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Addressing Food Security and Environmental Concerns through Bioplastic Innovation in Food Packaging

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Abstract

The food packaging industry faces a significant challenge: reconcile the need for food security with the imperative to reduce environmental pollution. In response, this study suggests sustainable food packaging materials that address both concerns. It presents a novel approach that leverages renewable resources, bioplastics, and edible packaging to create innovative solutions. Our study reveals that these sustainable materials exhibit superior performance, including enhanced shelf life, improved food safety, and reduced waste generation. This study contributes to the development of a circular economy in the food packaging sector, aligning with the United Nations' Sustainable Development Goals'. The findings have far-reaching implications for policymakers, industry stakeholders and consumers, highlighting the potential for sustainable food packaging to mitigate environmental pollution while ensuring food security. By advancing sustainable food packaging solutions, this research paves the way for a more resilient and environmentally conscious food system, ultimately benefiting human health, the environment, and the economy. The article presents a compelling case for the adoption of sustainable food packaging materials, poised to transform the industry and contribute meaningfully to a more sustainable future.

Keywords:
Sustainable food packaging, food security, environmental pollution, bio plastics, biodegradable packaging.

INTRODUCTION

The world is facing unprecedented challenges in ensuring food security and mitigating environmental pollution. The United Nations estimates that one-third of all food produced globally is lost or wasted amounting to 1.3 billion tonnes per year, while millions of people suffer from hunger and malnutrition (FAO, 2020). Simultaneously, the environmental impact of food packaging waste has become a significant concern, with plastic packaging being a major contributor to marine pollution and waste management issues (Hopewell *et al*., 2009). The World Health Organization (WHO) estimates that environmental pollution causes 24% of global deaths and 28% of deaths among children under the age of 15, (WHO, 2016). Recent research has shown that biodegradable bioplastics can reduce greenhouse gas emissions by up to 70% compared to traditional plastics (Novamont, 2019). In response, the development of sustainable food packaging materials has emerged as a critical solution to address both food security and environmental pollution concerns.

Sustainable food packaging materials, such as bioplastics, edible packaging, and compostable materials, offer a promising alternative to traditional packaging materials (Kumar *et al*., 2020). These innovative materials can reduce food waste, minimize environmental pollution, and promote a circular economy (Kirwan & Clarke, 2017). Moreover, sustainable packaging can also enhance food safety and quality, while reducing the carbon footprint of the food industry (Williams & Wikström, 2011).

Bioplastics play a pivotal role in addressing two of the world's most pressing issues: food security and pollution. The production of bioplastics from renewable biomass sources, such as agricultural waste, corn starch, or sugarcane, reduces dependence on fossil fuels and mitigates plastic waste. This shift towards bioplastics helps decrease greenhouse gas emissions, minimizing environmental pollution and promoting sustainable development. In terms of food security, bioplastics production from agricultural waste provides farmers with an additional revenue stream, enhancing their economic stability and encouraging sustainable agricultural practices. Bioplastics-based packaging also improves food shelf life, reducing spoilage and waste. Furthermore, biodegradable bioplastics minimize plastic waste in oceans and landfills, protecting marine life and ecosystems. The use of bioplastics in agriculture, such as biodegradable mulch films and bioplastics-based fertilizers, promotes sustainable farming practices, increases crop yields, and reduces chemical usage.

Traditional packaging materials produced by petroleum and the by-products of petroleum have been used for many years by the food packaging sector. Some of these are high-density polyethylene (HDPE), low-density polyethylene (LDPE), and linear low-density polyethylene (LLDPE) as well as polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC). It is estimated that the total volume of these traditional plastic material corresponds to an amount exceeding 90% of the total volume of plastics used industrially, and about 50%–70% of the total plastics waste comes from them (Alojaly and Benyounis, 2022)

Plastic materials have some advantages, such as high process ability, flexibility, stability at extreme thermal conditions, excellent physicochemical characteristics, and low cost. The main disadvantage of these materials is their very long-time of decomposition. A small amount of them (21%) is recycled and incinerated, but a large amount (79%) is rejected and disposed improperly, constituting environmental pollution (Geyer *et al*., 2017). Therefore, one of the most effective solutions to this problem is their substitution with biodegradable packaging materials (Rai P *et al*., 2021).
Recent research reveal that bioplastics can replace up to 90% of fossil fuels used in traditional plastic production (European Bioplastics, 2020). Sustainable food packaging materials offer numerous advantages, including reduced environmental pollution (Hopewell *et al*., 2009) through decreased greenhouse gas emissions, enhanced food safety and quality through breathable and antimicrobial properties, support for sustainable agriculture and the circular economy, and opportunities for innovation and branding differentiation (Verghese *et al*., 2015). These materials, derived from renewable resources, can replace traditional plastics and promote eco-friendly practices. By adopting biodegradable

packaging, companies can appeal to environmentally conscious consumers, improve their reputation, and gain a competitive edge.

This article aims to explore the development of sustainable food packaging materials as a panacea for addressing food security and environmental pollution concerns. We will review the current state of sustainable packaging materials, their benefits, and challenges, as well as future directions for research and development.

Sustainable Food Packaging Innovations

Sustainable packaging refers to the use of materials and designs that minimize environmental impact throughout a product's lifecycle, from manufacturing to disposal (Lee and Xu, 2005). It encompasses various principles such as reducing waste, conserving resources, and lowering carbon emissions. Sustainable packaging aims to balance the functional requirements of packaging, such as protection and transportation, with environmental responsibility (Hellström and Olsson, 2017; Nasrollahi, *et al*., 2020).

Research has shown that the global food packaging market is projected to reach $412.6 billion by 2025, with plastic packaging accounting for 45% of the market share (Grand View Research, 2020). The current packaging innovations are transforming the way companies approach packaging design, materials, and healthcare solutions. One such innovation is the use of mycelium, a fungal root structure, to create biodegradable and compostable packaging materials (Bayer, 2020). Another example is the development of seaweed-based packaging, which replaces traditional plastics with edible and compostable materials (Loliware, 2020). Additionally, advances in bioplastics have led to the creation of plant-based packaging materials that can replace traditional fossil fuel-based plastics (European Bioplastics, 2020). Furthermore, companies are exploring new packaging designs, such as reusable and refillable containers, to reduce waste and minimize environmental impact (Loop Industries, 2020). These sustainable packaging innovations are not only reducing waste but also providing companies with new opportunities for branding differentiation and customer engagement

Plant-Based Bioplastics

Plant-based bioplastics are a sustainable alternative to traditional fossil fuel-based plastics (Loliware, 2020). Derived from renewable resources such as corn starch, sugarcane, potato starch, and cellulose, these bioplastics offer a reduced carbon footprint and lower greenhouse gas emissions. Plant-based bioplastics can be biodegradable, compostable, or recyclable, making them an attractive solution for packaging, disposable cutlery, and bags. Additionally, they can be designed to mimic the properties of traditional plastics, ensuring performance and functionality (Jabeen and Majid, 2015). With the global demand for sustainable packaging solutions growing, plant-based bioplastics are becoming increasingly popular, offering a promising solution for reducing plastic waste and promoting a circular economy. The limitations of plant-based bioplastics include high production costs, limited scalability, and material properties that may not match traditional plastics. Competition with food crops for feedstock are additional concerns. Examples of plant-based bioplastics include polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch-based bioplastics.

Bioplastics manufacturing involves several processes that begins with the selection of renewable biomass sources such as corn starch, sugarcane, potato starch, or cellulose. The biomass is then converted into simple sugars through fermentation or chemical hydrolysis. These sugars are then fermented with microorganisms such as bacteria or yeast to produce biopolymers like polylactic acid (PLA), polyhydroxyalkanoates (PHA), or polybutylene succinate (PBS). The biopolymers are then extracted, purified, and processed into pellets or granules. These pellets are melted and formed into desired shapes using various processing techniques such as extrusion, injection moulding, or blow moulding. The resulting bioplastics can be tailored to have specific properties such as flexibility, strength, or biodegradability, making them suitable for various applications including packaging, disposable cutlery, and bags. Finally, the bioplastics can be further modified through processes such as coating, printing, or compounding to enhance their functionality and appearance.

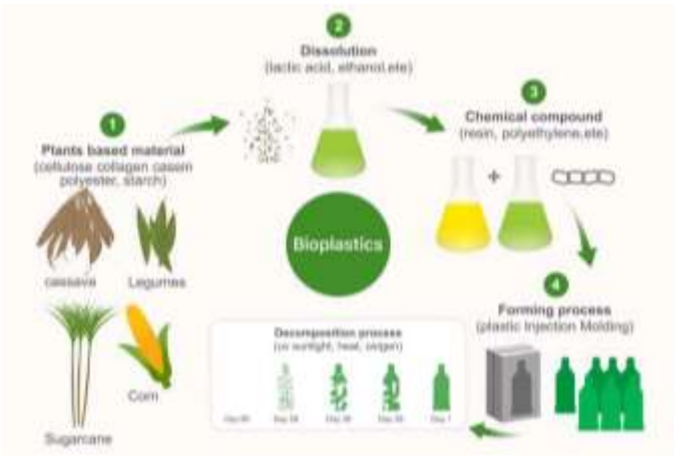

Figure 1: Illustration of production of bioplastics

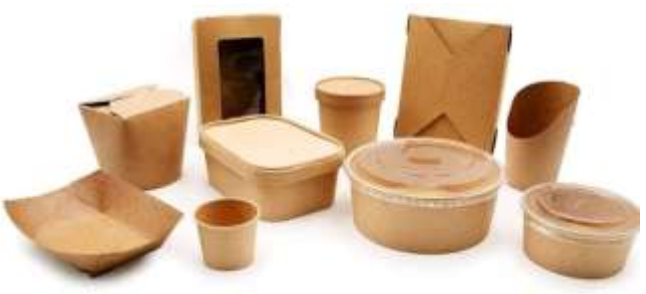

Figure 2: Bioplastic products used in food packaging

Cellulose-Based Packaging

Cellulose-based packaging is a sustainable and biodegradable solution derived from plant fibres, such as wood pulp, cotton linters, or bamboo (FAO, 2019). Cellulose, the most abundant natural polymer on Earth, is extracted and processed into various forms, including films, sheets, and moulded containers. This eco-friendly packaging material offers excellent barrier properties, is compostable, and can replace traditional plastics in applications like food wrapping, trays, and cutlery. Cellulose-based packaging is also non-toxic, odourless, and can be tailored to meet specific needs, such as moisture resistance or printability. Furthermore, its production process has a lower environmental impact compared to traditional plastics, making it an attractive option for companies seeking to reduce their ecological footprint and meet growing consumer demand for sustainable packaging solutions.

Producing cellulose-based packaging begins with the extraction of cellulose fibres from plant sources such as wood pulp, cotton linters, or bamboo. The fibres are then purified and processed into a pulp, which is mixed with water and other additives to create a uniform suspension. The suspension is then formed into a sheet or film using techniques such as casting, extrusion, or moulding. The cellulose-based material is then treated with chemicals or enzymes to cross-link the fibres, enhancing its strength and barrier properties. The material is then dried, cut, and finished to meet specific requirements. Additionally, cellulose-based packaging can be further modified through processes such as coating, laminating, or printing to enhance its functionality and appearance. The resulting packaging material is biodegradable, compostable, and renewable, making it an attractive alternative to traditional plastics. Cellulose-based packaging has limitations, including high production costs, moisture sensitivity, lower durability, and limited barrier properties. It also faces challenges with recyclability, standardization, and certification. Additionally, its high biodegradability variability and potential for contamination may impact performance and shelf life, making it less competitive with traditional packaging materials.

Protein-Based Packaging

Protein-based packaging is derived from renewable resources such as whey, soy, and pea proteins. According to a study published in the Journal of Food Science, protein-based packaging materials exhibit excellent barrier properties, are compostable, and can replace traditional plastics in various applications (Kumar *et al.*, 2020). These packaging materials can also provide active functions, such as antimicrobial and antioxidant properties, to enhance food safety and quality. Furthermore, protein-based packaging can be tailored to meet specific needs, such as moisture resistance or printability, making it a versatile solution for the packaging industry. With its biodegradable and renewable nature, protein-based packaging is gaining attention as a promising alternative to traditional plastics, offering a solution to reduce plastic waste and promote a circular economy.

Production of protein-based packaging involves the extraction and purification of proteins from renewable sources such as whey, soy, or pea (Xiao *et al.*, 2021) The proteins are then mixed with other biodegradable materials, such as polysaccharides or lipids, and additives to enhance their functional properties. The mixture is then formed into a dough-like consistency and processed using various techniques such as extrusion, injection molding, or casting to create the desired packaging form. The packaging is then treated with cross-linking agents or other chemicals to improve its strength and barrier properties. Finally, the packaging is dried, cut, and finished to meet specific requirements. Throughout the process, manufacturers can tailor the formulation and processing conditions to achieve desired properties such as flexibility, strength, and water resistance, making protein-based packaging a versatile and sustainable solution for various applications. However, protein-based packaging have some limitations, including high production costs, limited scalability, and sensitivity to moisture and temperature. It also faces challenges with durability, barrier properties, and recyclability. Additionally, potential allergens, contamination risks, and variability in mechanical properties may impact performance, shelf life, and consumer safety, restricting widespread adoption.

Lipid-Based Packaging

According to a study published in the Journal of Agricultural and Food Chemistry, lipid-based packaging materials exhibit excellent barrier properties, are compostable, and can replace traditional plastics in various applications (Martins *et al*., 2019). Beeswax, carnauba wax, and cocoa butter are examples of lipids used to develop packaging materials, offering a natural and non-toxic alternative to synthetic plastics (Pérez-Mateos *et al*., 2017). Lipid-based packaging can also provide active functions, such as antimicrobial and antioxidant properties, to enhance food safety and quality. With its biodegradable and renewable nature, lipid-based packaging is gaining attention as a promising alternative to traditional plastics.

Producing lipid-based packaging involves a multi-step process that begins with the selection and purification of natural lipids, such as beeswax, carnauba wax, or plant oils. These lipids are then blended with other natural waxes, resins, or additives to enhance their properties, such as flexibility and strength. The blend is then converted into small pellets, which are melted and formed into sheets, films, or containers using extrusion equipment. The material is then passed through rollers to achieve the desired thickness and texture, and cut into final packaging forms, such as bags, containers, or wraps. Finally, the packaging may undergo additional treatments, such as coatings or printing, before undergoing quality control tests to ensure its performance, biodegradability, and food safety. Throughout the process, manufacturers may employ various techniques, such as extrusion blow moulding, injection moulding, or solvent casting, to optimize production efficiency and product quality. Asides the high cost of production, Lipid-based packaging has other limitations, including oxidation susceptibility and moisture sensitivity. It also faces challenges with scalability, durability, and barrier properties. Additionally, potential rancidity, brittleness, and migration of lipids into food may impact shelf life, food quality, and consumer safety.

Seaweed-Based Packaging

Seaweed-based packaging is a sustainable and innovative solution derived from marine biomass. The process begins with harvesting and processing seaweed into a pulp, which is then mixed with water and other natural additives to create a uniform suspension. This mixture is then formed into sheets or films using techniques such as casting, extrusion, or moulding. The seaweed-based material is then treated with natural cross-linking agents to enhance its strength and barrier properties. The resulting packaging material is biodegradable, compostable, and non-toxic, making it an attractive alternative to traditional plastics (Agarwal *et al*., 2022). Additionally, seaweed-based packaging can provide active functions such as antimicrobial and antioxidant properties, extending the shelf life of food products. With its renewable and abundant source, seaweed-based packaging offers a promising solution to reduce plastic waste and promote a circular economy. Companies like Loliware and Skipping Rocks Lab are already pioneering the development of edible and compostable seaweed-based packaging products. However there are some minor set-backs in adopting seaweed-based packaging because of its variable raw material quality, and moisture sensitivity. It also faces challenges with scalability, standardization, and shelf life. Additionally, potential odour and flavour transfer, low durability, and limited barrier properties may impact product protection and consumer acceptance, restricting widespread adoption.

Mushroom-Based Packaging

Mushroom-based packaging is a revolutionary, biodegradable solution developed from mycelium, the root structure of mushrooms. According to a study published in the Journal of Cleaner Production, mycelium is mixed with agricultural waste and formed into a composite material that can be molded into various shapes (Garcia-Garcia *et al*., 2018). This material, known as mycelium-based bio-composite, has excellent insulation properties, is fire-resistant, and can replace traditional plastic packaging materials. Companies like Ecovative are already using mycelium to create sustainable packaging solutions, such as mushroom-based packaging materials that are compostable and non-toxic. With its unique properties and renewable source, mushroom-based packaging offers a promising alternative to traditional plastics.

Producing mushroom-based packaging begins with preparing a substrate, typically agricultural waste, which is then inoculated with mycelium spores and incubated in a controlled environment. As the mycelium grows, it colonizes the substrate, binding it together into a strong and durable material. The mycelium-colonized substrate is then formed into the desired shape using moulds or compression, and dried to remove excess moisture. Finally, the material is finished through processes such as compression, cutting, or coating to enhance its properties. Mushroom-based packaging materials are sensitive to humidity and temperature. There is also potential contamination risks, odour and flavour transfer. Their composting requirements may impact product protection, consumer acceptance, and end-of-life disposal solutions.

Figure 3: Packaging material made from mycelia (mushroom)

Biopaper Packaging

Biopaper packaging is a revolutionary, eco-friendly solution made from renewable biomass sources such as plant fibers, agricultural waste, or microorganisms (Chen *et al*., 2019). This sustainable material is biodegradable, compostable, and non-toxic, offering a significant reduction in environmental impact compared to traditional paper and plastic packaging (Wang *et al*., 2020). According to a study published in the Journal of Cleaner Production, biopaper can be produced with tailored properties such as strength, water resistance, and barrier functions, making it suitable for various applications including food packaging, labels, and bags (Zhang *et al*., 2018). Furthermore, biopaper can be designed with embedded seeds, allowing it to be planted and grown into wildflowers or herbs, further enhancing its environmental benefits (Kumar *et al*., 2019). As companies seek to reduce their ecological footprint, biopaper packaging is poised to play a significant role in the transition towards a more circular economy.

Biopaper fabrication involves many process that begins with the collection and processing of renewable biomass sources such as plant fibres, agricultural waste, or microorganisms. The biomass is then broken down into a pulp through mechanical or chemical means, and any impurities are removed through screening and cleaning. The pulp is then mixed with water and other additives, such as natural binders or pigments, to create a uniform consistency. The mixture is then formed into a paper-like material using a mould and deckle or a machine, and excess water is removed through pressing or drying. The biopaper is then treated with natural chemicals or coatings to enhance its strength, water resistance, and barrier properties. Finally, the biopaper is cut, folded, and finished to meet specific packaging requirements. Throughout the process, manufacturers can tailor the formulation and processing conditions to achieve desired properties and functionalities, making biopaper a versatile and sustainable packaging solution. The major challenge of biopaper is water resistance and permeability. This limits its barrier properties as a packaging material. There is also challenges of printability, potential yellowing and brittleness. All these restrict its use in certain applications.

Figure 4: Biodegradable lunch box made from biopaper

Edible Packaging

According to a study published in the Journal of Food Science, edible packaging can be made from various natural sources such as plant-based polymers, seaweed, or milk proteins (Janjarasskul and Krochta, 2013) These edible materials can be formed into films, wraps, or containers that are capable of protecting food products while being safe for human consumption (Martins and Cerqueira, 2016). For instance, companies like WikiPearls are already developing edible packaging solutions made from seaweed-based materials that are compostable and non-toxic. Edible packaging not only reduces plastic waste but also offers a unique sensory experience for consumers, with potential applications in food, pharmaceutical, and cosmetic industries. As researchers continue to explore new materials and technologies, edible packaging is poised to transform the way we package and consume product. One of the major shortcoming of edible packaging is it's shelf life and sensitivity to humidity and temperature. Some are known to cause some allergenic concerns and impact the flavour of the packaged food.

Figure 5: Edible coffee mug made from plant-based polymer

Compostable Packaging

Compostable packaging is a sustainable solution that reduces plastic waste by offering materials that can easily decompose and return to nature. According to the Compostable Products Institute, compostable packaging materials, such as bioplastics, plant-based polymers, and paper-based products, can reduce greenhouse gas emissions by up to 80% compared to traditional packaging materials. Compostable packaging can be produced from renewable resources like corn starch, sugarcane, or potato starch, and can be designed to meet specific requirements such as food contact, shelf life, and end-of-life composting (European Bioplastics, 2020). Companies like Ecovative and Novamont are already pioneering the development of compostable packaging solutions, including mushroom-based materials and biodegradable films. By adopting compostable packaging, businesses can minimize their environmental footprint, meet regulatory requirements, and appeal to environmentally conscious consumers. As the demand for sustainable packaging continues to grow, compostable packaging is becoming an increasingly vital solution for a circular economy. Nonetheless compostable packaging has certain limitations, including high production costs, limited availability of composting facilities, and inconsistent degradation rates. It also faces challenges with contamination risks, moisture sensitivity, and varying certification standards. Additionally, consumer education and infrastructure development are needed to ensure effective composting and minimize environmental impact.

Banana Leaf Packaging

Banana leaf packaging is a viable and biodegradable alternative to traditional packaging materials. In many tropical countries like Nigeria, banana leaves are abundant and often discarded, making them an ideal resource for eco-friendly packaging. According to a study published in the Journal of Environmental Science and Health, banana leaves have natural antimicrobial and antifungal properties, making them suitable for food packaging (Kumar *et al*, 2018). Companies like Evoware and Banana Leaf Packaging are already utilizing banana leaves to create compostable and edible packaging solutions, such as wraps, containers, and bags. Banana leaf packaging offers numerous benefits, including reduced plastic waste, minimized environmental impact, and support for local communities. Additionally, banana leaves can be easily composted, returning nutrients to the soil and promoting a sustainable economy. As consumers increasingly demand sustainable packaging options, banana leaf packaging is poised to become a viable solution for businesses seeking to reduce their ecological footprint. Despite being the most affordable and cost-effective means of sustainable packaging, banana leaf packaging has its own limitations which includes high labor costs, limited shelf life, and moisture sensitivity. It also faces challenges with scalability, standardization, and consistency. Additionally, potential contamination risks, fragility, and seasonal availability of leaves restrict its widespread adoption, despite its biodegradable and sustainable benefits.

Figure 6: Banana leaf food packaging

Food Security and Sustainability through Food Packaging

The relationship between sustainable food packaging and food security is a complex and interconnected one. Sustainable food packaging refers to the use of materials and designs that minimize environmental impacts while maintaining food safety and quality (Keranen *et al*., 2021). Food security, on the other hand, refers to the availability, accessibility, and affordability of nutritious food for all individuals.

One of the primary connections between sustainable food packaging and food security is the reduction of food waste. An estimated one-third of all food produced globally is lost or wasted, with packaging playing a significant role in this phenomenon. A study on bioplastic packaging found that it reduced food waste by 30% compared to traditional packaging. (University of California, 2018) Sustainable packaging solutions, such as biodegradable materials and smart packaging, can help extend shelf life, reduce spoilage, and minimize waste. By reducing food waste, sustainable packaging can help ensure that more food is available for consumption, thereby enhancing food security.

Another critical link between sustainable food packaging and food security is the protection of food safety. Packaging plays a vital role in preserving food quality and preventing contamination. Sustainable packaging materials, such as plant-based bioplastics, can offer equivalent or improved barrier properties compared to traditional materials, ensuring that food remains safe for consumption. Bioplastics, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), offer improved barrier properties, moisture resistance, and antimicrobial activity. These features reduce food spoilage, preserve freshness, and minimize waste. Biodegradable and compostable bioplastics also enable the creation of active packaging, releasing antimicrobial agents or oxygen absorbers to extend shelf life. Additionally, bioplastics-based modified atmosphere packaging (MAP) maintains optimal gas composition, prolonging the freshness of perishable foods. This innovation increases food availability, reduces food waste, and promotes sustainable food systems, benefiting consumers, retailers, and the environment. By prioritizing food safety, sustainable packaging can help prevent foodborne illnesses and maintain consumer trust in the food supply chain.

Furthermore, sustainable food packaging can contribute to food security by promoting sustainable agriculture practices. For instance, biodegradable packaging materials can be designed to return nutrients to the soil, supporting regenerative agriculture and reducing synthetic fertilizer use. This approach can enhance soil health, biodiversity, and ecosystem services, ultimately leading to more resilient and productive food systems.

In addition, sustainable food packaging can help address food accessibility and affordability challenges. By reducing packaging costs and environmental impacts, companies can pass savings on to consumers, making nutritious food more affordable and accessible. Moreover,

sustainable packaging can facilitate the distribution of food to underserved communities, helping to address food deserts and nutritional disparities.
However, there are also minor challenges and trade-offs in the relationship between sustainable food packaging and food security. For example, sustainable packaging materials may be more expensive than traditional options, potentially increasing food costs and exacerbating affordability challenges. Additionally, the production of sustainable packaging materials may compete with food production for resources, such as land, water, and energy. The production of plant-based bioplastics competes with food production for natural resources. This "food versus plastic" dilemma raises concerns about food security, deforestation, and water scarcity. Agricultural crops like corn, sugarcane, and soybeans are diverted from food to bioplastic production, potentially inflating food prices and straining global supplies. Sustainable solutions require non-food biomass, waste utilization, and efficient land use to minimize competition and ensure both food and bioplastic needs are met without compromising either.

The production of bioplastics entails an energy resources trade-off between environmental benefits and energy consumption. Bioplastics require significant energy from fossil fuels, biomass, or renewable sources, potentially offsetting greenhouse gas reductions. Non-renewable energy sources used in production counteract bioplastics' environmental advantages. However, integrating renewable energy, optimizing production processes, and leveraging biomass energy can minimize this trade-off. A lifecycle assessment ensures that bioplastics' overall environmental footprint remains positive, balancing energy demands with sustainability goals. Efficient energy management is crucial. Nevertheless, it is crucial to navigate the challenges and trade-offs associated with sustainable packaging to ensure that food security and environmental quality is not compromised. Ultimately, a balanced approach that prioritizes both sustainable packaging and food security is essential for creating a more equitable and sustainable food system.

Current State of Sustainable Food Packaging

The current state of sustainable food packaging is a dynamic and evolving landscape, driven by increasing environmental concerns, consumer awareness, and regulatory pressures (Bojanowska and Sulimierska, 2023) As the food industry continues to grapple with the challenges of reducing waste, conserving resources, and mitigating climate change, sustainable food packaging has emerged as a critical area of focus.

One of the primary drivers of change in the food packaging industry is the growing awareness of environmental concerns. The production, distribution, and disposal of food packaging materials contribute significantly to greenhouse gas emissions, waste management issues, and resource depletion. In response, companies are adopting sustainable materials, such as bioplastics, paper, and glass, which offer reduced environmental impacts compared to traditional packaging materials.

The concept of a circular economy is also gaining traction in the food packaging industry. This approach emphasizes the importance of reducing waste, reusing materials, and recycling to minimize environmental impacts. Companies are exploring innovative packaging designs, such as refillable containers and packaging-free products, to reduce waste and promote sustainability. Consumer awareness and demand for sustainable packaging are also driving change in the food packaging industry (Chirilli *et al*., 2022) Many consumers are willing to pay a premium for products with sustainable packaging, and companies are responding by adopting eco-friendly packaging solutions. This shift in consumer behaviour has created a market-driven incentive for companies to prioritize sustainability in their packaging decisions.

Regulatory frameworks are also playing a crucial role in promoting sustainable food packaging. Governments around the world are implementing policies and regulations to support the transition to sustainable packaging, such as the European Strategy for Plastics in a Circular Economy. These regulatory frameworks provide a critical foundation for driving change in the food packaging industry. Technological advancements are also transforming the sustainable food packaging landscape. Biodegradable materials, smart packaging, and active packaging are just a few examples of the innovative technologies being developed to improve the sustainability of food packaging. These technologies offer improved functionality, reduced environmental impacts, and enhanced consumer experiences.

Supply chain collaboration and communication are essential for achieving sustainable food packaging. Companies are working together to develop and implement sustainable packaging solutions, share best practices, and drive innovation. This collaborative approach recognizes that sustainable food packaging is a shared responsibility that requires collective action. Despite these advances, challenges persist in the sustainable food packaging landscape. While challenges remain, the food packaging industry is poised for continued transformation as companies, consumers, and governments work together to create a more sustainable future.

Challenges of Sustainable Food Packaging

The pursuit of sustainable food packaging is a noble endeavour, driven by the need to reduce environmental impacts, promote eco-friendly practices, and ensure a healthier planet for future generations. However, this quest is not without its challenges, which are multifaceted and complex.

One of the primary challenges is the balancing act between sustainability and food safety. Research have shown that bioplastics can reduce carbon footprint by 50-80% compared to traditional plastics (Bioplastics Association, 2020). Packaging plays a critical role in preserving food quality and preventing contamination. Sustainable packaging materials, such as bioplastics and compostable materials, must meet the same rigorous safety standards as traditional packaging materials. This requires significant research, development, and testing to ensure that sustainable packaging solutions do not compromise food safety.

Another significant challenge is cost. Sustainable packaging materials and technologies are often more expensive than traditional options, making it difficult for companies to adopt sustainable practices without passing on the added costs to consumers (Rahim *et al.*, 2016) This can be a significant barrier to adoption, particularly for small and medium-sized enterprises. However, in low-resource settings, sustainable packaging is achieved through locally sourced, biodegradable materials and minimal waste designs. Strategies include agricultural waste reuse, refillable containers, composting programs, and community-based initiatives. Low-cost, open-source technologies and circular economy approaches reduce waste, promote economic development, and minimize environmental impact, driven by local innovation.

The availability of raw materials can pose a big setback to bioplastic production. Dependence on agricultural crops (e.g., corn, sugarcane) can be affected by climate change, seasonal fluctuations, and food security concerns. Limited access to non-food biomass and high costs of feedstock sourcing hinder scalability and economic viability.

Scalability is another challenge facing sustainable food packaging. As demand for sustainable packaging grows, manufacturers must scale up production to meet demand. This requires significant investments in infrastructure, equipment, and personnel. Moreover, scaling up sustainable packaging production can lead to unintended environmental consequences, such as increased energy consumption and resource depletion.

Energy consumption is a significant limitation to bioplastic production. Processing biomass requires substantial energy, often derived from fossil fuels, offsetting bioplastics' environmental benefits. High temperatures, pressures, and chemical reactions increase energy demands. Additionally, transportation and processing of raw materials contribute to energy consumption. This energy intensity raises production costs, reduces competitiveness with traditional plastics, and undermines the environmental advantages of bioplastics, making it challenging to achieve scalable and sustainable production.

Furthermore, consumer education and awareness are significant challenges. Many consumers are unaware of the environmental impacts of traditional packaging or the benefits of sustainable packaging. Educating consumers about sustainable packaging options and encouraging behavioural change is essential for driving demand and promoting adoption.

Regulatory frameworks also pose a challenge to sustainable food packaging. Lack of standardized regulations and certifications can create confusion and inconsistencies in the market, making it difficult for companies to navigate the sustainable packaging landscape (White *et al*., 2015)

In addition, the development of sustainable packaging materials is a complex process, requiring significant research and development. Biodegradable materials, for example, must be designed to break down quickly and safely without leaving toxic residues.

Lastly, the infrastructure for recycling and composting sustainable packaging is often lacking. Inadequate waste management systems can lead to sustainable packaging ending up in landfills or oceans, defeating the purpose of sustainable packaging.

The challenges of sustainable food packaging are significant and multidimensional. Addressing these challenges will require collaboration, innovation, and a commitment to sustainability from companies, governments, and consumers. By working together, we can overcome these challenges and create a more sustainable food packaging system that benefits both people and the planet.

Cost Implication of Sustainable Packaging

The cost of transitioning from traditional plastics to bioplastics is a significant consideration for industries and governments worldwide. The initial investment required for the transition can be substantial, ranging from $5 million to $5 billion, depending on the industry, production volume, and location (Bioplastic Association, 2020). This includes research and development expenses, equipment upgrades, raw material costs, and scaling up production. One of the primary short-term costs is research and development expenses, which can range from $500,000 to $5 million (Grandview Research, 2020). Companies must invest in developing new bioplastic materials, formulations, and production processes to replace traditional plastics. Additionally, existing manufacturing equipment may need modifications or replacements to accommodate bioplastic production, costing between $1 million to $10 million.

The cost of raw materials is another significant factor. Bioplastic feedstocks, such as biomass or sugarcane, can be 10-20% more expensive than traditional plastic feedstocks (Nasrollahi *et al*, 2020). However, as demand increases and production economies of scale improve, bioplastic feedstock can become cheaper. Scaling up production also requires significant investments in new facilities, equipment, and personnel, estimated at $50 million to $500 million (European Bioplastics, 2020)

Despite these initial costs, the long-term benefits of transitioning to bioplastics can offset the investment. Companies can reduce material costs, lower energy costs, and benefit from government incentives, such as tax breaks, subsidies, or grants. Moreover, adopting bioplastics can enhance brand reputation, potentially increasing sales and revenue. Regulatory compliance is another significant advantage, as companies can avoid potential fines or penalties by transitioning to bioplastics. In the long term, the cost savings from transitioning to bioplastics can be substantial. For instance, bioplastic production often requires less energy than traditional plastic production, resulting in cost savings.

To mitigate the transition costs, companies can explore strategic partnerships, collaborations, and investments. Governments can also provide support through policies, regulations, and incentives. As the demand for sustainable products grows, companies that adopt bioplastics can gain a competitive edge, improve their brand reputation, and contribute to a more environmentally friendly future. Also steps must be taken to ensure scalability and market penetration of bioplastics. Governments and industries must invest in infrastructure development, research, and innovation to reduce production costs. Standardization and certification protocols should be established. Consumer education and awareness campaigns can increase demand. Policy incentives, tax breaks, and subsidies can level the playing field with traditional plastics. Additionally, extended producer responsibility and closed-loop recycling systems must be implemented to address end-of-life management and promote a circular economy.

Ultimately, the cost of transitioning from traditional plastics to bioplastics is a necessary investment for a sustainable future. While the initial costs may seem daunting, the long-term benefits and savings make it a worthwhile endeavour. As technologies continue to evolve and economies of scale improve, the cost of bioplastics will decrease, making them an increasingly viable alternative to traditional plastics.

Benefits of Going Green with Food Packaging

The benefits of sustainable food packaging are multifarious and far-reaching, impacting not only the environment but also the economy and society as a whole. As the world grapples with the challenges of climate change, resource depletion, and waste management, sustainable food packaging has emerged as a critical component of a more sustainable future.

One of the most significant benefits of sustainable food packaging is its reduced environmental impact. Traditional packaging materials, such as plastics and Styrofoam, contribute to greenhouse gas emissions, deforestation, ocean and land pollution. In contrast, sustainable packaging materials, such as bioplastics, paper, and glass, are designed to minimize waste, reduce carbon footprints, and promote recyclability. In the year 2020 Coca-Cola bottling company made their bottles from 30% bioplastics. A move which was highly applauded because it reduced their carbon footprint by 12% (Coca-Cola, 2020). This was followed suit by Pepsi Company later that year with the aim of reducing greenhouse emissions by 25%.

Sustainable food packaging also offers economic benefits. By reducing packaging waste and minimizing the use of non-renewable resources, companies can lower their production costs and enhance their bottom line. Bioplastics production costs are 20-30% lower than traditional plastics (European Bioplastics, 2020). According to European Bioplastic market report in 2020, bioplastics market is projected to grow from $4.4 billion (2020) to $65.6 billion (2025). Moreover, sustainable packaging can be a valuable marketing tool, enabling companies to differentiate themselves from competitors and appeal to environmentally conscious consumers. Unilever company makes use of biodegradable packaging for their Lipton tea bags and in 2023 they also introduced recyclable packaging for Knorr seasoning cubes. Procter and Gambler company became the favourite of so many nursing mothers when they introduced their biodegradable diaper, inspite of the relatively higher cost compared to other diapers, they were still topping the market sales. L'Oréal a leading cosmetic brand also joined the sustainable packaging band wagon by introducing bioplastic packaging for their make up products in 2022

In addition to environmental and economic benefits, sustainable food packaging also has social benefits which includes creation of new jobs in the research, packaging, marketing, sales, manufacturing and logistics sector. According to the International Renewable Energy Resource Agency, Bioplastics is estimated to create over 100,000 new jobs in 2025. In the United States of America, bioplastics generated over 40,000 new jobs between 2015 – 2020 (Bioplastics Association, 2020) By promoting sustainable agriculture practices and reducing food waste, sustainable packaging can help ensure global food security and support rural development.

Furthermore, sustainable packaging can contribute to public health by reducing exposure to toxic chemicals from traditional plastics and promoting safe food handling practices. Carcinogenic chemicals like Bisphenol A (BPA) and Vinyl Chloride have been link to breast and liver cancer respectively and they are commonly used in the manufacturing of traditional plastics. Research have also shown that Sustainable food packaging can reduce the risk of exposure to food borne illnesses and food poisoning (Center for Disease Control and Prevention, 2020)

Another significant benefit of sustainable food packaging is its potential to drive innovation. As companies seek to develop more sustainable packaging solutions, they are investing in research and development, driving technological advancements and creating new business opportunities. Nigerian manufacturing companies like Lagos-based Polydime Nigeria Ltd and Abuja-based Global Biofuels Ltd are championing the course of innovation in the packaging industry. Other start-ups Ecoplastics, Greenpack and Bioplus Nigeria Plc.

Ultimately, sustainable food packaging can play a critical role in promoting a green economy (Guillard *et al*., 2018), because unlike conventional plastic, bioplastic take lesser time to degrade (1-10 years). Common plastics take: PET (10-20 years), HDPE (20-100 years), PVC (100-500 years), LDPE/PP (100-500 years), and Polystyrene (500+ years). Microplastics persist indefinitely. Factors like UV radiation, temperature, and moisture influence degradation, resulting in microplastics that remain for thousands of years. With the emergence of bioplastic packaging that is recyclable, reusable, or biodegradable, companies can reduce waste, promote resource efficiency, and support a more regenerative economic model.

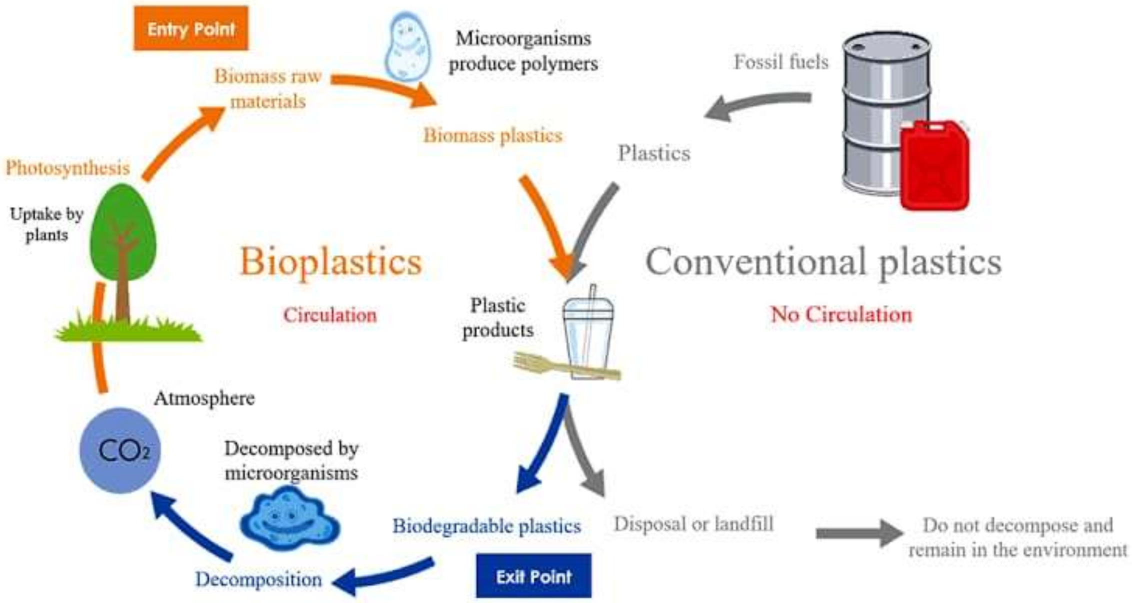

Figure 7: Life cycle and recycling of plastics

A Future Perspective to Sustainability

The future of sustainable food packaging is a promising and rapidly evolving landscape, driven by innovation, consumer demand, and environmental necessity (Chadha *et al*., 2022). As the world deals with its growing environmental challenges, sustainable food packaging is poised to play a critical role in reducing the environmental footprint of the food industry. Bioplastics production capacity is expected to increase from 2.1 million tonnes in 2020 to 4.8 million tonnes by 2025, (European Bioplastics, 2020). In the near future, we can expect to see a significant shift towards biodegradable and compostable packaging materials, such as plant-based bioplastics, mushroom-based packaging, and seaweed-derived materials. These innovative materials will not only reduce plastic waste but also promote a sustainable economy, where packaging materials are designed to be recycled, reused, or biodegradable.

Another key trend shaping the future of sustainable food packaging is the adoption of smart packaging technologies. These technologies, such as temperature sensors, RFID tags, and intelligent labels, will enable real-time monitoring of food freshness, quality, and safety, reducing food waste and improving supply chain efficiency.

The future of sustainable food packaging also holds significant opportunities for advancements in packaging design and functionality. For example, edible packaging, packaging-free products, and minimalist packaging designs will become increasingly popular as consumers demand more sustainable and convenient packaging solutions.

Furthermore, the future of sustainable food packaging will be characterized by increased collaboration and standardization across the industry. Companies, governments, and NGOs will work together to develop common standards, guidelines, and certifications for sustainable packaging, facilitating a more cohesive and effective transition towards a more sustainable food system.

In addition, the future of sustainable food packaging will be shaped by changing consumer behaviours and preferences. As consumers become more environmentally conscious and informed, they will demand more sustainable packaging options, driving companies to innovate and adapt to meet these expectations.

Finally, the future of sustainable food packaging holds significant potential for reducing food insecurity and promoting sustainable agriculture practices. By developing packaging solutions that extend shelf life, improve food safety, and support local food systems, sustainable food packaging can play a critical role in ensuring global food security and promoting sustainable agriculture practices. The future of sustainable food packaging is a bright and exciting one, full of innovation, opportunity, and promise. As we move forward, it is essential that we prioritize sustainability, collaboration, and consumer needs, ensuring a food system that is more environmentally conscious, socially responsible, and economically viable for generations to come.

CONCLUSION

In conclusion, the development of sustainable food packaging materials is a crucial step towards addressing the pressing issues of food security and environmental pollution. As the global population continues to grow, the need for innovative and eco-friendly packaging solutions becomes increasingly urgent. Sustainable food packaging materials offer a panacea for these concerns by reducing food waste, minimizing environmental impacts, and promoting a circular economy. By adopting sustainable packaging practices, we can ensure a safer, more reliable, and more environmentally conscious food system for future generations. Furthermore, the development of sustainable food packaging materials can drive economic growth, create new business opportunities, and support sustainable agriculture practices. Therefore, it is imperative that researchers, policymakers, and industry leaders collaborate to accelerate the development and adoption of sustainable food packaging materials, ultimately contributing to a more food-secure and environmentally sustainable world. These stakeholders can come in the area of funding research and innovations, establishing of more bioplastic production firm to meet increasing demand, creating public awareness on the need to transition to sustainable packaging, giving incentives to motivate eco-friendly companies and lastly enact and implement laws and policies that encourages sustainability.

Data Availability: The data used for this article are publicly available online and at the Dennis Osadebay University E-Library.

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