A Brief Review of Biomaterials Used To Create Sustainable Plastic Films For Food Packaging Applications

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I. Introduction

a. Background on Plastic Films

Flexible plastic food packaging has played a crucial role in the development and stability of the global food system and continues to be one of the most widely used packaging materials for food items because of its utility, availability, and low cost (American Chemistry Council, 2024; "Global Fresh Food Packaging Market Segment Forecasts, 2021-2028," 2021; Marsh & Bugusu, 2007; Morris, 2024; New York State Department of Environmental Conservation, 2023). A plethora of evidence illustrates that conventional flexible plastic food packaging derived from fossil fuels lacks circularity and is problematic in the environment as a material (Bittrich Vargas et al., 2023; Di et al., 2021; Marsh & Bugusu, 2007; Trasande et al., 2024; US EPA, 2017). In addition to wreaking havoc on the environment, synthetic plastic polymers when used in food packaging can leach toxic chemicals into the foods they enclose leading to serious negative health outcomes for consumers (Alamri et al., 2021; Kataria et al., 2015; Marsh & Bugusu, 2007; Muncke et al., 2020). Synthetic plastic polymers have desirable packaging qualities, but other materials with healthier environmental and human health outcomes, like glass, metals, or bioplastics, are available and viable alternatives (Alamri et al., 2021; Bittrich Vargas et al., 2023; Ferreiro & Monteiro, 2023).

b. Purpose of this Review

This review aims to identify strengths and weaknesses of the most promising alternatives to synthetic, fossil fuel derived flexible plastic film packaging in the context of food packaging. By looking at several biomaterials from both a food safety and life cycle perspective, this examination sought to identify the most sustainable materials that still serve the crucial purpose of protecting, preserving, and extending the life of food contained within the material. Discussion and examination surrounding economic feasibility, viability, and scalability was included to better understand how relevant business communities may make informed packaging material investment decisions. This examination aims to empower food manufacturers to select a flexible food packaging film that is both economical, functional, healthy, and sustainable.

II. Evaluation Criteria for Use in Food Packaging

While there are ample tests available and qualities desired for a substance to be deemed viable as a safe, high-quality, and sustainable food packaging material, there is no widely agreed upon rubric for evaluating materials holistically and including factors like environmental impact and economic viability. Different studies tend to focus on different traits at differing levels of detail. Many researchers have highlighted the topics included in this review in their research, but there is not widespread consensus as to which factors hold the greatest importance and how each trait should be assessed (Anugrahwidya et al., 2021; Cruz et al., 2022; Dolci et al., 2024; Gamage et al., 2024; Hong et al., 2021; Jabeen et al., 2015; Mayuri et al., 2023a). This is likely because of different incentives and priorities across stakeholders. Still, several broad categories emerge as a general rubric and this review will perform its evaluation using the four traits detailed below.

a. Performance

A food packaging material can be evaluated using mechanical and chemical properties, for example permeability, breakability, and temperature sensitivity, to determine how useful the material is as a packaging and what types of food it is suited for (Bamps et al., 2022; Hong et al., 2021; Marsh & Bugusu, 2007). This review will broadly categorize the physical, mechanical, and barrier traits of films as indicators of performance. While this is an oversimplification of these traits, it is a necessary simplification of this role to enable cross examination among other, less often observed factors. In this review, performance also includes a food packaging material's marketability, consumer acceptance, and other less scientific, but notable qualities that make a material attractive to food manufacturers (Alamri et al., 2021; Marsh & Bugusu, 2007). Performance is a crucial starting point, as without proper performance a material has little or no value to a food manufacturer.

b. Safety

This review looks at safety from two perspectives, potential contamination with toxic chemicals and resistance to microbial growth, to determine which bioplastic materials show promising abilities to meet stringent food safety requirements.

Safety is a relative term. Food packaging is heavily regulated throughout the world to ensure an item's packaging does not jeopardize human health, but differing regulatory bodies have different standards (Thapliyal et al., 2024; Vaughn, 2016). Many plastic films derived from fossil fuels have a negative effect on human health by leaching toxic chemicals into the foods they interact with, but because the science in this area is fairly recent few regulatory bodies recognize this risk (Jadhav et al., 2021; Kadac-Czapska et al., 2023; Muncke et al., 2020). There are more than 11,000 chemicals found in different quantities and at different stages of production across plastic food packaging items (Groh et al., 2020).

Both bioplastic and traditional fossil fuel-based plastic materials can be modified to possess antimicrobial qualities which are essential to maintaining food freshness and preventing ingestion of harmful bacteria, but the amount of protection can vary significantly based on process and materials used (Alkarri et al., 2024; Bajer, 2024; Ferreiro & Monteiro, 2023; Saied et al., 2024). New materials must be heavily scrutinized to ensure they do not put human health at risk or contaminate the foods they package (Gamage et al., 2024; Thapliyal et al., 2024; V. M. & Edison, 2023).

c. Environmental Impact

While many forms of food packaging, like cardboard and glass, are commonly recycled, plastic stands out for its inability to be effectively recycled at cost and scale (Di et al., 2021). Many recognize plastic as a waste disposal challenge and as having a largely linear life-cycle (Di et al., 2021; Dolci et al., 2024; US EPA, 2017), yet plastic consumption, and the subsequent waste and environmental pollution it generates, has boomed in recent decades (Eriksen et al., 2023). Bioplastic packaging appears as a promising, more-circular counter to fossil fuel-derived plastic packaging, but its creation still involves a number of natural resources, and its biodegradation is not guaranteed. Life Cycle Assessment (LCA) standards can be used to determine the environmental impact of bioplastics and compare different alternatives to fossil fuel-derived plastics and to one another. These standards, developed by the International Organization for Standardization, are widely used and enable a thorough analysis of the environmental impact of food packaging materials through collection of raw materials, production, use, and disposal (International Organization for Standardization, 2006). However, comprehensive life cycle assessments for many new biomaterials are limited, and at times existing life cycle assessments prove irrelevant as they do not reflect the scale of production necessary for widespread adoption. This review will attempt to focus on the extraction process, manufacturing, and biodegradability of materials to assess their environmental impact.

d. Economic Feasibility

Plastic is an economic powerhouse. An estimated 22% of all plastic sales in 2023 can be attributed to packaging, and about two-thirds of packaging waste across all materials is attributable to food packaging given the scale and frequency of food purchases (American Chemistry Council, 2024; Marsh & Bugusu, 2007). Food manufacturers began using plastic packaging, as opposed to glass or metals, because it was cheaper, lighter, and more versatile (Marsh & Bugusu, 2007), thus an economic lens is crucial when discussing alternatives to fossil fuel-derived plastic packaging. To assess economic feasibility, this review will focus on cost to manufacture and cost and cost and availability of manufacturing inputs.

III. Review of Bioplastic Materials

a. Chitin and Chitosan

Chitin is found in fungi, insect shells, fish scales, and arthropod exoskeletons, and is a widely available, often wasted resource (Davis et al., 2024; Iñiguez-Moreno et al., 2024; Mwita et al., 2024; Rameshthangam et al., 2018). To extract chitin from raw materials, two primary methods, biological and chemical, have emerged and, especially for commercial applications, chemical extraction is most widely used for its low cost and high yield (Kozma et al., 2022). While there are more eco-friendly extraction options, like vegetable oils as solvents or fermentation processes, they are expensive, less researched, have smaller yields, and are not widely used commercially (Burke & Kerton, 2023; Kozma et al., 2022). The deacetylation of chitin results in chitosan, a commonly used polymer in the food and drug industries, and the creation of most chitin-based bioplastic films requires this conversion step (Davis et al., 2024; Iñiguez-Moreno et al., 2024; Narudin et al., 2022; Pavlova & Tnisova, 2021).

Pure chitosan films are brittle and have limited performance, thus chitosan must be combined with other polysaccharides, plasticizers, and/or proteins in order to be presented as a viable alternative to fossil fuel-derived plastic films (Fiallos-Núñez et al., 2024; Milbreta et al., 2024; Shi et al., 2024). Chitosan shows extremely promising antimicrobial qualities and this trait makes it attractive for synthesizing with other materials as well (Avila et al., 2022; Jiang et al., 2023).

b. Pectin

Pectin is primarily extracted from fruits, both the traditionally wasted and edible portions, and is often combined with other plasticizers, like glycerol, to produce flexible films suitable for food packaging uses (Dirpan et al., 2024; Liu et al., 2007; Spinei et al., 2024). Pectin extraction is traditionally performed using solvents, primarily acids, and heat to isolate pectin found in fruits and other plant matter (Abdel Hamid et al., 2022; Riyamol et al., 2023). Most traditional extraction processes use synthetic chemicals, like chloroform, that are toxic to both humans and the environment (Jacquel et al., 2008). Recent developments of new, more sustainable methods of pectin extraction require more research to determine cost-effectiveness and viability, but some of these methods involve less or no toxic chemicals and offer promising advancements in sustainability (Riyamol et al., 2023).

One of the most studied and promising uses of pectin is as an alternative to synthetic waxes that have been traditionally used for packaging and preserving fruits and vegetables (Dirpan et al., 2024; Yadav et al., 2023). Pectin can be made edible and non-toxic in its final film form allowing for both easy disposal and application directly to consumable items, like the exterior of an apple or peach (Dirpan et al., 2024; Dobrucka et al., 2024; Song et al., 2024).

c. Polyhydroxyalkanoates (PHAs)

Polyhydroxyalkanoates, or PHAs, compose a wide variety of microbe-based polymers that are produced primarily through fermentation (Bhatia et al., 2024; Manikandan & Lens, 2023). PHAs are built up in cells and then extracted using a variety of methods with the most common and commercially accepted method employing chemical solvents to modify the cell membrane barrier and allow for extraction and isolation of PHAs (Abate et al., 2024; Jacquel et al., 2008). PHAs' applications to food packaging are widespread and well-studied and PHA-derived plastics are generally more rigid and durable than other bioplastics (Buntinx et al., 2024; Genovesi et al., 2023; Patiño Vidal et al., 2024). PHAs are often used as a plasticizer and blended with other natural materials, like starches, chitosan, or pectin, to improve durability while maintaining biodegradability (Cheng et al., 2024). PHA-derived plastics are also often reinforced with another, more antimicrobial material, such as zinc or chitin, to improve performance as a food packaging material and prevent microbe growth (Cheng et al., 2024; Patiño Vidal et al., 2024).

d. Starches

Starches can be derived from a variety of sources including but not limited to corn and other fruits and vegetables, plant roots, plant leaves, and nuts (Arias et al., 2024; Fatima et al., 2024). Starches on their own have limitations as a food packaging material, primarily poor performance and a lack of antimicrobial qualities, and as such starch is most commonly combined with other substances, like chitosan or cellulose, to improve its characteristics and performance as a viable alternative to fossil fuel-based plastic (Fatima et al., 2024; Muñoz-Gimena et al., 2023). Starch extraction is primarily a physical process of blending, centrifugation, heating, and drying, and rarely does starch extraction require the use of toxic chemicals (Onyeaka et al., 2022). Starch is notable for its widespread availability and low cost to process and extract (Fatima et al., 2024; Onyeaka et al., 2022).

IV. Discussion of Biopolymers

a. Performance

Independently none of the four polysaccharides discussed in this review would provide for a viable food packaging alternative to fossil fuel-derived plastic based on performance. However, bioplastic performance, like many food packaging materials, is greatly enhanced when multiple substances are synthesized to obtain desirable traits from each. The four substances referenced above are commonly combined with both one another and alternative substances, both natural and synthetic, to produce desirable performance outcomes, especially enhanced durability and barrier protection (Cheng et al., 2024; EVCIL, 2024; Mayuri et al., 2023b; Wan Yusof et al., 2024; Wardejn et al., 2024). Performance is not a primary limiting factor to widespread bioplastic production because while all these materials have limitations on their own, their combinations with one another and other natural additives have led to a number of viable, high-performing options to replace traditional fossil-fuel derived films (Cakıroglu et al., 2020; Cui et al., 2023; Dobrucka et al., 2024; Malm et al., 2021; Marano et al., 2022; Milbreta et al., 2024; Ren et al., 2023; Revutskaya et al., 2024).

b. Safety

Chitosan can act as a powerful antimicrobial coating when applied to various other materials (Avila et al., 2022; Iñiguez-Moreno et al., 2024; Roman et al., 2024; School of Chemical Sciences, Universiti Sains Malaysia, 11800 USM, Pulau Pinang, Malaysia et al., 2024; Wardejn et al., 2024). While pectin, starches, and PHAs are not on their own antimicrobial, they can be combined with chitosan, essential oils, and a variety of other substances to produce food packaging products that resist microbial growth (Kalia et al., 2021; Moeini et al., 2022; Socha et al., 2024; Wardejn et al., 2024).

While bioplastics are generally found to be safer than their fossil fuel-derived plastic counterparts, some studies have identified harmful chemical leaching can occur in bioplastics similar to leaching that occurs in fossil fuel-derived plastics (Riboni et al., 2023; V. M. & Edison, 2023). More research is needed to evaluate the safety of bioplastic films, as their production processes often include toxic chemicals (Gamage et al., 2024; Riboni et al., 2023).

c. Environmental Impact

All four of the substances reviewed in this paper are abundantly available, however only pectin, starch, and chitin are readily available in nature. Creation of PHAs requires fermentation which results in variable carbon dioxide emissions depending on the size of production (Zhong et al., 2009). Chitosan is primarily extracted from sea creatures (though there is interest in increasing fungi production capacity), and as such chitosan is a product of the fishing industry, which is notorious for polluting the earth's oceans and damaging marine ecosystems (Jones et al., 2020; Turner et al., 1999). Both pectin and starch are agricultural products from various sources thus they carry their own land, water, and nutrient use considerations which are difficult to quantify given the variety of sources (Abdel Hamid et al., 2022; Adewumi et al., 2024; Riyamol et al., 2023).

The most widely used manufacturing processes for chitin, pectin, and PHAs are primarily chemical processes and generate wastewater containing toxic chemicals that must be managed and disposed of properly to avoid environmental harm (Abate et al., 2024; Abdel Hamid et al., 2022; Riyamol et al., 2023; Verardi et al., 2023). Starch extraction generally does not require toxic chemicals (Wan Yusof et al., 2024). All four materials studied in this review require energy, mainly for heating, in their production processes, but at varying levels (Abate et al., 2024; Abdel Hamid et al., 2022; Fatima et al., 2024; Riyamol et al., 2023; Verardi et al., 2023).

All four materials, pectin, chitosan, starch, and PHAs, are generally regarded as biodegradable in soil (Anugrahwidya et al., 2021; Meereboer et al., 2020; Onyeaka et al., 2022; Spinei et al., 2024; Swiontek Brzezinska et al., 2024). There are some cases, however, where these materials are blended with materials that do not biodegrade.

While this review has not discussed the environmental impacts of other, more traditional food packaging material production processes and lifecycles, such as those of fossil fuel-derived plastics, it is important to note there are many negative impacts, both localized and global, to traditional food packaging production and these impacts are well documented (Dolci et al., 2024). Bioplastic production is an important evolution of fulfilling society's packaging needs, and understanding environmental impacts in bioplastic production is crucial to ensuring it is a positive development towards a sustainable future.

d. Economic Feasibility

The price of fossil fuel-derived plastic packaging is dynamic, and tends to track quite closely to the global price of oil (Issifu et al., 2021). This carries many implications for bioplastic interest and demand, and it also makes price comparisons of bioplastic materials and their fossil fuel-derived counterparts quite variable. In general, however, the production of bioplastics is associated with significantly higher economic costs than traditional plastic manufacturing (Dirpan et al., 2024; Fatima et al., 2024; Leong et al., 2017; Riofrio et al., 2021). The reasoning behind these higher costs varies depending on the specific bioplastic. For example, PHA production in its current state primarily utilizes large quantities of sterilized substrates to feed bacteria which can be costly to procure and process (G.-Q. Chen, 2010; Choi & Lee, 1999). Starch and pectin are two of the cheapest inputs, but to produce a viable bioplastic they are often blended with other polymers which adds additional costs (Gadhave et al., 2018). Chitosan can be extracted from seafood waste, which in some cases companies are paid to dispose of, but processing this waste into useable chitosan is costly (Riofrio et al., 2021). The economics of bioplastics continue to evolve, and each new efficiency or discovery has the potential to lower production costs and make fossil fuel-derived plastics less appealing for food packaging manufacturers.

V. Findings

The most advanced and promising replacements for synthetic, fossil fuel-derived plastic food packaging appear to be blended bioplastics that encompass a variety of substances both present in and excluded from this review. Blends of materials to create bioplastics show adequate performance, microbial resistance, and are friendlier to the environment than fossil fuel-derived plastic packaging. Because blending substances is both common and attractive, it is necessary to study both the inputs and outputs of these processes. While bioplastics offer promising advancements in biodegradability, their production processes pose land-use questions, generate toxic chemicals, and can require large amounts of energy. It is vital that as the bioplastic industry grows so too does its regard, concern, and friendliness for the environment.

The economics of bioplastics are quite intriguing and deserve further scrutiny. Studies that can produce a holistic cost analysis noting the true cost of plastics, for example damage to fisheries or human health, would be particularly insightful. Further, as bioplastic production protocols become further defined, advanced, and scaled, the savings associated with traditional plastic use will narrow. While bioplastic products are not economically cheap for food manufacturers to use, they are extremely profitable for producers to produce and demand for all four materials included in this review is forecasted to grow (Dirpan et al., 2024; Fatima et al., 2024; Leong et al., 2017; Riofrio et al., 2021). This incentivizes companies to continue investing and innovating.

VI. Future Research

A clear, standardized rubric for evaluating food packaging materials holistically would improve future reviews on this topic, but the creation of such would be difficult, as different stakeholders have different priorities when selecting and evaluating a material. Further, more studies are needed to evaluate the potential effects of leaching in the context of bioplastic food packaging, as this has been identified as a concern with traditional plastics and could also be happening among bioplastic food packaging.

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