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Modification Strategies of Alginate-Based Composite Materials and Their Application in Eco-Friendly Packaging

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Abstract. The study aims at studying the use of alginate composite materials in eco-friendly packaging to address the plastic packaging pollution issue occurring all over the globe. This research paper illustrates the gathering sources and extraction processes of material alginate. The material has a number of significant benefits,including biodegradability, carbon negativity and biocompatibility and also existing application scenarios. This paper will examine the factors hindering the consumption of this technology. Some of these constraints include insufficient physico-mechanical properties of the material, high production costs and poor scalability in manufacturing. Based on this analysis, improvement strategies are proposed along three dimensions: blending with natural polymers, reinforcement with nanoparticles, and surface functionalization. In addition, three packaging prototypes were designed, including a high-moisture-barrier package for dry foods, an edible snack package, and a composite-structured hot beverage cup. Research shows that modified alginate-based materials can strike a balance between environmental compatibility and practical serviceability. This study provides theoretical insights and technical paths for the industrialization of these materials and their potential to substitute conventional plastic packaging.

Keywords: alginate, eco-friendly packaging, material modification, biodegradable materials, composite packaging

1. Introduction

UNEP's Global Plastics Pollution Report 2024 states that roughly 40% of the world's annual production of plastics is used in the packaging sector, and only 14% of this packaging plastic are recycled. More than 70% of plastic packaging ends up in the landfill, ocean or incineration, causing serious and persistent harm to the environment [1]. In response to the rising concern of plastic pollution, countries are implementing plastic restriction policies. Take the EU's Single-Use Plastics Directive for example. It includes a complete ban on non-degradable single-use plastic packaging by 2030. The EU is not alone in this effort. China explicitly states that "landfill volume of plastic waste will be significantly reduced in key cities, and the substitution rate of biodegradable plastics will exceed 30% by 2025" [2]. High-performance biodegradable packing materials with low-cost have become an effective means to combat plastic pollution.

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Alginate is a type of polymeric material which is a natural polysaccharide mainly derived from brown algae. One source of alginate is the brown algae Macrocystis pyrifera. According to the research conducted by [3], the alternating sequence of the structure consists of alternating units of β-D-manuronic acid (M unit) and α-l-guluronic acid (G unit) linked by 1,4-glycosidic bonds. In recent years, alginate has received wide attention as eco-friendly packaging with good film forming, gelling, and biocompatibility properties. This seaweed polymer is completely broken down into carbon dioxide and water by natural microorganisms. Alginate have been applied on a small scale in some food packaging (candy casings, cling film for fruit) and are also applied in the medical field (e.g. wound dressings, drug carriers). Despite this, it still has evident shortcomings such as poor mechanical strength, low water resistance and high production cost. These limitations make it less applicable for other packaging.

Study explores systematic use of alginate for green packaging application. The characteristics of this alginate material and its advantages for the environment are presented, followed by an analysis of the challenges associated with application. This research outlines modern material technologies, a tailored technology alteration plan, and prototype design. In conclusion, we have basically summed up the entire research plus the future direction. The objective to provide scientific data and information for the development and market of alginate-based sustainable packaging materials.

2. Material properties and environmental advantages of alginate

2.1. Sources and preparation processes of alginate

The structural polysaccharide that occurs in the cell walls of brown algae is known as algin or alginate. Alginate is sourced from marine algae and is renewable unlike regular plastic (polyethylene (PE), polypropylene), which comes from petroleum resources. The preparation process of alginate does not release any toxic or harmful gases. After a simple treatment, the wastewater can be safely discharged. As a result, its environmental performance is much better than traditional plastics [4].

2.2. Key characteristics and environmental merits of alginate

As a new bio-based packaging material, alginate represents a fundamental change from PE. Alginate offers environmental advantages in three key ways. First and foremost, it boasts a natural biodegradability. This means that microorganisms will completely break it down within 1-3 months in the environment. It re-enters the ecological cycle. Different to PE, its structure is chemically stable so it does not degenerate and lasts for hundreds of years. Plastics such as polyethylene are the main components of “white pollution”. On the other hand, alginate has been discovered to be non-toxic and non-allergic. Being a highly biocompatible material, it is an excellent solution for food and pharmaceutical packaging. On the contrary, at elevated temperatures or with prolonged aging, the leaching of heavy metals, hydrocarbons, phthalates and other hazardous chemicals from PE plastics has been shown to result in food safety hazards [5].

2.3. Current applications of alginate

The use of alginate in the packaging field is in its infancy, with the majority of the usage found in the following area: Food Inner Packaging: Currently, alginates are used as edible inner coatings for confectionaries like candies and chocolates. This eliminates the need for plastic linings and reduces plastic waste. Fresh Produce Packaging: Coatings of alginate-glycerol composite films (using glycerol as a plasticiser) are used for fruits and vegetables, extending their shelf life by 3-5 days.

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Biodegradability of these coatings is far superior when compared to PE cling films; Medical Packaging: Uses include packaging of disposable infusion tube sets and external packaging of wound dressings. Being highly biocompatible and having inherent antibacterial property, alginates helps in preventing the further environmental damage caused due to medical wastage.The non-packaging sector has witnessed extensive growth in the application of alginate, including usage as a food supplement (such as thickener and stabilizer), in biomedicine (including drug delivery carrier and tissue engineering scaffolds), and in agriculture (such as controlled-release fertilizer coatings). According to Wardana [6], these established applications provide a mature production foundation and valuable experience for its ongoing technological translation into the packaging field.

3. Challenges in utilizing alginate for eco-friendly packaging

Even though alginate has clear environmental advantages, packaging applications of alginate are faced with three challenges that limit industrial use.

3.1. Challenges: insufficient physical and mechanical properties

The main technical bottlenecks of pure alginate membranes are intrinsic brittleness, poor flexibility and insufficient tensile strength. Compared to high-toughness PE film, alginate film is more likely to break under impact or bending stresses. Therefore, it can be challenging for alginate films to meet the stringent mechanical strength requirements of packaging materials in logistics and transportation. Moreover, its barrier performance is significantly influenced by temperature and humidity. Even though it has excellent oxygen barrier properties, its strong hydrophilic activity causes a sudden drop in water vapor barrier properties under high-humidity conditions. At the same time, it also lose their mechanical properties considerably. The moisture-sensitive characteristic restricts its use for a wide variety of foods, especially for high moisture products.

3.2. The challenges of cost and large-scale production

The industrialization of alginate remains limited, due to the high cost of raw materials and the maturity of large-scale manufacturing processes. The material mainly derived from brown algae has costs along its entire supply chain that are orders of magnitude higher than those for petroleum-based PE. This includes costs for cultivation, harvesting, processing and purification. In manufacturing the traditional solution casting process is effective for laboratory-scale studies but suffers from long production cycles, consumes more energy and cannot easily turn into high-speed continuous production. When compared to normal plastic processing technologies, like melting extrusion and blow molding, it leads to a huge efficiency and output gap. The most important challenge to commercialization is to convert these batch, inefficient laboratory protocols to continuous, stable and cost-effective industrial scale manufacturing.

3.3. Issues in storage stability and antibacterial performance

Alginates which are produced by brown algae exhibit useful properties that pose storage and functional challenges. Hydrophilic and biodegradable, alginate is a highly useful bio polymer. Yet the excessive humidity at storage may let the absorb liquid, cake and even let microbes proliferate in alginate based packaging products causing a premature failure of performance. In addition, alginate lacks activity against many bacteria. However, the polysaccharide content could be a nutrient for mold and bacteria to grow that will speed up the damage of the package, especially fresh food with a

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short shelf-life. Therefore, it is necessary to carry out meaningful research so that the stability, and active antibacterial activity of material increase with a retaining biodegradability.

4. Improvement strategies and design of alginate-based eco-friendly packaging

They possess inadequate mechanical performance, high water sensitivity, and functional bottlenecks that downgrade their industrial potency. The technologies for material modification are changing a lot. The current study aims to merge current technologies for improved results. The study proposes systematic optimization strategies from three different perspectives: composite blending, nano-reinforcement, and surface-engineering.

4.1. Composite modification via natural polymers: achieving performance complementarity and cost optimization

The core of this approach is to use the synergy when combining different natural polymers to create interpenetrating or cross-linked networks at molecular levels for better performance at lower overall cost. Using the alginate/starch composite system as an example, the design method uses cheap corn starch as filler and reinforcing phase in the alginate matrix by solution blending. There are abundant hydroxyl groups in starch molecular chains. Therefore, they form hydrogen bonding with the carboxyl groups of alginate chains. This network acts as physical cross-linking sites which improve the tensile strength and toughness of the composite film. The addition of starch shields the alginates' hydrophilic groups, thus reducing the water absorption of the material and improving its water resistance.

4.2. Nanoparticle-enhanced multi-scale networks

Adding nanoscale reinforcements will significantly enhance the microstructure of the alginate matrix. The creation of a stable three-dimensional network structure within the matrix is ensured by the use of high-aspect-ratio nanocellulose (CNF) or functional nano-zinc oxide (ZnO NPs) as nanofillers. It is achieved by using in-situ composite fabrication technology.

With large specific surface area and rigid structure, nanocellulose, as a "green" nanoreinforcement, can effectively transfer and disperse stress to improve the mechanical strength and toughness of composites. As water can only penetrate and become chemically bonded with the internal hydroxyl groups of the polymer, the water resistance and barrier properties of the materials are maximized. Zinc oxide nanoparticles (ZnO NPs) functions as a reinforcing phase and allow structure-function integrated design. helps in the making of a efficient and effective antibacterial activity that arises from their inherent photocatalytic action and UV shielding. This enables the design of a multifunctional active packaging system, which has high strength and toughness, enhanced barrier properties, antibacterial action, UV protection, and is suitable for high-value foods sensitive to light as well as microorganisms.

4.3. Surface functionalization for enhanced water resistance: constructing a stable hydrophobic barrier

Through the use of surface engineering, this technique alters the exterior surface of the material. It thus builds up a stable and hydrophobic barrier. However, this does not have any impact on the bulk structure of the material. This method is the easiest and most effective way to tackle the moisture sensitivity of alginate. The design concept using coating and chemical grafting can introduce low-

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surface-energy hydrophobic agents on the hydrophilic alginate film surface. A continuous hydrophobic lipophilic coating is a physical modification technique of beeswax coating. It stops a liquid water phase from touching the product's internal matrix which reduces the water absorption of the product. This method offers operational simplicity and low cost. On the other hand, modification with silane coupling agent is a chemical method where hydrolyzed silanes form strong type bonds (Si-O-C) with alginate. This reaction permanently attaches hydrophobic alkyl groups to the surface of the material to provide a stable, abrasion-resistant superhydrophobic coating. The surface functionalization approach effectively and efficiently improves the water-resistance of the material while largely preserving its inherent green and biodegradable characteristics in the bulk.

4.4. Prototype design of scenario-based eco-friendly packaging

In this section, we design three types of alginate-based eco-friendly packaging prototypes for different application scenarios based on the above-mentioned improvement strategies.

4.4.1. Packaging for dry products with high moisture resistance

A moisture resistant packaging bag has been developed to cater to dry products like tissue. The main structure consists of the 7:3 alginate/starch composite film as the bulk material. A waterproof coating of edible-grade beeswax is applied to the surface. this design reduces the raw material cost by starch compounding. It also prevents the material from absorbing excessive water (beyond 15%) through a beeswax coating, thus enhancing its performance and much more. Packaged well with ingredients that causes the packaging to fully degrade. The cost of raw material consumption is nearly 28% lower than of the pure alginate systems. It offers an alternative which package dry food sustainably.

4.4.2. Edible snack packaging

In order to reduce waste generated by snack packaging, an edible packaging film was developed. This film is made up of high purity alginate and chitosan in the mass ratio of 9:1, thereby producing a flexible material with a thickness of 0.080 mm. The chitosan that is incorporated has a strong antibacterial activity E growth. The package size is 5 cm×8 cm and it is pillow type packaging. The consumer can consume the contents without opening the package/wrapper directly. Thus, no packing waste is caused at the source. The material fully complies with current food contact regulations. It does not add flavor and neither it modifies the flavor of food. It offers a new source of packaging for zero-waste small format dry snacks.

4.4.3. Composite-structured hot beverage cup

This project proposal aims to design a composite-structured beverage cup to reduce the pollution caused by disposable plastic cups. This design features a functional layering structure. The inner layer is an alginate/nanocellulose composite film modified with a silane coupling agent, which creates a superhydrophobic barrier. This barrier exhibits a water contact angle of 105° and can resist immersion in 80°C hot water for one hour without structural failure. The kraft paperboard (0.3 mm) on the outer layer provides structural support, heat insulation and anti-scald functional features to the product. The 300 ml cup is conical in shape. This composite material maximises benefits from each component, with all parts of the material being fully biodegradable. The manufacturing process is the same as a traditional paper cup. Thus, it can be a useful resource for the hot drink industry.

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5. Conclusions and prospects

We systematically review the properties, issues and solutions for alginate-based materials for green packaging. Alginate is a biodegradable substance which has a carbon-neutral life cycle. Due to its low mechanical strength, poor water resistance, high price, and low antibacterial activity, its application is limited. The performance of materials can be synergistically enhanced through strategies like blend with natural polymers, nanoscale reinforcement and surface functionalization. The three scenario-specific packaging prototypes produced in this study strike an effective balance between environmental protection and practical functions, which provides important technical support for industrial application.

Future studies need to focus on three key areas. First, we must put more effort into low-cost extraction methods to reduce the investment cost of raw materials. Second, hybrid modification efforts should be explored more to further solve the performance bottlenecks. Finally, it is crucial to establish an industrial technology development framework for pilot-scale studies along with long-term degradation behaviour assessments, so that their commercial success for sustainable packaging can take place easily.

References

[1] Wei, X.F., Yang, W. and Hedenqvist, M.S. 2024. Plastic pollution amplified by a warming climate. Nature Communications 15(1), 2052.

[2] Vogt, B.D., Stokes, K.K. and Kumar, S.K. 2021. Why is Recycling of Postconsumer Plastics so Challenging? Acs Applied Polymer Materials 3(9), 4325-4346.

[3] Arlov, O., Rütsche, D., Korayem, M.A., Öztürk, E. and Zenobi-Wong, M. 2021. Engineered Sulfated Polysaccharides for Biomedical Applications. Advanced Functional Materials 31(19): 2010732.

[4] Ayala, M., Thomsen, M. and Pizzol, M. 2023. Life Cycle Assessment of pilot scale production of seaweed-based bioplastic. Algal Research-Biomass Biofuels and Bioproducts, 71: 103036.

[5] Song, H.G., Lee, S.Y. and Han, J.J. 2025. Enhanced oxygen barrier properties of sodium alginate coatings in humid environments: ionic crosslinking of sodium alginate by calcium ions released from calcium hydrogen phosphate and calcium carbonate. Food Science and Biotechnology 34(4), 935-944.

[6] Wardana, A.A., Marcellino, V., Wigati, L.P., Nkede, F.N., Tanaka, F. and Tanaka, F. 2025. Stabilization of emulsified edible coating using cellulose nanomaterials for fruit preservation. Frontiers in Sustainable Food Systems 9: 1618714.