

Towards sustainable food packaging using natural compounds: A review of current research update

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Abstract

The food packaging industry faces significant challenges due to the negative impacts of conventional packaging materials, particularly plastics. These materials contribute to pollution, degrade slowly, and pose risks to both human health and the environment through chemical leaching. Consequently, there is an increasing demand for safer and more sustainable packaging alternatives. Natural compounds, including biopolymers and bioactive substances, provide biodegradable options that mitigate these risks. This review examines various natural materials used for environmentally friendly packaging, such as essential oils, plant extracts, polysaccharides, proteins, lipids, chitosan, cellulose, and starch. This review highlights recent innovations, including advanced biopolymer formulations, hybrid materials, and nanotechnology-based enhancements, which improve the mechanical, antimicrobial, and antioxidant properties of natural packaging solutions. It also presents comparative analyses of these materials, addressing biodegradation rates, life-cycle assessments (LCAs), and their environmental benefits relative to traditional plastics. The review further investigates challenges related to scalability, cost-effectiveness, and regulatory barriers, while also discussing emerging technologies such as machine learning for optimizing materials. The findings offer actionable insights that promote sustainable food packaging solutions aimed at addressing global health and environmental concerns.

Keywords: Antimicrobial activity, Antioxidant activity, Biopolymers, Safe food packaging, Lipids, Plant extracts

Abbreviations:

PE	Polyethylene
PP	Polypropylene
PET	Polyethylene terephthalate
BPA	Bisphenol A
PLA	Polylactic acid
SDG	Secoisolariciresinol diglucoside
PHA	Polyhydroxyalkanoates
SFE	Supercritical fluid extraction
UAE	Ultrasound-assisted extraction
MAE	Microwave-assisted extraction

1. Introduction

The food packaging industry has seen significant changes throughout history, driven by advances in material science and evolving societal needs. In ancient times, civilizations used natural materials such as leaves, animal skins, and woven fibres for food packaging. These early methods helped store and preserve food, marking the start of packaging innovation (Thapliyal et al., 2024). During the Industrial Revolution, new materials such as glass and metal containers emerged, which were more durable and improved food protection and shelf stability. The most transformative change came in the mid-20th century with the introduction of synthetic polymers, especially plastics like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET). These plastics quickly became the most popular materials for food packaging due to their versatility, affordability, and barrier properties, transforming the global food and beverage industries (Asgher et al., 2020; Thapliyal et al., 2024). This comprehensive review examines advances in sustainable food packaging, focusing on developments in natural compounds and significant research has explored renewable, biodegradable materials addressing both environmental impact and functionality, in line with modern industry standards. By reviewing recent innovations in biopolymers, bioactive substances, and other natural compounds, this study evaluates their potential to replace conventional plastics and support a circular economy in food packaging (Agarwal et al., 2023; Barage et al., 2022; Cheng et al., 2024; D’Almeida and de Albuquerque, 2024; Dörnyei et al., 2023; Hamed et al., 2022; Islam et al., 2023; Jacob et al., 2024; Jahangiri et al., 2024; Kóczán and Pásztor, 2024; Nicolescu et al., 2023; Norton et al., 2022; Saharan and Wadhwa, 2024; Versino et al., 2023; Wang et al., 2023; Weligama Thuppahige and Karim, 2022; Westlake et al., 2022; Zhao et al., 2021).

However, despite their advantages, synthetic plastics have introduced severe environmental and health issues. Their non-biodegradable nature leads to persistent pollution in marine and terrestrial environments, where they can take centuries to degrade (Kumar et al., 2021). The production and disposal of plastics also lead to greenhouse gas emissions and environmental harm, with synthetic compounds such as bisphenol A (BPA) and phthalates leaching into food, causing health issues like endocrine disruption, reproductive problems, and cancer (Iroegbu et al., 2021; Ziani et al., 2023). In addition, the occurrence of microplastics in our food and water supplies, frequently resulting from packaging, worsens these concerns, as research now links microplastic ingestion to potential cellular and tissue damage (Ullah et al., 2022). The urgency of these issues has led to an

intensified search for sustainable packaging solutions. In the challenges posed by conventional food packaging materials, particularly synthetic plastics, there is a growing push for sustainable packaging solutions.

Recent advances have identified natural compounds derived from renewable sources as promising alternatives. These materials, including biopolymers sourced from polysaccharides, proteins, and lipids, and bioactive substances such as essential oils and plant extracts, are inherently biodegradable and have smaller environmental footprints compared to traditional plastics (Al Mahmud et al., 2024; González-López et al., 2023). These natural materials are generally less toxic, they reduce health risks, making them more suitable for food applications. Emerging research shows that biopolymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHA) can serve as effective packaging materials, while compounds like chitosan and cellulose offer antimicrobial and antioxidant properties, enhancing both food safety and shelf life (Bhowmik et al., 2022; Siddiqui et al., 2023). The growing concern for environmental issues and the increasing demand among consumers for sustainable products has led to a significant shift towards exploring viable alternatives (Gupta et al., 2020; Muneer et al., 2021). This review investigates the potential of natural compounds as safer and more sustainable solutions for food packaging, focusing specifically on biodegradable materials such as biopolymers, essential oils, and plant extracts (Onyeaka et al., 2022). These materials provide the industry with environmentally responsible and health-oriented packaging alternatives (Boccalon & Gorrasi, 2022). This comprehensive analysis evaluates the effectiveness of these natural materials in preserving food quality, reducing carbon footprints and waste, and ensuring safety for various food packaging applications (Muneer et al., 2021; Gupta et al., 2020). The review aims to establish a correlation between natural compounds and sustainable packaging efforts, enhancing understanding and encouraging the adoption of these materials in the market. By doing so, it creates opportunities for innovative and responsible packaging solutions that align with global sustainability goals. The review identifies future research directions to promote the widespread use of environmentally friendly packaging solutions. By bridging the gap between the environmental challenges posed by synthetic plastics and the opportunities that natural compounds present, this review provides a comprehensive roadmap for advancing sustainability in the food packaging industry (Boccalon & Gorrasi, 2022; Zhang & Sablani, 2021).

2. Classification of plastic and biodegradable materials for food packaging

Food packaging is important for keeping food safe and fresh. It acts as a barrier against things like moisture, oxygen, and contaminants that can damage food quality, safety, and shelf life (Bhowmik et al., 2022). At the same time, the packaging industry has a vital role in protecting the environment, as traditional materials contribute a lot to pollution, which makes it urgent to find new and eco-friendly solutions (Duda-Chodak et al., 2023; Thapliyal et al., 2024). The food packaging sector is increasingly focusing on materials that are functional, safe, and good for the environment (Al Mahmud et al., 2024). As a result, there is growing interest in biodegradable materials that aim to reduce the use of fossil fuels and lessen environmental impact. Food packaging materials can be divided into two main categories: conventional plastics and biodegradable materials. This division helps to understand their properties and effects on the environment, while also pointing out the challenges in developing sustainable packaging solutions.

2.1 Conventional Plastics

For many years, conventional plastics like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) have been the main materials used in food packaging industry. These plastics are popular because they are versatile, strong, and provide excellent barriers against moisture, light, and oxygen, which helps keep food fresh (Asgher et al., 2020). However, they are mostly made from non-renewable, petroleum-based resources and are designed to be long-lasting and resistant to natural degradation processes. Consequently, they are significant contributors to environmental pollution, persisting in landfills and marine environments for hundreds of years, posing long-term threats to ecosystems and wildlife (Iroegbu et al., 2021; Kumar et al., 2021).

The entire lifecycle of conventional plastics, starting from the raw material extraction, through manufacturing, usage, and disposal, contributes substantially to greenhouse gas emissions and resource depletion. It is estimated that plastics make up about 6% of global oil consumption, adding to the burden on limited fossil resources (Ali et al., 2023). Moreover, conventional plastics often contain chemical additives, such as bisphenol A (BPA) and phthalates, which can leach into food products, posing serious health risks, including hormonal disruptions, reproductive issues, and increased cancer risks (Ullah et al., 2022; Ziani et al., 2023). These additives are widely used to enhance plastic flexibility and durability, have led to significant health concerns, particularly

for food-contact materials (Manzoor et al., 2022). To understand the environmental impact of these plastics better, we can use tools like life-cycle assessments (LCAs) and measure CO₂ emissions. For instance, while PET has a lower environmental footprint than some non-recyclable plastics, it still contributes considerably to greenhouse gas emissions during its production.

2.2 Biodegradable materials

Biodegradable materials present a promising, sustainable alternative to conventional plastics in food packaging (González-López et al., 2023). These materials can be classified into two categories: i) natural biodegradable materials and ii) synthetic biodegradable materials. They are derived from renewable resources like polylactic acid (PLA), starch, cellulose, and chitosan (Bhowmik et al., 2022). Biodegradable materials can decompose into non-toxic components through microbial activity, significantly reducing environmental impact (Dai et al., 2022). Unlike synthetic plastics, these materials decompose in natural environments such as compost facilities, soil, or water when they are disposed of correctly (Al Mahmud et al., 2024). In addition, biodegradable materials typically require less energy to produce and result in lower greenhouse gas emissions compared to conventional plastics. This reduction in energy consumption aligns with global efforts to minimize carbon footprints and conserve natural resources (Kaur et al., 2023). However, the effectiveness and biodegradability of these materials can vary widely based on their composition and environmental conditions. Proper infrastructure and waste management practices are essential to fully realize the potential benefits of biodegradable materials (Kumar et al., 2023).

Quantitative comparisons show the environmental advantages of biodegradable materials over conventional plastics. For example, producing PLA generates about 68% fewer CO₂ emissions compared to conventional plastics like PET. Natural polymers like cellulose decompose faster in nature than synthetic alternatives like PLA. Life-cycle assessments (LCAs) for bio-based polyethylene (PE) and polypropylene (PP) show less reliance on fossil fuels but emphasize the need for better recycling and waste management systems. By distinguishing between biodegradable and non-biodegradable plastics and between natural and synthetic biodegradable materials, this classification creates a clearer framework for assessing environmental benefits. Future advancements in recycling technologies and industrial composting systems will further enhance the sustainability of food packaging materials (Cheng et al., 2024).

2.3 Non-biodegradable materials

Non-biodegradable materials are substances that remain in the environment for a long time because natural processes cannot break them down. Common examples of non-biodegradable materials include plastics, glass, metals, synthetic fibres, and electronic waste (E-waste) (Zhang et al., 2020). The introduction of bioplastics has added complexity to conversations about non-biodegradable materials. While bioplastics are often considered a more sustainable choice, research shows that about half of the current bioplastic market consists of non-biodegradable types (Rahman & Bhoi, 2021). This situation creates new challenges in waste management. The disposal of these materials at the end of their life cycle poses significant issues for governments and policymakers.

The production process for non-biodegradable bioplastics typically starts with biomass. This biomass undergoes several modification techniques. These techniques include pretreatment, hydrolysis, and fermentation, which produce bioethanol. This bioethanol is then converted into bioplastics (Rahman & Bhoi, 2021). Notable examples of non-biodegradable bioplastics include bio-polyethylene (bio-PE), bio-polypropylene (bio-PP), bio-polyethylene terephthalate (bio-PET), bio-polytrimethylene terephthalate (Bio-PTT), and bio-polyamide (bio-PA). The chemical structures of these bioplastics are quite like traditional fossil-based plastics. This similarity contributes to their resistance to degradation (Rahman & Bhoi, 2021).

The widespread use of non-biodegradable materials, including certain bioplastics, mainly results from their versatility and low cost. Glass is often used for various containers and decorative items. Metals, such as aluminium and steel, play critical roles in construction and manufacturing industries. Electronic waste consists of outdated phones, computers, and appliances, with its quantity increasing due to rapid technological progress. This type of waste frequently contains hazardous elements, such as heavy metals and toxic chemicals. When not disposed of properly, electronic waste can pose serious risks to ecosystems and human health, impacting various ecosystem services and sustainable development goals (Kumar et al., 2021).

The environmental impact of non-biodegradable waste, including waste from bioplastics, is significant. Large amounts of plastic waste, including bioplastics, accumulate in oceans, rivers, and landfills. This accumulation adversely affects wildlife and disrupts natural systems. For instance, marine animals often ingest plastic debris, mistaking it for food, which can lead to internal injuries or even death (Andrady, 2011). Additionally, glass and metal waste can take

thousands of years to decompose, occupying valuable space in landfills and contributing to urban pollution.

Scientific innovations are leading to alternatives to non-biodegradable materials. Research is underway to develop biodegradable packaging. These new options decompose naturally, thereby causing less harm to the environment. Furthermore, improved waste management technologies are being explored. Techniques such as catalytic pyrolysis for bio-PE and bio-PP, as well as gasification for other bioplastics, are being studied as methods to convert waste into usable fuels (Rahman & Bhoi, 2021). Overall, the understanding of non-biodegradable materials and their impacts on the environment continues to grow. The search for sustainable alternatives is essential for reducing the negative effects of waste on ecosystems and human health. The challenge remains to balance the benefits of these materials with their environmental costs.

3. Environmental implications and sustainability

The environmental impact of food packaging materials goes beyond just their disposal; it includes the entire lifecycle from production to degradation (Ncube et al., 2020). Conventional plastics, such as polyethylene and polypropylene, significantly harm the environment throughout their lifecycle. This harm arises from their reliance on fossil fuels and the high energy needed for extraction, processing, and waste management (Jiao et al., 2024). Extracting fossil fuels can lead to habitat destruction and pollution, while processing and disposing of plastics contribute to greenhouse gas emissions and various pollutants (Kumar et al., 2021). Moreover, the buildup of plastic waste in landfills and oceans poses serious threats to biodiversity and human health due to leachate contamination and the ingestion of microplastics by wildlife (Ullah et al., 2022; Ziani et al., 2023).

On the other hand, biodegradable materials reduce these environmental impacts by lowering fossil fuel use and pollution during production and disposal (Samir et al., 2022). Biodegradable alternatives, like polylactic acid (PLA), chitosan, and starch-based polymers, come from renewable resources and can break down naturally under certain conditions. For effective biodegradation, specific temperature, moisture, and microbial activity conditions are required, which are typically found in industrial composting facilities. This process helps reducing the demand for fossil fuels and decreases waste accumulation in the environment (Dai et al., 2022; Kaur et al., 2023). The advancement of biopolymers and composites continues to promote eco-

friendly packaging solutions, enhancing the functional properties of these materials (Al Mahmud et al., 2024). The PLA-based packaging generally needs temperatures around 58 °C and high humidity to degrade completely within 3-6 months in industrial composting settings, whereas home composting conditions may not always provide the necessary environment (Rezvani Ghomi et al., 2021; Samir et al., 2022). The production of biodegradable materials generally requires less energy and produces fewer greenhouse gases compared to petroleum-based plastics, making them a more sustainable choice. The life cycle assessments (LCA) indicate that producing PLA generates approximately 68% fewer greenhouse gas emissions than producing traditional plastics, aligning with global sustainability goals to reduce carbon emissions and conserve finite natural resources (Arijeniwa et al., 2024; Jiao et al., 2024).

The transition to biodegradable alternatives is essential for addressing the environmental issues associated with conventional plastics. The utilization of natural compounds for safer packaging allows for a balance that preserves both food quality and ecological health (Ncube et al., 2020). However, the success of these materials in reducing waste depends significantly on the availability of proper composting and recycling infrastructure. Investments in industrial composting technologies and heightened public awareness regarding the specific conditions necessary for biodegradation are crucial to ensure the effectiveness of biodegradable packaging (Duda-Chodak et al., 2023; Fortunati et al., 2019; Singh et al., 2022). In a long run, promoting a culture of sustainability in the food packaging industry will enhance environmental responsibility and aid in global efforts to tackle climate change and reduce plastic pollution (Kumar et al., 2021). This transition involves commitments to developing recycling and composting technologies and raising public awareness about biodegradable and compostable packaging. By fostering a responsible approach to packaging, the industry can balance the demands of food preservation and environmental stewardship, ultimately contributing to a healthier planet and more sustainable future (Rezvani Ghomi et al., 2021).

4. Chemistry of phytochemicals

Phytochemicals are naturally occurring bioactive compounds found in plants (Nahar and Sarker, 2019). These compounds play critical roles in plant defence, helping plants fend off pathogens, herbivores, and various environmental stressors. Recent research has garnered significant attention on phytochemicals due to their potential health benefits, antimicrobial properties, and roles in food

preservation and safety (Rathee et al., 2023). They are important in the development of innovative food packaging solutions, offering natural and functional benefits that synthetic additives often do not provide (Dai et al., 2022). Understanding phytochemicals requires classifying these compounds according to their chemical structures and functional properties, which is essential for their effective utilization in food and health applications. The main categories of phytochemicals include polyphenols, terpenoids, alkaloids, and sulphur-containing compounds, each offering unique bioactive properties (Nahar and Sarker, 2019).

4.1 Polyphenols

They are among the most extensively researched phytochemicals due to their potent antioxidant properties (Nahar and Sarker, 2019). They play a vital role in protecting food from oxidative damage by neutralizing free radicals, thus enhancing food quality and extending shelf life (Bhowmik et al., 2022; Dai et al., 2022). Polyphenols are divided into several subclasses, including flavonoids, phenolic acids, lignans, and stilbenes (Nahar and Sarker, 2019). These diverse compounds are abundant in a variety of plant-based foods, such as fruits, vegetables, grains, and teas, providing a natural means of preservation that maintains nutritional quality over time (Ullah et al., 2022).

By preventing oxidative and microbial damage, polyphenols help ensure that food products remain safe and appealing to consumers for longer periods, making them highly valuable in both food production and packaging (Sun et al., 2024). Their inclusion in food packaging technology represents a significant step towards creating sustainable and health-oriented preservation methods (Angane et al., 2022).

4.1.1 Flavonoids

They are a diverse group of polyphenols, encompassing subgroups such as flavonols, flavones, flavanones, flavanols, anthocyanins, and isoflavones (Nahar and Sarker, 2019). Notable representatives of flavonoids include quercetin, kaempferol, and catechins (**Figure 1**). Quercetin and kaempferol are particularly appreciated for their potent antioxidant, anti-inflammatory, and antimicrobial properties, making them invaluable in the realms of food preservation and packaging (Dai et al., 2022).

Flavonoids are found abundantly in commonly consumed foods like apples, berries, onions, and teas, thus providing a readily available source for potential dietary benefits and incorporation into packaging solutions (Ullah et al., 2022). Catechins, especially abundant in green tea, are known for their ability to reduce inflammation and protect cells from oxidative stress, further emphasizing their importance in health-promoting food and packaging initiatives (Siddiqui et al., 2023). These attributes make flavonoids an attractive option for enhancing the ecological and functional profiles of food packaging materials (Angane et al., 2022).

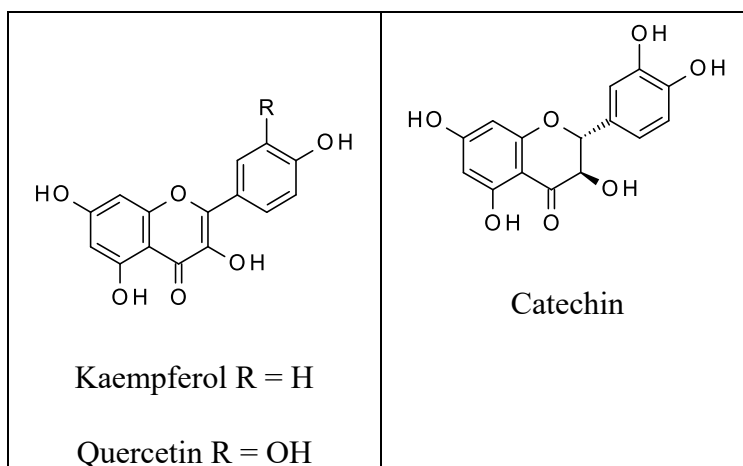


Figure 1: Structure of catechin, kaempferol and quercetin.

4.1.2 Phenolic acids

This group include compounds such as caffeic acid, ferulic acid, and gallic acid (**Figure 2**). These compounds are found in various fruits, vegetables, and whole grains. They are known for their strong antioxidant and anti-inflammatory properties, which help maintain the integrity and safety of food products (Bhowmik et al., 2022). By neutralizing free radicals, phenolic acids reduce oxidative stress, thereby extending shelf life and improving food safety (Dai et al., 2022). In addition, their antimicrobial properties further support food preservation, making phenolic acids valuable for food packaging applications, where they can serve as natural preservatives (González-López et al., 2023). This ability positions phenolic acids as promising agents in food packaging solutions, naturally enhancing food safety and shelf life while meeting the modern demand for sustainable packaging (Ncube et al., 2020).

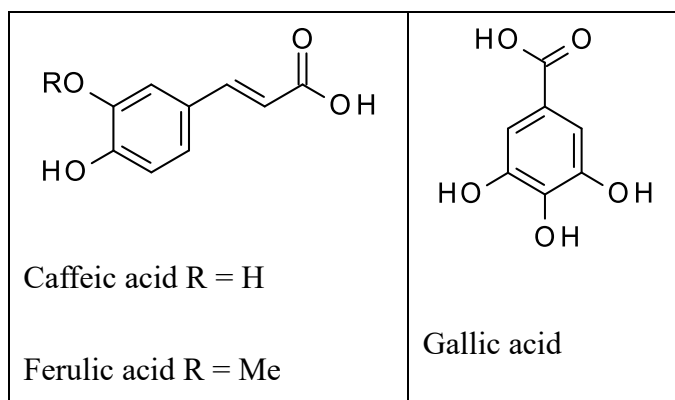


Figure 2: Structure of caffeic, ferulic acid and gallic acids.

4.1.3 Lignans

Found predominately in seeds, whole grains, and vegetables. A notable example is secoisolariciresinol diglucoside (SDG) (**Figure 3**), which exhibits both antioxidant and estrogenic activities. These properties contribute to various health benefits, including the reduction of risks associated with hormone-related cancers (González-López et al., 2023). The antioxidant activity of lignans helps combat oxidative stress, which is essential for maintaining cellular health and preventing the initiation of cancerous processes (Dhyani et al., 2022). Meanwhile, their estrogenic activity can modulate hormone-related functions in the body, offering protective effects against cancers that are influenced by hormonal levels. Due to their health benefits, lignans are increasingly being researched for their potential incorporation into functional food products and innovative packaging materials that may provide health benefits alongside nutritional value (Siddiqui et al., 2023).

4.1.3 Stilbenes

Resveratrol (**Figure 3**) is the most prominent stilbene, commonly found in grapes, berries, and peanuts. It is renowned for its cardioprotective, anti-inflammatory, and anticancer properties. These health benefits stem from its potent antioxidant capabilities, which help neutralize free radicals and reduce oxidative stress in the body (Al Mahmud et al., 2024). Its incorporation into food packaging can enhance the overall antioxidant profile of packaged foods, potentially extending shelf life while providing consumers with additional health benefits. This innovative

use of stilbenes highlights the move towards active packaging solutions that align with current health and wellness trends (Ullah et al., 2022).

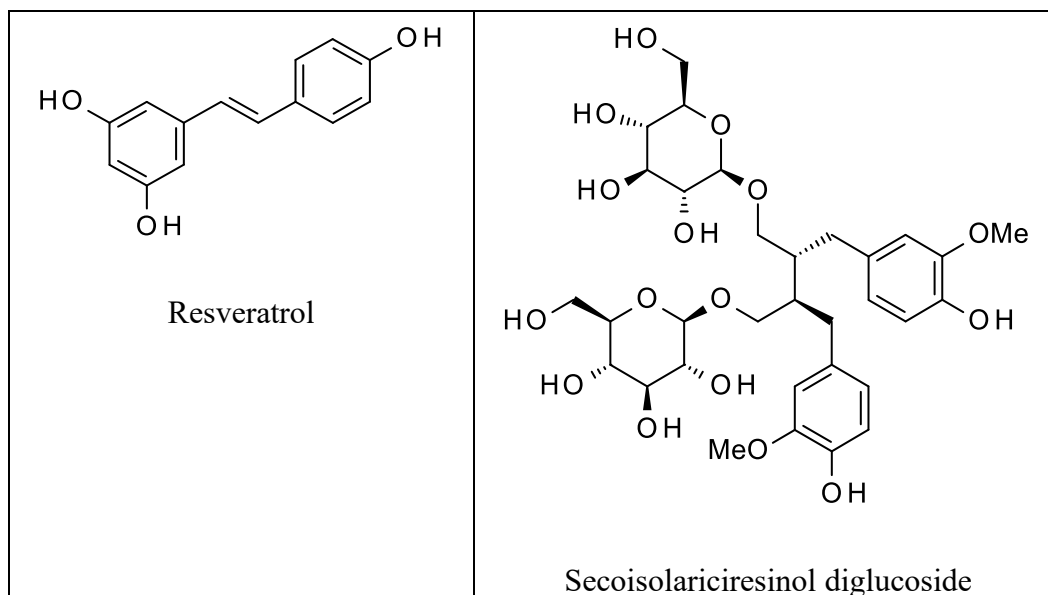


Figure 3: Structure of resveratrol and secoisolariciresinol diglucoside.

4.1.4 Phenylpropanoids

Eugenol (4-allyl-2-methoxyphenol) is a phenylpropanoid with analgesic, antioxidant, anti-inflammatory, and antimicrobial properties. It is effective against bacteria such as *Salmonella typhi*, *Escherichia coli*, and *Staphylococcus aureus*, as well as fungi, and serves as the primary active component of clove oil. Eugenol's antioxidant and antibacterial activities make it suitable for use in food packaging, where it also enhances the hydrophobicity of materials (Beltrán and Valdés, 2021).

Vanillin derived from vanilla beans, is a widely used flavouring agent with strong antimicrobial and antioxidant properties, effective against molds, yeasts, and bacteria. It is used in food preservation, cosmetics, textiles, and pharmaceuticals. Similarly, Cinnamaldehyde found in cinnamon essential oil, exhibits potent antimicrobial activity by disrupting microbial cell membranes due to its phenolic structure. Both compounds are valuable in enhancing product shelf life and safety (Beltrán and Valdés, 2021).

4.2 Terpenoids

These are a diverse class of organic compounds derived from isoprene units (C_5H_8). They are categorized into different groups based on the number of isoprene units they contain, such as monoterpenes, sesquiterpenes, diterpenes, and triterpenes (Nahar and Sarker, 2019). Terpenoids are renowned for their aromatic properties and exhibit a wide range of biological activities, including antimicrobial, anti-inflammatory, and anticancer effects.

4.2.1 Monoterpenes

These compounds are composed of two isoprene units and are commonly found in essential oils, with examples including limonene and menthol (**Figure 4**). Limonene, prevalent in citrus oils, contributes to the distinctive aroma of citrus fruits and possesses antimicrobial properties (Nahar and Sarker, 2019). It is widely used in flavouring, food preservation, and natural packaging solutions due to its potential health benefits, including anti-inflammatory effects. Menthol, found in mint, also offers antimicrobial capabilities, making it valuable in both culinary and medicinal applications (Nahar and Sarker, 2019).

Thymol and carvacrol are monoterpenes found in thyme and oregano essential oils, known for their distinct aromas. Both compounds are used as flavouring agents and safe food preservatives due to their antimicrobial and antioxidant properties. However, their high volatility and temperature sensitivity pose challenges for incorporation into polymer films. These properties make them valuable but require careful handling in food applications (Beltrán and Valdés, 2021)

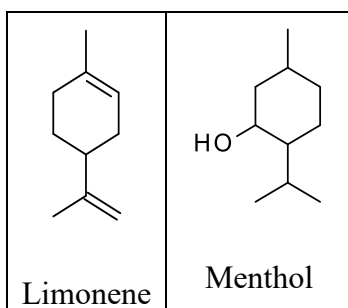


Figure 4: Structure of limonene and menthol.

4.2.2 Sesquiterpenes

These compounds are composed of three isoprene units and are predominantly found in essential oils (Nahar and Sarker, 2019) and typical examples include farnesene and humulene (**Figure 5**). Sesquiterpenes exhibit notable antimicrobial and anti-inflammatory activities, making them beneficial for natural food preservation strategies (de Cássia Da Silveira e Sá et al., 2015). Farnesene is used to control the spoilage of fresh produce due to its ability to inhibit microbial growth. These properties make sesquiterpenes integral to extending the shelf life and maintaining the quality of food products (Masyita et al., 2022).

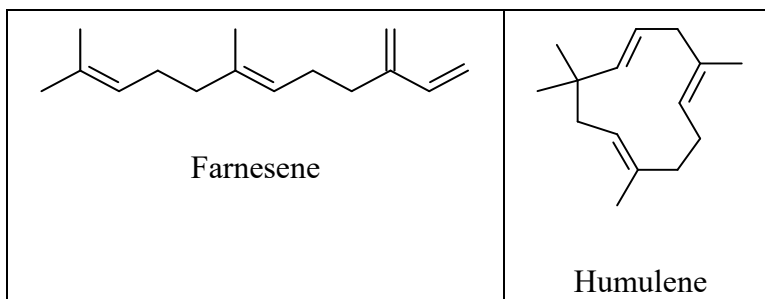


Figure 5: Structure of farnesene and humulene.

4.2.3 *Diterpenes and triterpenes*

They are consisting of four isoprene units, and triterpenes, composed of six, are known for their diverse range of bioactivities (Nahar and Sarker, 2019). They include a large group of compounds such as retinoids and saponins and examples include vitamin A and ginsenoside Rg1, respectively (**Figure 6**), which are recognized for their anticancer, anti-inflammatory, and immune-boosting effects (Zhu et al., 2023). These properties have spurred interest in their application for developing bioactive food packaging materials. By incorporating such compounds into packaging, it is possible to provide not only preservation benefits but also additional health advantages to consumers (Perera et al., 2023; Siddiqui et al., 2023). This approach capitalizes on the multifaceted benefits of these compounds, promoting a holistic and sustainable strategy in food packaging solutions.

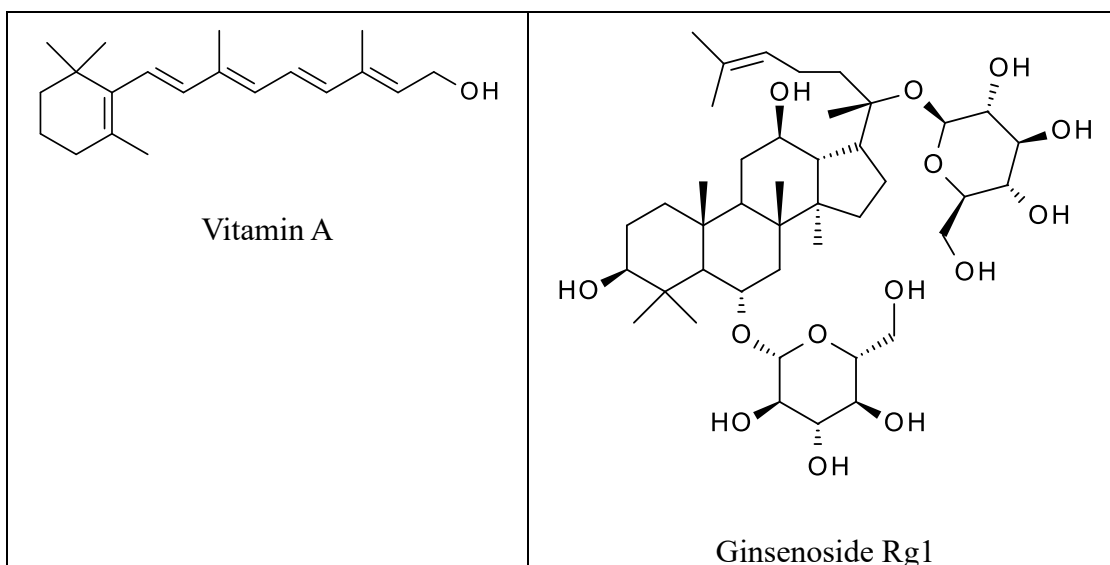


Figure 6: Structure of retinoids (e.g. vitamin A) and saponins (e.g. ginsenoside Rg1).

4.3 Alkaloids

They are naturally occurring compounds found in various plant species, representing a diverse group of phytochemicals characterized by their nitrogen content (Nahar and Sarker, 2019). These nitrogen-containing compounds hold vast potential for biological, medicinal, and pharmacological applications, making them valuable in both traditional and modern medicine (Cordell, 1981). As global attention shifts towards natural therapeutic agents due to their lower toxicity when compared to synthetic alternatives, interest in exploring the therapeutic properties and applications of alkaloids is rapidly increasing (Letchuman et al., 2024).

Recent research has focused on understanding the ecological and molecular factors that influence the medicinal properties of alkaloids. This includes comparative analyses of alkaloid potency across various plant species, considering how environmental factors such as soil composition and climate can impact alkaloid concentration and efficacy (Kaur et al., 2023). Such insights are significant for harnessing the benefits of these compounds in food packaging and preservation, enhancing food safety, and extending shelf life.

4.3.1 *Pyrrrolizidine alkaloids*

Compounds such as senecionine (**Figure 7**) are primarily found in plants from the Senecio genus. While these compounds raise safety concerns due to their potential toxicity, they are also being investigated for their protective roles against microbial spoilage in food packaging applications

(Ullah et al., 2022). Their inherent antimicrobial properties can effectively inhibit the growth of foodborne pathogens, significantly extending the shelf life of food products and enhancing overall food safety.

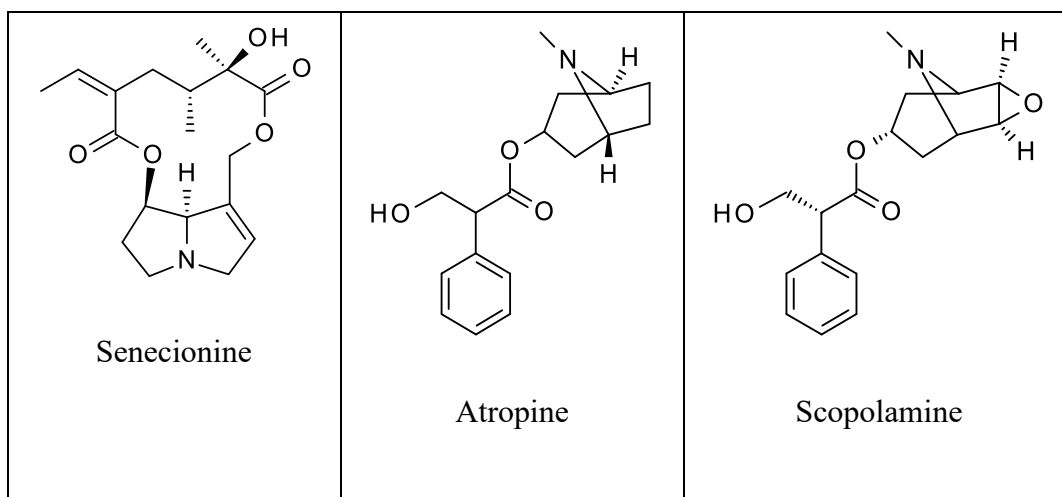


Figure 7: Structure of senecionine, atropine, and scopolamine.

4.3.2 *Tropane alkaloids*

Compounds including atropine and scopolamine (**Figure 7**) are derived from plants like *Atropa belladonna* (belladonna) and *Hyoscyamus niger* (henbane). These alkaloids are known for their therapeutic effects and have potential applications in the development of food packaging materials aimed at preserving food quality (Kumar et al., 2021). Atropine and scopolamine exhibit antimicrobial properties, which can be beneficial in prolonging the freshness and safety of packaged food products.

4.3.3 *Isoquinoline alkaloids*

Compounds such as berberine and morphine (**Figure 8**), represent significant compounds in the realm of pharmacology (Nahar and Sarker, 2019). Berberine, extracted from plants like *Berberis* species, is recognized for its antimicrobial properties and offers potential applications in food packaging aimed at preventing spoilage and enhancing food safety (Pinto et al., 2023). Morphine, widely known for its analgesic effects, showcases the exploration of alkaloids with structures that may possess antimicrobial functions beneficial in food packaging applications.

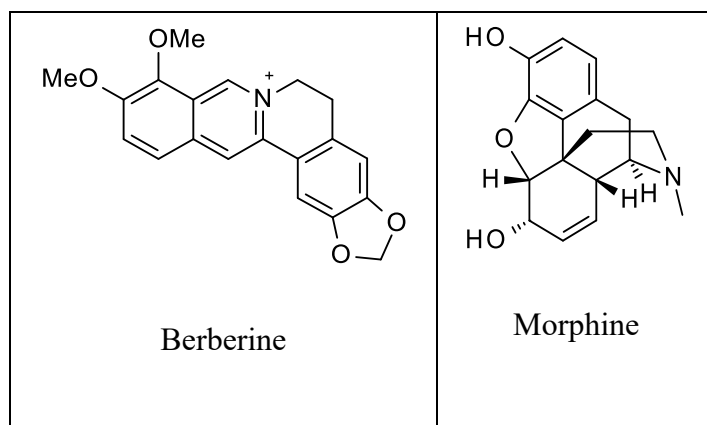


Figure 8: Structure of berberine and morphine.

4.3.4 Indole alkaloids

Compounds including vincristine and reserpine (**Figure 9**), are notable for their significant therapeutic roles in medicine, particularly in the treatment of various diseases. These compounds are derived from plants like *Catharanthus roseus* (commonly known as Madagascar periwinkle) and *Rauwolfia serpentina* (also known as Indian snakeroot), which have been used in traditional medicine for centuries (Cordell, 1981).

Reserpine is primarily employed in hypertension management, working by affecting neurotransmitter storage in nerve endings. This modulation reduces the sympathetic nervous system's output, consequently lowering blood pressure (Ullah et al., 2022). Its historical use underscores the importance of natural compounds in pharmacology.

Vincristine, on the other hand, is widely used in cancer treatment due to its ability to inhibit cell division by interfering with the formation and function of the mitotic spindle during mitosis. This action makes vincristine invaluable in oncology, particularly for treating certain types of leukaemia and lymphomas (Dhyani et al., 2022). The successful application of these alkaloids highlights their potential utility beyond traditional medicine into the realm of food safety and packaging. By utilizing the bioactive properties of indole alkaloids in packaging solutions, researchers aim to create materials that not only preserve food quality but also exert positive health impacts on consumers. This innovative approach could transform packaging materials into more than just protective barriers, actively supporting overall well-being through the incorporation of therapeutic compounds, thereby addressing both food safety and health concerns (Al Mahmud et al., 2024).

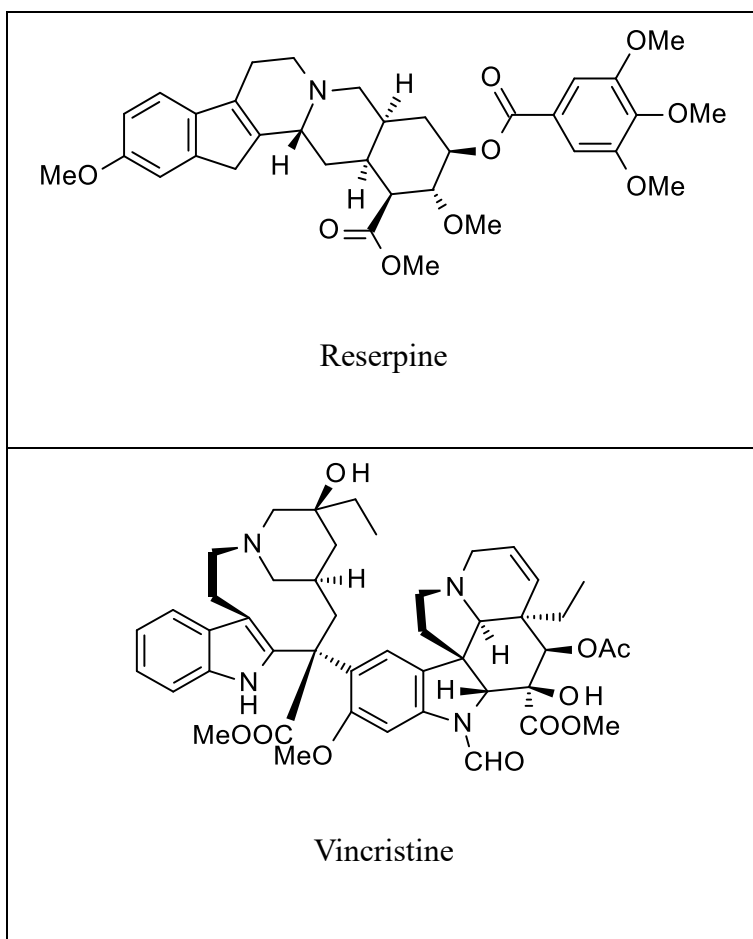


Figure 9: Structure of reserpine and vincristine.

4.4 Sulphur-containing compounds

They are primarily found in cruciferous vegetables and *Allium* species, such as garlic and onions. These compounds play essential roles in both plant defence mechanisms and human health, offering a range of benefits including chemopreventive, antimicrobial, and cardioprotective properties (Nahar and Sarker, 2019).

4.4.1 Glucosinolates

They are sulphur-containing compounds present in vegetables such as broccoli, cabbage, and Brussels sprouts. Upon hydrolysis, these compounds yield bioactive isothiocyanates, which are known for their potential chemopreventive properties. They operate by inducing detoxification enzymes, exhibiting antioxidant activities, and inhibiting carcinogenesis (Ullah et al., 2022). Their

unique ability to activate natural detoxification systems makes them particularly appealing for the development of functional foods and health-enhancing packaging materials (Dhyani et al., 2022). Allyl isothiocyanates derived from glucosinolate hydrolysis by myrosinase, has a pungent, sulphurous aroma typical of Brassica vegetables. It is highly volatile and used in food packaging as an antimicrobial agent against *S. aureus* and *E. coli* (Beltrán and Valdés, 2021). Packaging materials infused with glucosinolates could help extend the shelf life of food while promoting consumer health benefits, aligning with trends towards cleaner, more natural products.

4.4.2 Organosulfur compounds

Compounds such as allicin and *S*-allyl cysteine (**Figure 10**), are abundant in garlic and onions. They are recognized for their potent antimicrobial properties, which can help combat various foodborne pathogens and spoilage organisms. These compounds offer numerous health benefits, including the ability to reduce cholesterol levels and provide cardiovascular protection (Nahar and Sarker, 2019).

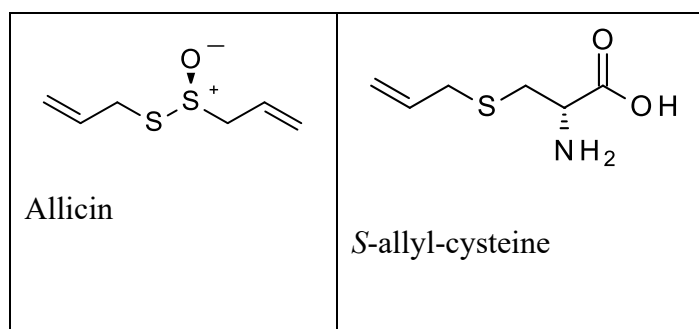


Figure 10: Structure of allicin and *S*-allyl cysteine.

Allicin, known for its strong odour, possesses significant therapeutic effects beyond its antimicrobial roles. Studies suggest it may also have anti-inflammatory and immune-boosting capabilities (Kaur et al., 2023). The incorporation of sulphur-containing compounds into food packaging aids in preservation by utilizing their natural antimicrobial and antioxidant properties. This practice aligns with health and wellness trends by enhancing the safety and longevity of food products. The potential of sulphur-containing phytochemicals to enhance food preservation strategies significantly affects both safety and consumer health (Ullah et al., 2022). This

connection provides a compelling rationale for their inclusion in innovative packaging solutions that emphasize sustainability and eco-friendliness (Kaur et al., 2023).

The incorporation of bioactive alkaloids into food packaging systems represents a progressive approach that enhances food preservation while addressing health and safety concerns related to synthetic materials (Dai et al., 2022; Gupta et al., 2023). Ongoing research into the extraction and application of these compounds is essential to unlock their full potential in food packaging. The integration of alkaloids into packaging materials allows the food industry to meet rising consumer demand for natural and safe alternatives while making significant strides toward environmental sustainability (Al Mahmud et al., 2024; Bhowmik et al., 2022).

The diverse classes of phytochemicals, including polyphenols, flavonoids, phenolic acids, lignans, stilbenes, terpenoids, and alkaloids, provide promising natural alternatives to synthetic preservatives in food packaging (Siddiqui et al., 2023). The enhancement of safety and quality in packaged foods aligns with the growing consumer preference for sustainable and health-conscious packaging solutions (Thapliyal et al., 2024; Zhao et al., 2023).

5. Specific Bioactive and natural compounds in food packaging

The integration of bioactive compounds into food packaging represents a significant advancement in addressing the challenges posed by traditional synthetic materials. Conventional plastics, such as those containing phthalates and bisphenol A (BPA), have been linked to health concerns due to their potential to leach harmful chemicals into food, leading to endocrine disruption, reproductive issues, and other serious health problems (Jiao et al., 2024; Ullah et al., 2022). Moreover, the environmental impact of these materials is profound, as their resistance to degradation contributes to persistent ecological damage, threatening biodiversity (Iroegbu et al., 2021).

Recent advancements in packaging technologies have focused on incorporating bioactive compounds from natural sources. These compounds, including plant extracts, essential oils, chitosan, lignans, and plant-derived vitamins, offer antimicrobial, antioxidant, and effective barrier properties that enhance the functionality of packaging materials (Al Mahmud et al., 2024; Thapliyal et al., 2024). By utilizing these natural elements, the functionality of packaging materials is significantly enhanced, which not only extends the shelf life of food products but also boosts food safety by reducing the risk of microbial contamination and chemical spoilage (Bhowmik et al., 2022).

5.1 Plant extracts and essential oils

Plant extracts and essential oils, like thyme oil, rosemary extract, and oregano oil, have gained popularity in food packaging due to their potent antimicrobial and antioxidant properties (Angane et al., 2022). These bioactive compounds are highly effective in inhibiting the growth of foodborne pathogens, such as *Escherichia coli* and *Staphylococcus aureus*, and preventing oxidation, which helps preserve the freshness and safety of packaged foods without relying on synthetic additives (Dai et al., 2022).

Essential oils achieve their antimicrobial effects by disrupting microbial cell membranes, leading to cell death and preventing spoilage (Bhowmik et al., 2022). Oregano oil, which contains active compounds like carvacrol and thymol, exhibits strong antibacterial properties and is particularly effective against pathogens like *Listeria monocytogenes* and *Salmonella enteritidis* (Kaur et al., 2023; Raybaudi-Massilia et al., 2008). The use of these natural products in food packaging not only assists in extending the shelf life of food but also meets consumer demand for safer, eco-friendly alternatives (Al Mahmud et al., 2024).

The use of natural products in food packaging is rapidly expanding. These products provide a sustainable alternative to synthetic chemicals and offer additional health benefits (Aziman et al., 2021; Babaei-Ghazvini et al., 2021; Coma et al., 2003; Petcu et al., 2023; Raybaudi-Massilia et al., 2008; Sultan et al., 2023; Tao et al., 2021; Vergis et al., 2015). An overview of some of these products, their sources, applications, and antimicrobial effects is shown in **Table 1**.

Table 1: Overview of some natural products involved in food packaging

Natural products	Sources	Food packaging applications	Role of active components in food packaging	Antimicrobial effects	References
Garlic (yellow variant), Onion (white variant)	Bulbs	Storage of chicken and beef meat at 40C (0 and 30 d)	Inhibition of the bacterial strains and a more effective role as butylated hydroxyl toluene (BHT)	Bacillus cereus, Staphylococcus aureus, Pseudomonas aeruginosa and Salmonella typhimurium	(Sultan et al., 2023)
Rosemary, cinnamon	The herb and spice extracts are from local traditional Chinese pharmacies and commercial suppliers.	Vacuum-packed fresh pork	Migrate to food or absorb antioxidative radicals to improve food quality and shelf-life	Escherichia coli, P. fluorescens, and Lactobacillus plantarum	(Raybaudi-Massilia et al., 2008)

Basil encapsulated with propolis	Seed	Food packaging films	Antibacterial effects of film illustrated acceptable efficiency for usage in food packaging system	Staphylococcus aureus, Escherichia coli	(Aziman et al., 2021)
Peppermint, rosemary, cinnamon, bell pepper, clove, mustard, coriander, cumin, thyme, ginger, black pepper, oregano, thyme, sage and vanillin	Leaves	Food storage	Safety of food and the possibility of extending the storage time	Listeria monocytogenes, Bacillus anthracis, Listeria innocua, Staphylococcus aureus, P. fluorescense, B. cereus and L. monocytogenes	(Tao et al., 2021)
Basil	Oil pressing unit (National Research Centre Giza, Egypt)	Food preservation	Antimicrobial inhibition against Gram-positive and Gram-negative bacteria, pathogenic yeast.	Escherichia coli, Staphylococcus aureus, Bacillus cereus bacteria and Candida albicans	(Coma et al., 2003)
Cinnamon, palmarosa, lemongrass, malic acid	Essential oils	Food preservation	Edible coating for improved shelf-life of fresh-cut melon from microbiological and physicochemical points of view	Salmonella enteritidis	(Babaei-Ghazvini et al., 2021)
Sage	Leaves	Food packaging films	Prolonging the storage of chicken breast meat	Staphylococcus aureus, Escherichia coli, and Salmonella typhimurium	(Petcu et al., 2023)
Oregano cinnamon, carvacrol	Essential oils from companies	Food storage	Inhibit the growth and kill Listeria during storage for vegetable products	Listeria gray	(Vergis et al., 2015)

5.1 Chitosan and lignans

Chitosan (**Figure 11**), derived from chitin found in the shells of crustaceans, is a natural polysaccharide that has garnered attention for its excellent film-forming properties and broad-spectrum antimicrobial activity, effectively combating bacteria, yeasts, and moulds (Kumar et al., 2020). It is widely used to develop biodegradable packaging films and coatings, which serve as effective barriers against moisture and gases, helping maintain food quality and extending shelf life (Siddiqui et al., 2023).

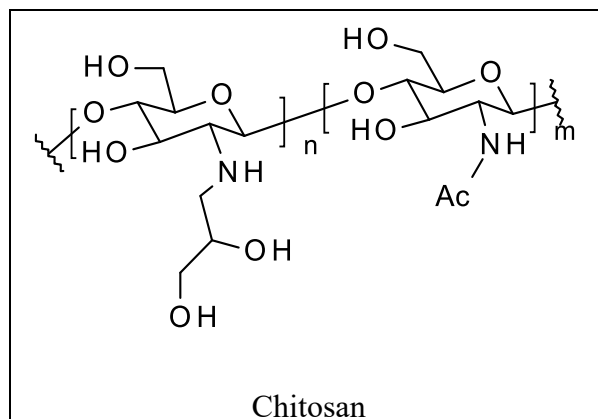


Figure 11: Structure of chitosan.

Lignans, which are primarily found in seeds, whole grains, and vegetables, also show promise in food packaging applications (Nahar and Sarker, 2019). Compounds like secoisolariciresinol diglucoside (SDG) possess antioxidant properties that help protect food from oxidative stress and spoilage (González-López et al., 2023). The integration of lignans into packaging materials enhances their structural integrity and offers additional health benefits, making them favourable for sustainable packaging solutions (Al Mahmud et al., 2024).

5.2 Plant-derived vitamins

Plant-derived vitamins, particularly vitamin E (α -tocopherol) and vitamin C (ascorbic acid) (**Figure 12**), are increasingly utilized in food packaging for their antioxidant properties. These natural antioxidants inhibit oxidative reactions that cause food spoilage, thereby extending shelf life (Nahar and Sarker, 2019). Specifically, vitamin E is effective in preventing lipid oxidation, which helps preserve the quality and freshness of oils, fats, and other lipid-containing foods (Ullah et al., 2022). Similarly, vitamin C stabilizes the colour, flavour, and nutrient content of fruits, vegetables, and beverages by inhibiting oxidation in aqueous environments (Samir et al., 2022).

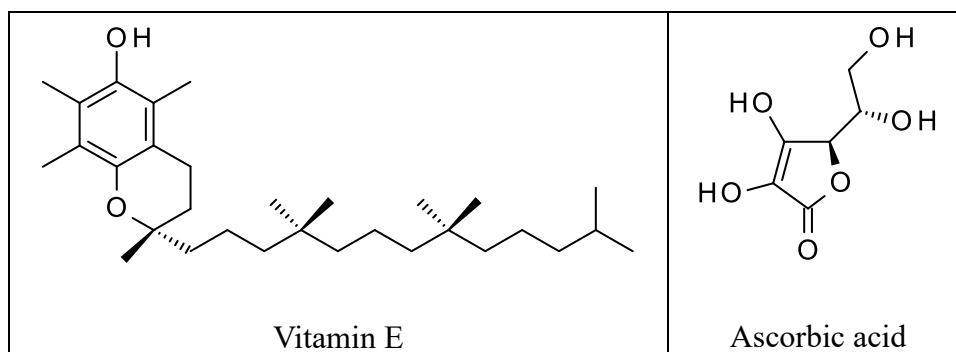


Figure 12: Structure of ascorbic acid and vitamin E.

The incorporation of these vitamins into packaging materials aligns with the rising demand for sustainable and functional packaging solutions that help reduce food waste while promoting consumer wellness (Fortunati et al., 2019). The integration of bioactive compounds into food packaging not only enhances food safety and quality but also addresses environmental concerns associated with traditional plastic packaging (Sheibani et al., 2024). The exploration and application of natural preservatives such as essential oils, flavonoids, chitosan, and plant-derived vitamins reflect a significant shift towards developing packaging solutions that are not only effective in preserving food but also environmentally responsible (Hussain et al., 2021; Lisboa et al., 2024).

The use of bioactive compounds like phytochemicals in food packaging demonstrates a promising strategy to address modern challenges faced by the food industry. By integrating these natural additives into packaging materials, manufacturers can utilize their functional properties to improve food preservation while minimizing dependence on synthetic preservatives. This is particularly important as consumer preferences increasingly lean toward products that are perceived as natural and free from harmful additives (Al Mahmud et al., 2024; Siddiqui et al., 2023).

6. Natural compounds in food packaging

The integration of bioactive compounds into food packaging represents a major stride in tackling the challenges posed by traditional synthetic materials. These compounds, derived from natural sources, enhance the functionality of packaging while promoting sustainability. Biopolymers such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), starch, and cellulose (**Figure 13**) are increasingly used in sustainable packaging due to their biodegradability and minimal environmental impact (Kumari et al., 2022; Perera et al., 2023). These materials offer significant

environmental benefits, decomposing into natural substances like water, carbon dioxide, and biomass under suitable conditions, thereby reducing waste accumulation in ecosystems (Zhao et al., 2023).

6.1 Polylactic acid (PLA)

This acid (**Figure 13**) is obtained from the fermentation of plant sugars and is renowned for its excellent barrier properties against moisture and odours, making it particularly suitable for various food packaging applications (Dai et al., 2022). One of its key advantages is that it biodegrades in industrial composting conditions, potentially reducing plastic waste and environmental impact (Al Mahmud et al., 2024). Studies have shown that PLA can decompose into natural elements within a few months, offering a practical and environmentally friendly alternative to conventional plastics (Thapliyal et al., 2024).

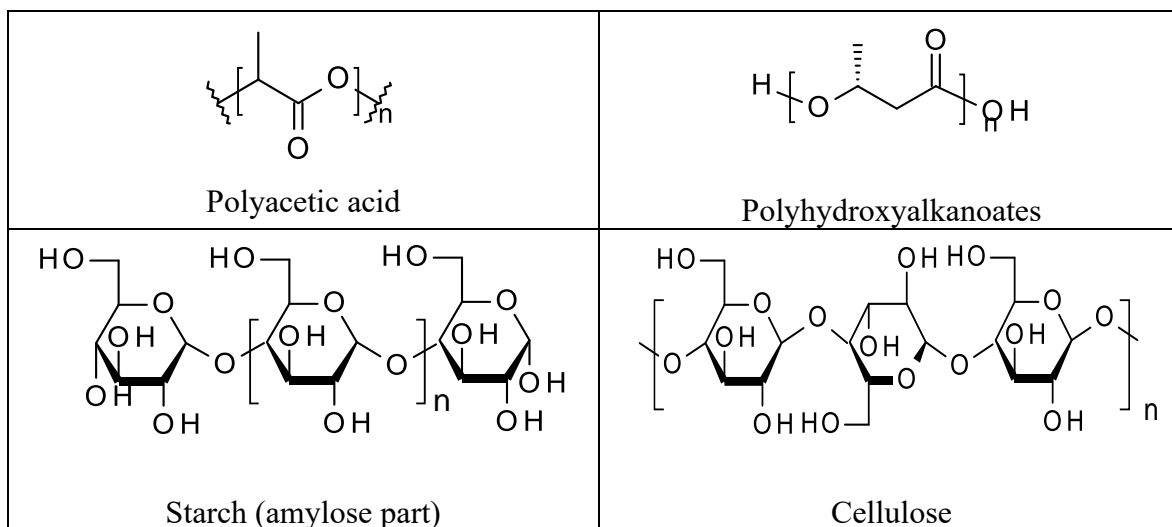


Figure 13: Structure of polyacetic acid, polyhydroxyalkanoates, starch and cellulose.

However, biopolymer-based green packaging faces challenges, including slow crystallization and a limited processing range. The development of high-performance PLA composites, such as those using conductive cellulose nanofiber (CNFene), has enhanced PLA properties. Adding 3 wt% CNFene significantly improved tensile strength (53.7 MPa), crystallinity (33.9%), and reduced cold crystallization temperature by 6.6°C. This strong interaction between CNFene and PLA creates a reinforced network that improves thermal stability and barrier properties. The optimized

PLA-C3 composite meets industrial demands, offering better processing windows, higher thermal decomposition temperatures, and reduced migration levels, making it suitable for green biopackaging (Yan et al., 2024).

6.2 Polyhydroxyalkanoates (PHAs)

These compounds (**Figure 13**) are fully biodegradable polymers produced through the microbial fermentation of sugars and lipids (González-López et al., 2023). They hold high potential for mitigating plastic waste due to their compatibility with natural degradation processes (Samir et al., 2022). PHAs exhibit excellent thermal stability and resistance to moisture and gases, allowing them to effectively package various food products, including perishable items (Bhowmik et al., 2022).

6.3 Starch-based biopolymers

They are sourced from crops such as corn, wheat, and potatoes and are widely used in packaging films and coatings (Ncube et al., 2020). Starch-based packaging materials provide a strong moisture barrier, essential for preserving the quality of fresh produce. Their biodegradable nature significantly helps in reducing plastic waste and environmental harm (Zhao et al., 2023). Additionally, the use of agricultural by-products for extracting starch enhances the sustainability of this packaging option, promoting the circular economy in the food system (Kumar et al., 2021). Biodegradable starch nanocomposites developed from corn starch/nanofibrillated cellulose (CS/NFC) and corn starch/nanofibrillated lignocellulose (CS/NFLC) through film casting show improved mechanical properties. Adding 1–5% NFC and NFLC enhances their performance while reducing water vapor transmission and air permeability, which are essential for food packaging. Although it lowers opacity, transparency, and tear index compared to control samples, the films show significant biodegradability, with over 81% weight loss after 40 days in soil. These results support the industrial potential of CS/NFC and CS/NFLC for sustainable packaging solutions (Malekzadeh et al., 2023).

6.4 Cellulose-Based Biopolymers

They are derived from plant sources, is used to create strong and transparent films with excellent oxygen barrier properties (Perera et al., 2023). These films are especially beneficial for vacuum-

packed products and snack foods that need a longer shelf life. Additionally, cellulose-based films are biodegradable, significantly reducing environmental impact compared to traditional plastics (González-López et al., 2023). The functional properties of cellulose films can be enhanced by adding natural additives, such as essential oils, which provide extra antimicrobial effects (Bhowmik et al., 2022). The replacement of single-use plastic delivery bags with cellulose-based alternatives presents a sustainable solution for reducing environmental pollution. However, the hydrophilic nature and limited mechanical strength of cellulose materials pose challenges. To overcome these issues, zinc oxide (ZnO)-cellulose composite films (CF-90) have been developed using a two-step process inspired by the structure of lotus leaves. This process involves depositing micro-nano ZnO and modifying the cellulose with stearic acid. The CF-90 film, fabricated at 90 °C, demonstrates significant improvements, including a 47.8% increase in tensile strength, exceptional UV protection with a UPF value of 1603.98, high thermal insulation, and remarkable superhydrophobicity with a water contact angle of 163.6°. These attributes position CF-90 as a promising solution for sustainable packaging in the express delivery sector (Liao et al., 2023).

6.5 Protein-Based Biopolymers

These are sourced from materials like casein, soy protein, and whey, are gaining popularity in food packaging (Dai et al., 2022). These materials can produce edible and biodegradable films that enhance the shelf life of various food products. Their ability to inhibit microbial growth while preserving sensory qualities makes them an attractive option for a wide range of food applications (Al Mahmud et al., 2024).

7. Technological innovations

Innovations in technology significantly enhance the quality and yield of natural compounds in sustainable food packaging. The ongoing advancements in technology, including novel extraction methods and the application of nanotechnology, further enhance the potential of these materials, ensuring they meet the requirements of modern food packaging while minimizing environmental impacts. Continued research and industry collaboration will be essential in overcoming existing challenges, optimizing the functionality of natural compounds in packaging, and promoting the widespread adoption of sustainable food packaging solutions (Al Mahmud et al., 2024). Despite the potential of natural compounds for creating sustainable food packaging, several significant

challenges and limitations must be addressed to achieve widespread adoption. These challenges include material properties, economic viability, regulatory frameworks, and consumer acceptance (Al Mahmud et al., 2024; Thapliyal et al., 2024). Regulatory uncertainties about the safety and labelling of biopolymers and bioactive materials further complicate their market acceptance. Overcoming these obstacles requires a multidisciplinary approach, integrating materials science, policy development, and consumer education to enhance the feasibility and implementation of sustainable packaging solutions (Ziani et al., 2023).

7.1 Advanced extraction techniques

These extraction techniques include Supercritical Fluid Extraction (SFE), Ultrasound-Assisted Extraction (UAE), and Microwave-Assisted Extraction (MAE) are essential for efficiently obtaining bioactive compounds from natural sources (Sarker and Nahar, 2012). These extraction techniques are particularly advantageous for preserving sensitive compounds and reducing solvent usage, promoting environmentally sustainable practices. These advancements in extraction technology contribute to the sustainable and efficient utilization of natural compounds in food packaging, promoting the development of safer and more effective solutions aligned with consumer expectations for environmental sustainability and product safety (Thapliyal et al., 2024).

7.1.1 Supercritical Fluid Extraction (SFE)

This method employs supercritical CO₂ to extract bioactive compounds without using toxic solvents, offering a clean and efficient extraction process (Sarker and Nahar, 2012).

7.1.2 Ultrasound-Assisted Extraction (UAE)

This technique utilizes ultrasonic waves to enhance extraction efficiency by disrupting cell structures, allowing for better solvent penetration and quicker recovery of bioactive materials (Sarker and Nahar, 2012).

7.1.3 Microwave-Assisted Extraction (MAE)

This method uses microwave energy to rapidly heat solvent-sample mixtures, promoting the efficient extraction of bioactive compounds. The microwaves cause the polar molecules within the sample to oscillate, generating heat that enhances the dissolution of target compounds (Sarker and

Nahar, 2012). MAE offers several advantages, including reduced extraction time, increased yield, and decreased solvent consumption, making it particularly valuable for extracting temperature-sensitive compounds.

7.2 Nanotechnology in food packaging

Nanotechnology has emerged as a transformative approach to enhance the functionality of natural compounds in food packaging. By incorporating nanoscale additives such as nanoclays, cellulose nanocrystals, and silver nanoparticles into biopolymers, researchers can improve mechanical strength, barrier properties, and stability of packaging materials (Ghasemlou et al., 2024; Zhao et al., 2023). Nanocomposites result in packaging solutions with enhanced properties, contributing to longer shelf life and better protection against environmental factors.

Nanocoatings, applied as thin layers of nanoparticles to packaging surfaces, also provide significant benefits. These coatings increase resistance to oxygen, moisture, and UV light while also offering antimicrobial properties. Such advancements lead to packaging materials that not only preserve food safety but also increase the overall performance in maintaining product quality (Hussain et al., 2024).

7.3 Blending and hybrid materials in packaging

The blending of natural compounds with other materials enhances their properties for specific food packaging applications (Perera et al., 2023). Biocomposites, which combine natural fibres like hemp or jute with biopolymers, create strong, lightweight, and biodegradable packaging materials (Hussain et al., 2024). Hybrid films, incorporating natural extracts or essential oils into biopolymer matrices, provide both antimicrobial benefits and maintain biodegradability. This dual functionality positions them as a sustainable alternative to conventional packaging materials. Moreover, incorporating these natural components into packaging not only enhances their preservation capabilities but also directly addresses the environmental issues associated with traditional petroleum-based plastic packaging (Asgher et al., 2020; Bhowmik et al., 2022).

The integration of natural compounds into food packaging is an effective strategy to enhance food safety, quality, and sustainability. The utilization of biopolymers and bioactive compounds such as essential oils, chitosan, and plant-derived vitamins not only improves the performance of

packaging materials but also aligns with consumer demand for eco-friendly solutions (Kumar et al., 2020; Siddiqui et al., 2023).

The ongoing advancements in technology, including novel extraction methods and the application of nanotechnology, further enhance the potential of these materials, ensuring they meet the requirements of modern food packaging while minimizing environmental impacts. Continued research and industry collaboration will be essential in overcoming existing challenges, optimizing the functionality of natural compounds in packaging, and promoting the widespread adoption of sustainable food packaging solutions (Al Mahmud et al., 2024).

8. Challenges and innovations in food packaging

The advancement of food packaging technologies is crucial in meeting the evolving demands of consumers and the food industry. As the push for sustainable packaging grows, there are significant challenges that must be addressed to ensure that innovative materials perform effectively in real-world applications. Among these challenges are mechanical and barrier properties, which are essential for maintaining food quality and safety. Natural packaging materials, such as biopolymers from renewable sources, present promising alternatives to conventional petroleum-based plastics. However, these materials often struggle to match the mechanical properties, like tensile strength, flexibility, and rigidity, of traditional plastics (Kumar et al., 2023; Perera et al., 2023). Biodegradable materials like polylactic acid (PLA) and starch-based films typically exhibit greater brittleness, limiting their application in high-demand food packaging environments (Asgher et al., 2020; Ncube et al., 2020).

The improvement of mechanical and barrier properties of natural compounds is essential. Advanced processing techniques, such as blending, plasticization, and chemical modifications, are being utilized to enhance the flexibility, strength, and overall performance of biopolymers (Bhowmik et al., 2022). These developments are vital for creating packaging solutions that not only meet stringent safety and quality standards but also align with the green initiatives being adopted across the food industry. As research in this area progresses, it will be imperative for manufacturers and researchers to collaborate in addressing various challenges, including production costs and scalability, regulatory compliance, and consumer acceptance of these materials (Samir et al., 2022). Advanced technologies like machine learning and deep learning offer potential to design and optimize biodegradable materials, helping predict properties, optimize

formulations, and simulate real-world performance. These tools can help predict material properties, optimize formulations, and simulate real-world performance, expediting the development of next-generation packaging solutions.

8.1 Mechanical and barrier properties

One of the primary obstacles in using natural compounds for packaging is achieving mechanical strength and barrier properties comparable to conventional plastics. Biopolymers, such as polylactic acid (PLA) and starch-based films, often exhibit lower tensile strength, flexibility, and resistance to moisture and gases compared to their petroleum-based counterparts (Kumar et al., 2023; Perera et al., 2023). This limits their use in applications requiring high durability and protection. For example, PLA and starch-based films tend to be more brittle and less moisture-resistant compared to polyethylene (PE) or polypropylene (PP), making them unsuitable for certain food packaging applications (Asgher et al., 2020; Ncube et al., 2020).

To address these limitations, advanced processing techniques are employed to enhance the mechanical and barrier properties of biopolymers. These methods include blending, plasticization, and chemical modifications, aimed at improving flexibility and durability (Bhowmik et al., 2022). However, these techniques often necessitate specialized equipment, high energy inputs, and specific processing conditions, which can increase production complexity and costs (González-López et al., 2023).

The chemical cross-linking can enhance the strength and flexibility of biopolymer films, but the selected chemicals must be safe for food contact to ensure consumer safety (Kaur et al., 2023). Addressing these challenges is crucial for improving the performance and cost-effectiveness of natural compound-based packaging materials, emphasizing the need for continued research and innovation to meet the stringent requirements of modern food packaging while supporting environmental sustainability goals (Dai et al., 2022).

8.2 Economic challenges

The production and processing of biopolymers and natural compounds for food packaging often incur higher costs than conventional plastics. The limited scale of current biopolymer production results in higher per-unit costs (Jiao et al., 2024). For instance, the production of polylactic acid (PLA) can be 20-30% more expensive than polyethylene due to the complex fermentation and

polymerization processes involved (Al Mahmud et al., 2024). The necessary infrastructure to produce, process, and recycle biopolymers demands significant upfront investment, posing a barrier for businesses striving to adopt more sustainable packaging solutions.

Improving the economic feasibility of natural compound-based packaging relies on scaling up production, optimizing processing methods, and reducing raw material costs through innovations in biotechnology and agricultural practices (Samir et al., 2022). Utilizing agricultural waste streams, such as corn stover and sugar beet pulp, as raw materials can help reduce costs and promote a circular economy model in food packaging (Ghasemlou et al., 2024; Ncube et al., 2020). Recent advancements in food packaging production, particularly those derived from agri-food waste and by-products, demonstrate promising market trends for sustainable development (Cristofoli et al., 2023).

8.3 Regulatory challenges

The regulatory environment presents significant obstacles to adopting natural compound-based food packaging solutions (Grazyna and Turek, 2022). One major issue is the lack of standardized guidelines and certifications for biopolymers and bio-based materials, complicating efforts to ensure safety, quality, and environmental compliance across different markets (Thapliyal et al., 2024). The inconsistencies within the regulatory landscape discourage manufacturers from adopting these materials due to the complexities involved in navigating diverse regulatory frameworks (Samir et al., 2022). Regulatory standards regarding the biodegradability, compostability, and food safety hinder consumer trust and market acceptance of biopolymer packaging. For instance, the absence of clear definitions and testing methods for biodegradability can create uncertainty for manufacturers and consumers alike. Therefore, the harmonization of regulations and the development of robust certification systems aligned with international standards are crucial for ensuring consistency and fostering confidence in biopolymer-based packaging solutions (Ziani et al., 2023). By addressing these regulatory challenges, the industry can pave the way for broader adoption of sustainable packaging solutions, ultimately benefiting both consumers and the environment.

8.4 Consumer acceptance

Consumer acceptance is vital for the widespread adoption of biopolymer food packaging (Hussain et al., 2024). Many consumers are accustomed to the performance and reliability of conventional plastics, which often outperform biopolymer alternatives in terms of strength, flexibility, and transparency (Singh et al., 2022). This perceived inferiority, along with a lack of awareness about the environmental benefits of biopolymers, contributes to consumer scepticism regarding natural alternatives (Gupta et al., 2023). The education of consumers on the environmental advantages and the practical benefits afforded by biopolymer packaging is imperative. The implementation of strategies such as the transparent labelling, the tailored marketing approaches, and the awareness campaigns is crucial (Dhyani et al., 2022). These strategies play a pivotal role in realigning consumer preferences towards sustainable solutions. In addition, they significantly contribute to the increase in demand for packaging based on natural compounds (Singh et al., 2022). As consumer awareness continues to grow, it will pave the way for a broader acceptance of biopolymer food packaging and contribute to a more sustainable future

8.5 Innovations and collaborations

The innovation in materials science, engineering, and policy is critical to overcoming these challenges (Fortunati et al., 2019). The development of cost-effective processing methods, such as optimizing the fermentation and polymerization processes for biopolymers, can significantly reduce production costs and increase competitiveness with conventional plastics (Kaur et al., 2023). The enhancement of the performance of natural materials through chemical modifications, cross-linking, or blending with other polymers can improve mechanical strength, flexibility, and barrier properties, thereby broadening their suitability for various packaging applications (Zhao et al., 2023). The establishment of comprehensive regulatory standards is vital for ensuring consistency, safety, and quality in biopolymer packaging. The efforts that are currently underway to harmonize these standards globally reflect the importance of standardization in this field (Grazyna and Turek, 2022). The collaborations among industry stakeholders, governmental bodies, and research institutions are critical in addressing barriers. Such partnerships facilitate the sharing of knowledge, the development of innovative solutions, and the implementation of supportive policies and standards (González-López et al., 2023).

9. The future outlook and recommendations

The future of natural compound-based food packaging is promising. Significant efforts aim to improve its effectiveness. The major focus is on the mechanical properties of biopolymers (Ibrahim et al., 2022; Kumar et al., 2023). A major focus is on the improvement of the mechanical properties of biopolymers, such as the enhancement of these materials through cross-linking, blending, and the incorporation of nanocellulose or natural fibres to increase durability (Dai et al., 2022). Research also aims to advance the barrier properties of these materials. The application of advanced coatings and nano-additives can improve the resistance to moisture, oxygen, and UV light, which helps to keep food fresh for longer periods (Singh et al., 2022). Nanomaterials, such as clay nanoparticles, show promise in the reinforcement of biodegradable films without affecting their compostability, thus maintaining their eco-friendly characteristics (Zhao et al., 2023).

Ongoing work is essential to the enhancement of production processes for these materials. The goals of the reduction of costs and improvement of extraction efficiency are critical in achieving greater viability for these natural compounds. The use of techniques such as genetic engineering and microbial fermentation can significantly enhance biopolymer yields, making these materials more competitive against traditional plastics (Rathee et al., 2023). The integration of natural compounds into food packaging offers a sustainable solution to the environmental and health challenges posed by conventional packaging materials. By addressing the challenges of mechanical properties, economic feasibility, regulatory frameworks, and consumer acceptance, the food packaging industry can accelerate the transition toward more eco-friendly practices. Collaborative efforts among stakeholders, supported by continuous innovation and technological advancement, are imperative to realizing the full potential of natural compounds in food packaging (Ghasemlou et al., 2024; Thapliyal et al., 2024).

10. Conclusion

Natural compounds derived from renewable sources offer promising solutions to the environmental and health challenges posed by conventional plastics in food packaging. Biopolymers, plant extracts, and bioactive compounds serve as sustainable and functional alternatives, aligning with the global emphasis on eco-friendly practices. However, challenges remain in achieving mechanical strength and barrier properties comparable to conventional plastics, reducing production costs, and navigating regulatory complexities. Despite these hurdles,

the future looks optimistic. The continuous advancements in science and technology are expected to enhance the properties of biopolymers and facilitate their adoption in food packaging.

A comparative analysis of various studies highlights the optimum properties of these materials, such as biodegradability, mechanical strength, and antimicrobial activity. These properties are crucial for the industry's growth and adoption. By employing innovations in extraction methods, life-cycle assessments, and advanced technologies like machine learning, the industry can further enhance the performance and scalability of biodegradable materials. The collaborative efforts among scientists, policymakers, and industry stakeholders are crucial for overcoming these barriers. By prioritizing natural materials, the food packaging industry can address consumer demands and promote environmental sustainability, thereby creating a greener future in which natural packaging solutions benefit both society and the planet.

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References

- Agarwal, A., Shaida, B., Rastogi, M., Singh, N.B., 2023. Food packaging materials with special reference to biopolymers-properties and applications. *Chem. Africa*. 6, 117-144. doi.org/10.1007/s42250-022-00446-w
- Al Mahmud, M.Z., Mobarak, M.H., Hossain, N., 2024. Emerging trends in biomaterials for sustainable food packaging: A comprehensive review. *Heliyon* 10. doi: 10.1016/j.heliyon.2024.e24122
- Ali, S.S., Abdelkarim, E.A., Elsamahy, T., Al-Tohamy, R., Li, F., Kornaros, M., Zuorro, A., Zhu, D., Sun, J., 2023. Bioplastic production in terms of life cycle assessment: A state-of-the-art review. *Envir. Sci. Ecotechnol.* 15, 100254. doi.org/10.1016/j.ese.2023.100254
- Andrady, A.L., 2011. Microplastics in the marine environment. *Mar. Pollut. Bull.* 62(8), 1596-1605. doi.org/10.1016/j.marpolbul.2011.05.030
- Angane, M., Swift, S., Huang, K., Butts, C.A., Quek, S.Y., 2022. Essential oils and their major components: an updated review on antimicrobial activities, mechanism of action and their potential application in the food industry. *Foods*. 11(3), 464. doi: 10.3390/foods11030464
- Arijeniwa, V.F., Akinsemolu, A.A., Chukwugozie, D.C., Onawo, U.G., Ochulor, C.E., Nwauzoma, U.M., Kawino, D.A., Onyeaka, H., 2024. Closing the loop: A framework for tackling single-use plastic waste in the food and beverage industry through circular economy-a review. *J. Environ. Manage.* 359, 120816. doi.org/10.1016/j.jenvman.2024.120816
- Asgher, M., Qamar, S.A., Bilal, M., Iqbal, H.M., 2020. Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. *Food Res. Int.* 137, 109625. doi:10.1016/j.foodres.2020.109625
- Aziman, N., Jawaid, M., Mutalib, N.A., Yusof, N., Nadrah, A., Nazatul, U., Tverezovskiy, V., Tverezovskaya, O., Fouad, H., Braganca, R., 2021. Antimicrobial potential of plastic films incorporated with sage extract on chicken meat. *Foods*. 10, 2812. doi: 10.3390/foods10112812
- Babaei-Ghazvini, A., Acharya, B., Korber, D.R., 2021. Antimicrobial biodegradable food packaging based on chitosan and metal/metal-oxide bio-nanocomposites: A review. *Polymers*. 13, 2790. doi: 10.3390/polym13162790

- Barage, S., Lakkakula, J., Sharma, A., Roy, A., Alghamdi, S., Almeahmadi, M., Hossain, M.J., Allahyani, M., Abdulaziz, O., 2022. Nanomaterial in food packaging: A comprehensive review. *J. Nanomaterials*. 6053922. doi.org/10.1155/2022/6053922
- Bhowmik, S., Agyei, D., Ali, A., 2022. Bioactive chitosan and essential oils in sustainable active food packaging: Recent trends, mechanisms, and applications. *Food. Packag. Shelf. Life*. 34, 100962. doi: 10.1016/j.fpsl.2022.100962
- Beltrán S, A and Valdés G, A., 2021. New Trends in the Use of Volatile Compounds in Food Packaging. *Polymers*. 13, 1053. https://doi.org/10.3390/polym13071053
- Boccalon, E., Gorrasi, G., 2022. Functional bioplastics from food residual: Potentiality and safety issues. *Compr. Rev. Food Sci. Food Safety*. 21, 3177–3204. doi:10.1111/1541-4337.12986
- Cheng, J., Gao, R., Zhu, Y., Lin, Q., 2024. Applications of biodegradable materials in food packaging: A review. *Alex. Eng. J*. 91, 70-83. doi.org/10.1016/j.aej.2024.01.080
- Coma, V., Deschamps, A., Martial-Gros, A., 2003. Bioactive packaging materials from edible chitosan polymer—antimicrobial activity assessment on dairy-related contaminants. *J. Food Sci*. 68, 2788-2792. doi: 10.1111/j.1365-2621.2003.tb05806.x
- Cordell, G.A., 1981. *Introduction to alkaloids: A biogenetic approach*. willy.
- Cristofoli, N. L., Lima, A. R., Tchoukouang, R. D. N., Quintino, A. C., & Vieira, M. C. (2023). Advances in the Food Packaging Production from Agri-Food Waste and By-Products: Market Trends for a Sustainable Development. *Sustainability*, 15(7), 6153. doi.org/10.3390/su15076153
- Dai, J., Sameen, D.E., Zeng, Y., Li, S., Qin, W., Liu, Y., 2022. An overview of tea polyphenols as bioactive agents for food packaging applications. *Lwt* 167, 113845. doi: 10.1016/j.lwt.2022.113845
- de Cássia Da Silveira e Sá, R., Andrade, L.N., De Sousa, D.P., 2015. Sesquiterpenes from essential oils and anti-inflammatory activity. *Nat. Prod. Commun*. 10(10), 1934578X1501001033. doi: 10.1177/1934578X1501001033
- Dhyani, P., Quispe, C., Sharma, E., Bahukhandi, A., Sati, P., Attri, D.C., Szopa, A., Sharifi-Rad, J., Docea, A.O., Mardare, I., 2022. Anticancer potential of alkaloids: a key emphasis to colchicine, vinblastine, vincristine, vindesine, vinorelbine and vincamine. *Cancer Cell Int*. 22, 206. https://doi: 10.1186/s12935-022-02624-9

- Dörnyei, K.R., Uysal-Unalan, I., Krauter, V., Weinrich, R., Incarnato, L., Karlovits, I., Colelli, G., Chrysochou, P., Fenech, M.C., Pettersen, M.K., 2023. Sustainable food packaging: An updated definition following a holistic approach. *Front. Sustain. Food Syst.* 7, 1119052. doi: 10.3389/fsufs.2023.1119052
- Duda-Chodak, A., Tarko, T., Petka-Poniatowska, K., 2023. Antimicrobial compounds in food packaging. *Int. J. Mol. Sci.* 24(3), 2457. doi: 10.3390/ijms24032457
- Fortunati, E., Mazzaglia, A., Balestra, G.M., 2019. Sustainable control strategies for plant protection and food packaging sectors by natural substances and novel nanotechnological approaches. *J. Sci. Food Agric.* 99, 986-1000. doi: 10.1002/jsfa.9341
- Ghasemlou, M., Barrow, C.J., Adhikari, B., 2024. The future of bioplastics in food packaging: An industrial perspective. *Food Packag. Shelf Life.* 43, 101279. doi: 10.1016/j.fpsl.2024.101279
- González-López, M.E., Calva-Estrada, S.d.J., Gradilla-Hernández, M.S., Barajas-Álvarez, P., 2023. Current trends in biopolymers for food packaging: a review. *Front. Sustain. Food Syst.* 7, 1225371. doi: 10.3389/fsufs.2023.1225371
- Grazyna, K., Turek, J., 2022. What Hinders the Development of a Sustainable Compostable Packaging Market? *Eur. J. Sustain. Develop.* 11(4), 180-180. doi: 10.14207/ejsd.2022.v11n4p180
- Gupta, H., Kumar, H., Kumar, M., Gehlaut, A.K., Gaur, A., Sachan, S., Park, J.-W., 2020. Synthesis of biodegradable films obtained from rice husk and sugarcane bagasse to be used as food packaging material. *Environ. Eng. Res.* 25, 506–514. doi:10.4491/eer.2019.191
- Gupta, R.K., Abd El Gawad, F., Ali, E.A., Karunanithi, S., Yugiani, P., Srivastav, P.P., 2023. Nanotechnology: Current applications and future scope in food packaging systems. *Measurement: Food*, 13, 100131. doi: 10.1016/j.meafao.2023.100131
- Hamed, I., Jakobsen, A.N., Lerfall, J., 2022. Sustainable edible packaging systems based on active compounds from food processing byproducts: A review. *Compr. Rev. Food Sci. Food Saf.* 21, 198-226. doi.org/10.1111/1541-4337.12870
- Hussain, M.A., Sumon, T.A., Mazumder, S.K., Ali, M.M., Jang, W.J., Abualreesh, M.H., Sharifuzzaman, S., Brown, C.L., Lee, H.-T., Lee, E.-W., 2021. Essential oils and chitosan as alternatives to chemical preservatives for fish and fisheries products: A review. *Food Control.* 129, 108244. doi: 10.1016/j.foodcont.2021.108244

- Hussain, S., Akhter, R., Maktedar, S.S., 2024. Advancements in sustainable food packaging: from eco-friendly materials to innovative technologies. *Sustainable Food Technol.* 2, 1297-1364. doi: 10.1039/D4FB00084F
- Ibrahim, I.D., Hamam, Y., Sadiku, E.R., Ndambuki, J.M., Kupolati, W.K., Jamiru, T., Eze, A.A., Snyman, J., 2022. Need for sustainable packaging: an overview. *Polymers.* 14, 4430. doi.org/10.3390/polym14204430
- Iroegbu, A.O.C., Ray, S.S., Mbarane, V., Bordado, J.C., Sardinha, J.P., 2021. Plastic pollution: a perspective on matters arising: challenges and opportunities. *ACS omega.* 6(30), 19343-19355. doi: 10.1021/acsomega.1c02760
- Islam, M., Saini, P., Das, R., Shekhar, S., Sinha, A., Prasad, K., 2023. Rice straw as a source of nanocellulose for sustainable food packaging materials: a review. *BioResources.* 18, 2351. doi:10.15376/biores.18.1.Islam
- Jacob, J., Linson, N., Mavelil-Sam, R., Maria, H.J., Pothan, L.A., Thomas, S., Kabdrakhmanova, S., Laroze, D., 2024. Poly (lactic acid)/nanocellulose biocomposites for sustainable food packaging. *Cellulose*, 1-46. doi.org/10.1007/s10570-024-05975-w
- Jahangiri, F., Mohanty, A.K., Misra, M., 2024. Sustainable biodegradable coatings for food packaging: challenges and opportunities. *Green Chem.* 26, 4934-4974. doi: [10.1039/D3GC02647G](https://doi.org/10.1039/D3GC02647G)
- Jiao, H., Ali, S.S., Alsharbaty, M.H.M., Elsamahy, T., Abdelkarim, E., Schagerl, M., Al-Tohamy, R., Sun, J., 2024. A critical review on plastic waste life cycle assessment and management: Challenges, research gaps, and future perspectives. *Ecotoxicol. Environ. Saf.* 271, 115942. doi: 10.1016/j.ecoenv.2024.115942
- Kaur, J., Singh, J., Rasane, P., Gupta, P., Kaur, S., Sharma, N., Sowdhanya, D., 2023. Natural additives as active components in edible films and coatings. *Food Biosci.* 53, 102689. doi: 10.1016/j.fbio.2023.102689
- Kóczán, Z., Pásztor, Z., 2024. Overview of Natural Fiber-Based Packaging Materials. *J. Nat. Fibers.* 21, 2301364. doi.org/10.1080/15440478.2023.2301364
- Kumar, R., Lalnundiki, V., Shelare, S.D., Abhishek, G.J., Sharma, S., Sharma, D., Kumar, A., Abbas, M., 2023. An investigation of the environmental implications of bioplastics: Recent advancements on the development of environmentally friendly bioplastics solutions. *Environ. Res.* 244, 117707. doi: 10.1016/j.envres.2023.117707

- Kumar, R., Verma, A., Shome, A., Sinha, R., Sinha, S., Jha, P.K., Kumar, R., Kumar, P., Shubham, Das, S., 2021. Impacts of plastic pollution on ecosystem services, sustainable development goals, and need to focus on circular economy and policy interventions. *Sustainability*. 13(17), 9963. doi: 10.3390/su13179963
- Kumar, S., Mukherjee, A., Dutta, J., 2020. Chitosan based nanocomposite films and coatings: Emerging antimicrobial food packaging alternatives. *Trends Food Sci. Technol.* 97, 196-209. doi: 10.1016/j.tifs.2020.01.002
- Kumari, S.V.G., Pakshirajan, K., Pugazhenti, G., 2022. Recent advances and future prospects of cellulose, starch, chitosan, polylactic acid and polyhydroxyalkanoates for sustainable food packaging applications. *Int. J. Biol. Macromol.* 221, 163-182. doi: 10.1016/j.ijbiomac.2022.08.203
- Letchuman, S., Madhuranga, H.D., Kaushalya, M., Premarathna, A.D., Saravanan, M., 2024. Alkaloids Unveiled: A Comprehensive Analysis of Novel Therapeutic Properties, Mechanisms, and Plant-Based Innovations. *Intell. Pharm.* 27. doi: 10.1016/j.ipha.2024.09.007
- Liao, Y., Wang C., Dong, Y., Yu, HY., 2023. Robust and versatile superhydrophobic cellulose-based composite film with superior UV shielding and heat-barrier performances for sustainable packaging. *Int J. Biolog. Macromol.* 253(5), 31, 127178. doi.org/10.1016/j.ijbiomac.2023.127178
- Lisboa, H.M., Pasquali, M.B., dos Anjos, A.I., Sarinho, A.M., de Melo, E.D., Andrade, R., Batista, L., Lima, J., Diniz, Y., Barros, A., 2024. Innovative and Sustainable Food Preservation Techniques: Enhancing Food Quality, Safety, and Environmental Sustainability. *Sustainability*. 16(18), 8223. doi: 10.3390/su16188223
- Malekzadeh, E., Tatari, A., Dehghani Firouzabadi, M., 2023, Preparation, characteristics, and soil-biodegradable analysis of corn starch/nanofibrillated cellulose (CS/NFC) and corn starch/nanofibrillated lignocellulose (CS/NFLC) films. *Carbohydr. Polym.* 309, 120699. doi.org/10.1016/j.carbpol.2023.120699
- Manzoor, M.F., Tariq, T., Fatima, B., Sahar, A., Tariq, F., Munir, S., Khan, S., Nawaz Ranjha, M.M.A., Sameen, A., Zeng, X.-A., 2022. An insight into bisphenol A, food exposure and its adverse effects on health: A review. *Front. Nutr.* 9, 1047827. doi: 10.3389/fnut.2022.1047827
- Masyita, A., Sari, R.M., Astuti, A.D., Yasir, B., Rumata, N.R., Emran, T.B., Nainu, F., Simal-Gandara, J., 2022. Terpenes and terpenoids as main bioactive compounds of essential oils, their

- roles in human health and potential application as natural food preservatives. *Food. Chem. X.* 13, 100217. doi: 10.1016/j.fochx.2022.100217
- Muneer, F., Nadeem, H., Arif, A., Zaheer, W., 2021. Bioplastics from biopolymers: An eco-friendly and sustainable solution to plastic pollution. *Polymer Sci. Series C* 63, 47–63. doi:10.1134/s1811238221010057
- Nahar, L., Sarker, S.D., 2019. *Chemistry for pharmacy students: general, organic and natural product chemistry.* John Wiley & Sons.
- 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. doi: 10.3390/ma13214994
- Nicolescu, C.M., Bumbac, M., Buruleanu, C.L., Popescu, E.C., Stanescu, S.G., Georgescu, A.A., Toma, S.M., 2023. Biopolymers produced by lactic acid Bacteria: characterization and food application. *Polymers.* 15, 1539. doi.org/10.3390/polym15061539
- Norton, V., Waters, C., Oloyede, O., Lignou, S., 2022. Exploring Consumers Understanding and Perception of Sustainable Food Packaging in the UK. *Foods.* 11(21), 3424. doi.org/10.3390/foods11213424
- Onyeaka, H., Obileke, K., Makaka, G., Nwokolo, N., 2022. Current research and applications of starch-based biodegradable films for food packaging. *Polymers* 14, 1126. doi:10.3390/polym14061126
- Perera, K.Y., Jaiswal, A.K., Jaiswal, S., 2023. Biopolymer-based sustainable food packaging materials: challenges, solutions, and applications. *Foods.* 12, 2422. doi:10.3390/foods12122422
- Petcu, C.D., Tăpăloagă, D., Mihai, O.D., Gheorghe-Irimia, R.-A., Negoită, C., Georgescu, I.M., Tăpăloagă, P.R., Borda, C., Ghimpețeanu, O.M., 2023. Harnessing natural antioxidants for enhancing food shelf life: Exploring sources and applications in the food industry. *Foods.* 12, 3176. doi:10.3390/foods12173176
- Pinto, L., Tapia-Rodríguez, M.R., Baruzzi, F., Ayala-Zavala, J.F., 2023. Plant antimicrobials for food quality and safety: Recent views and future challenges. *Foods.* 12(12), 2315. DOI: 10.3390/foods12122315
- Rahman, M.H., Bhoi, P.R., 2021. An overview of non-biodegradable bioplastics. *J. Clean. Prod.* 294, 126218. doi:10.1016/j.jclepro.2021.126218

- Rathee, P., Sehrawat, R., Rathee, P., Khatkar, A., Akkol, E.K., Khatkar, S., Redhu, N., Türkcanoglu, G., Sobarzo-Sánchez, E., 2023. Polyphenols: natural preservatives with promising applications in food, cosmetics and pharma industries; problems and toxicity associated with synthetic preservatives; impact of misleading advertisements; recent trends in preservation and legislation. *Materials*. 16(13), 4793. doi: 10.3390/ma16134793
- Raybaudi-Massilia, R.M., Mosqueda-Melgar, J., Martín-Belloso, O., 2008. Edible alginate-based coating as carrier of antimicrobials to improve shelf-life and safety of fresh-cut melon. *Int. J. Food Microbiol.* 121, 313-327. doi:10.1016/j.ijfoodmicro.2007.11.010
- Rezvani Ghomi, E., Khosravi, F., Saedi Ardahaei, A., Dai, Y., Neisiany, R.E., Foroughi, F., Wu, M., Das, O., Ramakrishna, S., 2021. The life cycle assessment for polylactic acid (PLA) to make it a low-carbon material. *Polymers*. 13(11), 1854. doi.org/10.3390/polym13111854
- Samir, A., Ashour, F.H., Hakim, A.A., Bassyouni, M., 2022. Recent advances in biodegradable polymers for sustainable applications. *Npj Mater. Degrad.* 6, 68. doi:10.1038/s41529-022-00277-7
- Saharan, N., Wadhwa, N., 2024. A Comprehensive Review of Biodegradable Polymers in Sustainable Packaging Applications. *Research & Reviews. JFST*. 13, 28-37. doi: 10.37591/RRJoFST
- Sarker, S.D., Nahar, L., 2012. *An introduction to natural products isolation*. Springer.
- Sheibani, S., Jafarzadeh, S., Qazanfarzadeh, Z., Wijekoon, J.O., Nafchi, A.M., 2024. Sustainable strategies for using natural extracts in smart food packaging. *Int. J. Biol. Macromol.* 267, 131537. doi: 10.1016/j.ijbiomac.2024.131537
- Siddiqui, S.A., Khan, S., Mehdizadeh, M., Bahmid, N.A., Adli, D.N., Walker, T.R., Perestrelo, R., Câmara, J.S., 2023. Phytochemicals and bioactive constituents in food packaging: A systematic review. *Heliyon*. 9, e21196. doi: 10.1016/j.heliyon.2023.e21196
- Singh, A.K., Kim, J.Y., Lee, Y.S., 2022. Phenolic compounds in active packaging and edible films/coatings: natural bioactive molecules and novel packaging ingredients. *Molecules*. 27(21), 7513. doi:10.1016/j.fbio.2023.102689
- Sultan, M., Abdelhakim, A., Nassar, M., Hassan, Y.R., 2023. Active packaging of chitosan film modified with basil oil encapsulated in silica nanoparticles as an alternate for plastic packaging materials. *Food Biosci.* 51, 102298. doi:10.1016/j.fbio.2022.102298

- Sun, S., Liu, Z., Lin, M., Gao, N., Wang, X., 2024. Polyphenols in health and food processing: antibacterial, anti-inflammatory, and antioxidant insights. *Front. Nutr.* 11, 1456730. doi: 10.3389/fnut.2024.1456730
- Tao, R., Sedman, J., Ismail, A., 2021. Antimicrobial activity of various essential oils and their application in active packaging of frozen vegetable products. *Food chem.* 360, 129956. doi: 10.1016/j.foodchem.2021.129956
- Thapliyal, D., Karale, M., Diwan, V., Kumra, S., Arya, R.K., Verros, G.D., 2024. Current status of sustainable food packaging regulations: Global perspective. *Sustainability.* 16(13), 5554. doi: 10.3390/su16135554
- Ullah, H., Hussain, Y., Santarcangelo, C., Baldi, A., Di Minno, A., Khan, H., Xiao, J., Daglia, M., 2022. Natural polyphenols for the preservation of meat and dairy products. *Molecules.* 27(6), 1906. doi: 10.3390/molecules27061906
- Vergis, J., Gokulakrishnan, P., Agarwal, R., Kumar, A., 2015. Essential oils as natural food antimicrobial agents: A review. *Crit. Rev. Food Sci. Nutri.* 55, 1320-1323. doi: 10.1080/10408398.2012.692127
- Versino, F., Ortega, F., Monroy, Y., Rivero, S., López, O.V., García, M.A., 2023. Sustainable and bio-based food packaging: A review on past and current design innovations. *Foods.* 12(5), 1057. doi.org/10.3390/foods12051057
- Wang, J., Liu, S., Huang, J., Cui, R., Xu, Y., Song, Z., 2023. Genetic engineering strategies for sustainable polyhydroxyalkanoate (PHA) production from carbon-rich wastes. *Environ. Technol. Innovation.* 30, 103069. doi: 10.1016/j.eti.2023.103069
- Weligama Thuppahige, V.T., Karim, M.A., 2022. A comprehensive review on the properties and functionalities of biodegradable and semibiodegradable food packaging materials. *Compr. Rev. Food Sci.* 21(1), 689-718. doi.org/10.1111/1541-4337.12873
- Westlake, J.R., Tran, M.W., Jiang, Y., Zhang, X., Burrows, A.D., Xie, M., 2022. Biodegradable active packaging with controlled release: principles, progress, and prospects. *ACS Food Sci. Technol.* 2(8), 1166-1183. doi/full/10.1021/acsfoodscitech.2c00070
- Yan, L., Abdalkarim, S.Y.H., Chen, X., Chen, Z.M., Lu, W., Zhu, J., Jin, M., Yu, H.Y., 2024. Nucleation and property enhancement mechanism of robust and high-barrier PLA/CNFene composites with multi-level reinforcement structure. *Compos. Sci. Technol.* 245, 110364. doi.org/10.1016/j.compscitech.2023.110364

- Zhang, H., Sablani, S., 2021. Biodegradable packaging reinforced with plant-based food waste and by-products. *Curr. Opin. Food Sci.* 42, 61–68. doi:10.1016/j.cofs.2021.05.003
- Zhang, S., Wang, J., Yan, P., Hao, X., Xu, B., Wang, W., Aurangzeib, M., 2020. Non-biodegradable microplastics in soils: A brief review and challenge. *J. Hazard. Mater.* 391, 124525. doi:10.1016/j.jhazmat.2020.124525
- Zhao, X., Wang, Y., Chen, X., Yu, X., Li, W., Zhang, S., Meng, X., Zhao, Z.-M., Dong, T., Anderson, A., 2023. Sustainable bioplastics derived from renewable natural resources for food packaging. *Matter.* 6, 97-127. doi:10.1016/j.matt.2022.11.006
- Zhu, Y., Chen, J., Li, J., Zhou, C., Huang, X., Chen, B., 2023. Ginsenoside Rg1 as a promising adjuvant agent for enhancing the anti-cancer functions of granulocytes inhibited by noradrenaline. *Front. Immunol.* 14, 1070679. doi: 10.3389/fimmu.2023.1070679
- Ziani, K., Ioniță-Mîndrican, C.-B., Mititelu, M., Neacșu, S.M., Negrei, C., Moroșan, E., Drăgănescu, D., Preda, O.-T., 2023. Microplastics: a real global threat for environment and food safety: a state of the art review. *Nutrients.* 15(3), 617. doi: 10.3390/nu15030617