

Sustainable Snacking: An Analysis of Chitosan, Cellulose, and Polyhydroxyalkanoate Material Alternatives to Plastic Snack Packaging

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Plastic pollution is amongst the world's biggest environmental crises. Despite a heightened awareness of this issue's prevalence and impact on both the health of the environment and humans, specialized solutions addressing overlooked contributors to plastic pollution have been limited. Single-use snack packaging, for instance, is common litter seen in parks, streets, and waterways that is not emphasized as heavily in the media and policy compared to plastic bottles and bags, despite being used just as frequently. According to the International Food Information Council 2022 Report, snacking in the U.S. has risen with nearly 3 in 4 Americans (73%) reported snacking at least once a day. The extensive scale of single-use snack packaging consumption makes it a significant, pervasive contributor to plastic waste. However, comparatively little research has compared various bio-alternatives to each other and to traditional synthetic single-use plastics, and little research is directed towards identifying an alternative which best suits the functional needs of snack-packaging. This paper uses a comparative analysis and life-cycle assessment approach to assess the sustainable and application potential of three plastic snack packaging alternatives: chitosan, cellulose, and polyhydroxyalkanoates. Five factors were considered in this analysis: sourcing, packaging functionality, economic costs, degradability, and disposal costs. This assessment found that while each alternative has some properties that are desirable in snack packaging, none of them fully embody all properties that would make for an obvious replacement for polypropylene (PP) and low-density polyethylene (LDPE)-the most commonly used plastics in snack packaging. Thus, a combination of these biopolymers using a multilayering method is likely the most viable approach to a transition to plastic alternatives.

Introduction

The world currently faces a major plastic problem. In 2018, the United States Environmental Protection Agency (EPA) reported that the United States had generated 35.7 million tons of plastic waste, with containers and packaging being the largest contributor at 14.5 million tons¹. Plastic is found in daily life products ranging from trash bags to clothes, and the synthetic polymer's inability to biodegrade has caused it to become increasingly present in water systems and marine food chains, exposing both ecosystems and humans to harmful chemicals².

Despite the negative impacts of plastic pollution, a transition away from plastic has not yet been realized. If nations as a collective continue to approach the plastic problem using current methods, it is unlikely that global sustainability goals such as the United Nation Environmental Programme's 2018 pledge to phase out plastic packaging that is not reusable, recycled, or compostable by 2025 will be met³. Most efforts to combat plastic pollution involve the recovery of plastic wastes, such as beach cleanups and government issued fines on the inappropriate disposal of plastics. While these initiatives help reduce some pollution, they only tackle plastic waste after the fact while a

full transition would target it from the outset, starting at the manufacturing of plastic products and encouraging the switch to plastic alternatives⁴. There is currently a lack of the latter effort due to various barriers including price, the need to maintain packaging functionality, and unfamiliarity with alternatives.

The greatest factor deterring most businesses from making the transition is the increased cost of alternatives compared to traditional plastic⁵. Concerns primarily revolve around potential decreases in revenue and consumer base, particularly if the costs are passed onto the consumer when businesses raise the price of their product to accommodate increased material prices. While there has been an increase in consumer preference for eco-friendly products, consumer demand has not been enough to push larger corporations, the main producers of plastic waste, to eliminate their plastic use⁴.

Functionality is also an important factor to consider that can impact decisions to adopt alternatives. In addition to its cost-effectiveness, plastic has such widespread applications due to its inertness, good barrier properties, and ability to take on rigid and flexible forms. If available alternatives are incapable of traditional plastic's many functions, corporations may not be willing to adopt them⁶.

A lack of familiarity with alternatives has also caused businesses to hesitate to fully transition away from plastic. While protecting the environment may align with a corporation's values, a lack of knowledge on what alternatives to choose could be a barrier preventing eco-friendly visions from being realized. Research and educational awareness have been promoted in recent years in an attempt to bridge this gap in environmental action⁵.

Furthermore, the problem of plastic waste is multifaceted and thus requires specific tailored solutions to be addressed holistically. To accomplish this, further research on previously overlooked areas is needed. Consider single-use snack packaging, a common plastic waste seen in parks, streets, and waterways. Over 2 in 5 global consumers (45%) snack in between meals, making single-use snack packaging a significant contributor to plastic waste⁷. Despite these figures, disproportionately more attention has been paid to policies that have become the face of the plastic waste reduction movement such as plastic bag bans, rather than also finding solutions to other major contributors of plastic pollution like snack packaging. Given the considerable amount of plastic waste from snack packaging created by the widespread consumption of snacks and its demonstrated negative environmental impacts, it is important for the snack industry to recognize their environmental impact and seek ways to move forward in sustainability^{6,8,9}.

In the food packaging sector, research and experimentation has centered on bio-based materials as a result of increased demand for eco-friendly and renewable alternatives to plastic packaging in recent years. This research has yielded a multitude of new innovations, including, but not limited to, the creation of bioplastics made from algae, corn, and shrimp shells.

Much of the literature has been focused on case studies on individual alternative materials while comparatively little attention has been paid to comparing the strengths and weaknesses of various bio-alternatives to each other and traditional synthetic single-use plastics. Presenting multiple alternatives within an analysis is valuable because it provides additional insights into their viability to meet the specific needs of manufacturers and users. Furthermore, little research in the realm of material analyses has been centered on targeting particular types of waste, including single-use snack packaging, and identifying sustainable alternatives that best suit the functional needs of that product. Thus, expansion of comparative-focused research and specialized innovation is needed to push forth the integration of sustainable food packaging in the food sector^{6,8,10}.

This review aims to bridge this gap in research by presenting a comprehensive analysis of three material alternatives to plastic snack wrapping packaging. Each material will be assessed based on various factors related to their environmental impact and potential applicability in the snack-sector of the food industry. Moreover, the life cycle of these materials from sourcing to waste will be discussed. It is important to take into

account what happens to packaging beyond its creation and life on retail shelves so as to avoid recreating the same problem posed by plastic on municipal waste accumulation. The goal of this analysis is to identify potential sustainable alternatives that snack companies and packaging manufacturers can utilize to help reduce plastic pollution.

Methods

Overview

This paper is a literature review on sustainable alternatives to plastic snack food packaging. The types of academic literature examined include experimental research, surveys on consumer perspectives, and articles assessing synthetic polymers based on their chemical structure and manufacturing mechanics, and sustainable alternatives. To ensure a high quality review of the literature, I conducted a comprehensive search of peer-reviewed journals using a wide range of key terms including but not limited to plastic, plastic alternatives, food packaging, snack packaging, bio-plastics, packaging functionality properties, market analysis, biodegradability studies, consumer packaging perceptions. When combined, these key terms generated relevant papers that explored the viability of prospective bio-based packaging materials. Databases searched include JSTOR, EBSCOhost, ScienceDirect, ProQuest, and Google Scholar. In addition, I compiled information from companies or NGOs who have advocated for, trialed, or implemented plastic packaging alternatives as well as news reports featuring real-life applications of sustainable alternatives.

Case Studies Selection

Within the realm of plastic snack packaging, this paper focuses on assessing alternatives for primary packaging and flexible snack packaging. Primary packaging categorizes packaging in direct contact with the product, such as individual wrappers⁸. Examples of snack packaging that fall under these two descriptors include chip bags, candy wrappers, and biscuit or granola bar wrappers.

The materials analyzed in this paper were selected in correspondence to the types of plastic most commonly used in specific snack packaging types listed above: *polypropylene (PP)* and *low-density polyethylene (LDPE)*. PP is a synthetic polymer and thermoplastic widely used for food packaging because of its applicability in both rigid and flexible packaging, toughness, easy processability, and low cost⁶. PP is also chemical resistant, has adequate barrier properties, and is high quality for heat sealing, an important factor considered in the manufacturing process and for the maintenance of food freshness⁸. LDPE, a synthetic polymer and thermoplastic, is commonly used for snack packaging because it is flexible and light-weight¹¹.

This paper will look at three alternatives, all of which are biopolymers:

Polyhydroxyalkanoates (PHAs), chitosan-based films, and cellulose-based films. There are currently many different sustainable plastic alternatives in the realm of packing materials. A few examples of those not included in this paper are algal-cellulose-based films and paper. This analysis focuses on these three materials due to their potential compatibility in replacing flexible snack packaging specifically.

PHA was selected for its potential as a PP and LDPE replacement due to its similarity in chemical structure to the petroleum-based polymers. These structural similarities open up the potential for PHA to meet the functional needs of plastic snack-packaging, all while being more eco-friendly compared to traditional synthetic plastics due to its biodegradability and sourcing from microorganisms rather than petroleum. Chitosan was selected for being a target of recent research of plastic alternatives in the medical and food industries and its potential as a general plastic film replacement. The ability to source chitosan from waste byproducts of the seafood industry also gives the material the potential to benefit both the food packaging and seafood consumption industries in terms of reducing environmental impacts and economic costs. Cellulose was selected due to its existing application across several snack companies who have incorporated sustainable snack packaging. While its adoption suggests that the material is functionally viable, the inability of some cellulose-based bioplastic packaging to degrade unless processed artificially in an industrial composter presents sustainability concerns, and ethical concerns in the labeling of such packaging as “eco-friendly”. It is in the interest of this study to explore whether cellulose truly stands as the most sustainable and functionally effective bio-alternative to plastic snack packaging compared to other candidates.

Assessment Framework

I conducted a comparative analysis on these case studies with the goal of understanding which material would be the most effective sustainable alternative to plastic snack packaging. Each alternative was assessed based on the following factors: *sourcing, packaging functionality, economic costs, degradability, and disposal costs.*

The category of sourcing considers the renewability of packaging source materials and the environmental impacts of the extraction and processing processes each alternative packaging material undergoes to be created.

Within functionality, various packaging properties will be considered: water vapor and oxygen barrier properties, mechanical behavior (flexibility/stiffness, strength, hardness, and ductility), and shelf-life. Good barrier properties are critical for food packaging as they are directly involved in improving shelf life. High oxygen barrier abilities, which are correlated with lower oxygen

permeability, can help extend shelf life by preventing excess oxygen exposure and helping maintain the moisture and gas balance of the environment inside the packaging¹². Similarly, good water vapor barriers help maintain the moisture content inside food packaging and as a result benefits the maintenance of food product quality and shelf life. This property is desirable across different snack types as even dried snacks such as dried fruits risk changing texture and lowering in freshness when their moisture content is altered¹³.

Economic costs discussed include the cost of source materials and the cost of manufacturing each alternative packaging material.

To close the loop of each material’s life cycle, this analysis looks at two end-of-life factors. First is degradability, which includes both biodegradability and compostability. Biodegradability refers to the material’s ability to decompose after interactions with biological elements in the environment such as microorganisms like bacteria or fungi. Often confused with biodegradability, compostability is another way to describe a material’s ability to break down into its basic components. What sets composting apart from biodegrading is that it requires a specific setting instead of degrading naturally⁹. Second is disposal costs, which include the monetary and energy cost required to manage packaging waste for that particular material, such as recycling, industrial composting, natural composting, or biodegrading.

Of the five factors considered, more weight was placed on packaging functionality and degradability of the alternatives. Packaging functionality is of particular importance because it is a necessary requirement in terms of the feasibility of implementing these alternatives in industries. Degradability is also highly regarded because of the interest of the sustainability of waste-reduction that this paper centers on.

Results

Chitosan

Sourcing: Chitosan is an extracted derivative of chitin, a protein structure material found in crustaceans, insects, and fungi². Produced at an enormous quantity of 1011 metric tons annually with 150,000 tons made available for consumer use through conversion processes, chitin is the most abundant biopolymer of animal origin and the most abundant biopolymer on earth after cellulose¹⁴. The current primary raw sources of chitin are wastes from the fishing industry such as the exoskeletons of shrimp, crab, crayfish, krill, and squid¹⁵.

Currently, the seafood processing industry produces extensive amounts of animal waste by-products. Around 75% of the weight of crustaceans is inedible, such as shells of shrimp and crabs, and is thus wasted. These seafood by-products pose major environmental and health hazards². Therefore, the extraction

of chitin from crustacean shells to be processed into chitosan and repurposed as a packaging material could be a solution to the negative environmental impacts of both plastic and seafood waste.

To form chitosan, chitin goes through a process called deacetylation that involves the removal of a compound's acetyl group². Chitosan can currently be obtained through two deacetylation methods. The first and the most widely used method in laboratory and industrial-scale production is thermo-chemical hydrolysis. To remove chitin's acetyl group, this process uses harsh chemicals including various strong acids while heating up the molecule using microwave irradiation. This method is favored due to its short extraction time, but it also involves high-energy consumption and large amounts of hazardous alkaline and acid wastes that can pollute the environment¹⁵. The chemical process can also be difficult to control, which makes it challenging to obtain chitosan with sufficient purity or consistent molecular weight¹⁶. The second method is enzymatic deacetylation, a biological process where an enzyme called chitin deacetylase is used to remove the molecule's acetyl groups. This method has attracted interest due to its eco-friendly nature. The use of enzymes overcomes the problems of irregular deacetylation and hazardous waste production caused by alkali and acid treatment, but requires a relatively long processing time¹⁵. While this method may cost more and thus not be suitable for mass production, its eco-friendly nature is an aspect to consider¹⁶.

Packaging Functionality: Chitosan films are already being used in various industries including the biomedical, agriculture, water treatment, cosmetics, textile, photography, chromatography, electronics, and paper industries, and its application has attracted interest from the food industry in recent years².

Looking at its barrier properties, chitosan's oxygen permeability is low and comparable to that of conventional plastic films used in food packaging. Chitosan films also have low water vapor barrier properties due to the material's hydrophilic nature¹⁷. Having a low water vapor barrier may present challenges to shelf life and packaging durability if the user intends to pack products that retain water, such as produce, in chitosan film. While chitosan's weak water barrier quality may make it a suitable candidate for common snacks such as chips and granola bars, its properties could limit itself to being suitable for other high-water-containing products such as fruits and vegetables.

In regards to its mechanical properties, chitosan films can have a tensile strength ranging from 6.85 MPa to 70.3 MPa-, which is comparable to other biopolymers and flexible synthetic polymers like LDPE, the material targeted for replacement in this paper¹⁶. This large range is caused by differences in chitosan molecular weight, which results from production methods utilizing different acid ratios, and whether or not a plasticizer was applied during chitosan film production. These tensile strength values indicate that chitosan can be used as a durable, but flexible packaging material¹⁷.

The main mechanical property that sets chitosan apart from synthetic plastic films is its lack of thermoplasticity and decreased thermal stability. These qualities cause films to degrade before their melting temperature, meaning they cannot go through certain industrial processing methods such as molding or heat sealing¹⁶. This presents barriers in the feasibility of implementing chitosan as an alternative packaging material because traditional plastic packaging relies heavily on processes that involve heat such as those listed above. Plasticizers and other synthetic materials can be integrated into the chitosan film to improve its thermal stability. Ongoing research into non-thermal processing methods such as high-pressure processing and plasma treatment could also give rise to a more environmentally-friendly technique of overcoming this issue¹⁸. For thickness and density, films created using biopolymers like chitosan alone are very brittle. To reduce brittleness and enhance the flexibility of chitosan films, plasticizers are often applied to the material¹⁷.

Plasticizers are compounds added to polymers to improve or modify its mechanical properties- such as promoting plasticity and flexibility- without altering the fundamental chemical character of that material¹⁹. But, while plasticizers can be used to help overcome limits in mechanical properties, they can also trade off with the material's other needed characteristics. One of the downsides of using plasticizers on chitosan is that they increase the permeability of the material. High levels of permeability are undesirable for food packaging applications because it causes losses in oxygen, water vapor, carbon dioxide and aromas, and thus impacts the quality and shelf life of the product¹⁷. Further, treatment with plasticizers could reduce the sustainability of the material, as most plasticizers are fossil-fuel based⁹. An alternative approach that can be used to overcome this issue is to reduce the polymer molecular weight, which thus reduces the amount of added plasticizer needed. However, while this method reduces permeability it does so at the cost of needed film flexibility¹⁷. Manufacturers must weigh between these various factors to find a balance between the film thickness, permeability, and flexibility that works best for the type of snack packaging they are trying to produce.

Chitosan's additional nontoxicity and antimicrobial properties help make it a promising food packaging candidate²⁰. Several studies have shown that chitosan has the ability to bind with ions and gradually release metallic nanoparticles, granting it antimicrobial properties². Ion binding has the ability to produce this antimicrobial effect because certain metal ions such as Zinc (Zn^{2+}) and Copper (Cu^{2+}) possess similar chemical properties as the essential compounds bacteria thrive on. By disrupting the metabolic pathways of the cell, metal ions inhibit bacterial growth or kill the bacteria²¹. The coating of these metallic ions onto chitosan films do not pose waste or health burdens because they are widely distributed in the natural environment. A majority of these ions even function as vital minerals in eu-

karyotes like humans¹⁶. Chitosan is currently the only known natural polysaccharide that has demonstrated antimicrobial activity against bacteria, yeast, and fungi, and this antimicrobial property can help extend product shelf life²².

These properties are useful for food preservation, increasing the shelf life of goods packaged in chitosan films compared to plastic packaging. Studies on pure chitosan films have shown success in the preservation of various food items including fruits, vegetables, fish, and meat². Zhang et al. (2017) conducted a study on the preservative properties of chitosan films using red grapes and observed that the grapes wrapped using pure chitosan film remained fresh for up to 15 days, while those wrapped in plastic films perished after 6 days²³.

Economic Costs: The cost of chitosan varies depending on multiple production factors. Riofrio et. al. conducted an economic viability study on the costs needed to process shrimp shells annually in Guayas-Ecuador and found that the production of 1 kg of Chitosan costs \$8.39, or 2.4 cents per chip bag (calculations based off of 0.1 oz chip bag). The economic model used took into account early investment in the chitosan production process, such as the construction of the manufacturing plant, in addition to material and operational costs over time²⁴.

Other studies that measured the cost of chitosan production in different regions turned out different results. Previous studies have found that the cost of chitosan production in Spain was \$14 for 1 kg or 3.9 cents per chip bag, 2.9 to 3.4 in Columbia, and 1.2 cents in the US^{24,25}. Factors behind the variability of the cost of chitosan production include methods of production utilized, equipment and reagents utilized, and import taxes. For example, chitosan films created using enzymatic deacetylation would cost more due to the product's lower productivity compared to other deacetylation methods¹⁶. These variables differ across manufacturing plants and countries, but for the comparative purposes of this analysis it can be estimated by averaging these values that the production cost of 1 kg of chitosan is around \$9.74, or 2.76 cents per chip bag²⁴. This value is a significant improvement from the cost of production of most biodegradable plastic alternatives, which cost around 8 to 10 cents per chip bag, and is comparable to that of fossil-fuel derived bags in widespread use in the food industry, which cost around 1 cent to produce²⁵.

Biodegradability/Compostability: Chitosan has been shown to demonstrate the ability to biodegrade naturally, some studies even cite that it has superior biodegradability compared to other bio-based materials^{2,17,25,26}. Unlike synthetic plastics and other plastic alternatives, chitosan is unique in that it doesn't break apart into smaller pieces, leaving traces of waste that will get consumed by small critters and move up the food chain. Instead, the chitosan dissolves and gets integrated into the soil, returning natural nutrients back into ecosystems²⁵.

Nakashima et al. (2005) found that the biodegraded weight loss of chitosan films was 98.9% after 1.5 months and 100%

after 2 months when buried in red clay, and 99.1% after 1.5 months and 100% after 2 months when buried in paddy soil. The chitosan films biodegraded faster in the paddy soil due to the presence of a higher number of decomposition bacteria²⁶. But experiments in recent years have demonstrated that chitosan can biodegrade at even faster rates in rainy and damp conditions due to its hydrophilic nature. In 2019, Neptune, a startup that innovated a chitosan-based packaging alternative, found that chitosan-based material can biodegrade completely when submerged in water and agitated for 60 seconds or when left in moist soil for five days²⁵.

Disposal Costs: Due to the material's high biodegradability, there are little to no economic costs associated with the disposal of chitosan films. Overall trends in biodegradability assessments of chitosan show that the material degrades more effectively in environments saturated with water^{2,17,25,26}. But the biodegradable nature of chitosan has yet to be tested in different end-of-life scenarios because considerations of chitosan as a packaging material are relatively recent. Therefore, more research must be done to determine the best disposal route for the material²⁰.

Cellulose

Sourcing: Cellulose, a structured polysaccharide consisting of linear chains of glucose units, is the most abundant organic biopolymer in the world and amongst the most widely used polymers in food packaging alongside synthetic plastic materials^{6,9,22,27}. Attainable from the cell walls of a wide range of plant sources including wood, agricultural crops, and algae, and produced by certain types of bacteria, cellulose is a low-cost, degradable, and highly renewable material^{9,27,28}. Wood is currently the primary raw material sourced for industrial cellulose production²⁹. However, while it is a renewable biomass source, the deforestation and intensive land and water use associated with wood cultivation combined with increased deforestation regulations makes wood an unfavorable material source for in regards to environment impact and market viability^{30,31}. Alternatively, manufacturers could reduce the carbon footprint of cellulose production by recycling existing biomass sources rather than cultivating new biomass materials such as wood and agricultural crops. One such opportunity exists in the large amount of agricultural waste including fruits, vegetables, plant stalks, and forest residues that can be repurposed into cellulose material²⁹. Capitalizing on these cellulose reserves to replace plastic packaging could help both food and plastic waste in a cost-effective manner.

Upon extraction, cellulose must be processed mechanically, chemically, or enzymatically to be used in food packaging. The production of cellulose has been successfully industrialized across international production lines in countries like the United States, Canada, and Japan, but many of these processes face

persistent issues^{28,32}. The difficult-to-recover inorganic acids, expensive catalysts, large water consumption, and high energy consumption involved in the processing of cellulose are important economic and environmental factors to consider.

Some approaches can be taken to reduce the negative environmental impact of cellulose production such as enzymatic hydrolysis, a biological reaction that involves the digestion of cellulose fibers with enzymes. By breaking down the cellulose, this method can reduce energy consumption needed for later processing stages and is also environmentally-friendly and sustainable. On the downside, enzymatic hydrolysis requires a longer reaction time and can thus decrease the efficiency of cellulose film production²⁸.

The sourcing of raw materials for cellulose from plant-based, mainly agricultural, sources has raised debate about its environmental impact. Foroughi et.al, (2021) has performed a life-cycle-assessment of cellulose and has found that it is not cellulose's sourcing that raises unique environmental concerns, but rather the energy, water, and chemical use required in the later stages of the material's processing. The existence of the option to source cellulose from agricultural waste leaves the sustainability of its sourcing to depend on the overall sustainability of the agricultural system and effectiveness of waste-to-resource relocation management, rather than the production of cellulose in particular³³. Overall, the production of bioplastics like those made from cellulose are more energy-intensive compared to that of fossil-fuel based plastics because they require additional processing to achieve the same final properties. The degree of its carbon footprint also depends heavily on the processing methods used, as there are various options that can be undertaken in the creation of cellulose. Several studies conducting life-cycle assessments on cellulose identify the energy-intensive enzymatic treatment like the enzymatic hydrolysis mentioned in the previous paragraph to be the main contributor of cellulose's environmental impact. However, it is also significant to note that while bioplastics like cellulose-based plastic may have a greater environmental impact in the cradle-to-grate, starting part of its life cycle, their overall carbon footprint is comparatively lower than that of synthetic plastics because of the environmental benefits of their biodegradability at the cradle-to-grave, disposal part of its life cycle^{33,34}.

Packaging Functionality: Cellulose derivatives embody a multitude of properties. One factor impacting its qualities is the type of production adopted. Cellulose can be treated with various acid types to enhance or achieve certain qualities. Furthermore, cellulose's characteristics depend on the raw material sources used. Bacteria-based cellulose have the most deviating characteristics and are more difficult to attain due to the limited number of bacterial species that can synthesize cellulose. While there are a range of properties embodied by plant-based derivatives, many of them share common underlying properties which will be explored in this section^{6,35}.

Regarding its mechanical properties, cellulose has high tensile strength due to its high crystallinity, or the structural alignment of molecules of the polymer. This indicates that cellulose can withstand high levels of stress, making it a durable material²⁹. But, the strong and structured intramolecular bonds of pure cellulose also make it stiff and brittle, giving it few applications in flexible packaging on its own. To achieve desired mechanical properties for flexible snack packing films, cellulose can undergo chemical, mechanical, or enzymatic modifications and be treated by plasticizers³⁵. However, as discussed in Chitosan-Packaging Functionality, plasticizers, which are synthetic and fossil-fuel based, have negative trade-offs in regards to environmental impacts. This is particularly significant in considerations of the sustainability of plastics such as cellulose-based plastics, as the use of plasticizers is a widespread, if not a necessary addition for the packaging functionality of the material. While the renewable and degradable component of cellulose is an improvement to fossil-fuel based plastics, until biodegradable alternatives to the use of plasticizers to assist the functionality of bioplastic materials are innovated and extensively applied to the industry, cellulose and other bioplastics will continue to introduce long-term waste to the environment³⁶.

Like chitosan, cellulose is a biobased biodegradable plastic that is prone to thermal degradation. This low thermal resistance may cause difficulties in the processing phases, as the material must be subjected to elevated temperatures as little as possible to avoid undersized altering of its mechanical properties⁹. Cellulose's lack of heat-sealing capacity indicates that it must be used in association with other thermoplastic polymers, synthetic or natural, to be applied as a functional packaging material³⁵. Plasticizers can also be applied to improve the processability of cellulose⁹.

For its barrier properties, cellulose's higher crystallinity provides more compact structure and density, increasing both mechanical strength and barrier properties because less space is allowed for the movement of molecules across the barrier²⁹. Research into specific cellulose derivatives has demonstrated that, in addition to superior gas barrier properties, nanocellulose possesses high oil barrier properties when used as coating, films, or layer-by-layer material- all of which comply with the structural breakdown of most snack packaging³⁵. However, cellulose films have a poor water vapor barrier due to the hydrophilic nature of cellulose's chemical compounds. The possession of a weak moisture-barrier could negatively impact the shelf life of moisture-containing products, and thus limit the types of goods that can be stored using this packaging^{22,29}.

Two additional qualities that can help with food preservation and extend product shelf life are antimicrobial and antioxidant properties. Antioxidant properties are beneficial because the oxidation of food products can decrease food's quality through changes in nutritional value, odors, and color and consequently result in food spoilage²². While pure cellulose itself does not ex-

hibit antimicrobial or antioxidant qualities, such can be achieved by incorporating active compounds that do, such as plant extracts and essential oils, into the material²⁹. Dannenberg et. al. (2017) found that cellulose acetate films incorporated with pink pepper essential oil demonstrated antibacterial activity against foodborne pathogens in sliced cheese³⁷. Han et. al. (2018) found that cellulose films coated with cinnamon essential oil demonstrated antimicrobial properties against the pathogens *E. coli* and *S. aureus*³⁸.

The preservation abilities of cellulose has been tested across various food types including fruits, vegetables, meats, cheeses, nuts, and more. Khaledian et. al. (2019) found that cellulose nanofibrils incorporated with ginger essential oil and citric acid extended the shelf life of meat up to 6 days³⁹. Bauer et. al. (2022) tested the antimicrobial activity of methylcellulose edible films produced with clove and oregano essential oil and found that it prevented spoilage fungi in bakery products and improved the shelf life of sliced bread up to 15 days⁴⁰.

Economic Costs: Cellulose is considered a cost-effective material due to its high market demand and bioavailability. Considering its applications across a wide variety of industries including but not limited to textiles, building materials, aerospace parts, and food packaging, investment into cellulose-based films is low risk³².

The price of cellulose fluctuates depending on the raw materials used, land and site cost, and processing methods undertaken such as treatment and refinement⁴¹. For example, as mentioned in Chitosan-Sourcing, enzymatic modification processes tend to be more costly¹⁶. Accounting for all possible plant-based derivatives and different treatment and production paths, the production cost for 1 kg cellulose varies from \$0.02 to \$226.85, or 0.006 to 64.31 cents per chip bag (calculations based off of 0.1 oz chip bag)³⁵. For specific cellulose derivatives, the production of 1 kg of nanocellulose costs between \$4.4 to \$11³². In comparison, fossil-fuel derived plastic bags only cost around 1 cent to produce²⁵. The average production cost of cellulose films is currently higher than that of traditional synthetic plastics because it requires more processing to achieve similar qualities. Though, some of these costs can be reduced as some of the coaters and laminators used to enhance plastic films can also be applied to cellulose-films³⁵.

The cost of cellulose production varies widely due to the large range of potential sourcing material that could be used. Because raw material that could be sourced, it is difficult to make a generalized prediction on the economic feasibility of cellulose production. Such is likely to vary across countries and what raw sources for cellulose are abundant in those regions.

Biodegradability/Compostability: Like the other biopolymers mentioned in this paper, cellulose is inherently biodegradable in natural environments. But it is important to note that the chemical modifications applied to cellulose films to obtain thermoplastic, mechanical, and other desired material properties

can hinder biodegradability or prevent full degradation. Furthermore, degradation rates can vary depending on the environmental conditions of the disposal location^{29,35,42}.

In regards to its general biodegradability abilities, cellulose's highly crystalline fiber structure and complex molecular bonding make it more difficult to decompose compared to other polysaccharide biopolymers. Furthermore, it is insoluble in water and most organic solvents.

To accommodate these two barriers, the decomposition of cellulose is naturally carried out by various microorganisms such as bacteria and fungi. These organisms secrete specific enzymes that are capable of breaking down cellulose's structure into simpler compounds⁴². Thus, to prevent the accumulation of bioplastics in nature, potentially recreating the plastic problem, the most effective disposal of cellulose packaging would be to collect and place it in a microbe-rich environment such as an industrial or home composter. Varying results from studies have shown that the complete degradation of cellulose films can take anywhere from 28-495 days, values that depend on soil type and environmental conditions⁴³.

Disposal Costs: The limited biodegradable abilities of cellulose, particularly modified cellulose, suggests that in order to promote sustainable disposal, cellulose bioplastic films ought not to be home composted and need to either be recycled or broken down through industrial composting⁴³. Cellulose bioplastics can be sent down the general organic fraction of the municipal solid waste stream, where it would be subject to anaerobic digestion processes or get industrially composted, if industrial composting processes are available at the waste treatment facility. In many developed countries, industrial composting is established in standard waste treatment facilities, mostly processing organic and agricultural products. While industrial composting is a convenient and cost-effective approach, it is currently not the most practical or environmentally-friendly process to dispose of bioplastics. Because the composting and digestion conditions (e.g. temperature, retention time) needed to break down bioplastics differ from that of waste, the processing of cellulose bioplastics using this method would result in large amounts of leftover non-degraded bioplastics and contaminated, unusable compost⁴⁴. To effectively dispose of cellulose bioplastic in an environmentally-conscious manner, the packaging could instead be processed through a specialized recycling or industrial composting stream. In comparison, the downside of this approach would be its higher cost of implementation, as establishing additional recycling and industrial composting facilities requires high energy use, manpower, and funds to operate⁴³.

Polyhydroxyalkanoates (PHAs)

Sourcing: Polyhydroxyalkanoates (PHA) are a family of naturally occurring polymers synthesized by bacteria cells. When placed in environments with excess carbon sources such as sugar

and lipids, and limited nutrients such as nitrogen, oxygen, and phosphorus, bacteria undergo a process of fermentation that results in the intracellular accumulation of PHA in the bacteria cell cytoplasm. PHA is produced to serve as a nutrient storage for bacteria during times of shortage^{9,45-48}. The most common carbon sources used to feedstock this microbial fermentation process are agricultural crops, municipal solid waste, and wastes produced by forest, agricultural, and dairy industries⁴⁹. As discussed in Cellulose-Sourcing, the repurposing and utilization of waste products as raw materials as opposed to the cultivation of new carbon sources would reduce the carbon footprint of PHA production. In industrial settings, bacteria are grown in controlled conditions and supplied with nutrients to speed up growth. Once the bacteria population reaches a desired size, the nutrient content is then changed to promote PHA synthesis^{9,47}.

Over 300 species of bacteria, fungi, and microalgae capable of producing PHAs have been reported, though very few produce the polymer with high productivity and a high production rate⁵⁰. The bacteria needed for PHA production can be obtained from pure cultures of bacterial colonies. This process is costly and contributes to PHA bioplastics's comparatively higher cost of production⁵¹. Alternatively, bacteria can be sourced from wastewater treatment plants, which produce large quantities of sewage sludge containing high quantities of bacteria. Environmental and health risks necessitate the safe management and disposal of sewer sludge, and this critical issue has motivated the waste management industry to explore methods of not only treating but also converting the sludge into value-added products like bioplastics. The treatment and usage of this sludge for PHA bioplastic production poses great economic potential and environmental benefits, as it would contribute to the disposal and decrease of sewer sludge in addition to the reduction of plastic waste⁵².

After fermentation, in order for PHA to be used as a bioplastic material, the PHA is isolated and extracted from the bacteria cells, purified, and then compounded into films⁴⁸. PHA can be extracted through chemical or biological methods. Chemical extraction is currently the main approach used to process PHA industrially, however this method comes with the downside of increased production cost, the degradation of polymers, and environmental issues associated with hazardous chemical waste disposal. Biological extraction methods could be a way of overcoming these drawbacks. One approach is to feed cells containing intracellular PHAs to animals or insects, and then collect the undigested PHAs from their excrement. Multiple studies investigating this method have shown that 90% of PHAs were recovered when cells were fed to insects, 90-97% with rats, and 89% with mealworms. Thus, this method could be substituted to make the extraction process of PHA less costly and more environmentally-friendly while maintaining similar quality and yield of PHA⁴⁵.

Packaging Functionality: PHAs exhibit minor structural

differences depending on the type of bacteria they are synthesized from, but retain similar overall properties. The member of the PHA family that exhibits characteristics most similar to polypropylene (PP)- the main plastic film used for snack packaging- is polyhydroxybutyrate (PHB)⁹. PHA's cellular structure can be further modified through genetic engineering to create materials with targeted characteristics related to melting point, degree of crystallinity, and a wide variety of mechanical properties. Structural diversity is beneficial in the context of food packaging as it allows manufacturers to use the same material for a diversity of packaging types and functions⁴⁸.

Collectively, PHAs are non-toxic, have excellent film-forming properties, and have similar mechanical characteristics to PP^{6,46,48,50}. PHA films are considered flexible with moderate elasticity levels comparable to that of traditional synthetic plastics⁴⁸. The main drawbacks of PHA's physical properties are its high crystallinity, which causes brittleness, and narrow thermal processing window, both of which make it difficult to process PHA films^{46,48}. Studies have observed that the crystallinity of PHA evolves over time, causing it to increase in brittleness with time as well. In the context of food packaging applications, aging could be factored into considerations of shelf life since it may impact the quality of the product over its lifetime. Secondly, PHA's melting temperature is similar to its thermal degradation temperature, giving it poor thermal stability. This poses challenges for the processing of PHA films because at temperatures near melting point the material would be amorphous and sticky, and thus difficult to handle⁴⁶.

However, the thermal properties of PHA are closer to that of PP compared to other biopolymers and these challenges have been overcome by improving PHA's physiochemical properties through modifications, allowing it to be used across industries⁴⁵. Plasticizers can be integrated in PHA films to reduce brittleness and improve elasticity- characteristics essential to flexible film packaging⁵³. Nanofillers or other biopolymers can also be blended with PHA films to reduce brittleness and improve thermal stability⁴⁵. PHAs blended with starch have shown to improve the material's lower tensile strength significantly while simultaneously reducing the cost of the film since starch is abundant and easy to obtain⁴⁶. Several of these additives and modifiers have proven to adequately improve PHA's properties, facilitating its processing and enabling its usage. Though, their impact on PHA's sustainability varies. As discussed in Chitosan-Packaging Functionality and Cellulose-Packaging Functionality, plasticizers would help overcome PHA's drawbacks while compromising its sustainability since they are fossil-fuel based and not degradable^{9,36}. The environmental impact of nanofillers varies as they are made from either organic or inorganic renewable materials, most of which are biodegradable. Biopolymers and starch, which are naturally-sourced, biodegradable, and often abundant in raw material, have a low environmental impact^{45,46}.

One of PHA's advantages is its barrier properties. While simultaneously the cause for weak mechanical properties, PHA's crystallinity grants it intermediate to high oxygen barrier properties because higher crystallinity results in higher oxygen barrier properties^{45,50}. In the reverse, additives used to improve flexibility such as plasticizers have shown to reduce the barrier properties of PHA films. Thus, manufacturers ought to consider both effects of crystallinity to strike a balance between good mechanical properties and maintaining adequate barrier properties⁵³. PHA has high water vapor properties due to its hydrophobic nature, making it capable of storing foods containing moisture and resilient to moisture damage^{45,48}. PHA films also have intermediate water vapor permeability, levels comparable to that of PP. In the context of food packaging, water vapor permeability helps create the right gas mixture needed to maintain food quality⁵³.

In regards to food preservation, a combination of PHA's excellent barrier properties and its potential to exhibit antioxidant and antimicrobial properties make PHA films a suitable candidate for snack food packaging. While pure PHA does not have antioxidant and antimicrobial properties, it can be blended with other natural compounds like phloretin to gain those beneficial characteristics. Phloretin is a natural phenol found in the leaves of various fruits and vegetables, most commonly apples. The compound has demonstrated antimicrobial activity against various food-borne pathogens with particular efficacy against *L. monocytogenes*, a bacteria that often contaminates products during food chain production, packing, and distribution. Mirpoor et al. (2023) conducted a study analyzing the preservation abilities of phloretin infused PHA films and found that apple samples packed with pure PHA film showed browning after 24 hrs while those packed with phloretin-treated PHA film showed browning much later after 72 hrs. Furthermore, the naturally-sourced additive is environmentally-friendly, as it is sourced from common agricultural crops and is biodegradable⁵⁴. Thus, PHA films integrated with phloretin could help control contamination of food along the food chain and prevent food spoilage, all while aligning with the sustainability goals of the packaging material.

Economic Costs: PHA is currently applied in the packaging industry as films for bottles, containers, bags, and other specialized products like utensils and used for various medical applications such as sutures, slings, bone plates, and skin substitutes^{9,45,55}. Due to its similarities in properties and functionality to synthetic plastics, PHA is being applied in more industries over time and has even intensified in production from 5.3 million to 17 million tons from 2013 to 2020⁴⁹.

The main economic challenge to the mass production of PHA is the material's high production costs^{9,45,46}. The production costs of PHA-based plastics are 20% to 80% higher than that of conventional fossil-fuel based plastics with an average production cost of \$5.77 per kg, or 1.64 cents per chip bag (calculations based off of 0.1 oz chip bag)^{48,56}. In comparison, fossil-fuel de-

veloped plastic bags only cost around 1 cent to produce²⁵. Unlike the other biopolymers mentioned in this analysis, PHA has a complicated synthesis process involving fermentation, isolation, and purification processes. These additional steps raise the costs of production for PHAs significantly⁹. The initial fermentation processes used to obtain PHA alone accounts for 40% of the material's total production cost⁴⁹.

Some of these costs can be reduced by reusing the same equipment used to process conventional plastics because PHA is also a thermoplastic⁹. The use of inexpensive carbon-containing materials created from bio-waste (stems, roots, leaves, stalks) such as agricultural lignocellulosic waste (LCW), a complex carbohydrate polymer composed of lignin, cellulose, and hemicellulose, to fuel the fermentation process can further minimize costs⁴⁹.

Despite its higher cost compared to synthetic plastics, PHA continues to be used in various industries. The primary motivator behind industries' decision to switch to PHA is a rising concern regarding human health and safety posed by the presence of toxic substances in plastics. This is particularly significant consideration for PHA's extensive applications in the medical industry⁵⁷. As food is closely tied to human health, the food and snack packaging industry may recognize the safety benefits of switching to PHA materials over their heightened cost.

Biodegradability/Compostability: PHAs are naturally biodegradable and retain their non-toxic nature after degradation^{9,45,46,49}. Due to its hydrophobic nature, PHA relies on microorganisms found in natural or artificial degradation environments like home or industrial composts to be broken down into simpler components⁵⁵. The biopolymer has also demonstrated the ability to degrade rapidly in a diverse range of settings, including aerobic, anaerobic, and saline environments. Altogether, these properties allow PHAs to be disposed of without harm to the environment⁴⁵.

The biodegradability of PHAs is impacted by various factors including climatic conditions, soil and water conditions (moisture, temperature, pH, oxygen and nutrient availability), the presence of microorganisms (bacteria, fungi, algae), and molecular composition⁴⁵. The main structural characteristic that impacts the biodegradability of PHA is crystallinity, which as mentioned in PHA-Packaging Functionality can vary depending on the sourcing and treatment of the PHA. High degrees of crystallinity are correlated with slower rates of degradation because molecules are more densely packed⁵⁸. In regards to climate, PHA films can biodegrade in both aerobic and anaerobic environments. The only difference between the two is that the degradation of PHA in aerobic conditions yields carbon dioxide and water, while its degradation in anaerobic conditions yields carbon dioxide and methane. Because both carbon dioxide and methane are greenhouse gasses, it would be more environmentally friendly to have PHA degrade in oxygenated, aerobic conditions⁵⁵. The degradation rates of PHAs can also

differ drastically across soil types. Kim et al. (2000) showed that PHA-derivative PHB degraded 98.9% in 25 days when placed in activated sludge soil compared to only degrading 7.1% in forest soil⁴⁵. The average degradation rate of PHA in an open environment with adequate humidity, oxygen, and microbes is 20-45 days⁵⁹.

Disposal Costs: PHA's hydrophobic nature and insolubility in water makes it more difficult to degrade, which poses the potential risk of waste accumulation⁴⁸. However, PHA's ability to biodegrade in a diversity of conditions including both soil and marine environments gives it an advantage over other biopolymers in regards to disposal⁴⁵. This is partially due to the fact that more organisms, such as microalgae found in marine environments, are capable of consuming PHA and reintegrating its nutrients back into the environment⁴⁸. Therefore, there is a possibility that the implementation of a comprehensive specialized composting system is not required to support large-scale distribution of PHA-based plastics.

Comparative Analysis

This section compares the three alternatives in five aspects to determine the potential of these materials as alternatives to plastic snack packaging. Table 1 summarizes the assessment of the properties embodied in the alternatives, highlighting strengths and weaknesses across the three. Mechanical and barrier properties are evaluated on a low-medium-high scale, while factors under other properties and degradability are rated on a binary scale indicating whether they embody that property or not.

Sourcing & Economic Costs

In the context of sourcing, cellulose is the most abundant biopolymer found on earth, followed by chitosan ranked second in the world, then PHA as the least abundant of the three alternatives^{14,27,49}. Cellulose also has the most diverse range of raw sources compared to the other two biopolymers. Examples include timber, agricultural crops, and agricultural plant waste, which are all cellulose reserves that are readily available, renewable, and low-cost^{9,27,28}. Chitosan is also highly accessible. Attainable from a diverse range of crustaceans, but also insects and fungi, there exists almost an endless supply of chitin in nature and the material currently lacks competing applications^{14,25}. In addition to great accessibility, chitosan and cellulose also present the opportunity to capitalize on reducing seafood and agricultural waste, respectively. On the other hand, PHAs are cultivated from certain bacterial species, which are not as readily obtainable as seafood and agricultural waste and thus more costly. Moreover, PHA is not readily extractable as these bacterial cells must go through an artificially-induced microbial fermentation process to create PHA, which increases the time and costs involved substantially^{9,45,46}.

For processing, PHA has the most processing requirements compared to cellulose and chitosan because in addition to extraction and refinement into film material, the creation of PHA films requires an initial microbial fermentation stage^{9,45}. The processing of chitosan is less costly than that of PHA, but more difficult to process than cellulose because beyond extraction from raw sources, it requires an additional deacetylation process to transform chitin and chitosan^{15,16}. Unique from the processing of chitosan and PHA, the recovery of cellulose through extraction has been successfully industrialized in production lines across the globe, fostering cost-effectiveness, efficiency, and consistency in their production³². However, it is important to note that despite these benefits, the production of cellulose currently still requires the use of harsh chemicals and high water and energy consumption²⁸.

For production costs, the price of cellulose fluctuates depending on source materials used but is generally low-cost with prices comparable to that of traditional synthetic plastics³². Chitosan films cost slightly more than cellulose, but are getting cheaper as new processing methods are being researched as a result of increasing interest from packaging and medical industries².

The biggest disadvantage of PHA is its high cost, causing it to lose out to the other two alternatives, chitosan and cellulose, whose total production costs are comparable. Thus, given their potential to be lower in sourcing and economic costs and ability to be created from repurposed waste materials, the material alternatives of chitosan and cellulose are favorable to PHA.

Packaging Functionality

In regards to packaging functionality, a weakness shared by all three alternatives is low thermal resistance and brittleness. Thermal resistance is necessary for snack packaging as films are subjected to high heat when packaging is processed through stages such as heat sealing³⁵. This is the greatest disadvantage of chitosan and cellulose^{2,35,45}. Secondly, high levels of brittleness are undesirable for snack packaging because it causes the material to be fragile and at risk of damage throughout the processing and handling processes⁴⁶. Brittleness can be improved by blending the biopolymers with plasticizers, but doing so could reduce the sustainability of the alternative packaging.

However, the impacts of brittleness are reduced if the material exhibits higher levels of tensile strength, a property that allows the material to withstand breakage under pressure and causes it to be more durable¹⁷. Thus, in the context of reducing brittleness, cellulose is superior because it exhibits high tensile strength while chitosan and PHA exhibit low tensile strength. But, high tensile strength can also trade off with flexibility, a critical property for snack packaging. While all three alternatives have good flexibility, PHA is reported to have mechanical properties most similar to polypropylene and low-density polyethylene, the synthetic plastics most found in snack packaging, due to

Table 1 Summarized Properties of Chitosan, Cellulose, and PHA Packaging Alternatives.

	Chitosan	Cellulose	PHA	PP (traditional plastic)
Economic Costs				
Average production cost	\$4.23-9.74/kg (varies by country)	\$0.02-226.85/kg (varies by source)	\$5.77/kg	\$0.5-3.52/kg (varies by country)
Mechanical Properties				
Tensile strength	low/varies	high	low	low
Flexibility	medium	medium/low	medium	high
Brittleness	high	medium/high	medium/high	low
Thermal resistance	low	low	low	medium/high
Barrier Properties				
Oxygen barrier	high	high	medium/high	low
Oxygen permeability	low	low	low	medium/high
Water vapor barrier	low	low	high	medium
Water vapor permeability	low	low	medium	high
Other Properties				
Nontoxic	yes	yes	yes	yes
Antioxidant	yes	possible with additives	possible with additives	no
Antimicrobial	yes	possible with additives	possible with additives	no
Degradability				
Biodegradable	yes	yes (limited environments)	yes	no
Compostable	yes	yes	yes	no
Water-Soluble	yes	no	no	no
Soil degradation rate	5 days (moist environment)	28-495 days (varies across soil types)	20-45 days (open environment)	--

its low tensile strength and intermediate flexibility^{6,48}. Thus, in terms of mechanical properties, PHA would be the most desirable alternative.

In the category of barrier properties, all three alternatives exhibit high oxygen barriers. PHA is the most desirable as it exhibits superior gas and water vapor barrier qualities. Conversely, a significant weakness of chitosan and cellulose is their low water vapor barrier properties. Unlike oxygen permeability, water vapor permeability is not always correlated with water vapor barrier, such as in the case of chitosan which has both low water vapor barriers and permeability due to its hydrophilic nature. The material is prone to absorbing water, which hinders its ability to block out water and transmit water through its film without getting damaged. Thus, due to its good oxygen and barrier qualities, PHA is the superior alternative.

Chitosan, cellulose, and PHA are all nontoxic, a necessary quality for safe food packaging, and have the potential to harbor antioxidant and antimicrobial properties which help prevent food spoilage and extend shelf life^{20,22,48}. However, chitosan is slightly superior in this aspect because it is inherently antioxidant and antimicrobial while cellulose and PHA need to be blended with other biopolymers or treated with essential oils before exhibiting those abilities^{2,29,54}.

Biodegradability, Compostability, & Disposal Costs

Of the three alternatives, chitosan has the fastest biodegradation rate of 5 days and is capable of degrading in diverse environments which resolves disposal concerns of waste accumulation. Furthermore, unlike cellulose, PHA, and other biopolymers, chitosan is unique in that it can reintegrate itself into natural environments rather than breaking into smaller micro-pieces due to its water solubility abilities⁵⁴.

Cellulose and PHA have high crystalline structures and are insoluble in water- factors that cause both alternatives to degrade at a slower rate. However, between the two, PHA is the favorable alternative due to its shorter average degradation period of 20-45 days and ability to degrade in diverse environments including aerobic and anaerobic environments and both land and marine environments^{45,55,59}. It is possible that this is impacted by the expanded number of microorganisms that can break down and reintegrate PHA into the environment- bacteria, fungi, algae⁴⁵. Cellulose, which can only be broken down by bacteria and fungi found in land environments, has the slowest biodegradation rate ranging from 28-495 days. While it is technically possible for cellulose to break down in marine environments, such would take significantly longer due to limited exposure to cellulose-digesting microorganisms^{42,43}.

Despite being a significant improvement compared to the thousands-year long degradation period of fossil-fuel based plastics, the limited biodegradability of cellulose, in both rate and scope, poses risks of waste accumulation. To avoid the recre-

ation of the plastic problem, bioplastics made from cellulose may need to be collected for disposal and sent to be recycled or composted. In addition to reducing the effectiveness of waste management, the implementation of specialized industrial recycling and composting facilities would be accompanied with transitional costs. Thus, chitosan presents the most sustainable disposal outcome.

Discussion

I assessed the viability of alternatives based on chitosan, cellulose, and polyhydroxyalkanoates (PHAs) and found that while each had valuable properties, none consisted of all to be a clear replacement for plastic: PHAs exhibit most similar physical properties to polypropylene (PP) and low-density polyethylene (LDPE), cellulose is most readily sourced and has the lowest economic costs, and chitosan has the best biodegradability abilities and lowest disposal costs. While not initially anticipated, the outcome of this analysis along with similar results presented in other papers suggest that a solution to plastic packaging would require an alternative that encompasses a mix of multiple alternatives. This is achievable through a multilayer packaging model.

Just as traditional snack packaging often possesses a multilayer structure with varied materials, such as chip bags packaged with propylene and metalized layers, sustainable food packaging alternatives can also incorporate multiple plastic material replacements⁶⁰. Multilayering is a widely applied process in the industrial-scale manufacturing of snack packaging⁶¹. This method enables manufacturers to employ unique and exceptional properties of different materials needed to meet the complex functional requirements of specific food packaging, such as enhanced barrier properties to maintain product shelf-life and freshness^{6,28}. For example, chitosan and cellulose can be mixed to combine the prior's antimicrobial properties with the latter's good barrier properties²⁸. Moreover, mixing certain materials together could help improve functional weaknesses. For instance, a chitosan-based film could be coated onto starch-based bioplastic to reduce the packaging's water absorption⁶⁰. Further research could assess the best combinations to optimize packaging functionality, but also other factors such as degradability. Multilayering has been criticized for being non-recyclable due to the practicality and cost barriers that come with processing traditional snack packaging- mainly composed of various plastics and aluminum⁶². However, the prospect of creating multilayered snack packaging solely out of biodegradable components like the materials discussed in this study could shift the practice towards a more sustainable path because the materials would not need to be separated to be disposed of, all while conserving the functional benefits that come along with the multilayering model.

The primary limitation of this study is that it did not assess all

possible properties revolving around food packaging. Additional topics that could have been considered include consumer perspectives, impact on packaging design potential, and additional environmental impacts of disposal. Though, these subjects also present areas for future research.

Of these factors, one that would be of great interest to manufacturers and businesses' is consumers' perspectives on products created with bio-based packaging alternatives. Food packaging type can influence attention, expectations, engagement, and ultimately consumers' purchase related decisions of products. A common trend across studies of consumer behavior have shown that there is a low likelihood that consumers will compromise on product fundamentals- such as quality, functionality, cost- for sustainable packaging⁶³.

Quality, which encompasses packaging appeal, could be a decisive factor in the success of alternative snack packaging. The SunChips 2010 compostable chip bag campaign is an example of how products made with alternative, bio-based packaging could be driven to failure for misaligning with consumer's expectations of packaging quality. The company's step towards sustainability was met with widespread complaints about the polylactic acid-based (a plant-based biopolymer sourced from corn) chip bags being excessively noisy due to the material's brittleness, resulting in their ultimate repeal⁶⁴. This example demonstrates the importance of taking into account packaging properties and their alignment with consumer expectations. The failure to utilize these compostable chip bags in extensive applications highlights potential barriers to the success of biopolymer alternatives chitosan, cellulose, and PHA as they all exhibit brittleness⁶. Past attempts and their failures can provide lessons learned that future applications can build upon.

Not only do consumer preferences affect the choice of alternatives, but, conversely, the presence of bio-based packaging can have positive effects on purchasing choices by evoking a sense of environmental responsibility and general product satisfaction within consumers. The prospect of helping reduce plastic waste and unique opportunities to reduce agricultural and seafood waste offered by cellulose and chitosan-based packaging present appealing choice incentives to the consumer^{63,65}. Donato et.al (2021) goes further to show that food wrapped in sustainable packaging is even often perceived as being of higher quality by consumers⁶⁵.

Quantitative studies that identify the factors that are most important to consumers in terms of packaging and its usability and practicality could be useful inputs in predicting whether biobased plastic packaging alternatives could succeed or fail in the market. Factors including appearance, practicality of usage (functionality, robustness, noise), cost, and perceived sustainability could be integrated in a comprehensive analysis. Information regarding consumer perspectives can be acquired through various methods, including surveys. Future research could further investigate consumer perspectives and the imple-

mentation, development,- and use of bioplastic packaging are related. Mixed-method approaches that combine the qualitative information of consumer feedback, quantitative data from demographic of consumers, and data on the viability and attractiveness of alternative packaging could be utilized to better develop alternatives that will be embraced by the market⁶⁶.

Conclusion

Using a comparative analysis and life-cycle assessment approach, this paper assessed the sustainable and application potential of three plastic snack packaging alternatives chitosan, cellulose, and polyhydroxyalkanoates based on sourcing, packaging functionality, economic costs, degradability, and disposal costs. This assessment found that while each alternative has some properties that are desirable in snack packaging, none of them fully embody all properties that would make for an obvious replacement for polypropylene (PP) and low-density polyethene (LDPE). Thus, a combination of these biopolymers through a multilayering method is likely the most viable approach to a transition to plastic alternatives. At the practical level, this research is relevant to businesses, manufacturers, and consumers alike. The results of this analysis yield valuable information corporations could use to better understand what is needed to make the switch away from plastic packaging and how to incorporate sustainability into their operations. This study also provides information to manufacturers on possible alternatives and the factors that should be considered when producing these alternatives. The case studies of alternative packaging materials found in this paper provide insight into processes involved in the creation of food packaging that could help consumers make more informed purchasing choices based on product packaging type. Furthermore, this research also increases visibility on the state of alternatives and the sustainable possibilities that consumers can advocate for. The negative effects of the exponential rise in plastic use have already been widely felt. The historic 2022 UN agreement between 175 nations to develop a legally binding agreement on plastic pollution by 2024 demonstrates the international recognition of the issue's severity, and it is in the best interest of these nations to seek out and effectuate comprehensive initiatives to halt the plastic crisis. Urgent actions from all sectors are needed to stop the continued inundation of plastic in the environment, our water systems, and all aspects of life. A shift towards the use of bio-based packaging alternatives would not only end plastic use within the snack industry, but also help push forward a greater transition away from plastic that would align with global sustainability goals. Plastic use is widespread in our daily lives; however, there are many contributors that are often overlooked in considerations of plastic waste such as snack packaging. Highlighting plastic alternatives in more specialized fields helps to raise awareness about these various contributors to plastic waste and can lead to additional

action to minimize plastic use in all aspects of life.

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