three algal suspensions were combined and further heated at 60 °C for 20 min. Gum arabic (3 g) was then incorporated into the combined algal solution and stirred at 70 °C for an hour using a magnetic stirrer.

Figure 2. Package coating method with green, brown, and red algae.

2.2.4. Process of Making the Packaging Bag

Rectangular panels (two sides, one front and one back) were cut from Jersey fabric with a porosity of 0.2 cm. These components were assembled on a flat surface, pinned at the seams, and subsequently stitched together, leaving the top edge open. A 2-inch cuff was created at the top opening and stitched closed to accommodate a drawstring. A cord inserted through the drawstring channel was secured with knots at both ends. Ripened tomatoes and apples were then placed within these knitted fabric packages.

2.3. Characterizations

The characterization of materials in this study involved a multifaceted approach to assess their suitability for packaging applications. Elemental analysis was performed using the EDS chemical method in conjunction with Scanning Electron Microscopy (SEM) to identify the composition of the samples. The Fourier Transform Infrared (FTIR) specroscopy was used to identify the functional groups on the algae-coated sample. Finally, the shelf life of the packaged fruits was evaluated by monitoring weight loss, texture, and juice content over time, assessing the packaging's effectiveness in preserving fruit quality during storage [22].

3. Results and Discussions

3.1. FTIR Analysis

Figure 3a depicts the FTIR spectrum of red, brown, and green algae, providing insights into its chemical composition. The broad absorption band observed in the 3300–3400 cm^{-1} range corresponds to hydroxyl (O–H) groups, primarily from polysaccharides, proteins, and residual water, indicative of the hydrophilic nature of the material [23]. A distinct peak near 2900 cm^{-1} signifies the presence of C–H stretching vibrations, which are characteristic of lipid and protein components [24]. The bands within 1500–1600 cm^{-1} can be attributed to conjugated C=C stretching vibrations, commonly associated with pigments like phycoerythrin and chlorophyll, unique to red algae [25]. Notably, peaks in the region of 1000–1150 cm^{-1} are linked to glycosidic C–O–C stretching vibrations, indicative of polysaccharides such as agar and carrageenan. These polysaccharides play a critical role in forming gel-like matrices, which enhance the material's barrier properties and provide functional coatings for fruit preservation by limiting water loss and microbial growth [26]. The detailed spectral data align with findings from previous studies on algal polysaccharides and their functional properties in food packaging applications [27].

3.2. SEM Analysis

The SEM micrographs in Figure 3b vividly illustrate the surface morphology of textile fibers coated with red algae, showcasing the distribution and texture of the coating. In contrast, Figure 3c presents the surface structure of the textile coated with a mixture of red, brown, and green algae, highlighting the composite effect achieved through the combination of these algae types. The surface is characterized by irregular and granular deposits of algae, which adhere effectively to the fibers, particularly in certain regions. These deposits create a roughened surface that enhances adhesion through mechanical interlocking. Furthermore, the increased surface area provided by the granules facilitates better contact and anchoring of the algae to the fibers. This morphology can also be attributed to the presence of extracellular polymeric substances (EPSs) secreted by the algae during the coating process. EPSs contain adhesive polysaccharides and proteins that promote both chemical bonding (e.g., hydrogen bonding) and van der Waals interactions with the fiber substrate, enhancing overall adhesion. The observed adherence mechanism is supported by studies demonstrating the role of surface irregularities in improving the mechanical stability of coatings in textile applications [28]. These findings underscore the significance of algae-coated textiles in creating sustainable packaging solutions with enhanced mechanical and functional properties, aligning with the growing interest in bio-based alternatives for food preservation [29].

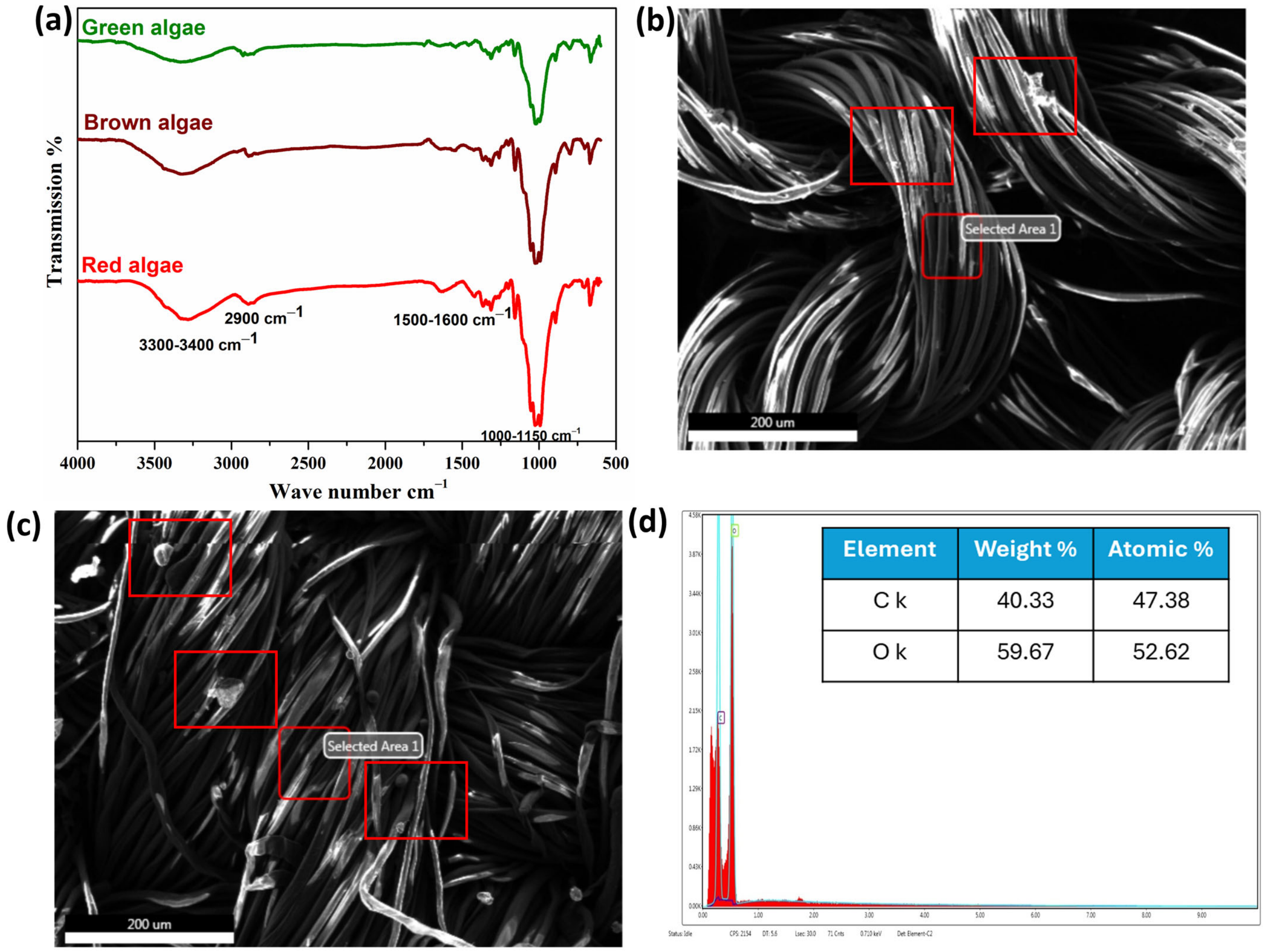

Figure 3. (**a**) FTIR spectrum, (**b**) SEM of red algae-coated fabric, (**c**) SEM of red, green, and brown algae-coated fabric, and (**d**) EDX analysis of the algae-coated sample.

3.3. EDX Analysis

To confirm the formulation of carbon and oxygen in packaging, an EDX analysis was conducted. One area was selected in the sample of red algae, and corresponding peaks are shown in Figure 3d. O k and C k both can be seen in the EDX spectrum in which the weight of oxygen was 59.67 and the weight of carbon was 40.33. At the same time, the atomic % in the spectrum was measured at 47.38 for carbon and 52.62 for oxygen. As a result, only carbon and oxygen elements were detected, which indicates the need for good packaging [30].

3.4. Texture Results for the Algae-Coated and Uncoated Knitted Sample

Texture profiles of tomatoes and apples stored in both algae-coated and uncoated knitted packaging were assessed over a 21-day period (Figures 4 and 5). The results indicated significant differences in texture between coated and uncoated fruits. Tomatoes packaged in algae-coated materials exhibited enhanced firmness and maintained surface integrity compared to control samples, suggesting that the algal coating mitigated texture degradation. Among the algae types, red algae, in combination with gum arabic, demonstrated superior texture preservation for tomatoes and apples, extending freshness beyond the 7-day shelf life observed in uncoated controls. While apples exhibited less pronounced texture changes overall, red algae-coated packaging still outperformed uncoated packaging in maintaining fruit firmness, offering the most promising results. This may be attributed to the most common antioxidants found in red algae, carotenoids, and polyphenols. These substances protect fruits from oxidative damage, which results in changes in the free radicals, so they act as a preservative that keeps fruits fresh for a long time. Also, the polysaccharides of red algae, such as agar and carrageenan. These gels serve as a physical barrier on the surface of the fruit, helping to keep it fresh for longer by reducing water loss and inhibiting microbial development. Red algae are a rich source of essential nutrients like vitamins and minerals. These nutrients added to fruits can promote the health and quality of fruits generally and elevate fruit resistance to rot. Due to their naturally slightly acidic pH level, red algae can inhibit the growth of mold and bacteria responsible for spoilage. This equilibrium of pH is helpful in preserving the freshness of fruits [31]. Moreover, red algae produce a gel-like substance that not only acts as a moisture retainer around the fruit but also precludes dryness. Using the antioxidant capacity, gel-forming ability, nutritional fortification, pH regulation, and moisture retention, favorably efficient mechanisms of red algae protect fruit and increase the shelf-life extension [32]. These findings suggest that algal coatings can effectively mitigate texture changes associated with storage, especially with red algae and a combination of red, brown, and green algae.

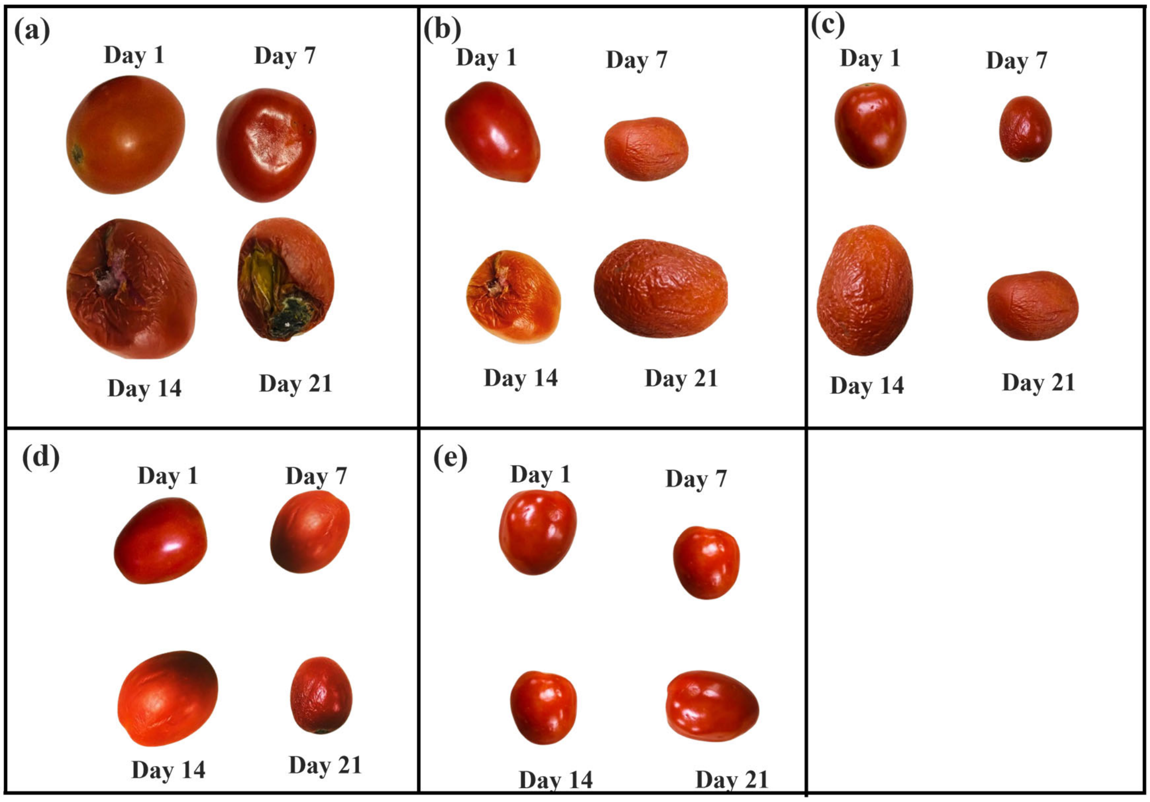

Figure 4. Texture of tomato stored in (**a**) uncoated knitted fabric packaging (control), (**b**) brown algae with gum arabic, (**c**) green algae with gum arabic, (**d**) red algae with gum arabic, and (**e**) green, brown, and red algae with gum arabic.

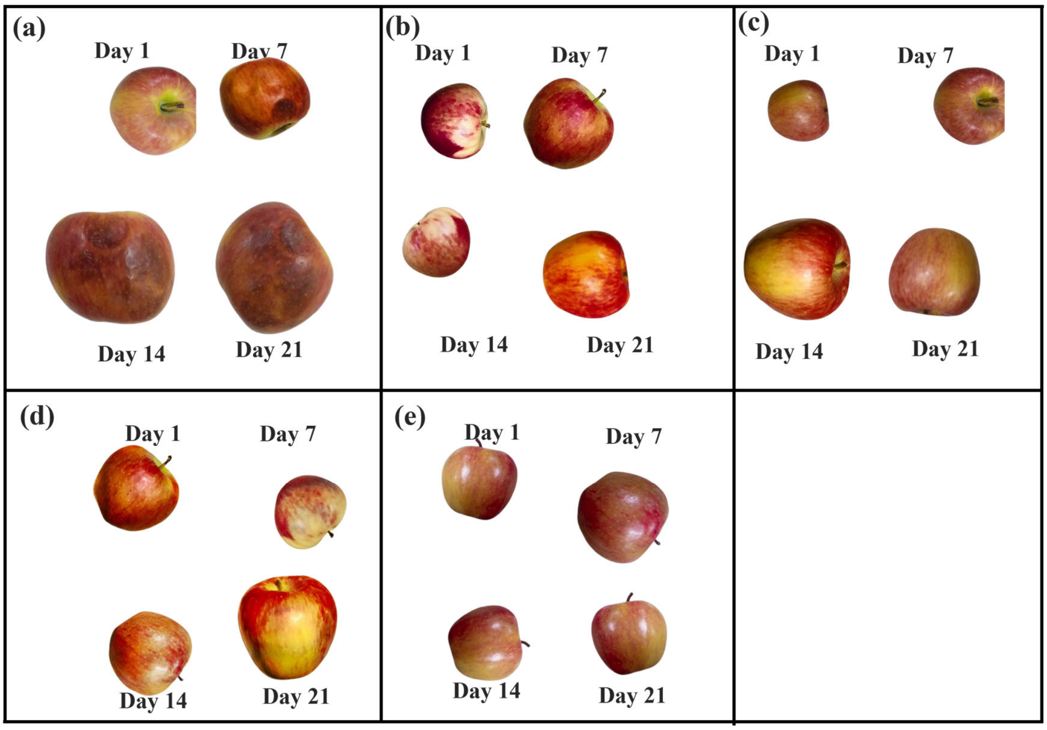

Figure 5. The texture of apples stored in (**a**) uncoated knitted fabric packaging (control), (**b**) red algae with gum arabic, (**c**) green algae with gum arabic, (**d**) brown algae with gum arabic, and (**e**) green, brown, and red algae with gum arabic.

3.5. Weight Loss Result for Coated and Uncoated Knitted Samples

A comprehensive analysis was conducted to evaluate the impact of algae-coated packaging on the shelf life of tomatoes and apples, compared to untreated packaging, over a 21-day period. Observations of weight loss and juice content for tomatoes and apples stored in both coated and uncoated knitted packaging were recorded at intervals of 7, 14, and 21 days, as shown in Figure 6, with error bars indicating good experimental consistency across all measurements. Precise measurements of weight loss, juice content, and visual changes were recorded for both sets of fruits throughout the observation period. The results indicated that tomatoes and apples stored in algae-coated packaging experienced significantly less weight loss than those in uncoated packaging, suggesting that the algae coating plays a protective role by minimizing moisture loss and preserving the fruits' weight and freshness. The data presented in Figure 6a,b, show that fruits stored in red (tomatoes 5.7% and apples 4.2%), brown (tomatoes 5% and apples 4.9%), and green (tomatoes 6% and apples 5.8%) algae-coated knitted packaging exhibited lower weight loss after 21 days, whereas fruits in uncoated packaging experienced the highest weight loss. The most significant juice and weight loss occurred between days 14–21 for uncoated samples, indicating a critical period for fruit preservation. Considerably, the fabric coated with a combination of green, brown, and red algae yielded superior results in maintaining weight (weight loss for tomatoes 4.2% and apples 3.8%) and juice content, surpassing both uncoated fabrics and those coated with individual algae types. This highlights the synergistic effect of the three algae in preserving the juice content and overall quality of the fruits. The tomatoes and apples stored in uncoated knitted fabric lost 11.2% and 10.8% of weight, respectively. The error bars throughout the storage period demonstrate the reliability and reproducibility of the experimental data, providing strong statistical support for the effectiveness of the algae coatings, particularly the combined formulation, in maintaining fruit quality during storage.

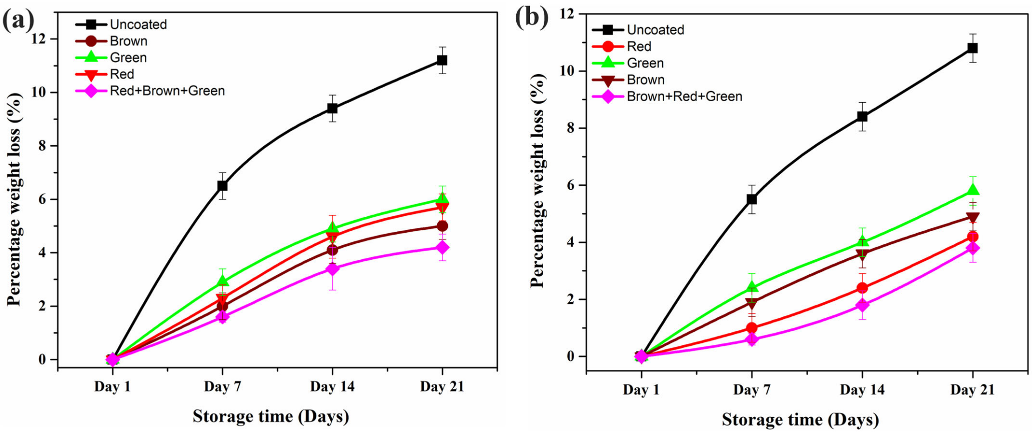

Figure 6. Weight loss percentage of (**a**) tomatoes and (**b**) apples.

3.6. Total Juice Content for Coated and Uncoated Knitted Samples

Figure 7a,b illustrate the total juice content of tomatoes and apples at various storage intervals, with error bars demonstrating consistent experimental reliability across all measurements. This analysis is critical in assessing the storage duration and consumer appeal of coated fruits compared to their uncoated counterparts. For tomatoes, initial juice content varied from 102 to 107 g, with brown algae showing the highest starting values, while apples demonstrated more uniform initial content across treatments (~97–98 g). A detailed analysis of juice content after 7, 14, and 21 days of storage revealed that the most significant juice loss occurred between days 14–21, particularly in uncoated samples. The results indicate that fruits stored in red algae-coated packaging retained high juice content (tomatoes 98 g and apples 91 g) as compared to brown (tomatoes 99 g and apples 93 g), and green (tomatoes 95 g and apples 90 g), while those in uncoated knitted packaging exhibited the lowest juice content (tomatoes 89 g and apples 85 g) after 21 days of storage. The error bars throughout the storage period indicate good experimental reproducibility and statistical reliability of the preservation effects. Notably, the fabric coated with a combination of green, brown, and red algae provided the best results (tomatoes 101 g and apples 95 g), outperforming both uncoated and individually coated fabrics. This consistent superior performance across both fruit types, supported by the error bar analysis, demonstrates the synergistic effect of these three algae types in preserving the juice content and overall quality of the fruits. There is limited published research on the use of algae as a coating material for packaging, and no studies have explored the comparison of red, brown, and green algae blends in fruit packaging.

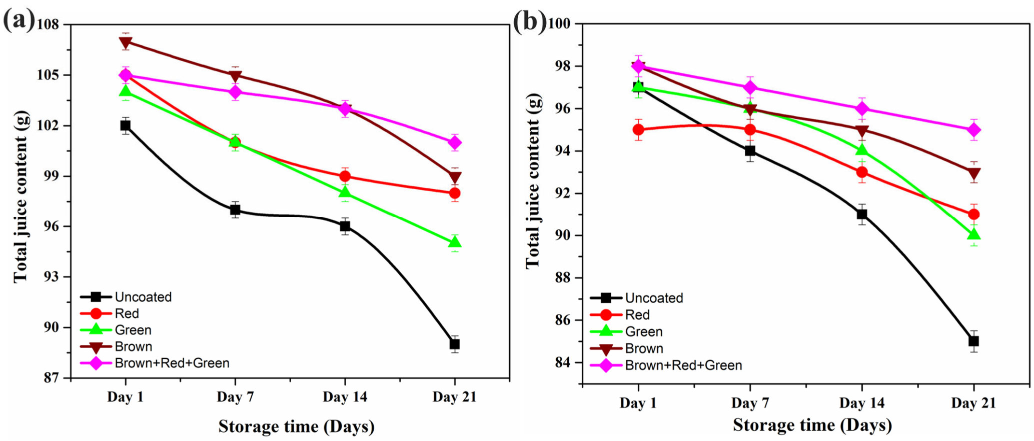

Figure 7. Total juice content of (**a**) tomatoes and (**b**) apples.

3.7. Mechanism of Algae for Fruit Protection

The mechanism of algae action for the protection of the fruits is shown in Figure 8. The ethylene production and respiration process of fruits can largely affect the quality and freshness they hold when being preserved. Fruits need glucose for energy, so they respire, and they produce heat, water vapor, and carbon dioxide (CO_2). The respiration rate is higher when fruits are not properly stored, and this causes fruits to rot faster [33]. Certain fruits produce ethylene gas, which speeds up ripening. Hence, fruits may be more likely to rot with a high concentration of ethylene. Decomposing fruits rotting also releases carbon dioxide [34]. The ability of algae to influence the respiratory rate of fruits is primarily a function of their active substances rather than the metabolic processes of living algae. Algal extracts, such as polysaccharides, proteins, and bioactive compounds, play a significant role in modulating gas exchange and enzymatic activity on the fruit surface. These substances can form a semi-permeable barrier, reducing oxygen penetration and ethylene release, thereby slowing the ripening process and extending shelf life. While living algae exhibit metabolic activities, the extracts derived from algae are specifically responsible for these preservation effects, acting as natural regulators of respiration and oxidative stress in fruits, as documented in previous studies [35]. It simply takes in oxygen and produces carbon dioxide; algae absorb the toxic elements fruit cells generate in addition to supplying nutrients and oxygen necessary for fruit cell respiration. In addition, the extracts derived from algae can act as signaling molecules whereby they invoke physiological responses to capitalize on the higher respiratory efficiency of the fruit [36].

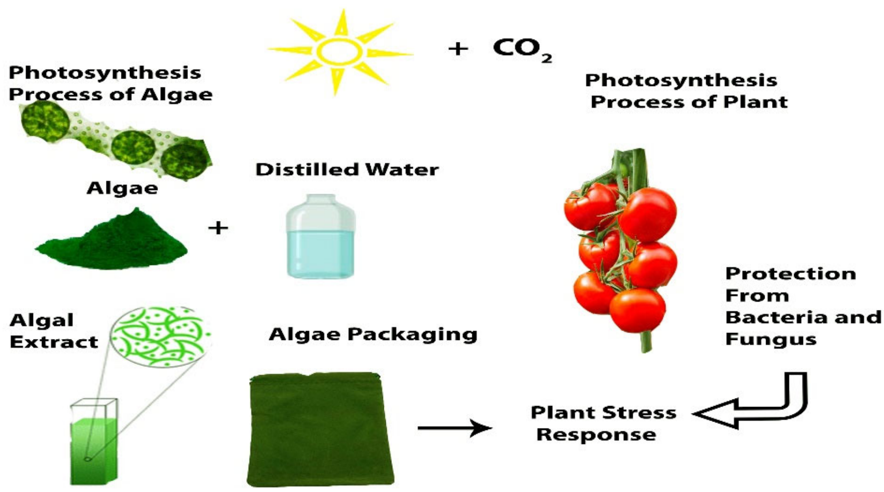

Figure 8. Proposed mechanism of algae action for the protection of the fruits.

4. Conclusions

This study demonstrates the potential of algae-based coatings on knitted textile packaging as a sustainable alternative for extending the shelf life of fruits. The findings revealed that red algae coatings provided superior preservation, particularly in maintaining texture and juice content, compared to green and brown algae. However, the synergistic effect of combining all three algae types yielded the most promising results, significantly reducing weight loss and preserving fruit quality over a 21-day period. Despite these encouraging outcomes, the study has certain limitations. The analysis was restricted to specific algae species and fruit types, and the long-term environmental impacts of using algae-derived coatings were not addressed. Furthermore, the molecular interactions between the bioactive compounds in algae and the fruit surface require further investigation to fully understand the preservation mechanisms. This approach is proposed as a sustainable alternative to conventional packaging, offering advantages such as reduced environmental impact and biodegradability through the bioactive compounds in algae. Future research should focus on exploring the scalability of algae-based coatings for industrial applications, incorporating diverse algae species to enhance functional properties, conducting molecular-level investigations of algae-derived bioactive compounds, and performing comparative studies between algae coatings and other bio-based packaging materials to benchmark performance. While the manuscript references recent studies, integrating additional citations from the latest research on algae-based materials, particularly from the past two years, could further enrich the discussion. Incorporating these aspects will not only strengthen the background of the study but also provide a robust foundation for future advancements in algae-based food packaging solutions. Globally, significant quantities of fruits and vegetables are wasted due to inadequate packaging solutions, accounting for approximately 30–40% of post-harvest losses. This research highlights the potential of algae-based coatings as an eco-friendly alternative to conventional packaging, which could play a crucial role in reducing such waste and promoting sustainability in the food supply chain.

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References

1. Lim, E.V.; Nilamani, N.; Razalli, N.M.; Zhang, S.; Li, H.; Haron, M.L.; Abdullah, A.L.; Yasin, Z.; Zanuri, N.M.; Hwai, A.T.S. Abundance and Distribution of Macro and Mesoplastic Debris on Selected Beaches in the Northern Strait of Malacca. *J. Mar. Sci. Eng.* **2023**, *11*, 1057. [CrossRef]
2. Matthews, C.; Moran, F.; Jaiswal, A.K. A review on European Union's strategy for plastics in a circular economy and its impact on food safety. *J. Clean Prod.* **2020**, *283*, 125263. [CrossRef]
3. Brown, M. Processing and Food and Beverage Shelf Life. In *Food and Beverage Stability and Shelf Life*; Kilcast, D., Subramaniam, P., Eds.; Woodhead Publishing Series in Food Science, Technology and Nutrition; Woodhead Publishing: Cambridge, UK, 2011; pp. 184–243. [CrossRef]
4. Guillard, V.; Gaucel, S.; Fornaciari, C.; Angellier-Coussy, H.; Buche, P.; Gontard, N. The Next Generation of Sustainable Food Packaging to Preserve Our Environment in a Circular Economy Context. *Front. Nutr.* **2018**, *5*, 121. [CrossRef]
5. Oyekanmi, A.A.; Kumar, U.S.U.; Abdul Khalil, H.P.S.; Olaiya, N.G.; Amirul, A.A.; Rahman, A.A.; Nuryawan, A.; Abdullah, C.K.; Rizal, S. Functional Properties of Antimicrobial Neem Leaves Extract Based Macroalgae Biofilms for Potential Use as Active Dry Packaging Applications. *Polymers* **2021**, *13*, 1664. [CrossRef]
6. Yildiz, H.; Karatas, N. Microbial exopolysaccharides: Resources and bioactive properties. *Process. Biochem.* **2018**, *72*, 41–46. [CrossRef]
7. Ke, F.; Liu, D.; Qin, J.; Yang, M. Functional pH-Sensitive Film Containing Purple Sweet Potato Anthocyanins for Pork Freshness Monitoring and Cherry Preservation. *Foods* **2024**, *13*, 736. [CrossRef]
8. Ali, A.M.M.; de la Caba, K.; Prodpran, T.; Benjakul, S. Quality characteristics of fried fish crackers packaged in gelatin bags: Effect of squalene and storage time. *Food Hydrocoll.* **2020**, *99*, 105378. [CrossRef]
9. Sani, M.A.; Tavassoli, M.; Salim, S.A.; Azizi-Lalabadi, M.; McClements, D.J. Development of green halochromic smart and active packaging materials: TiO2 nanoparticle and anthocyanin-loaded gelatin/κ-carrageenan films. *Food Hydrocoll.* **2022**, *124*, 107324. [CrossRef]
10. Yadav, M.; Chiu, F.-C. Cellulose nanocrystals reinforced κ-carrageenan based UV resistant transparent bionanocomposite films for sustainable packaging applications. *Carbohydr. Polym.* **2019**, *211*, 181–194. [CrossRef]
11. Lara, B.R.B.; de Andrade, P.S.; Junior, M.G.; Dias, M.V.; Alcântara, L.A.P. Novel Whey Protein Isolate/Polyvinyl Biocomposite for Packaging: Improvement of Mechanical and Water Barrier Properties by Incorporation of Nano-silica. *J. Polym. Environ.* **2021**, *29*, 2397–2408. [CrossRef]

12. Colla, G.; Rouphael, Y. Microalgae: New Source of Plant Biostimulants. *Agronomy* **2020**, *10*, 1240. [CrossRef]
13. Michalak, I.; Chojnacka, K. Algae as production systems of bioactive compounds. *Eng. Life Sci.* **2014**, *15*, 160–176. [CrossRef]
14. Takaichi, S. Carotenoids in Algae: Distributions, Biosyntheses and Functions. *Mar. Drugs* **2011**, *9*, 1101–1118. [CrossRef]
15. Mondal, K.; Bhattacharjee, S.K.; Mudenur, C.; Ghosh, T.; Goud, V.V.; Katiyar, V. Development of antioxidant-rich edible active films and coatings incorporated with de-oiled ethanolic green algae extract: A candidate for prolonging the shelf life of fresh produce. *RSC Adv.* **2022**, *12*, 13295–13313. [CrossRef]
16. Domozych, D.S.; Ciancia, M.; Fangel, J.U.; Mikkelsen, M.D.; Ulvskov, P.; Willats, W.G.T. The Cell Walls of Green Algae: A Journey through Evolution and Diversity. *Front. Plant Sci.* **2012**, *3*, 82. [CrossRef]
17. Nowicka-Krawczyk, P.; Komar, M.; Gutarowska, B. Towards understanding the link between the deterioration of building materials and the nature of aerophytic green algae. *Sci. Total. Environ.* **2021**, *802*, 149856. [CrossRef]
18. Miyagishima, S.-Y.; Tanaka, K. The Unicellular Red AlgaCyanidioschyzon merolae—The Simplest Model of a Photosynthetic Eukaryote. *Plant Cell Physiol.* **2021**, *62*, 926–941. [CrossRef]
19. Rosdi, F.N.M.; Salim, N.; Roslan, R.; Abu Bakar, N.H.; Sarmin, S.N. Potential Red Algae Fibre Waste as a Raw Material for Biocomposite. *J. Adv. Res. Appl. Sci. Eng. Technol.* **2023**, *30*, 303–310. [CrossRef]
20. Aziz, E.; Batool, R.; Khan, M.U.; Rauf, A.; Akhtar, W.; Heydari, M.; Rehman, S.; Shahzad, T.; Malik, A.; Mosavat, S.H.; et al. An overview on red algae bioactive compounds and their pharmaceutical applications. *J. Complement. Integr. Med.* **2020**, *17*, 20190203. [CrossRef]
21. Mekinić, I.G.; Skroza, D.; Šimat, V.; Hamed, I.; Čagalj, M.; Perković, Z.P. Phenolic Content of Brown Algae (*Pheophyceae*) Species: Extraction, Identification, and Quantification. *Biomolecules* **2019**, *9*, 244. [CrossRef]
22. Shafiei, R.; Mostaghim, T. Improving shelf life of calf fillet in refrigerated storage using edible coating based on chitosan/natamycin containing Spirulina platensis and Chlorella vulgaris microalgae. *J. Food Meas. Charact.* **2021**, *16*, 145–161. [CrossRef]
23. Feng, G.-D.; Zhang, F.; Cheng, L.-H.; Xu, X.-H.; Zhang, L.; Chen, H.-L. Evaluation of FT-IR and Nile Red methods for microalgal lipid characterization and biomass composition determination. *Bioresour. Technol.* **2013**, *128*, 107–112. [CrossRef] [PubMed]
24. Simonescu, C.M. Application of FTIR Spectroscopy in Environmental Studies. In *Advanced Aspects of Spectroscopy*; Farrukh, M.A., Ed.; IntechOpen: Rijeka, Croatia, 2012.
25. Monsoor, M.A.; Kalapathy, U.; Proctor, A. Improved Method for Determination of Pectin Degree of Esterification by Diffuse Reflectance Fourier Transform Infrared Spectroscopy. *J. Agric. Food Chem.* **2001**, *49*, 2756–2760. [CrossRef]
26. Elhattab, N.; Daghbouche, Y.; Hattab, M.; Piovetti, L.; Garrigues, S.; Guardia, M. FTIR-determination of sterols from the red alga Asparagopsis armata: Comparative studies with HPLC. *Talanta* **2006**, *68*, 1230–1235. [CrossRef]
27. Abdul Khalil, H.P.S.; Suk, W.Y.; Owolabi, F.A.T.; Haafiz, M.K.M.; Fazita, M.; Deepu, G.; Hasan, M.; Samsul, R. Techno-functional Properties of Edible Packaging Films at Different Polysaccharide Blends. *J. Phys. Sci.* **2019**, *30*, 23–41. [CrossRef]
28. Latif, R.; Wakeel, S.; Khan, N.Z.; Siddiquee, A.N.; Verma, S.L.; Khan, Z.A. Surface treatments of plant fibers and their effects on mechanical properties of fiber-reinforced composites: A review. *J. Reinf. Plast. Compos.* **2018**, *38*, 15–30. [CrossRef]
29. Saleh, R.I.; Kim, M.; Cha, C. Comprehensive Enhancement of Mechanical, Water-Repellent and Antimicrobial Properties of Regenerated Seaweed and Plant-Based Paper with Chitosan Coating. *Coatings* **2021**, *11*, 1384. [CrossRef]
30. El-Gendy, N.S.; Nassar, H.N.; Ismail, A.R.; Ali, H.R.; Ali, B.A.; Abdelsalam, K.M.; Mubarak, M. A Fully Integrated Biorefinery Process for the Valorization of Ulva fasciata into Different Green and Sustainable Value-Added Products. *Sustainability* **2023**, *15*, 7319. [CrossRef]
31. Rosenthal, A.; Torrezan, R.; Schmidt, F.L.; Narain, N. Preservation and Processing of Tropical and Subtropical Fruits. In *Postharvest Biology and Technology of Tropical and Subtropical Fruits*; Yahia, E.M., Ed.; Woodhead Publishing Series in Food Science, Technology and Nutrition; Woodhead Publishing: Cambridge, UK, 2011; pp. 419–484. [CrossRef]
32. Arad, S.; Levy-Ontman, O. Red microalgal cell-wall polysaccharides: Biotechnological aspects. *Curr. Opin. Biotechnol.* **2010**, *21*, 358–364. [CrossRef]
33. Alam, A.U.; Rathi, P.; Beshai, H.; Sarabha, G.K.; Deen, M.J. Fruit Quality Monitoring with Smart Packaging. *Sensors* **2021**, *21*, 1509. [CrossRef]
34. Wittenbach, V.A.; Bukovac, M.J. Cherry Fruit Abscission: A Role for Ethylene in Mechanically Induced Abscission of Immature Fruits1. *J. Am. Soc. Hortic. Sci.* **1975**, *100*, 302–306. [CrossRef]
35. Singh, S.; Singh, P. Effect of temperature and light on the growth of algae species: A review. *Renew. Sustain. Energy Rev.* **2015**, *50*, 431–444. [CrossRef]
36. Weraduwage, S.M.; Micallef, B.J.; Grodzinski, B.; Taylor, D.C.; Marillia, E.-F. 4.16—Roles of Dark Respiration in Plant Growth and Productivity. In *Comprehensive Biotechnology*, 3rd ed.; Moo-Young, M., Ed.; Pergamon: Oxford, UK, 2011; pp. 196–210. [CrossRef]