Review:

Review on Melanin Application as an Antibacterial and Antioxidant Agent in Food Packaging

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Abstract: *One of the solutions to reduce food waste is creating innovative food packaging to lengthen its shelf life. This type of packaging can be produced by incorporating natural antimicrobials and antioxidation agents such as melanin. Various biologically active and multifunctional properties are associated with this biomacromolecule, i.e., antioxidants, antibacterial properties, and free radical scavengers. Thus, melanin is an indispensable component. It is expected that food packaging manufactured from natural materials containing melanin will have several advantages, including biodegradability, antioxidant ability, and antibacterial activity. A review of melanin as an antibacterial and antioxidant agent from many different sources that is utilized as an additive in food packaging is presented.*

Keywords: *antibacterial; antioxidant; food packaging; melanin*

INTRODUCTION

Plastics have emerged as pivotal foundational materials extensively utilized across various sectors, including agriculture, healthcare, electronics, packaging, transportation, aerospace, and other fields [1-2]. Globally, plastics are primarily used in packaging, producing nearly half of the generated plastic waste [3]. Plastic production in 1950 amounted to around 2 million tons, increasing to 368 million tons in 2019, or plastic consumption increased by around 180 times [4]. This expansion threatens the environment because only 8% of plastic waste can be processed through recycling, and nearly 50% is in landfills [1]. On the other hand, there has been an increase in the demand to lengthen the shelf life of food by using unique packaging materials. There has been a recent trend toward substituting synthetic polymers with more renewable and biodegradable materials to improve material sustainability and effectiveness for increasing the shelf life of various foods. This shift could be linked to the recycling problems of conventional packaging and the biocompatibility, edibility, and non-toxic properties of biodegradable polymers [5].

Edible packaging is one form of biodegradable polymers [6]. Edible packaging can be classified based on applications in edible coatings and films [7]. For instance, they have been produced to create a semipermeable coating for preserving fruits and vegetables. This coating material can reduce the stored fruits' ripening rate, weight loss, and respiration rate, thus prolonging the shelf life of agricultural products [8]. The mechanism of this function is done by reducing the exchange of gases between the fruits and the surroundings, lowering the oxygen availability to inhibit enzymes responsible for ripening [9]. It is strongly advised that antimicrobial and antioxidant food packaging can be applied to lengthen the shelf life of food [10].

One of the antioxidant/antimicrobial agents incorporated in the applied edible coating on fruits was melanin. When the tomatoes coated with chitosan-melanin complex were kept at room temperature for 16 d, they became more firm, had more significant phytochemical characteristics, and experienced less degradation than the fruit that served as the control. Consequently, applying a chitosan-melanin complex to tomatoes prolongs their shelf life while maintaining market demand. Collectively, these data highlight that chitosan-melanin complex film can lengthen the shelf life of fruits and vegetables while improving their ability to prevent deterioration. This is accomplished by reducing respiration rates and preventing ripening by decreasing the evolution of ethylene and carbon dioxide [11]. It has been established that chitosan-melanin complex film can reduce respiration rates while simultaneously increasing decay control. Pullulan polysaccharide/xanthan gum (PXG) composite films have been improved by adding melanin from grape seed extract (GSE). GSE enhanced antibacterial and antioxidant activities, mechanical strength, UV protection, and water resistance. The shelf life of fresh-cut apples is effectively extended; thus, it is an excellent material for food packaging [12].

Packaging plays an important role in the food industry. However, businesses that deal with food packaging have significantly emphasized the science behind the creation of coatings and films. These additives originated from natural polysaccharides, proteins, and lipids derived from plant, animal, or synthetic sources such as resin [13]. The research topic referred to as "food packaging" has been gaining more popularity over the past couple of years (Fig. 1). A search was carried out using the online database SCOPUS, with the terms "food" and "packaging" as the search terms. The investigation was limited to the recent ten-year period. The total number of articles related to this subject has tripled since 2013. Aesthetics, environmental sustainability, operational efficiency, user-friendliness, technological innovation, and aesthetics are currently the primary focuses of the evolution of food packaging. The main purpose is to maintain food safety while enhancing product quality, reducing the environmental impact, and providing a more satisfying experience for customers and clients.

It has been established that coatings and films containing natural plant and animal pigment extracts can either slow down or hinder the growth of bacteria and preserve the food's quality [14]. One of the methods that can be utilized is using chemicals with antimicrobial and antioxidant properties. Melanin is one of the pigments that can be used in these coatings and films with those functions [15]. Knowing its potential, the application of melanin in food packaging was discussed in this review.

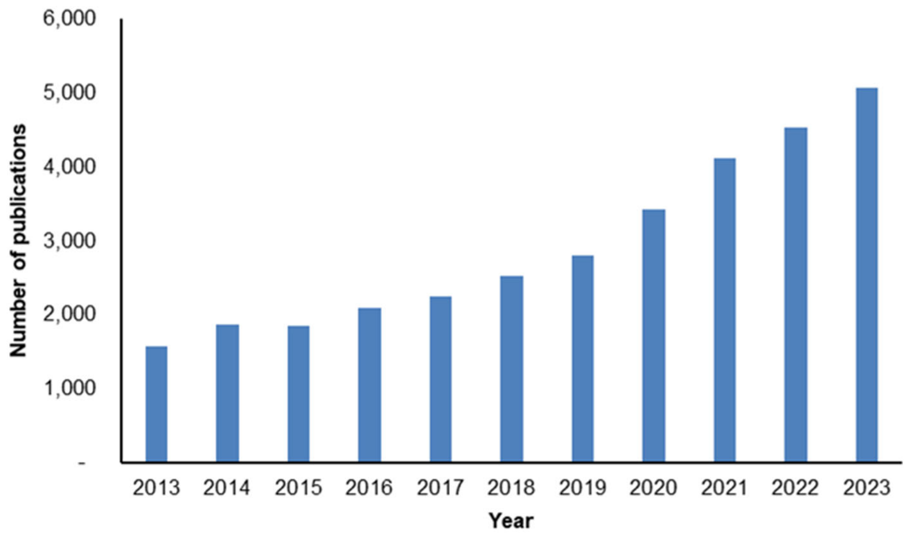

Fig 1. Number of publications in the last ten years, considering the descriptors 'food' AND 'packaging' searched on SCOPUS on May 29th, 2023

Melanin has been extensively studied as a material for additive food packaging. The structure and properties of melanin are briefly introduced, followed by a summary of its advantages and the progress of research related to melanin as a functional additive in composite films [16]. The classification, sources, and degradation of melanin, along with the description of its structure, characterization, and properties, are discussed. Additionally, the novel biological activity of melanin and its applications are covered [17]. The general aspects of melanin, highlighting its biological activity, along with a description of melanin nanoparticles (MNP) and their use as additives in packaging films, as well as their role as reducing and capping agents and in biomedical applications, were comprehensively reviewed [15]. This review presents a comprehensive overview of melanin from various sources, focusing on its antibacterial and antioxidant properties and its use as an additive in food packaging.

■ CLASSIFICATION OF MELANIN

The pigment melanin can be found in most of the various forms of life in the natural world. Natural melanin molecules can be classified into several distinct classes: eumelanin, pheomelanin, neuromelanin, allomelanin, and pyomelanin, as can be seen in Fig. 2 [18]. This classification is based on the molecular structures of melanin [18-19]. Additionally, there is a substance known as synthetic melanin, which is in addition to the five major types of melanin. It is also possible to classify melanin pigments based on their color; for instance, pheomelanin is yellow or reddish-brown, while neuromelanin, eumelanin, and allomelanin range from brown to black [18]. Pyomelanin also has a brown-black color [20].

Eumelanin, pheomelanin, and neuromelanin (particularly linked to the nervous system) are primarily present in animal tissues, whereas allomelanin and pyomelanin are predominantly observed in microorganisms and plants [21]. Both pheomelanin and eumelanin can be found in relatively significant quantities in skin, hair, and eyes [21-22]. Nevertheless, eumelanin provides photoprotection for the skin and eyes. In contrast, pheomelanin is susceptible to photodegradation, leading to the production of hydrogen peroxide and superoxide anions when exposed to UV radiation. Eumelanin is a highly effective optical absorber, shielding the skin and eyes from potential damage caused by excessive light [21]. Moreover, eumelanin functions as an antioxidant agent by effectively scavenging reactive oxygen species (ROS) and countering photic or oxidative stress induced by UV radiation [23]. Consequently, it can safeguard pigmented tissues from oxidative harm. Eumelanin also has antibacterial and antifungal activity [24].

Neuromelanin is a dark polymer pigment produced by groups of catecholaminergic neurons in the brain. Dopamine and 5-*S*-cysteinyl dopamine are the two components used to produce neuromelanin, a

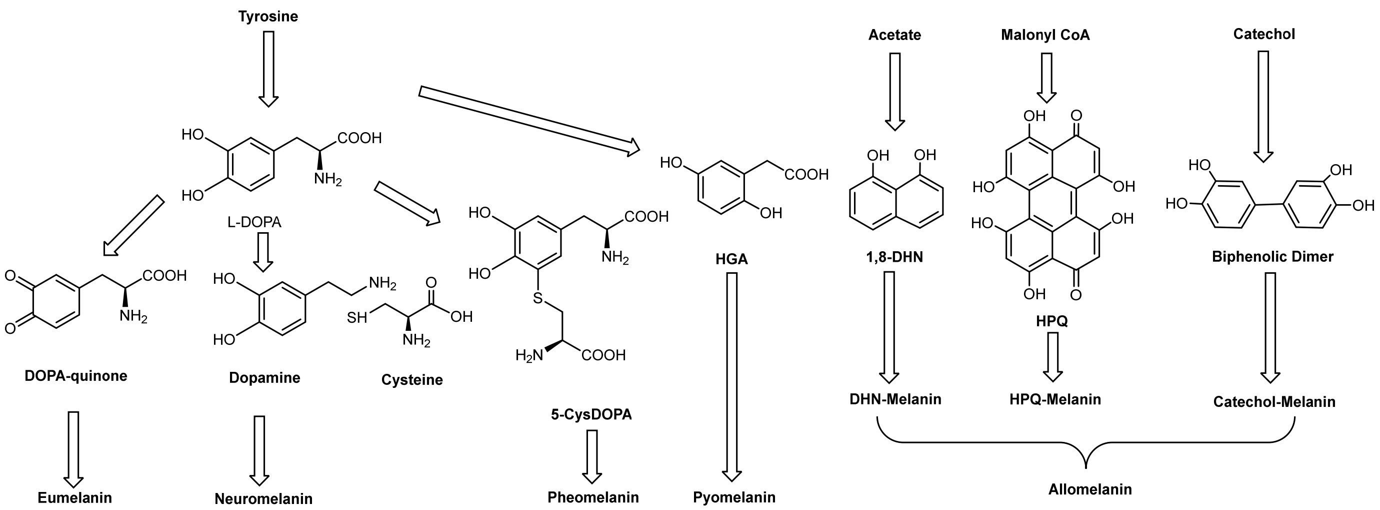

Fig 2. Simplified metabolic routes of five distinct types of melanin, modified from Cao et al. [18]

combination of eumelanin and pheomelanin [22]. Allomelanin and pyomelanin are two types of nitrogen-free melanin [25]. Allomelanin showed high radical trapping activity like ascorbic acid and was a potent antioxidant inside the cells [26]. Pyomelanin is an antibacterial and antifungal agent, effectively countering microbial external threats, particularly pathogenic ones, while diminishing biofouling and chelating heavy metals [27]. Synthetic melanin produced from dopamine exhibited a stronger effect than naturally occurring melanin [15]. It has high antioxidant activity, improved UV shielding, hydrophobicity, and mechanical capabilities of nanocomposite film [28]. It also has high antimicrobial activity [15]. The chemical oxidation of specific diphenolic precursors or the oxidation of L-tyrosine or L-DOPA catalyzed by tyrosinase is two methods that can be utilized to produce synthetic melanin, a pigment comparable to eumelanin [29].

■ SOURCES OF MELANIN

In the natural environment in which they are located, melanin can be found in virtually every type of living thing. The term "melanin" refers to a group of pigments that are intricate and have a variety of structures. The pigments that are responsible for the color of the skin are called melanin. Because of this, it is recommended that this definition be followed by classifying melanin into at least five basic categories following the source. This will allow for a more concise understanding of melanin and its structure. According to its origin, melanin has several different forms: derived from animals, plants, fungi, bacteria, and synthetic sources [22]. The several sources of melanin are listed in Table 1, along with their effects.

■ EXTRACTION OF MELANIN

Melanin extraction is a highly intricate process due to its diverse nature and complex structure. However, the source mainly determines the extraction process [25,40]. Isolating it in its purest form can be challenging because it is often connected to a subcellular component. In most cases, melanin extraction was accomplished by utilizing an alkali technique, followed by an acid hydrolysis technique for purification. Finally, washing was achieved using a centrifuge technique [41]. Because melanin is frequently insoluble in water, the range of applications that may be executed with it is limited. Alkaline solutions can dissolve melanin [22].

One of the obstacles that must be conquered to produce melanin and extract it from these sources is the fact that the majority of melanin is formed inside melanosomes and is tightly bound to specific cellular components such as proteins or minerals or is tightly attached to the inner side of the cell wall when it is produced [42]. Consequently, isolating melanin involves subjecting it to rigorous chemical treatments to remove

Table 1. Some sources of various types of melanin

Type of melanin	Sources	Effect	Ref.
Animal melanin	Black soldier fly	Improve the antioxidant function of broilers	[30]
	Sepia ink	High antioxidant activity comparable to ascorbic acid	[31]
Plant melanin	Date palm fruit watermelon seed	Improve antioxidant and antibacterial activity	[32-33]
Fungal melanin	*Scleroderma citrinum*	Inhibited the growth of pathogens and high antioxidant activity	[34]
	Lachnum YM30	Inhibited the growth of pathogens	[35]
Bacterial melanin	*Pseudomonas balearica* strain	Demonstrated a significant amount of scavenging activity of the stable free radical DPPH and improved antioxidant activity against a phytopathogenic bacteria	[36]
	Streptomyces glaucescens	Exhibited inhibition 57.2% radical scavenging activity	[37]
Synthetic melanin	Polymerization of nanoparticles DHN	Improved free radical scavenging activity	[38]
	Epigallocatechin-3-gallate (EGCG) MNP	Exceptional antibacterial action and powerful antioxidant activity against infections that are transmitted by food consumption	[39]

the entire protein component, cell debris, and nutrients. Within the scope of this paper, we shall examine five distinct techniques for extraction and purification. Each strategy considers beneficial and detrimental aspects of the overall design (Table 2).

APPLICATION OF ANTIOXIDANT AND ANTIMICROBIAL-CONTAINING MELANIN COATINGS/FILMS ON FOOD

The antibacterial and antioxidant capabilities of food packaging are dependent on the presence of antimicrobial and antioxidant agents. These agents can be classified as either natural or synthetic based on the sources of the chemicals that are used in their production [44-45]. It is not difficult to get the naturally occurring antibacterial and antioxidant substances, and there is a slight probability that they will become contaminated. It is necessary to employ extraction methods that are exceedingly complicated to extract naturally occurring antibacterial chemicals from raw materials [46]. Antioxidants and antimicrobials are essential commodities to combat the significant food waste generated. Synthetic antibacterial agents are more cost-effective and have a higher activity level than natural ones. Natural antibacterial agents have only a lower activity level [47]. When compared to natural antibacterial agents, however, synthetic antibacterial agents are frequently more hazardous than their natural counterparts [48].

Antibacterial Activity

Melanin's ability to inhibit the growth of germs is yet another crucial component that has to be researched. Some research results have demonstrated that melanin pigments can inhibit the growth of germs [31,49]. Variations in the chemical structure, the content, and the material's particle size are likely responsible for the varying degrees of antibacterial activity that are seen [50]. The antibacterial component known as melanin, which is utilized in edible coatings and films, is released in a very slow and steady manner when it is applied to food surfaces. As a consequence of this, a sizeable quantity of the antimicrobial agent is preserved, which, in turn, contributes to the extension of the shelf life of food products by inhibiting the growth of germs [51]. By utilizing edible coatings and films that include antibacterial and antioxidant components, it is feasible to ensure that food is safe to consume. Because of this, it is possible to incorporate them into a wide range of culinary products. Inflammation of cells, disruption of lysosome function, protein denaturation, electrostatic disruption, DNA damage, mitochondrial damage, and

Table 2. Advantages and disadvantages of melanin extraction methods [43]

Procedure	Advantage	Disadvantage	Application
Alkali extraction and acid precipitation	cost-effective	low-extraction efficiency and requires significant time	Chicken (tissues), cuttlefish (ink), *Inonotus hispidus* mushroom
Microwave- and ultrasonic-assisted extractions	increase melanin yield and shorten the extraction time	requires high energy	Cuttlefish (ink), alpaca (fiber), *I. hispidus* mushroom, *Auricularia auricula*
Acid precipitation	cost-effective	using corrosive solvents and time-consuming	*A. auricula*, *Streptomyces hyderabadensis* 7VPT5-5R (culture medium)
Enzyme-assisted extraction	quickly disrupts cell membranes, facilitates the release of active substances inside cells, and maintains the specific structure and morphology of melanin	prolong production time and ultimately increase production costs	Chicken (tissues), Cuttlefish (ink), *A. auricula*
Ionic liquid extraction	preserve the original structure of melanin, require simple and environmentally safe chemicals	requiring complex processes and costly precursors	human hair, alpaca fibers, *S. hyderabadensis* 7VPT5-5R (culture medium)

cell membrane breakdown are all protected. Melanin's packaging system is responsible for this protection [52].

Melanin is unaffected by heat and frequently goes through a breakdown process involving multiple stages [15]. This is a vital step in guaranteeing that the antibacterial components of food packaging continue to be effective throughout the product's shelf life and while it is being distributed. One of the many possible applications for melanin is coating various packaging materials, including plastic, paper, and other composite materials. Melanin has many potential applications [53]. Due to this phenomenon, the food packaging industry can benefit from increased diversity in its application. To summarize, it is strongly recommended that research and development of antimicrobial food packaging be carried out as soon as possible. It is of the utmost importance that scientists take immediate action to develop and manufacture antibacterial drugs that are both highly effective and relatively safe [54].

Crude melanin pigment proved effective in controlling microbial growth [36]. For instance, melanin produced by *Streptomyces* sp. has demonstrated antibacterial properties against both *L. vulgaris* and *E. coli* [55]. Melanin extracted from *P. rettgeri* demonstrated the ability to hinder the growth of *P. aeruginosa* [56]. A separate report demonstrated that melanin derived from *A. auricula* effectively suppressed the biofilm formation of *E. coli*, *P. aeruginosa* and *P. fluorescens* [57]. Melanin extracted from *Lachnum* YM30 exhibited antibacterial activity against *V. parahaemolyticus* and *S. aureus*. The antimicrobial activity was primarily due to membrane disruption, increased cell content leakage, and reduced cell membrane potential [35].

Antibacterial packaging films incorporating melanin as an additive have also been reported recently. A polyhydroxybutyrate-based film incorporating nanomelanin extracted from a *Pseudomonas* sp. could form a biofilm that resisted multi-drug resistant strains of *S. aureus* [58]. In a separate report, PLA-based film incorporating melanin extracted from *A. bisporus* demonstrated strong antibacterial effects against *E. faecalis*, *P. aeruginosa*, and *P. putida*. However, it did not exhibit significant activity against *E. coli* and *S. aureus*. The variance in antimicrobial efficacy could be attributed to differences in molecular structure, composition, and particle size [59]. The antibacterial properties of carrageenan-based films containing melanin sourced from *Sepia* ink were assessed against foodborne pathogenic bacteria, *E. coli* and *L. monocytogenes*. The antibacterial effectiveness depended on the concentration of melanin, which had a greater potency against *E. coli* than *L. monocytogenes* [60]. The antibacterial mechanism of packaging film containing melanin can be seen in Fig. 3 [61].

Antioxidant Activity

Studies conducted in recent years have demonstrated that melanin can operate as antibacterial

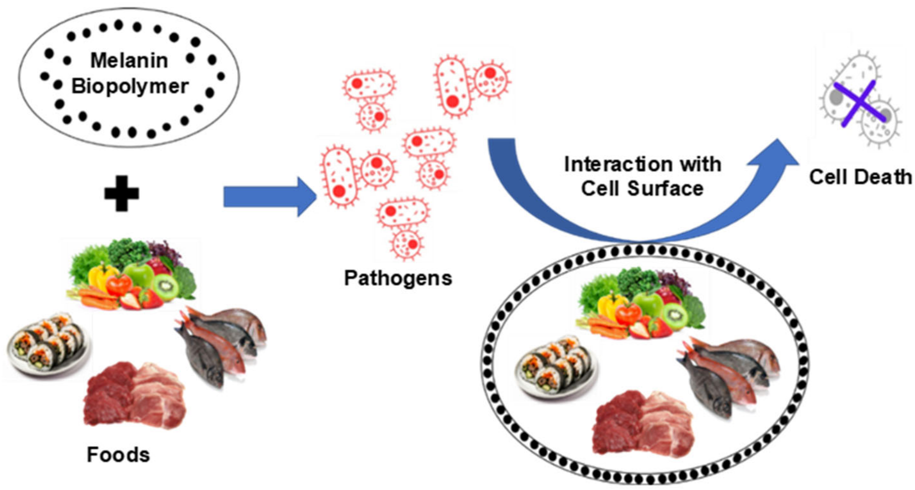

Fig 3. Schematic illustration of the antibacterial mechanism of antibacterial packaging film containing melanin

and antioxidant agents, which can be utilized in a wide range of applications, including the packaging of food [34]. Melanin has been shown to possess significant antibacterial and antioxidant properties. According to *in vivo* and *in vitro* research, melanin has been demonstrated to possess a wide range of health-promoting properties, including antioxidant and immunomodulatory activity, hypoglycemic and hypolipidemic effects, and protective effects on the liver and gastrointestinal tract [43]. A naturally occurring chemical, melanin, can be found in the human body and the environment in which it grows. The fact that it is both natural and risk-free is one of its characteristics. Consequently, using melanin in food packaging as an antibacterial and antioxidant agent may thus be a more secure alternative to use synthetic chemicals [45].

Melanin can be produced either synthetically or naturally [58]. Since it possesses these characteristics, it is a desirable alternative to synthetic antioxidants and can be used in their place. Both eumelanin and pheomelanin molecules contain oxidizing (*o*-quinone) and reducing (*o*-hydroquinone) moieties when broken down into parts. These molecular components are found in melanin. Through electron donation or collection, these moieties are accountable for the quenching of ROS or reactive nitrogen species [15]. It is well known that the antioxidant action of melanin may be linked back to the scavenging of free and peroxide radicals and the activity of lipid peroxidation [23].

Recent studies have indicated that melanin extracted from natural resources exhibited remarkable antioxidant potency, largely attributed to its ability to scavenge ROS. Cuttlefish ink melanin demonstrated a DPPH scavenging activity ranging from 86.3–94.8%, comparable to vitamin C at an equivalent dose [62]. The scavenging efficiency of squid melanin on $O_2{\bullet}$ and $\bullet OH$ surpasses that of commercialized antioxidant carnosine [63]. Melanin derived from watermelon seeds displayed 90% DPPH and ABTS radicals scavenging [33]. Melanin extracted from *I. hispidus* demonstrated scavenging rates of 82.31% for DPPH, 67.73% for $\bullet OH$ and 99.58% for ABTS [64]. Melanin pigment derived from *S. djakartensis* NSS-3 showed scavenging potential ranging from 32.25 to 94.82% across concentrations of 1.25 to 100 μg/mL [65]. The DPPH scavenging capacity varies 54–70%, with the highest inhibition percentage observed at 100 μg/mL and the lowest at 20 μg/mL, using crude melanin from *S. lessoniana* ink [66]. The antioxidant mechanism of packaging film containing melanin can be seen in Fig. 4 [52].

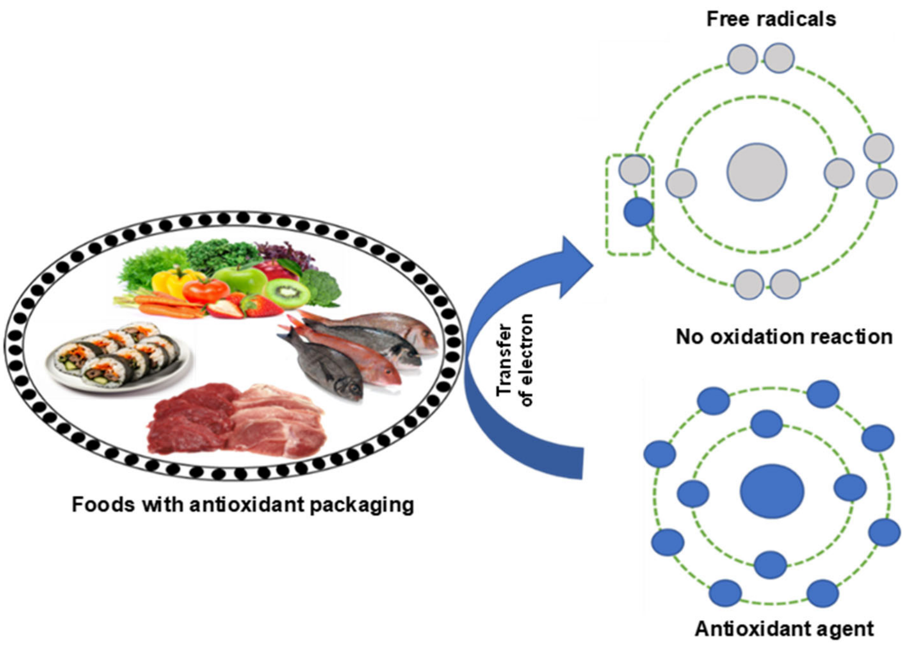

Fig 4. Schematic illustration of the antioxidant mechanism of antioxidant packaging film containing melanin

Melanin Coatings/Films on Food Packaging

The food packaging industry desperately needs antibacterial and antioxidant agents of the highest quality. It is possible to maintain a considerable quantity of antimicrobial agents on the surface of the food because the antimicrobial agents contained in edible coatings and films are released onto the food surfaces at a maintained rate. This is because the antimicrobial agents are released onto the surfaces of the food ingredients [67]. Inhibiting the growth of germs, which leads to the enhanced shelf life of food goods, this antimicrobial chemical helps food products maintain their freshness for longer [68]. Due to the potential advantages that edible coatings and films could have concerned food, recent research has demonstrated a substantial interest in these materials [69]. The effects of melanin-derived antioxidants and antimicrobials integrated into food packaging are described in detail in Table 3.

Fruit and vegetables

Fruits and vegetables have been indispensable in preparing every cuisine [73]. The consumption of fruits and vegetables is not only essential for human beings because they are a source of energy, but they also contain a wide range of vitamins, dietary fibers, and phytochemicals that possess potent antioxidant properties and have the potential to rid the body of

Table 3. Melanin-derived antioxidant/antimicrobials incorporated in food packaging

Biopackaging	Melanin source (antimicrobial/antioxidant agent)	Concentration	Melanin integration	Mechanical properties effect	Applied on products	Target Pathogen	Result/effects	Ref.
Carrageenan/ Cu-NMPs	cuttlefish ink	0.25, 0.50, 1.00, and 1.50%	Mixed with Cu^{2+} and Carr, formed Carr/Cu-NMPs films	After the addition of Cu-NMPs, the tensile strength (TS) of the composite films initially increased slightly. However, as the concentration of Cu-NMPs was further increased to 0.5%, the TS decreased	tomatoes	n.i*	The highest level of hardness was maintained after being stored for fifteen days.	[70]
Alginate/NP	watermelon seeds	0.10, 0.25, and 0.50%	Mixed with alginate formed Ag/NP films	The TS and elongation at break (EB) increased with higher melanin content	n.i*	*E. coli* and *S. aureus*	The films that were examined showed an improvement in their ability to scavenge free radicals, and they also showed a reduction in the increase of mycobacterial counts.	[33]
LDPE/GSE/ Mel/ZnONP	*Sepia* ink	0.10%	Mixed with LPDE, GSE, ZnONP formed LDPE/GSE/Mel/ ZnONP film-coated wrapping paper	The TS and EB of the LDPE film significantly decreased after incorporating the fillers (GSE/Mel/ZnONP)	sandwich and gimbab	*E. coli* and *L. monocytogenes*	In both the sandwich and the gimbab packing, the growth of coliform bacteria was shown to be reduced.	[53]
CMC/Mel	watermelon seeds	0.25%	Mixed with CMC formed CMC/Mel film	The addition of melanin did not have a significant effect on TS and EB values	n.i*	*E. coli*, *S. aureus*, *C. albicans*, *P. aeruginosa*, *B. cereus*	A change in the optical density of the liquid medium and an inhibition of the development of microorganisms on solid media.	[71]

Biopackaging	Melanin source (antimicrobial/antioxidant agent)	Concentration	Melanin integration	Mechanical properties effect	Applied on products	Target Pathogen	Result/effects	Ref.
Gelatin/MNP	squid ink	0.25, 0.50, and 1.00%	Mixed with gelatin formed Gelatin/Mel film	The mechanical TS, EB, and stiffness (EM) of the gelatin film increased significantly after incorporating MNP	n.i*	n.i*	The antioxidant activity increased significantly after blending with MNP and reached 90.00% compared to without MNP.	[49]
Pectin/NMPs	cuttlefish ink	0.25, 0.75, 1.25, and 2.00%	Mixed with pectin formed PC/NMPs films	The inclusion of NMPs notably enhanced both TS and EB of the PC/NMPs films	chicken, beef and pork	*L. monocytogenes*	The percentage of *L. monocytogenes* inhibited by the PC/NMPs films reached 90%.	[50]
PP/PBAT/Mel	*Sepia* ink	0.05, 0.15, 0.25, and 0.50%	Mixed with PBAT and PP, formed PP/PBAT/Mel films	After incorporating melanin, TS, EB, and EM of the composite films initially showed a slight increase, followed by a decrease upon reaching a melanin concentration of 0.50%	potatoes	n.i*	Potatoes were efficiently protected from becoming green by packaging them in PP/PBAT/Mel film and then storing them under fluorescent light for 6 d.	[72]

Notes: n.i* = not indicated; Cu-NMPs = copper-melanin nanoparticles; NP = nanoparticle; LDPE/GSE/Mel/ZnONP = low-density polyethene/grapefruit seed extract/melanin/zinc oxide nanoparticles; CMC/Mel/AgNPs = bioactive carboxymethyl cellulose/melanin/silver nanoparticles; MNP = melanin nanoparticles; NMPs = natural melanin nanoparticles; PP/PBAT/Mel = polypropylene/polybutylene adipate-co-terephthalate/melanin.

harmful free radicals [74]. Microbial decay is the factor that contributes the most to the degradation of fruits and vegetables (fresh or fresh-cut), which are the types of perishable items that cause the most significant amount of loss to the food industry after harvesting. Some studies indicate that this is the factor that contributes the most to the degradation of these types of items [75].

Researchers are likely more concerned about the microbiological safety of fresh-cut products than processed foods because fresh-cut things are frequently consumed in their unprocessed state [76]. While preparing fruits and vegetables, they undergo several processes that cause an unpleasant color and appearance. The polyphenol oxidase enzyme is responsible for this phenomenon with the help of oxygen [77]. This enzyme is responsible for converting phenolic substances into pigments with a dark color [78]. The primary contributor to the loss in quality of fresh fruit after harvesting is the deterioration brought on by microbes through the decay process [79]. There is little question that applying chemical therapies may slow down the decay. Nevertheless, the efficiency of these treatments will decline as resistant strains continue to emerge in the aftermath of the treatments. Using naturally occurring antibacterial compounds is a novel approach to reduce postharvest losses [51].

Combining antimicrobials with various food packaging technologies is key in designing antimicrobial packaging for fresh and fresh-cut fruits (coatings or films) [80]. When different postharvest actions are being carried out to prevent or limit the growth of microorganisms and the contamination that they produce (storage, transportation) [81]. The utilization of coatings and films that contain a variety of natural antioxidants and antibacterials can minimize the losses that occur in fresh produce while simultaneously maximizing product quality. Recent papers have examined these substances' antioxidant and antibacterial effects [51].

Meat/fish products

An intriguing alternative to using synthetic compounds in coatings and films for meat products would be to incorporate melanin-derived substances into edible coatings and films. This would allow for the desired antioxidant and antimicrobial effects and guarantee the product's long-term viability. Therefore, more thorough attention should be focused on exploring these characteristics (antioxidant and antimicrobial) of coatings and films created from melanin for their application in the meat business. In most instances, the compounds formed from melanin interact synergistically to limit microbes' growth, which is one of the factors contributing to the preservation of meat products. For instance, a recent study found that adding an extract from cuttlefish ink exhibited high-efficiency and short-term bactericidal activity against foodborne pathogenic bacteria, such as *L. monocytogenes*. When the sterilization rate reached more than 90%, the operation would be finished in about 5 min when considered complete [50].

Other food products

Many food commodities can be coated with edible melanin films, such as baked items, fruits, dairy products, fried meals, meat products, and vegetables. Items sold in bakeries have a shelf life of 3 to 4 days if they are not well managed, and the fundamental cause that contributes to their deterioration is the fungi growth in overly damp environments [82]. The product has a shelf life that is not as long as it could be considered desirable. This can be accomplished by modifying the environment in which the product is stored or the material it is packaged in, thus the storage time of the product is increased [83].

Following a period of 24 h, the coliform bacteria that were contained within the sandwich and gimbab packaging that was coated with LDPE/GSE/Mel/ZnONP developed very slowly. After that, the growth of coliform bacteria in the sandwich packaging dropped. However, the total coliform bacteria in the gimbab packaging remained at the same value during the same period. Although both packing methods had the same quantity of bacteria, this was the case. Because of the vigorous antibacterial activity of the LDPE composite film, the microbial growth rates of the sandwich and gimbab that were packaged with the LDPE/GSE/Mel/ZnONP-coated paper were significantly reduced [53].

■ CHALLENGES AND FUTURE PERSPECTIVE

The level of awareness among consumers has increased, and along with this elevation in knowledge comes an increase in consumers' expectations regarding the quality of the food they consume [84]. The correct packaging and environmental responsibility are included in these demands. For this reason, packaging development needs to consider the origins of raw materials, biocompatibility, longevity, mechanisms for food preservation, disposal procedures, and environmental impact [85]. Regarding the product's food packaging, the active components' origins, which include antibacterials and antioxidants, are of the utmost significance. Consumer acceptance, concerns regarding the safety of melanin and regulatory parameters, economic factors, production capacity, commercial viability, sensory attributes, and financial aspects are important factors to consider when deciding whether or not to incorporate melanin into the packaging matrix [86].

Regarding the food sector, products that come into close contact with melanin should not be considered safe for human consumption. To ensure the product's safety and purity, the regulatory standards at each stage must be adhered to while manufacturing the material for food packaging [87]. The Federal Food, Drug, and Cosmetic Act (FFDCA) and the United States Food and Drug Administration are the two agencies that are responsible for active packaging in the United States [86,88]. In subsequent work, the naturally available melanin resources should be employed to reduce the likelihood of food deterioration. A substantial amount of an active component can be found in natural resources, and it is possible to extract this component for use in operations that involve processing food goods and packaging food items. A field that needs to be investigated is the commercial potential of the natural elements. Extraction optimization, incorporation procedure, and concentration optimization will be emphasized as areas of study that are crucial in the active packaging application.

■ CONCLUSION

Melanin, a naturally occurring pigment, is both abundant and inexpensive. Its diverse physicochemical properties make it versatile for various applications. More research is needed to fully understand its structure and function before it can be widely used in materials.

Due to its strong antioxidant and antibacterial properties, melanin is an excellent additive for functional composite films, offering significant potential for use in packaging to preserve food quality and extend shelf life. However, further research is needed to enhance melanin production, including improving extraction and purification processes for both natural and synthetic variants. Additionally, its toxicity profile and how it can be modified for enhanced functionality are crucial aspects that need further exploration.

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■ CONFLICT OF INTEREST

The authors declare no known competing financial interests or personal ties that could influence this work.

■ AUTHOR CONTRIBUTIONS

The idea was conceived by Chandra Wahyu Purnomo, Agus Prasetya, and Joko Wintoko. Zainal Mustakim, Fitri Nur Kayati, and Chandra Wahyu Purnomo wrote and revised the manuscript. All authors agreed to the final version of this manuscript.

■ REFERENCES

[1] Ding, Q., and Zhu, H., 2023, The key to solving plastic packaging wastes: Design for recycling and recycling technology, *Polymers*, 15 (6), 1485.

[2] Yang, N., Sun, Z.X., Feng, L.S., Zheng, M.Z., Chi, D.C., Meng, W.Z., Hou, Z.Y., Bai, W., and Li, K.Y., 2015, Plastic film mulching for water-efficient agricultural applications and degradable films materials development research, *Mater. Manuf. Processes*, 30 (2), 143–154.

[3] Ibrahim, I.D., Hamam, Y., Sadiku, E.R., Ndambuki, J.M., Kupolati, W.K., Jamiru, T., Eze, A.A., and Snyman, J., 2022, Need for sustainable packaging: An overview, *Polymers*, 14 (20), 4430.

[4] Nayanathara Thathsarani Pilapitiya, P.G.C., and Ratnayake, A.S., 2024, The world of plastic waste: A review, *Cleaner Mater.*, 11, 100220.

[5] Kaya, M., Ravikumar, P., Ilk, S., Mujtaba, M., Akyuz, L., Labidi, J., Salaberria, A.M., Cakmak, Y.S., and Erkul, S.K., 2018, Production and characterization of chitosan based edible films from *Berberis crataegina*'s fruit extract and seed oil, *Innovative Food Sci. Emerging Technol.*, 45, 287–297.

[6] Gupta, V., Biswas, D., and Roy, S., 2022, A comprehensive review of biodegradable polymer-based films and coatings and their food packaging applications, *Materials*, 15 (17), 5899.

[7] Paidari, S., Zamindar, N., Tahergorabi, R., Kargar, M., Ezzati, S., Shirani, N., and Musavi, S.H., 2021, Edible coating and films as promising packaging: A mini review, *J. Food Meas. Charact.*, 15 (5), 4205–4214.

[8] Pham, T.T., Nguyen, L.L.P., Dam, M.S., and Baranyai, L., 2023, Application of edible coating in extension of fruit shelf life: Review, *AgriEngineering*, 5 (1), 520–536.

[9] Vargas-Torres, A., Becerra-Loza, A.S., Sayago-Ayerdi, S.G., Palma-Rodríguez, H.M., García-Magaña, M.L., and Montalvo-González, E., 2017, Combined effect of the application of 1-MCP and different edible coatings on the fruit quality of jackfruit bulbs (*Artocarpus heterophyllus* Lam) during cold storage, *Sci. Hortic.*, 214, 221–227.

[10] Martins, V.G., Romani, V.P., Martins, P.C., and Filipini, G.S., 2019, "Innovative Packaging That Saves Food" in *Saving Food*, Eds., Galanakis, C.M., Academic Press, Cambridge, MA, US, 171–202.

[11] Tan, C., Faqir, Y., Zeng, Y., Huang, Y., Ocloo, E.A., Kaleri, A.R., Kalhoro, M.T., Ma, J., and Aslam, M., 2022, Investigation of biomechanical characteristics of novel chitosan from dung beetle and its application potential on stored tomato fruit, *J. Food Meas. Charact.*, 16 (6), 4551–4563.

[12] Zheng, M., Zhu, Y., Zhuang, Y., Tan, K.B., and Chen, J., 2023, Effects of grape seed extract on the properties of pullulan polysaccharide/xanthan gum active films for apple preservation, *Int. J. Biol. Macromol.*, 241, 124617.

[13] Kumar, N., Pratibha, P., Prasad, J., Yadav, A., Upadhyay, A., Neeraj, N., Shukla, S., Petkoska, A.T., Heena, H., Suri, S., Gniewosz, M., and Kieliszek, M., 2023, Recent trends in edible packaging for food applications-perspective for the future, *Food Eng. Rev.*, 15 (4), 718–747.
[14] Lin, D., Sun, L.C., Chen, Y.L., Liu, G.M., Miao, S., and Cao, M.J., 2022, Shrimp spoilage mechanisms and functional films/coatings used to maintain and monitor its quality during storage, *Trends Food Sci. Technol.*, 129, 25–37.
[15] Roy, S., and Rhim, J.W., 2022, New insight into melanin for food packaging and biotechnology applications, *Crit. Rev. Food Sci. Nutr.*, 62 (17), 4629–4655.
[16] Liu, L., Xu, H., Gao, L., Zhao, Y., Wang, H., Shi, N., Guo, L., and Liu, P., 2022, Application of melanin as biological functional material in composite film field, *Sci. Eng. Compos. Mater.*, 29 (1), 126–139.
[17] Guo, L., Li, W., Gu, Z., Wang, L., Guo, L., Ma, S., Li, C., Sun, J., Han, B., and Chang, J., 2023, Recent advances and progress on melanin: From source to application, *Int. J. Mol. Sci.*, 24 (5), 1–26.
[18] Cao, W., Zhou, X., McCallum, N.C., Hu, Z., Ni, Q.Z., Kapoor, U., Heil, C.M., Cay, K.S., Zand, T., Mantanona, A.J., Jayaraman, A., Dhinojwala, A., Deheyn, D.D., Shawkey, M.D., Burkart, M.D., Rinehart, J.D., and Gianneschi, N.C., 2021, Unraveling the structure and function of melanin through synthesis, *J. Am. Chem. Soc.*, 143 (7), 2622–2637.
[19] Ghattavi, K., Homaei, A., Kamrani, E., and Kim, S.K., 2022, Melanin pigment derived from marine organisms and its industrial applications, *Dyes Pigm.*, 201, 110214.
[20] Lorquin, F., Piccerelle, P., Orneto, C., Robin, M., and Lorquin, J., 2022, New insights and advances on pyomelanin production: From microbial synthesis to applications, *J. Ind. Microbiol. Biotechnol.*, 49 (4), kuac013.
[21] Xie, W., Pakdel, E., Liang, Y., Kim, Y.J., Liu, D., Sun, L., and Wang, X., 2019, Natural eumelanin and its derivatives as multifunctional materials for bioinspired applications: A review, *Biomacromolecules*, 20 (12), 4312–4331.
[22] Solano, F., 2014, Melanins: Skin pigments and much more–types, structural models, biological functions, and formation routes, *New J. Sci.*, 2014 (1), 498276.
[23] Brenner, M., and Hearing, J.V., 2008, The protective role of melanin against UV damage in human skin, *Photochem. Photobiol.*, 84 (3), 539–549.
[24] Ushakova, N.A., Dontsov, A.E., Sakina, N.L., Brodsky, E.S., Ratnikova, I.A., Gavrilova, N.N., Bastrakov, A.I., Kozlova, A.A., and Nekrasov, R.V., 2017, Melanin properties at the different stages towards life cycle of the fly *Hermetia illucens*, *Ukr. J. Ecol.*, 7 (4), 424–431.
[25] Pralea, I.E., Moldovan, R.C., Petrache, A.M., Ilieş, M., Hegheş, S.C., Ielciu, I., Nicoară, R., Moldovan, M., Ene, M., Radu, M., Uifălean, A., and Iuga, C.A., 2019, From extraction to advanced analytical methods: The challenges of melanin analysis, *Int. J. Mol. Sci.*, 20 (16), 3943.
[26] Mavridi-Printezi, A., Menichetti, A., Mordini, D., Amorati, R., and Montalti, M., 2023, Recent applications of melanin-like nanoparticles as antioxidant agents, *Antioxidants*, 12 (4), 863.
[27] Lorquin, F., Ziarelli, F., Amouric, A., Di Giorgio, C., Robin, M., Piccerelle, P., and Lorquin, J., 2021, Production and properties of non-cytotoxic pyomelanin by laccase and comparison to bacterial and synthetic pigments, *Sci. Rep.*, 11 (1), 8538.
[28] Roy, S., Van Hai, L., Kim, H.C., Zhai, L., and Kim, J., 2020, Preparation and characterization of synthetic melanin-like nanoparticles reinforced chitosan nanocomposite films, *Carbohydr. Polym.*, 231, 115729.
[29] Ju, K.Y., Kang, J., Pyo, J., Lim, J., Chang, J.H., and Lee, J.K., 2016, pH-Induced aggregated melanin nanoparticles for photoacoustic signal amplification, *Nanoscale*, 8 (30), 14448–14456.
[30] Chen, X., Jin, J., Hou, F., Song, B., Li, Z., and Zhao, Y., 2022, Effects of black soldier fly larvae oil on growth performance, immunity and antioxidant capacity, and intestinal function and microbiota of broilers, *J. Appl. Poult. Res.*, 31 (4), 100292.
[31] Roy, S., and Rhim, J.W., 2019, Agar-based antioxidant composite films incorporated with

melanin nanoparticles, *Food Hydrocolloids*, 94, 391–398.

[32] Alam, M.Z., Ramachandran, T., Antony, A., Hamed, F., Ayyash, M., and Kamal-Eldin, A., 2022, Melanin is a plenteous bioactive phenolic compound in date fruits (*Phoenix dactylifera* L.), *Sci. Rep.*, 12 (1), 6614.

[33] Łopusiewicz, Ł., Macieja, S., Śliwiński, M., Bartkowiak, A., Roy, S., and Sobolewski, P., 2022, Alginate biofunctional films modified with melanin from watermelon seeds and zinc oxide/silver nanoparticles, *Materials*, 15 (7), 2381.

[34] Łopusiewicz, Ł., 2018, *Scleroderma citrinum* melanin: Isolation, purification, spectroscopic studies with characterization of antioxidant, *World Sci. News*, 94 (2), 115–130.

[35] Xu, C., Li, J., Yang, L., Shi, F., Yang, L., and Ye, M., 2017, Antibacterial activity and a membrane damage mechanism of *Lachnum* YM30 melanin against *Vibrio parahaemolyticus* and *Staphylococcus aureus*, *Food Control*, 73, 1445–1451.

[36] Zerrad, A., Anissi, J., Ghanam, J., Sendide, K., and El Hassouni, M., 2014, Antioxidant and antimicrobial activities of melanin produced by a *Pseudomonas balearica* strain, *J. Biotechnol. Lett.*, 5 (1), 87–94.

[37] El-Naggar, N.E.A., and El-Ewasy, S.M., 2017, Bioproduction, characterization, anticancer and antioxidant activities of extracellular melanin pigment produced by newly isolated microbial cell factories *Streptomyces glaucescens* NEAE-H, *Sci. Rep.*, 7 (1), 42129.

[38] Zhang, H., Huang, C., Zhang, J., Wang, C., Wang, T., Shi, S., Gu, Z., and Li, Y., 2022, Synthetic fungal melanin nanoparticles with excellent antioxidative property, *Giant*, 12, 100120.

[39] Zhao, W., Liang, X., Wang, X., Wang, S., Wang, L., and Jiang, Y., 2022, Chitosan based film reinforced with EGCG loaded melanin-like nanocomposite (EGCG@MNPs) for active food packaging, *Carbohydr. Polym.*, 290, 119471.

[40] Chongkae, S., Nosanchuk, J.D., Pruksaphon, K., Laliam, A., Pornsuwan, S., and Youngchim, S., 2019, Production of melanin pigments in saprophytic fungi *in vitro* and during infection, *J. Basic Microbiol.*, 59 (11), 1092–1104.

[41] Wang, L.F., and Rhim, J.W., 2019, Isolation and characterization of melanin from black garlic and *Sepia* ink, *LWT*, 99, 17–23.

[42] Toledo, A.V., Franco, M.E.E., Yanil Lopez, S.M., Troncozo, M.I., Saparrat, M.C.N., and Balatti, P.A., 2017, Melanins in fungi: Types, localization and putative biological roles, *Physiol. Mol. Plant Pathol.*, 99, 2–6.

[43] Yang, X., Tang, C., Zhao, Q., Jia, Y., Qin, Y., and Zhang, J., 2023, Melanin: A promising source of functional food ingredient, *J. Funct. Foods*, 105, 105574.

[44] Farid, N., Waheed, A., and Motwani, S., 2023, Synthetic and natural antimicrobials as a control against food borne pathogens: A review, *Heliyon*, 9 (6), e17021.

[45] El-Naggar, N.E.A., and Saber, W.I.A., 2022, Natural melanin: Current trends, and future approaches, with especial reference to microbial source, *Polymers*, 14 (7), 1339.

[46] Ponphaiboon, J., Krongrawa, W., Aung, W.W., Chinatangkul, N., Limmatvapirat, S., and Limmatvapirat, C., 2023, Advances in natural product extraction techniques, electrospun fiber fabrication, and the integration of experimental design: A comprehensive review, *Molecules*, 28 (13), 5163.

[47] Suvarna, V., Nair, A., Mallya, R., Khan, T., and Omri, A., 2022, Antimicrobial nanomaterials for food packaging, *Antibiotics*, 11 (6), 729.

[48] Bose, I., Roy, S., Pandey, V.K., and Singh, R., 2023, A comprehensive review on significance and advancements of antimicrobial agents in biodegradable food packaging, *Antibiotics*, 12 (6), 968.

[49] Shankar, S., Wang, L.F., and Rhim, J.W., 2019, Effect of melanin nanoparticles on the mechanical, water vapor barrier, and antioxidant properties of gelatin-based films for food packaging application, *Food Packag. Shelf Life*, 21, 100363.

[50] Liang, Y., Zhao, Y., Sun, H., Dan, J., Kang, Y., Zhang, Q., Su, Z., Ni, Y., Shi, S., Wang, J., and

Zhang, W., 2023, Natural melanin nanoparticle-based photothermal film for edible antibacterial food packaging, *Food Chem.*, 401, 134117.
[51] Manzoor, A., Yousuf, B., Pandith, J.A., and Ahmad, S., 2023, Plant-derived active substances incorporated as antioxidant, antibacterial or antifungal components in coatings/films for food packaging applications, *Food Biosci.*, 53, 102717.
[52] Deshmukh, R.K., and Gaikwad, K.K., 2024, Natural antimicrobial and antioxidant compounds for active food packaging applications, *Biomass Convers. Biorefin.*, 14 (4), 4419–4440.
[53] Shankar, S., Bang, Y.J., and Rhim, J.W., 2019, Antibacterial LDPE/GSE/Mel/ZnONP composite film-coated wrapping paper for convenience food packaging application, *Food Packag. Shelf Life*, 22, 100421.
[54] Huang, T., Qian, Y., Wei, J., and Zhou, C., 2019, Polymeric antimicrobial food packaging and its applications, *Polymers*, 11 (3), 560.
[55] Vasanthabharathi, V., Lakshminarayanan, R., and Jayalakshmi, S., 2011, Melanin production from marine *Streptomyces*, *Afr. J. Biotechnol.*, 10 (54), 11224–11234.
[56] Laxmi, M., Kurian, N.K., Smitha, S., and Bath, S.G., 2014, Melanin and bacteriocin from marine bacteria inhibit biofilms of foodborne pathogens, *Indian J. Biotechnol.*, 15 (3), 392–399.
[57] Bin, L., Wei, L., Xiaohong, C., Mei, J., and Mingsheng, D., 2012, *In vitro* antibiofilm activity of the melanin from *Auricularia auricula*, an edible jelly mushroom, *Ann. Microbiol.*, 62 (4), 1523–1530.
[58] Kiran, G.S., Jackson, S.A., Priyadharsini, S., Dobson, A.D.W., and Selvin, J., 2017, Synthesis of Nm-PHB (nanomelanin-polyhydroxy butyrate) nanocomposite film and its protective effect against biofilm-forming multi drug resistant *Staphylococcus aureus*, *Sci. Rep.*, 7 (1), 9167.
[59] Łopusiewicz, Ł., Jędra, F., and Mizieińska, M., 2018, New poly(lactic acid) active packaging composite films incorporated with fungal melanin, *Polymers*, 10 (4), 386.
[60] Roy, S., and Rhim, J.W., 2019, Preparation of carrageenan-based functional nanocomposite films incorporated with melanin nanoparticles, *Colloids Surf., B*, 176, 317–324.
[61] Michael, H.S.R., Subiramanian, S.R., Thyagarajan, D., Mohammed, N.B., Saravanakumar, V.K., Govindaraj, M., Maheswari, K.M., Karthikeyan, N., and Ramesh Kumar, C., 2023, Melanin biopolymers from microbial world with future perspectives—A review, *Arch. Microbiol.*, 205 (9), 306.
[62] Fahmy, S.R., Ali, E.M., and Ahmed, N.S., 2014, Therapeutic effect of *Sepia* ink extract against invasive pulmonary aspergillosis in mice, *J. Basic Appl. Zool.*, 67 (5), 196–204.
[63] Guo, X., Chen, S., Hu, Y., Li, G., Liao, N., Ye, X., Liu, D., and Xue, C., 2014, Preparation of water-soluble melanin from squid ink using ultrasound-assisted degradation and its anti-oxidant activity, *J. Food Sci. Technol.*, 51 (12), 3680–3690.
[64] Hou, R., Liu, X., Xiang, K., Chen, L., Wu, X., Lin, W., Zheng, M., and Fu, J., 2019, Characterization of the physicochemical properties and extraction optimization of natural melanin from *Inonotus hispidus* mushroom, *Food Chem.*, 277, 533–542.
[65] El-Zawawy, N.A., Kenawy, E.R., Ahmed, S., and El-Sapagh, S., 2024, Bioproduction and optimization of newly characterized melanin pigment from *Streptomyces djakartensis* NSS-3 with its anticancer, antimicrobial, and radioprotective properties, *Microb. Cell Fact.*, 23 (1), 23.
[66] Khandelwal, S., Devi, N.R., Subramaniyan, M., and Pappu, S., 2023, Physicochemical characterization and therapeutic potential of ink from squid, *Sepioteuthis lessoniana, 3 Biotech*, 13 (12), 418.
[67] Chawla, R., Sivakumar, S., and Kaur, H., 2021, Antimicrobial edible films in food packaging: Current scenario and recent nanotechnological advancements- A review, *Carbohydr. Polym. Technol. Appl.*, 2, 100024.
[68] Fadiji, T., Rashvand, M., Daramola, M.O., and Iwarere, S.A., 2023, A review on antimicrobial packaging for extending the shelf life of food, *Processes*, 11 (2), 590.
[69] Salgado, P.R., Ortiz, C.M., Musso, Y.S., Di Giorgio, L., and Mauri, A.N., 2015, Edible films and coatings

containing bioactives, *Curr. Opin. Food Sci.*, 5, 86–92.

[70] Liang, Y., Han, Y., Dan, J., Li, R., Sun, H., Wang, J., and Zhang, W., 2023, A high-efficient and stable artificial superoxide dismutase based on functionalized melanin nanoparticles from cuttlefish ink for food preservation, *Food Res. Int.*, 163, 112211.

[71] Macieja, S., Środa, B., Zielińska, B., Bartkowiak, A., and Łopusiewicz, Ł., 2022, Bioactive carboxymethyl cellulose (CMC)-based films modified with melanin and silver nanoparticles (AgNPs)—The effect of the degree of CMC substitution on the *in situ* synthesis of AgNPs and films' functional properties, *Int. J. Mol. Sci.*, 23 (24), 15560.

[72] Bang, Y.J., Shankar, S., and Rhim, J.W., 2020, Preparation of polypropylene/poly (butylene adipate-co-terephthalate) composite films incorporated with melanin for prevention of greening of potatoes, *Packag. Technol. Sci.*, 10 (33), 443–441.

[73] von Braun, J., Afsana, K., Fresco, L.O., and Hassan, M.H.A., 2023, *Science and Innovations for Food Systems Transformation*, Springer Nature, Cham, Switzerland.

[74] Tavassoli-Kafrani, E., Gamage, M.V., Dumée, L.F., Kong, L., and Zhao, S., 2022, Edible films and coatings for shelf life extension of mango: A review, *Crit. Rev. Food Sci. Nutr.*, 62 (9), 2432–2459.

[75] Alegbeleye, O., Odeyemi, O.A., Strateva, M., and Stratev, D., 2022, Microbial spoilage of vegetables, fruits and cereals, *Appl. Food Res.*, 2 (1), 100122.

[76] Yousuf, B., Wu, S., and Siddiqui, M.W., 2021, Incorporating essential oils or compounds derived thereof into edible coatings: Effect on quality and shelf life of fresh/fresh-cut produce, *Trends Food Sci. Technol.*, 108, 245–257.

[77] Zhang, S., 2023, Recent advances of polyphenol oxidases in plants, *Molecules*, 28 (5), 2158.

[78] Kim, S., 2020, Antioxidant compounds for the inhibition of enzymatic browning by polyphenol oxidases in the fruiting body extract of the edible mushroom *Hericium erinaceus*, *Foods*, 9 (7), 951.

[79] Lufu, R., Ambaw, A., and Opara, U.L., 2020, Water loss of fresh fruit: Influencing pre-harvest, harvest and postharvest factors, *Sci. Hortic.*, 272, 109519.

[80] Duda-Chodak, A., Tarko, T., and Petka-Poniatowska, K., 2023, Antimicrobial compounds in food packaging, *Int. J. Mol. Sci.*, 24 (3), 2457.

[81] Zoellner, C., Al-Mamun, M.A., Grohn, Y., Jackson, P., and Worobo R., 2018, Postharvest supply chain with microbial travelers: A farm-to-retail microbial and visualization framework, *Appl. Environ. Microbiol.*, 84 (17), e00813-18.

[82] Thomas, R.M., Falegan, C.R., Olojede, A.O., Oludipe, E.O., Awarun, O.D., and Daodu, G.O., 2023, Nutritional and sensory quality of *Ofada* rice sourdough bread made with selected lactic acid bacteria strains, *Heliyon*, 9 (10), e20828.

[83] Saranraj, P., Stella, D., and Reetha, D., 2012, Microbial cellulases and its applications: A review, *Int. J. Biochem. Biotechnol.*, 1, 1–12.

[84] Chirilli, C., Molino, M., and Torri, L., 2022, Consumers' awareness, behavior and expectations for food packaging environmental sustainability: Influence of socio-demographic characteristics, *Foods*, 11 (16), 2388.

[85] Versino, F., Ortega, F., Monroy, Y., Rivero, S., López, O.V., and García, M.A., 2023, Sustainable and bio-based food packaging: A review on past and current design innovations, *Foods*, 12 (5), 1057.

[86] Ilyas, R.A., Sapuan, S.M., Megashah, L.N., Ibrahim, R., Atikah, M.S.N., Ainun, Z.M.A., Aung, M.M., SaifulAzry, S.O.A., and Lee, C.H., 2021, "Regulations for Food Packaging Materials" in *Bio-based Packaging: Material, Environmental and Economic Aspects*, John Wiley & Sons, Inc., Hoboken, New Jersey, US, 467–494.

[87] Vasile, C., and Baican, M., 2021, Progresses in food packaging, food quality, and safety—controlled-release antioxidant and/or antimicrobial packaging, *Molecules*, 26 (5), 1263.

[88] Marone, P.A., 2016, "Food Safety and Regulatory Concerns" in *Insects as Sustainable Food Ingredients: Production, Processing and Food Applications*, Eds., Dossey, A.T., Morales-Ramos, J.A., and Rojas, M.G., Academic Press, San Diego, US, 203–221.