Evaluating Technologies to Reduce the Environmental Impact and Cost-Effective Food Packaging

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Abstract

The packaging industry is currently the third largest industry in the world with ⅔ being food packaging. Currently, plastic makes up over ⅔ of the materials used in food packaging which is harmful to the environment and human health due to the carcinogenic chemicals, Phthalates and Bisphenols, contained in high-density polyethylene plastic. Active packaging composed of antimicrobial materials is a promising alternative for food safety and stability that is cost-efficient, sustainable, and scalable. Antimicrobial materials can combat microorganisms, such as bacteria and fungi, which pose a serious threat to food safety and packaging due to contamination that diminishes the food's shelf life and quality. In this research paper, we aim to obtain the best options for antimicrobial materials that fulfill the food packaging and safety needs of a rising world population. We will analyze multiple scholarly articles to discuss several alternatives to high-density polyethylene plastic. Nanotube technology is promising due to its absorption of ethylene excreted from fruit cells, oxidizing meat packages, and ultimately deterring microorganism proliferation through naturally occurring essential oils and metals that line the nanotubes. Nanotube technology will enhance food safety and food packaging, expand the food industry to be able to support the world's growing population and ensure that world hunger is heavily reduced. Bamboo is another potential solution due to its natural antimicrobial agents, biodegradability, aesthetic appeal, and high strength-to-weight ratio. With growing environmental pressures and an increasing demand for sustainable packaging alternatives, these antimicrobial materials have the potential to enhance food safety and reduce climate change.

Introduction

Due to the growing world population, the need for reliable and environmentally safe food packaging methods is hastily increasing. Packaging methods are extremely complicated as manufacturers must tackle food safety issues while simultaneously being able to ship out large amounts of agricultural products affordably. Food contamination and spoilage are the most common food safety issues impacting nearly ⅓ of the food produced for human consumption (FAO, 2020). Implementation of antimicrobial materials in packaging can reduce spoilage and contamination, delivering a safe fresh product to consumers. The food safety advantage of antimicrobial materials comes from their ability to prevent the initial growth of several microorganisms such as bacteria and fungi. In this commentary, there will be an analysis of each natural resource; bamboo, bioplastics, and metals (copper and silver) along with inorganic and organic nanoparticles (NP) and their relation to food safety. Additionally, this research paper will approach the financial aspect of cost efficiency for the manufacturers. Expenses are imperative when analyzing food packaging, especially with large global distribution systems. Food manufacturers will have to balance the expenses of innovative packaging materials with business costs to maintain profits.

Problem Statement

Due to packaging plants utilizing plastic and materials derived from easily contaminated petroleum, future advancements must be made to extend the shelf stability and safety of foods while reducing the amount of waste that is generated by the use of high-density polyethylene plastics. The global issue of food waste occurring due to insufficient attention during food packaging is immense as around 13% of food production is lost between harvest and retail and 40% of food production is wasted in grocery stores with even larger amounts wasted in people's homes (United Nations, 2022). The United Nations (UN) holds seventeen goals for Sustainable Development that can help combat food waste to produce a more ecological and ethical society worldwide. Out of these goals, Industry, Innovation, Infrastructure, and Zero Hunger are the most pertinent as they partially resolve the issue of food waste with the implementation of more sustainable food packaging.

Out of the Sustainable Development Goals (SDGs), number nine: Industry, Innovation, and Infrastructure centralizes its focus on developing new technologies, products, and facilities that are manufactured at high quality and efficiency. This way these innovations are sustainable, ethical, and beneficial which improves societies, especially in developing countries that lack resources. The solution of using antimicrobial agents such as silver, copper, bamboo, and nanotechnology to support the issue of food waste is an ideal example of this specific goal as it demonstrates industries being innovated to be more efficient by limiting food waste (UN, 2023).

Furthermore, SDG number two: Zero Hunger is a complex, global issue as one out of every five kids is malnourished globally (UNICEF, 2023). However, this is not the only concern when looking at Zero Hunger as there are numerous other issues including maintaining stable food production, increasing agriculture productivity, and ultimately resolving food waste. NIFA has invested 123.5 million for 527 food loss and waste problems to assist with this issue. If industries incorporate new technologies such as antimicrobials, then initial contamination of bacteria will be prevented. To do this, industries must employ scientists and researchers who will work together to ascertain the most effective antimicrobial compound to fully prevent certain types of hazardous bacteria. This will help reduce food spoilage during transport, helping to alleviate world hunger (UN, 2023).

The National Institute of Food and Agriculture (NIFA) addresses global issues such as food loss and waste, and it reports that 8 billion dollars worth of food is wasted every year (Kundamal, 2023). The amount of food that is wasted daily hurts the farmers who work to produce it and puts food in landfills that could have been used to feed 2 billion famished people in the world (World Food Program, 2022). NIFA mentions how the majority of food waste happens when food either rots in the field, gets incinerated, or ends up in landfills. Food loss and waste are not only a detriment to malnourished individuals but also a burden to the ecosystem as it accounts for 8 to 10% of all greenhouse gas emissions (UN, 2011). NIFA has contributed significant resources to research and evaluate solutions to fix this conflict; it has invested 123.5 million for 527 food loss projects to reduce food waste (NIFA 2023). In addition, NIFA could start investing in antimicrobial agents such as silver, copper, bamboo, and nanotube technology as they would mitigate food from spoiling and then being thrown into landfills. For example, factories could utilize silver-lined tools and machinery to produce food that would prevent any fungi from harming the produce during the initial production stage. The global issue of food waste can gradually be eliminated if antimicrobial agents are implemented during the packaging and transportation processes, allowing food products to arrive to consumers in safe conditions.

Methods

To answer the prompt, we gathered information from the National Library of Medicine, Gale, and Science Direct. To learn more about the basics of food packaging, we searched for “plastic food packaging”, “effects of food packaging”, and “environmental impact of packaging”. With some background established on the topic, we decided to focus on the finance, technology, and food safety aspects of food packaging by performing broad searches on EBSCO and Google Scholar using the keyword aspects “finance on food packaging,” “manufacturing technology,” and “food safety,” to focus on these topics.

Our background research led us to understand that current food packaging is not environmentally friendly, cost-effective, or healthy for humans. Once we learned more about the negative impacts of plastic food packaging, we started looking more into new materials that could be used for packaging by searching, “green plastics” and “antimicrobial materials” for “food packaging.” Further research led us to propose antimicrobial materials as a cost-effective and environmentally friendly material for food packaging.

We used a total of twenty-five articles to write a non-systematic literature review on plastic food packaging contamination and antimicrobial materials as an environmentally friendly solution. The review was made of research from primary and secondary sources ranging from past research papers, literature reviews, and research statistics to fully understand the overarching concept.

Background

Food Packaging and Food Safety

Food packaging is essential in the food industry as it is utilized to safely protect and prolong the life of food items while keeping the distribution of food products inexpensive and efficient. The most popular material for food packaging is plastics; the packaging industry is the number one consumer of synthetic plastics globally (Ude, 2020). However, there are many highly toxic chemical substances in plastic packaging such as Phthalates and Bisphenols which both cause cancer and disrupt hormones. Paper and glass are also used to manufacture packaging materials and combined with plastics, they make up over ⅔ of the materials used for food packaging. The packaging industry, due to single-use plastics derived from fossil fuels such as on-the-go snacks, and ready-made meals, is the leading contributor to environmental waste. Currently, as petroleum reserves are exhausted, it is a pressing issue to find an alternative for high-density polyethylene plastic food packaging (Ncube, 2020).

During the manufacturing process of plastics, chemical substances such as Phthalates and Bisphenol can transfer to the food in a process called migration. During migration, chemicals are transferred when the high-density polyethylene plastic touches the food products. The migrated substances are diffused through polymeric molecules of the plastic which are then absorbed from the surface of the plastic packaging material (Panou, 2024). They are then absorbed into the interface between the food and packaging plastic. Finally, the chemical gets transferred into the food which can lead to ingestion by consumers. This can cause detrimental effects such as hormonal disruption. Although the principle of migration is used to extend the shelf life of products, such as antistatic media in packaging and controlled diffusion of medicines from the net of plastics, in some scenarios the migration of unwanted chemicals and compounds into food creates food safety issues. Harmful transfers included plasticizers from PVC plastics, flame retardants from the plastic coatings of TVs and computers, and Phthalates and Bisphenol from plastic packaging to food and medicine. The chemicals transferred can alter the flavor profile of food and the active compounds in medicine which render them either useless or harmful. The European Commission passed conservative regulations that the overall migration limit shouldn't be over 60 mg/Kg in food (Panou, 2024).

There are four hazards in food safety: Microbiological hazards, chemical hazards, physical hazards, and allergens. Microbiological hazards include bacteria, fungi, and viruses. Chemical hazards include water, cleaning agents, and pesticides. Physical hazards include things such as broken glass shards in food. Allergens include cross-contamination from different food products that can cause anaphylaxis in certain individuals which can result in death. There have been three major advances in food packaging. The first one is active packaging that directly interacts with the food to prolong shelf life. The second advancement is intelligent packaging which monitors the conditions of the packaged food and environment. The last major advancement is antimicrobial packaging which both makes food packaging safer but also more environmentally friendly and reactive to different environments (Alamri et al., 2021).

The latest innovations in food packaging technology are more sustainable and have the potential to create more efficient and affordable food packaging solutions. Innovations such as active-release packaging systems include antimicrobial packaging which slows and kills microorganisms. Researchers and developers are conducting studies on new antimicrobial agents to obtain safer food packaging quality. Furthermore, research has been conducted on nanotechnology, including antimicrobial innovations that aspire to resolve food packaging issues such as contamination, spoilage, and shelf life extension. Some examples of innovations in antimicrobial materials for food packaging materials include surgically inserting antimicrobial materials into a polymer-made surface and assimilating essential oils into edible films to create active edible films. Besides active edible films, antimicrobial materials have numerous other applications including antimicrobial coatings that preserve food product freshness.

Bioplastics are also proposed as an alternative to help the environment as they have low greenhouse gas emissions compared to high-density polyethylene plastics. Polylactic acid is a favored bioplastic, however, it is not widely used due to its high-cost performance. Petrochemical plastics can also be used for food packaging due to their cheap cost, good tensile properties, and effective barrier against oxygen, carbon dioxide, and water vapor. Currently, it is being used as both a flexible and rigid form of packaging because it can be classified as a thermoplastic or a thermoset. Thermoplastics can be reprocessed using heat to mold them into various shapes ideal for food packaging, making them recyclable. In contrast, thermosets cannot be reprocessed by heat, rendering them unsustainable materials.

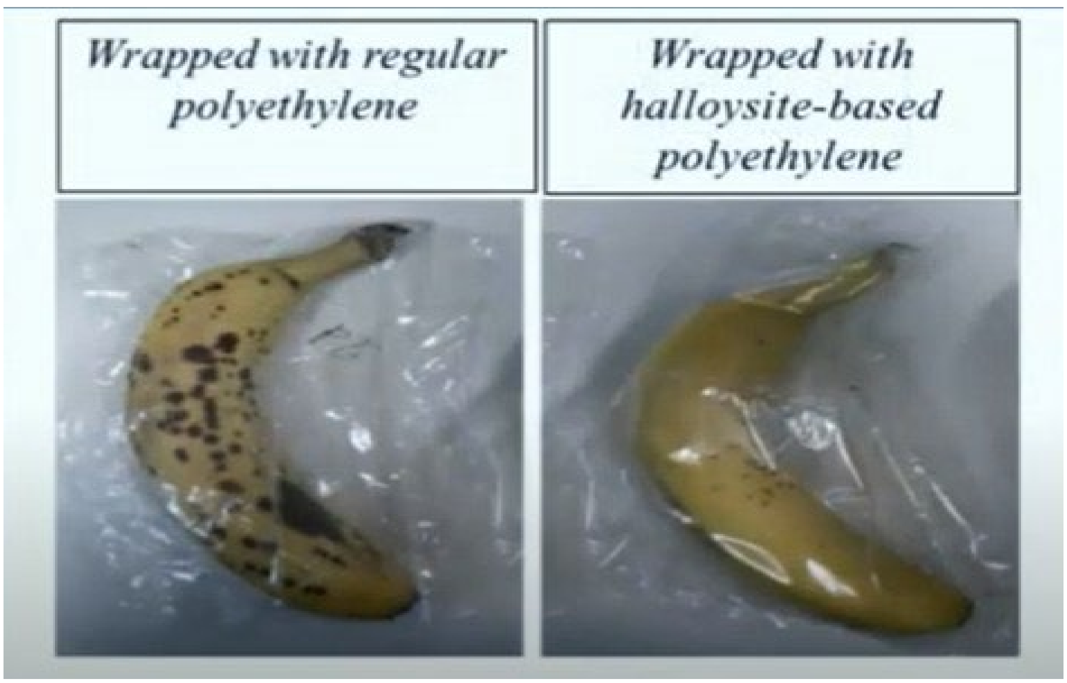
It is estimated that by 2050 there will be a 50% increase in food supplies required due to the increase in population, leading to an increase in demand for food packaging globally. This increase in demand for packaging emphasizes the need for innovative solutions that reduce food waste by keeping the existing food palatable and fresh. As the plastics in food packaging break down, they turn into microplastics which are incredibly harmful as they are more easily digestible by humans and harder to eliminate from the environment. For example, in a process called bioaccumulation, these microplastics enter the food chain through fish and then harm the entire ecosystem. To lower plastic waste and prevent harmful environmental processes such as bioaccumulation, there needs to be more efficient waste management such as green packaging. There are three types of green packaging: reusable packaging, such as reusing glass; recyclable packaging, like reprocessing and reusing paper; and biodegradable packaging, such as cotton sacks that can break down without damaging the environment.

Biopolymers are produced by living organisms or derived from biomass. They degrade in a reasonable period and avoid the environmental problems typically seen in high-density polyethylene plastics. They can be produced using extracted biomass such as starch or cellulose, chemical synthesis with renewable biobased monomers such as polylactic acid (PLA), and microorganisms or genetically modified bacteria. Biopolymers can reduce plastic waste and lower greenhouse gas emissions during the food packaging process. PLA, a biopolymer, is an environmentally friendly biodegradable thermoplastic polyester, which can break down in 2 years when disposed of. In comparison, petroleum-based plastics, like polyethylene terephthalate (PET), take 500-1000 years to decompose. However, most plastic products that are sold to consumers are PET. When composted with other biomass like compost soil, PLA can break down within 3-4 weeks. PLA can be molded in various shapes, has favorable mechanical properties, and its performance is similar to petroleum-based plastics. Both PLA and PET are petroleum-based and have similar tensile strength and elasticity. However, polylactic acid consumes 36% less energy and 44% less carbon dioxide to manufacture. PLA also has many advantages for food packaging including excellent transparency, permeability to carbon dioxide compared to oxygen, water resistance, chemical resistance to oils, thermal processability, and biodegradability. The FDA regulates food safety and the safety of substances that interact with food, ensuring that all food products available to the public are safe for consumers. Food manufacturers are in charge of meeting the safety requirements of food manufactured by new technology (FDA, 2023). In terms of migration, the Food and Drug Administration (FDA) approved lactic acid monomers, including PLA, as a safe food ingredient (Ncube, 2020).

Nanoparticle technology refers to threading or coating that is based on antimicrobial essential oils or green biopolymers (Bose, 2023). Even one of its variations, Halloysite-based Polyethylene, can reduce the amount of the hormone ethylene while being able to keep the food in the packaging stable (Ünal, 2017). By reducing the amount of ethylene, nanoparticle technology extends the shelf life of perishable food items and also contributes to food safety by inhibiting the growth of microorganisms that can lead to foodborne illnesses. These green biopolymers enhance the functionality of food packaging and address environmental concerns that benefit current and future generations.

Figure 1

Banana in polyethylene (Ünal, 2017).

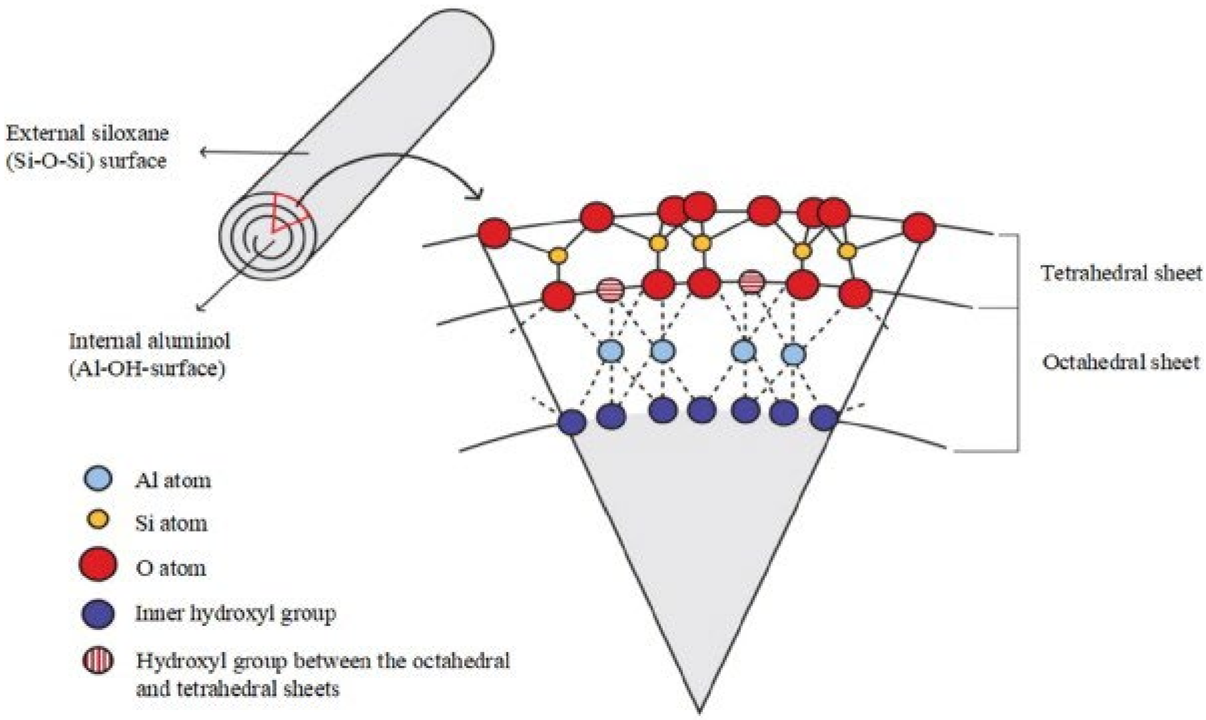


Note. The image above illustrates the ripening process of two Cavendish bananas over two weeks. The banana on the right displays fewer spots, indicating a reduced presence of the hormone ethylene.

The wrapping material is holly site-based Polyethylene, a type of material that is clay-covered and is composed of organic materials like silicon and antimicrobial essential oils. Its composition allows it to be optimal for Ethylene Scavenging, a process of removing ethylene from an environment, as well as being 90% better at killing bacteria than traditional polyethylene plastics (Ünal, 2017). Nanotube technology barriers are extremely efficient in preventing the initial spread of microorganisms as compared to moisture and oxygen barriers as they completely prevent any movement of microorganisms.

Figure 2

Structural composition of Hallosite-based nanotubes (Fakhruddin et al., 2021)

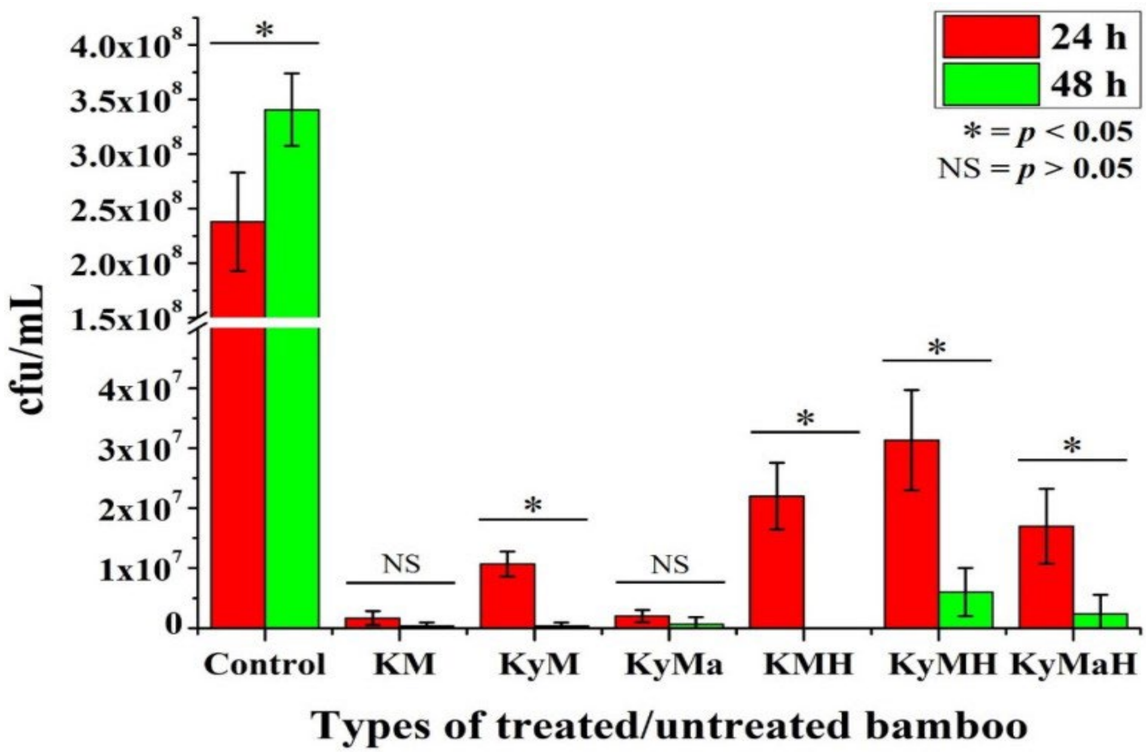


Note. The image illustrates the chemical and structural composition of Hallosite-based nanotubes(HNT). It emphasizes the complex layers that nanotube technology has and how each one is made of different atoms that serve different purposes.

Bamboo is also a great option when looking at potential ecologically friendly packaging because bamboo naturally has antimicrobial properties (AMP) with some species like Kyoto-Moso and Kyushu-Madake having excellent AMPs (Ramful et al., 2022). These AMPs are naturally embedded into bamboo and when bamboo is implemented into food packaging, these AMPs will begin preventing the initial spread of microorganisms and improving food safety and packaging.

Figure 3

Colony-forming units (Ramful et al., 2022)



Note. Colony-forming units (CFU) with various types of antibacterial agents of bamboo species testing for E. coli colonies after 24 and 48-hour periods *= statistically significant difference, NS = no significant difference. The specimens talked about are KyM & KyMa.

The graph represents different types of bamboo being affected by E. Coli, a common bacteria contracted by eating meats that are already carrying the bacteria. After the span of twenty-four to forty-eight hours of being exposed to the bacteria, it is clear that the two subspecies of bamboo performed exceptionally well compared to the regular control group. Apart from the antimicrobial aspect, bamboo is also invasive in the United States of America meaning it grows extremely quickly and can be better industrialized for farming than any other biodegradable packaging material plant. It has been shown that bamboo has been successfully grown in southern regions of the United States (Vivas et al., 2024). Due to this rapid growth, antimicrobial properties, and environmental benefits, industrialized bamboo has the potential to be one of the best industry-leading packaging methods.

Manufacturing

The packaging process is one of the most important processes during food manufacturing as it is responsible for maintaining food quality for transportation and storage. It also extends shelf life as it prevents the deterioration of food and drinks. While packaging helps protect the food, it also helps in marketing products, indicating tampering, and controlling portions. Food packaging also contains important information about the food, such as nutrients, and makes handling food convenient from production to the consumer (Han, 2020).

Metal packaging is currently being used for food packaging to lower its environmental impact. Metal packaging materials make up 15% of the total packaging material worldwide. According to a market intelligence report, the market for metal cans was estimated at 47.88 billion dollars in 2018 and has an annual growth rate of 3.39%. Metal packaging can be recycled, can be easily converted into different shapes, and provides a great barrier between light and gas. Its reusability lowers land waste, however, there are large amounts of carbon dioxide emissions from manufacturing factories. The factories also release harmful toxic chemicals and exhausting resources. Current research and policies are working on creating a better balance between the positives and negatives (Deshwal, 2019).

Finances

Over 750 billion dollars worth of food is thrown out globally with ~25% of that being residential meal waste that is disposed of due to poorly designed packaging resulting in food being spoiled and inedible before its calculated expiration date (Bose, 2023) While numerous different solutions could be applied to address the global issue of food waste, the most effective solution must directly solve the financial issue that impacts the entire world through many different job levels. This leads to many solutions that are built to accommodate a limited budget rather than what is best for humans and the environment. Over the last decade, as the market for biodegradable packaging has rapidly grown, finding the most cost-effective antimicrobial alternative has become increasingly crucial.

It has been shown that although materials like silver and copper are good natural antimicrobial agents, utilizing them in packaging is not only costly but also quickly depletes our global supply of these precious metals. If companies implemented copper and silver for food packaging, not only would the initial cost of the metals be immense, but the added costs of the increased weight on transport vehicles would quickly compound. This would lead the food packaging companies to lose money, causing the direct incorporation of copper and silver into food packaging to not be an economically sound decision. A better implementation would be putting coatings on tools utilized in food production facilities as the added weight of the metal coatings would not cause a huge difference to currently existing tools and these tools would be able to stop the initial spread of harmful bacteria through the antimicrobial properties of silver and copper. These coatings would also not cost too much as they do not utilize too much silver and copper, but rather small amounts that are added onto existing tools.

Bamboo is a great option for antimicrobial packaging due to its potential abundance as an invasive species. Although there is a high outlook on the benefits of bamboo, it currently lacks affordability to the manufacturers as bamboo is costly compared to the competitors of polyethylene plastics because of its current low amount of domestic farming. While bamboo has a few economic downsides compared to nanotube technology, it still stands as a reliable and effective antimicrobial material. Bamboo can be used as an alternative to current high-density polyethylene plastic food packaging and has been projected to have a massive ripple effect as more companies adopt this sustainable alternative. A study found that in years to come, bamboo alone in the cosmetic packaging market is "projected to exhibit a compound annual growth rate (CAGR) of 2.3% from 2023 to 2030." (Vivas et al., 2024). As the years pass and more farming operations appear in the southern regions of America, consumers should expect to see bamboo appear more often in food packaging.

Similarly, nanoplastics are a viable option because of their affordability and international abundance. Nanotube technology is a financially viable option because it is designed to waste the least amount of space, thus optimizing the package space and reducing the amount of materials needed to produce the packaging. The engineering behind the design of nanotube technology has a long-lasting effect on environmental costs as it can help reduce the carbon emissions from transportation because they can fit more units in trucks and shipping containers. Nanotube technology has also been shown to be a part of polymers that are commonly used in diverse industries like automotive, electrical, electronics construction, and most recently packaging. (Sikora et al., 2019). Due to this, nanotube technology is readily available and cheap to manufacture and is also naturally abundant and found in immense deposits in the form of aluminosilicate clay ($Al_2Si_2O_5(OH)_4nH_2O$) (Fakhruddin et al., 2021). From an economic perspective, nanotube technology does not have any major complications apart from the actual process and development of packaging specific for individual companies' products to be manufactured.

Solutions

When analyzing solutions for food waste during the packaging process, the four most effective solutions are silver, copper, bamboo, and nanotube technology. Silver and copper are metals with numerous antimicrobial properties that kill bacteria. Following the metals, bamboo and nanotube technology are both solutions that are environmentally friendly and antimicrobial. These four resources are key elements in assessing the problem of food waste. The essence of antimicrobial products is to eliminate any microorganisms that cause food spoilage, therefore extending food shelf life and ensuring food safety.

Silver is an extremely effective antimicrobial material due to its numerous antimicrobial actions such as disruption of cell membranes, binding to proteins, inhibition of DNA replication, production of reactive oxygen species (ROS), and inhibition of biofilm formation, a process where polymicrobial environments are created which have physical resistance to antibiotics. Silver is composed of ions that disrupt cell membranes by binding to proteins and phospholipids which causes cell death. By binding to proteins, silver ions interrupt cellular metabolism, hindering the growth of microorganisms. Additionally, silver ions attach to nucleic acids such as RNA and DNA, impeding the replication of microorganisms, which further obstructs microorganism growth. Moreover, silver ions speed up the production of reactive oxygen species, which causes damage to cellular components, ultimately killing the cells of microorganisms. Finally, silver ions also prevent the creation of biofilm formations due to silver ions inhibiting the adhesion of microorganisms to surfaces on food packages and dissolving existing biofilms.

Silver has numerous applications in food safety and packaging such as films, coatings, and containers. Fusing them with silver nanoparticles that constantly release silver ions will protect against microbial contamination. Implementing silver ions into food storage and tools is an easier and more scalable solution that maintains both the freshness and safety of food products. Adding edible silver nanoparticles to food could create a protective barrier that both extends shelf life and reduces microbial growth, however incorrect amounts of silver can harm humans so the correct dosages must be calculated by scientists. The safest implementation would be to utilize silver-lined tools in manufacturing facilities to have all of the food safety benefits of silver while limiting the risk of argyria as consumers are never ingesting silver directly. While this implementation has already begun in some companies, if more companies and industries would switch to silver-lined tools, an extra layer of protection would be added to food products worldwide and create improved food safety, quality, and shelf life.

Copper is pretty similar to silver in the methods it stops the growth of microorganisms, however, while copper is cheaper, it is more unstable. While silver is stable and inert, copper is unstable, which means food packagers must use increased caution to prevent negative reactions to the food. They must properly contain the copper particles so they don’t leave a metallic taste on the food or cause copper poisoning due to an excess amount of copper. Despite copper’s instability, its abundance and cheaper price make it a more viable option than silver for widespread usage, especially when budget constraints are heavy. Furthermore, due to copper’s instability, lower amounts of copper still have potent antimicrobial capabilities, increasing copper’s ability to act as a cost-effective antimicrobial material.

Due to its versatility and abundance, bamboo proves to be a very effective antimicrobial material. It has numerous benefits with few disadvantages such as discouraging the growth of microorganisms, which helps bamboo resist not only bacteria but also insects, fungi, and marine borers. Besides being resistant to microorganisms, bamboo itself contains some natural antibacterial elements, such as bamboo kun, which hinders the proliferation of microorganisms. All these aspects support bamboo as a greatly valued antimicrobial and sustainable packaging material. Furthermore, bamboo is one of the fastest-growing plants in the world with it growing 91 centimeters a day, contributing to the scalability and affordability of this material. Furthermore, bamboo has an immense root system that regenerates itself, a characteristic that saves time and money because farmers don't have to replant bamboo. In addition, since the bamboo packaging materials produced are compostable and biodegradable, they are less harmful to the environment than the current plastic packaging materials. Furthermore, bamboo is highly aesthetic, since an intrinsically refined outward look is distinctive of the plant itself, which transfers onto packaged goods, consequently adding value to food packaging and thus maintaining profits.

Apart from this, bamboo has low environmental impact, high strength and resilience, moisture reduction, and chemical-free safe contact with food. First, Bamboo has a low environmental impact as cultivation requires fewer insecticides and fertilizer than other crops, which in turn reduces the amount of dangerous chemicals that go into water sources through runoff. The strength-to-weight ratio is high for bamboo, making it durable yet light for rough handling and transportation of food products. Thirdly, bamboo is naturally resilient and flexible; hence, it can resist tearing. To this effect, bamboo has natural moisture reduction that insulates food from outside humidity and moisture, thus extending the shelf life. Compared with plastic packing, which involves hazardous chemicals, bamboo can directly contact food without the potential for harmful substances to seep into the food from the packing. Finally, bamboo also has high-quality heat insulation which allows it to maintain the temperature of the food that is packaged. This temperature regulation allows it to preserve the quality and safety of perishable foods while reducing the need for energy consumption as less heat insulation is needed when bamboo is substituted. Considering the natural antimicrobial properties, sustainability, and abundance of bamboo, it makes an outstanding choice for innovative food packaging materials.

Although all these naturally found antimicrobial materials are possible solutions, none came close to the cost-effectiveness and antimicrobial benefits of holy site-based polyethylene nanotube packaging. This type of packaging was researched by Dr.Ünal, a lead developer and researcher at a university in Türkiye, and what she found was that this type of material addresses multiple bacterial issues and is very cost-effective. The issue that this plastic can tackle is the fact that it can handle and kill off microbes better than regular plastic, at roughly a 90% improved efficiency rate. It was also shown to slow down the hormonal reaction of ethylene, the hormone that causes ripening, three times slower (Ünal, 2017). Lastly, for its benefits, holly site-based polyethylene has been shown to delay meat spoiling because of its low oxygen transpiration rate, meaning that it will not allow for oxygen to transpire through the packaging as much as regular plastic, but rather regulates the transportation of oxygen, which is a leading cause in refrigerated meat going bad. As for cost-effectiveness, it is very reliable for biodegradable plastic as there is an abundant supply (Ünal, 2017).

Conclusion

Solving the problem of inadequate food packaging materials is vital in supporting the growing world population and reducing the world's environmental impact to slow climate change. Plastic packaging was estimated to be produced at a rate of 14.5 million tons in 2018 (US EPA, 2023). With most plastic packaging only being used once, wasted plastic pollutes the water and soil creating microplastics. Substituting plastics with new materials that are just as efficient but also environmentally friendly is critical to developing sustainable food packaging processes that preserve human health and the environment.

The amount of total plastic production has been exponentially increasing from 1.5 to 400.3 million metric tons from 1950 to 2022 with food packaging making up 50% of the pollution from plastics made from fossil fuels, the environmental impact of food packaging has been simultaneously increasing (Statista, 2022). From a global population of 2.5 billion in 1950 to an 8 billion population in 2022 and an estimated population of 9.7 billion in 2050, the need for a cost-efficient and environment-friendly alternative to plastic packaging has become imperative. Without innovation, the amount of plastic consumption will continue to increase leading to more pollution which exacerbates climate change's impact to negatively harm millions and eventually billions of humans.

After extensive research, we concluded that the most efficient methods for food packaging are nanotube technology and bamboo specimens like Kyoto-Moso alongside Kyushu-Madake. Despite the numerous benefits of silver and copper such as hindering microorganism growth, the downside is the expensive cost attached to the mining of metals, causing silver and copper to be less scalable for widespread usage for food production. Furthermore, metals are not plentiful, and scaling up the usage of metals could threaten the endangered ecosystems of many species of wildlife, rendering metals an inadequate source of antimicrobial material. Thus we concluded that nanotube technology offers antimicrobial agents stopping bacteria from growing as well as the anti-ripening agents it contains, while also being clay and plant-based, allowing for the plastic to be biodegradable. Bamboo was our alternative to nanotube technology as it also has similar properties such as being naturally antimicrobic through bamboo kun while also being extremely environmentally friendly as it causes less pollution than other naturally grown substances such as paper. Unlike metals, bamboo is also able to absorb over 80 tons of CO_2 per acre per year while being grown.

Even though nanotube technology has a negative public perception because of potential leaching into food products such as meat, studies have shown that the levels of the nanoplastics present are well below the safety limit as regulated by the FDA. These low levels below the safety limit emphasize that nanotube technology improves food safety overall with no adverse health risks when compared to their common Ethylene counterparts. Bamboo is produced naturally with no harmful chemicals that could affect the food which allows it to have zero risk when in direct contact with food, allowing it to be an excellent antimicrobial material that enhances food packaging.

This helps our world as a whole because it helps achieve the SDG of sustainability, contributing to reaching Zero Hunger. By incorporating nanotube technology into food packaging, we will be able to shift the world to be less reliant on non-renewable resources while significantly improving the efficiency and sustainability of our food systems. This is because packaged foods will be able to last longer on the shelf and not harbor bacteria, allowing for less food to go to waste, which directly correlates to the reduction of pollution and climate change. The addition of bamboo into food packaging would acclimate the world to addressing environmental challenges, which would not only foster a healthier planet but also support the well-being of current and future generations. By increasing food safety and preservation, bamboo and nanotube technology will play a crucial role in advocating for environmental sustainability while ensuring global food security.

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References

Alamri, M. S., Qasem, A. A. A., Mohamed, A. A., Hussain, S., Ibraheem, M. A., Shamlan, G., Alqah, H. A., & Qasha, A. S. (2021). Food packaging's materials: A food safety perspective. *Saudi Journal of Biological Sciences*, *28*(8), 4490–4499. https://doi.org/10.1016/j.sjbs.2021.04.047

American Chemical Society. (2017, August 22). *Clay-based antimicrobial packaging keeps food fresh* [Video recording]. https://www.youtube.com/watch?v=6nlf1KbLNxY

Claudio, L. (2012). Our food: Packaging & public health. *Environmental Health Perspectives*, *120*(6), a232–a237. https://doi.org/10.1289/ehp.120-a232

Deshwal, G. Kr., & Panjagari, N. R. (2020). Review on metal packaging: Materials, forms, food Applications, safety, and recyclability. *Journal of Food Science and Technology*, *57*(7), 2377–2392. https://doi.org/10.1007/s13197-019-04172-z

Duda-Chodak, A., Tarko, T., & Petka-Poniatowska, K. (2023). Antimicrobial compounds in food packaging. *International Journal of Molecular Sciences*, *24*(3), 2457. https://doi.org/10.3390/ijms24032457

Fadiji, T., & Pathare, P. B. (2023). Technological advancements in food processing and packaging. *Processes*, *11*(9), 2571. https://doi.org/10.3390/pr11092571

Fakhruddin, K., Hassan, R., Khan, M. U. A., Allisha, S. N., Razak, S. I. A., Zreaqat, M. H., Latip, H. F. M., Jamaludin, M. N., & Hassan, A. (2021). Halloysite nanotubes and halloysite-based composites for biomedical applications. *Arabian Journal of Chemistry*, *14*(9), 103294. https://doi.org/10.1016/j.arabjc.2021.103294

Food loss and waste. (n.d.). Retrieved July 8, 2024, from https://www.nifa.usda.gov/topics/food-loss-waste

Gale—Product login. (n.d.-a). Retrieved July 8, 2024, from https://galeapps.gale.com

Goal 2: Department of Social Affairs. (n.d.). Retrieved July 8, 2024, from https://sdgs.un.org/goals/goal2

Goal 9: Department of Social Affairs. (n.d.). Retrieved July 8, 2024, from https://sdgs.un.org/goals/goal9

Han, J. H. (2014). Chapter 1—A review of food packaging technologies and innovations. In J. H. Han (Ed.), *Innovations in Food Packaging (Second Edition)* (pp. 3–12). Academic Press. https://doi.org/10.1016/B978-0-12-394601-0.00001-1

Innovation at the intersection of food packaging and food safety. (n.d.). Retrieved July 8, 2024, https://www.food-safety.com/articles/8330-innovation-at-the-intersection-of-food-packag ing-and-food-safety

Jiang, Y., Zhang, Y., & Deng, Y. (2023). Latest advances in active materials for food packaging and their application. *Foods*, *12*(22), 4055. https://doi.org/10.3390/foods12224055

Karmaus, A. L., Osborn, R., & Krishan, M. (2018). Scientific advances and challenges in safety evaluation of food packaging materials: Workshop proceedings. *Regulatory Toxicology and Pharmacology*, *98*, 80–87. https://doi.org/10.1016/j.yrtph.2018.07.017

Mura, P., Maestrelli, F., Cirri, M., & Mennini, N. (2022). Multiple roles of chitosan in mucosal drug delivery: An updated review. *Marine Drugs*, *20*(5), 335. https://doi.org/10.3390/md20050335

Ncube, L. K., Ude, A. U., Ogunmuyiwa, E. N., Zulkifli, R., & Beas, I. N. (2020). Environmental impact of food packaging materials: A review of contemporary development from conventional plastics to polylactic acid-based materials. *Materials*, *13*(21), 4994. https://doi.org/10.3390/ma13214994

Nutrition and food systems. (n.d.). Retrieved July 8, 2024, from https://www.nifa.usda.gov/topics/nutrition-food-systems

Openathens. (n.d.). Retrieved July 8, 2024, from https://login.openathens.net/auth/lcps.org/

Ramful, R., Sunthar, T. P. M., Kamei, K., & Pezzotti, G. (2022). Investigating the antibacterial characteristics of Japanese bamboo. *Antibiotics*, *11*(5), 569. https://doi.org/10.3390/antibiotics11050569

Sikora, J. W., Gajdoš, I., & Puszka, A. (2019). Polyethylene-matrix composites with halloysite nanotubes with enhanced physical/thermal properties. *Polymers*, *11*(5), 787. https://doi.org/10.3390/polym11050787

The 17 Goals. (n.d.). Retrieved July 8, 2024, from https://sdgs.un.org/goals

Types of hazards. (n.d.). Food Safety Authority of Ireland. Retrieved July 8, 2024, from https://www.fsai.ie/Business-Advice/Running-a-Food-Business/Food-Safety-Managemen t-System-(HACCP)/Types-of-Hazards

Vasile, C., & Baican, M. (2021). Progresses in food packaging, food quality, and safety—Controlled-release antioxidant and/or antimicrobial packaging. *Molecules*, *26*(5), 1263. https://doi.org/10.3390/molecules26051263

Vivas, K. A., Vera, R. E., Phillips, R. B., Forfora, N., Azuaje, I., Zering, K., Chang, H., Delborne, J., Saloni, D., Dasmohapatra, S., Barbieri, C., Venditti, R. A., Marquez, R., & Gonzalez, R. (2024). An economic analysis of bamboo plantations and feedstock delivered cost in the Southern US for the manufacturing of fiber‐based bioproducts. *Biofuels, Bioproducts and Biorefining*, bbb.2634. https://doi.org/10.1002/bbb.2634