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Antimicrobial nanomaterials in food packaging and preservation

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The rising global challenge of food spoilage has led to significant economic losses and jeopardizes food security worldwide. This has led to the generation of innovative and sustainable preservation techniques. This review explores the use of antimicrobial nanomaterials in food packaging and preservation as a promising solution to the global challenge of food spoilage. Nanomaterials have outstanding properties that include efficient antimicrobial capabilities, biodegradability and improved barrier properties. The mechanism of antimicrobial action of these nanomaterials such as disruption of the cell membrane, generation of reactive oxygen species (ROS), and damage of the cell's DNA, make them effective against the action of pathogenic microorganisms. The mechanistic chemistry of antimicrobial nanomaterials involves the disruption of the cell wall, intracellular penetration, oxidative stress, signal transduction modulation, ion release and synergistic effects, and direct nano-bio interactions. Nanomaterials undergo diverse transformation processes including aggregation, agglomeration, dissolution, chemical speciation, protein corona and bio-molecular interactions. Although nanomaterials offer substantial benefits, there are still challenges such as risks of toxicity, regulatory setbacks, scalability and environmental impacts that affect their adoption. Future research focusing on improving the safety of nanomaterials, incorporating emerging technologies like 3D printing will further revolutionize antimicrobial nanomaterials for food packaging and preservation, which will facilitate food safety, reduce waste and meet global food security demands.

1 Introduction

Food spoilage, a critical global issue that poses a threat to food security, causes a reduction in the nutritional value of food and sustainable food systems. 30–50% of the total food produced is lost annually in Africa as discussed by the Food and Agriculture Organization (FAO),[1] contributing to environmental wastes, economic losses and starvation. The deterioration of food occurs from harvesting (the farm) to processing, and from storage to consumption. Food spoilage is any undesirable change in taste, texture, color, or odor, which reduces the nutritional value, and safety of food products. The case of food spoilage is severe among developing countries which have limited infrastructure for preservation and storage. The causes of this spoilage include biological, chemical and physical processes. Microorganisms such as bacteria (*Salmonella*, *Escherichia coli*) and fungi (yeasts and molds) deteriorate food or release toxic products that promote spoilage.[2] For example, molds on bread produce visible spots and off-flavors and also an increased population of bacteria causes the souring of food. Food enzymes present naturally in food facilitate deterioration, for instance, the over-ripening of plantain. External factors such as insects (*e.g.* weevils in grains) and rodents in poor storage facilities also encourage degradation of food. Several environmental factors contribute to the degradation of food. High heat and cold destroys the protein and vitamin content of food. Excessive freezing and further thawing affect food as their cells break when partially frozen at low temperature.[3] High moisture promotes microbial growth like molds and yeasts.[4] The phytochemicals in food gets destroyed when exposed to air or oxygen. For example, rancidity in oil and browning of fruits which occur when they are exposed to oxygen due to oxidation. Exposure of light-sensitive components of food, vitamins (*e.g.* vitamin C in orange) and minerals to light deteriorates them. Food spoilage occurs in three forms: physical, chemical and microbial. The physical spoilage occurs as a result of external factors such as temperature, moisture or pressure such as the formation of ice crystals when food is frozen and thawed which affects the texture of the food. Chemical spoilage, which is caused as a result of chemical factors such as metabolism of microorganisms, oxidation or breakdown of essential compounds in food such as the browning of fruits when exposed to air which affects the taste, color or smell of the fruit. Microbial spoilage is

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caused by an increase in the microbial population in food or as a result of the toxic compounds (*e.g.* the toxins released by *Clostridium botulinum* in canned foods) they produce which causes off-flavors, slime formation and foul odors.[3]

Each of the spoilage types poses a threat which requires effective preservation techniques to overcome them. Conventional preservation methods such as salting, drying, canning, and heat treatment have been employed to combat food spoilage. However, these techniques have their limitations. Excessive salting as in the case of meat curing, poses health risks *e.g.* hypertension.[5] Excessive heat treatment causes the degradation of essential vitamins like vitamin C in fruits and vegetables. Chemical compounds such as Sodium benzoate when used in excess poses long-term health risks. In developing countries, the lack of proper storage facilities such as cold storage also facilitates spoilage. These challenges facilitate the need of an innovative and sustainable preservation methods that maintains food quality and safety. Recent research highlights nanotechnology as a promising solution to food spoilage.

Nanomaterials are unique structures which are made of nanoparticles have dimensions from 1 to 100 nm.[6] These materials are thermally stable, non-toxic, and possess properties that protects against the growth of pathogenic microorganisms, without sacrificing the nutritional quality of the food.[7] These nanomaterials like the silver dioxide and titanium dioxide are incorporated in food packaging to enhance the appearance, taste, and food agent.[6] Throughout manufacturing, processing, packaging, storage and transport, nano sensors developed using nanotechnology have been employed to identify contaminations in food.[8]

In the recent past, research on nanomaterials for food packaging has been tremendously increased; for instance, number of publications have been increased by 11 times from 2015 to 2024 (Fig. 1).

The main objective of this seminar paper is to provide a comprehensive review of nanomaterials, their types, antimicrobial mechanisms, and advantages over traditional preservation methods, as well as explore methods for incorporating them into food packaging to reduce spoilage and enhance food security. It aims to contribute to the growing field of nanotechnology in food systems.

2 Food spoilage and the role of packaging

Any undesirable change in taste, texture, color, odor, that causes a reduction in the nutritional content, quality and safety of

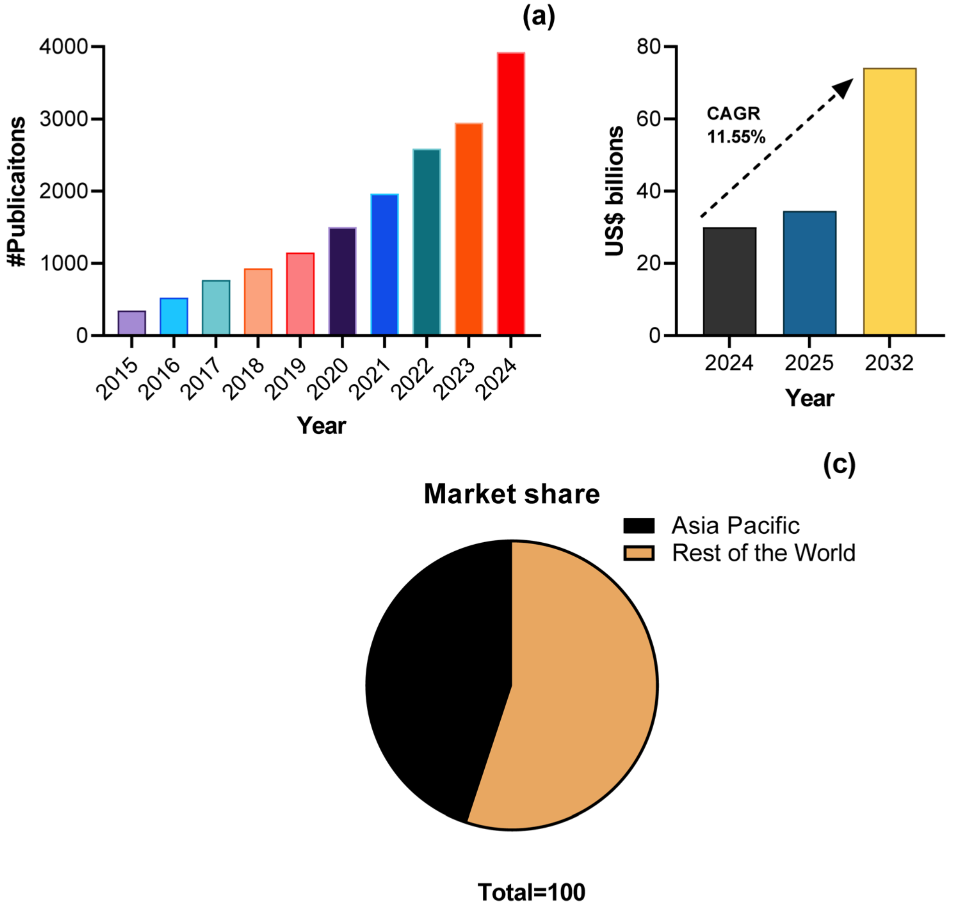


Fig. 1 Research and market trends for nanomaterials in food packaging, (a) annual number of publications on "nanomaterials for food packaging" from 2015–2024,[9] (b) global market growth trend for nanotechnology in food packaging, (c) regional market share distribution for nanotechnology-based food packaging applications.[10]

food products is referred to as food spoilage. This makes food unfit for consumption. Particularly in developing countries where proper storage facilities are not really available, the issue of food spoilage is of a great challenge because it does not only affect the economy negatively but also places risks on the health of those that consume them.[11]

Mafe,[12] states that food spoilage is caused by various factors: microbial contamination, physical changes and chemical reactions. Microbial contamination which is caused as by the presence of pathogenic microorganisms like bacteria or fungi is one of the major factors promoting food spoilage,[13] or their toxic products. Physical spoilage is as a result of temperature fluctuations, mechanical damage, loss or addition of moisture that may degrade food and reduce its quality. Lastly, chemical spoilage, which is caused as a result of chemical factors such as metabolism of microorganisms, oxidation or breakdown of essential compounds in food such as the browning of fruits when exposed to air which affects the taste, color or smell of the fruit.

Food packaging is a dynamic system of preserving food against microbial contamination, oxidation, chemical degradation, moisture and mechanical damage. Even during the storage, movement and consumption of food, they act as a barrier against the factors that facilitate food spoilage by ensuring extended shelf life by reducing oxygen exposure, prevents microbial growth, ensure customers safety and maintain food quality.[14] Common methods of food packaging like the modified atmosphere packaging (MAP) and the vacuum packaging, prevent spoilage as well as limit waste by maintaining quality during storage and transport. Packaging methods such as the use of glass, polyethylene or plastics were used to package food. However, these traditional packaging methods have their limitations. The non-biodegradable property and limited barrier of plastics have raised environmental concerns.[15] The traditional methods of packaging lacks antimicrobial properties and are unable to monitor food quality.

Several preservation techniques have been employed alongside packaging to combat food spoilage. These preservation techniques include: freezing, pickling, canning, curing, fermentation, drying, and sugaring.[16] Freezing involves storing food at temperatures below freezing point in order to preserve the food's taste, texture and nutritional value. Pickling is a preservation technique where food is stored in a solution containing vinegar or brine. In curing, food products are coated with salt to reduce its moisture content and also prevent rancidity by lowering the oxidation process. Fermentation, another preservation technique where microorganisms like yeasts and bacteria are used to convert the carbohydrates in food to organic acids so as to improve its flavor, texture and nutritional value. Drying or dehydration includes the reduction in the moisture content of food product.[17] Sugaring simply involves coating food with sugar in order to absorb its moisture content, adds taste as well as prolong the freshness of food product.

Despite the numerous benefits of these preservation techniques, they have been found to have several limitations. Like excessive salting, as in the case of meat curing, poses health risks *e.g.* hypertension.[5] Excessive heat treatment causes the degradation of essential vitamins like vitamin C in fruits and vegetables. In developing countries, the lack of proper storage facilities such as cold storage also facilitates spoilage. In drying and freezing methods of preservation, shrinking of the food product, reduction in texture, nutrient and organic properties cause an overall loss in quality of the product.[18] These challenges encourage the need of an innovative and sustainable preservation and packaging methods that maintains both the food quality and safety. Recent research highlights nanotechnology as a promising solution to food spoilage.

2.1 Emergence of nanotechnology in food preservation

To address the limitations associated with traditional packaging methods including shorter shelf life, inferior packaging against environmental factors, and non-sustainability, modern developments have greatly revolutionized the packaging industry. These improvements are made to increase quality, safety, and environment-friendliness of food products. Incorporating nanotechnology is one of the most revolutionary advancements, emerged in the 1990s, with improved functionality.[19] In nanotechnology, materials are manipulated at the nanoscale (1–100 nm) to produce unique structures with improved properties.[6] The production of better packaging materials with improved features and performance, that addresses both the consumers demand and industry challenges has been achieved through the use of this technology. The adoption of nanotechnology grew in the early 2000s, which is due to increasing demand for safe and sustainable packaging as well as development in the field of material science. This rising demand for improved packaging as promoted in the field of nanotechnology, more insights for research. Due to the nanoscale of nanomaterials, they exhibit unique properties like improved structural and thermal stability, and increased surface area to foster the binding and destruction of microbial cells, which makes them ideal for modern packaging applications. Nanotechnology improves the functionality of packaging materials in several ways.

Nanotechnology demonstrates better gas and water (embedding nanoparticles into polymer matrices creates a path that does not allow the free flow of gas and moisture molecules, thereby reducing the permeability of the packaging material,[20] which further protects better perishable goods like food and pharmaceuticals, from microbial contamination and oxidative degradation), resistance, improved durability and mechanical strength (that is, it also makes the packaging material during transportation and storage, more resistant to physical damage), thermal and barrier properties (it gives the packaging material the ability to withstand extreme temperatures without altering the nutritional content of the food), and also as antimicrobials(the most promising applications of nanotechnology which plays an important part in maintaining safety and preservation of food) to prevent spoilage of packaged foods through the utilization of nanomaterials like the silver nanoparticles as well as zinc oxide nano particles.[20] Nanotechnology offers opportunities even beyond preservation and safety, like the

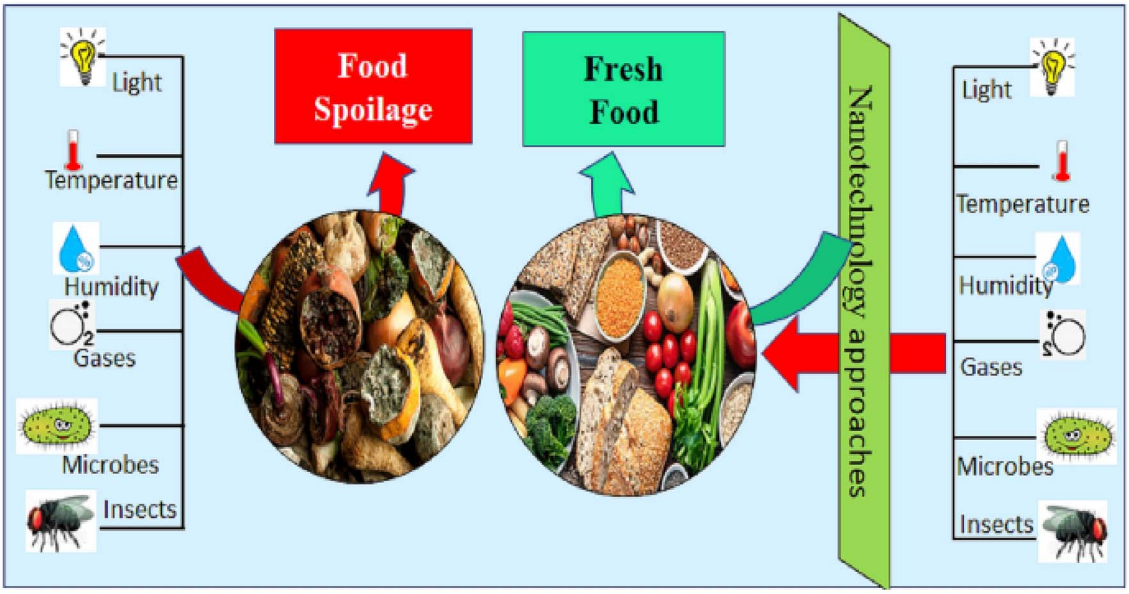


Fig. 2 Nanotechnology approaches to food products. The importance of nanotechnology approaches to food products. The left-hand side shows how light, temperature, humidity, gases, microbes and insects from the environment leads to food spoilage. The right-hand side indicates that nanotechnology protect and kept the food fresh even the presence of the environmental conditions.

usage of nano sensor that monitors the freshness of food products by detecting spoilage indicators such as changes in pH levels or volatile organic compounds.[21] The lighter, thinner and more resource efficient designs enabled by nanomaterials can help reduce the amount of raw material required for packaging. In addition, the biodegradability of some nanomaterials further supports its eco-friendly attribute. These innovations paved the way for sustainable and better solutions, as addressed in subsequent sub sections. The nanotechnology approaches are shown in Fig. 2.

2.2 Definition and types of nanomaterials

Joudeh and Linke,[22] defined nanotechnology as the manipulation of matter that possess one characteristic dimension at the least measured in nanometers and ranges from 1–100 nm. Compared to traditional packaging methods, incorporation of nanomaterials into packaging confers packaging materials with superior structural strength, improved protection and films against the microbial growth, to detection of pathogen and consumer awareness of the safety status of the food through nano sensing.[23]

The various types of nanomaterials used for food packaging include: the silver nanoparticles (AgNPs), which due to their high surface area-to-volume ratio serves as great ingredients in packaging materials. When AgNPs are incorporated into polymers like polyethylene, they provide antimicrobial effects by inhibiting harmful microorganisms like *Escherichia coli* and enhance gas barrier properties, extending shelf life.[24] Titanium dioxide nano particles (TiO_2NP), on the other hand, due to its photocatalytic activity which is promoted its ability to produce reactive oxygen species (ROS), low cost, safety and non-toxicity possess elevated efficiency, broad spectrum antibacterial efficiency.[25] A polymer matrix with uniform composite structure is formed as a result of the great dispersibility and high specific surface area of TiO_2NP which enhances the mechanical strength, toughness as well as thermal stability.[26] This further preserve that the nutritional value and the sensory qualities of food products is maintained. Thirdly, zinc oxide nano particles (ZnONPs), which are nanoparticles with unique characteristics like the absorption of ultraviolet rays, antimicrobial qualities which are excellent agents in preserving the freshness and sustain the quality of food products intact for a long period of time.[26] The U.S. Food and Drug Administration (FDA) of zinc oxide as a "GRAS" (Generally Regarded As Safe) substance,[25] as provided manufacturers and consumers with the assurance that this nanoparticle is safe and risk-free. The incorporation of these particles into polymer matrices like polyethylene, PLA (polylactic acid), polypropylene, have facilitate the production of packaging films that possess both antibacterial and ultra violet blocking abilities.

A composite film was developed using polyvinyl and zinc oxide nanoparticle as the main film-forming substrates, alongside sorghum straw powder, through a method that involves blending and casting, and improved thermal stability and barrier properties was observed.[11] Fourthly, the silicon dioxide nano particles (SiO_2NP), also known as nano silica, which are coated or incorporated into polymer matrices to increase the strength, stability and toughness of plastic packaging materials. In the food packaging sector, SiO_2NP is used as an anti-caking agent to prevent clumps and increase the flow of powdered products, and also to prevent the freshness and flavor of food for a long period of time by inhibiting the proliferation of microbes like *Escherichia coli*,*Listeria monocytogenes* and *Staphylococcus aureus*, upon little additions (*e.g.* blueberry extracts packaged with nano silica).[12] Chitosan nano particle, the fifth nano particle, is a macromolecule gotten from chitin.[20] Its low level of toxicity, and excellent film forming capabilities, makes it an excellent vehicle for incorporating additives, biodegradability, biocompatibility, antioxidant, anticoagulants and antimicrobial properties that protects from the actions of harmful microorganisms such as the Gram-positive and Gram-negative bacteria as well as fungi.[14] Its capabilities to function as an antimicrobial are as a result of the relationship that occur between the charged cell membranes and the cationic properties of the microorganisms which destroys the membrane of the cell and lead to the contents of the cell leaking out.[26] The sixth nanoparticle, polylactic acid (PLA) nano particles, which is also referred to as polylactide, is a biodegradable plastic made from sugar, corn, beet, or maize starch with desirable qualities like transparency, flexibility, permeability and processability.[26] The poor gas barrier capabilities and the expensive cost of production of PLA prevented its use widely.[26] The combination of PLA with other types of nano particles like the titanium dioxide to form composites from recent research in nano composite technology have greatly enhanced the use of PLA in the food sector. Lastly, the nano sensors, that possess tremendous capabilities both physically and chemically at the nanoscale, which ranges from accessing environmental factors affecting food to monitoring of pathogenic microorganisms such as *Salmonella* and *Escherichia coli*.[27] It monitors the changes in temperature, gas, moisture and chemical changes that might cause the deterioration of food.[8] In food packaging, nanomaterials such as AgNPs, ZnONPs, TiO_2NPs and SiO_2NPs are incorporated into different polymer matrices such as polylactic acid (PLA), polyethylene (PE) and chitosan, highlighting their function and practical limitation (Table 1).

Table 1 Methods by which nanomaterials are incorporated into polymer matrices

Polymer matrix	Nanomaterials	Antimicrobial mechanisms and target microorganisms	Packaging function	Key limitations	References
Polylactic acid (PLA)	AgNPs	Ag^+ release, ROS generation, membrane disruption against *E. coli*, *Staphylococcus aureus*, *Micrococcus luteus*	Biodegradable antimicrobial films	High cost and fragility of PLA	28
PLA	ZnONPs	Zn^{2+} release and oxidative stress against *E. coli*, *Salmonella* and spoilage bacteria	Active biodegradable, antimicrobial and improved food packaging	Agglomeration at high NP loading, prolonged ROS can potentially pose challenges in control and maintenance	29
PLA	TiO_2NPs	Photocatalytic ROS under UV/visible light against *E. coli*, *S. aureus*	UV-protective, antimicrobial films	Light dependence for activity	30
PLA	SiO_2NPs	Improved nanoparticle dispersion and barrier properties against *S. aureus, E. coli*	Reinforced and biodegradsble polymer matrix	Processing incorrectly may render it ineffective; its odor may impact the taste of packaged food	31 and 32
Polyethylene (PE)	AgNPs	Cell wall and membrane damage, intracellular damage, increased ROS production against *E. coli*, *Salmonella*, *Listeria monocytogenes*	Long life plastic food wraps	High risk of migration in acidic medium or food; tendency of AgNPs to aggregate due to small size	33
Polypropylene (PP)	ZnONPs	Zn^{2+} release, membrane disruption and dissolution against Gram-negative and Gram-positive bacteria	Extended shelf life, exhibit hydrophobicity, enhances barrier	Possible ZnO migration particularly for acidic foods	29 and 34
Chitosan	AgNPs	Ag^+ release and electrostatic interaction against *Candida albicans*, *E. coli*	Effective bactericidal properties, membrane disruption, edible antimicrobial coatings	Aggregation, dispersability and instability	35 and 36
Chitosan	ZnONPs	ROS and Zn^{2+} release, potent bacterial inhibition against *B. subtilis*, *E. coli*	Decreased permeability to oxygen, water vapor and light transmission and solubility; biodegradable antimicrobial films	Possible ZnO migration particularly for acidic foods, May self assembles into agglomerate, ROS production may impact food quality and packaging integrity	29
Chitosan	TiO_2NPs	ROS generation causes photocatalytic antimicrobial action against foodborne pathogens	Enhanced hydrophobicity and mechanical properties, excellent antimicrobial activity	Toxicity at high concentration	37 and 38

2.3 Mechanisms of antimicrobial action

The various mechanisms of antimicrobial action involve: for silver nano particles, its shape, the charge on its surface and size determines its antimicrobial effects. Compared to other nanomaterials, as a result of the large surface area to volume ratio and the crystallographic structures on the surface of AgNPs, they are known for their strong antimicrobial efficacy. Their mechanism of action include: the adhesion to cell membrane (AgNPs bind to the cell membrane of the microorganism, alter its membrane structure and permeability, also due to its weak and the structure of the permeable membrane, the cellular content as well as ATP of the cell is leaked out which in turn impair the transport activity of the cell), penetration inside the cell and nucleus (once the AgNPs have penetrated the cell, they cause the dysfunction of the mitochondria, they destabilize the ribosomes and denature proteins next and then, interfere with the normal functioning of the DNA of the microorganism leading to its destruction), and cell toxicity (which is caused as a result of the relationship between the sulfur contained in the proteins found in the cell wall of microorganisms, in particular, bacteria, and the Ag^+ ions which produces in the cell wall of the bacteria a disturbance that is irreversible).[39] The toxic nature of the cell is assumed to be the main antibacterial mechanism in accessing the antibacterial action of AgNPs. The mechanism of nano particles action is shown in Fig. 3.

The mechanism of action of titanium dioxide nanoparticle on the other hand is through the photocatalytic oxidation reactions of the nano particle. When a photon of light greater than the gap of the band energy gets absorbed by a TiO_2 catalyst, reactions with photocatalytic oxidation reactions occurs.[40] As a result, from the valence band to the conduction band, an electron (e^-) and a positive hole (h^+) is generated at the same time. Water molecule gets broken in the TiO_2 positive hole into hydrogen gas (H_2) and the hydroxyl radical (OH). The hydroxyl radicals formed further react with themselves to form hydrogen peroxide (H_2O_2). These reactive oxygen species (ROS) or H_2O_2 can breakdown organic compounds and destroy the activities of the cell. The photocatalytic action of TiO_2 causes several damages to cell membrane by ROS which is the followed by the loss of vital cellular functions like the disruption of DNA replication processes.[41]

Zinc oxide nanoparticles mechanism of action occurs in several ways. The cell wall and components of the cell such as

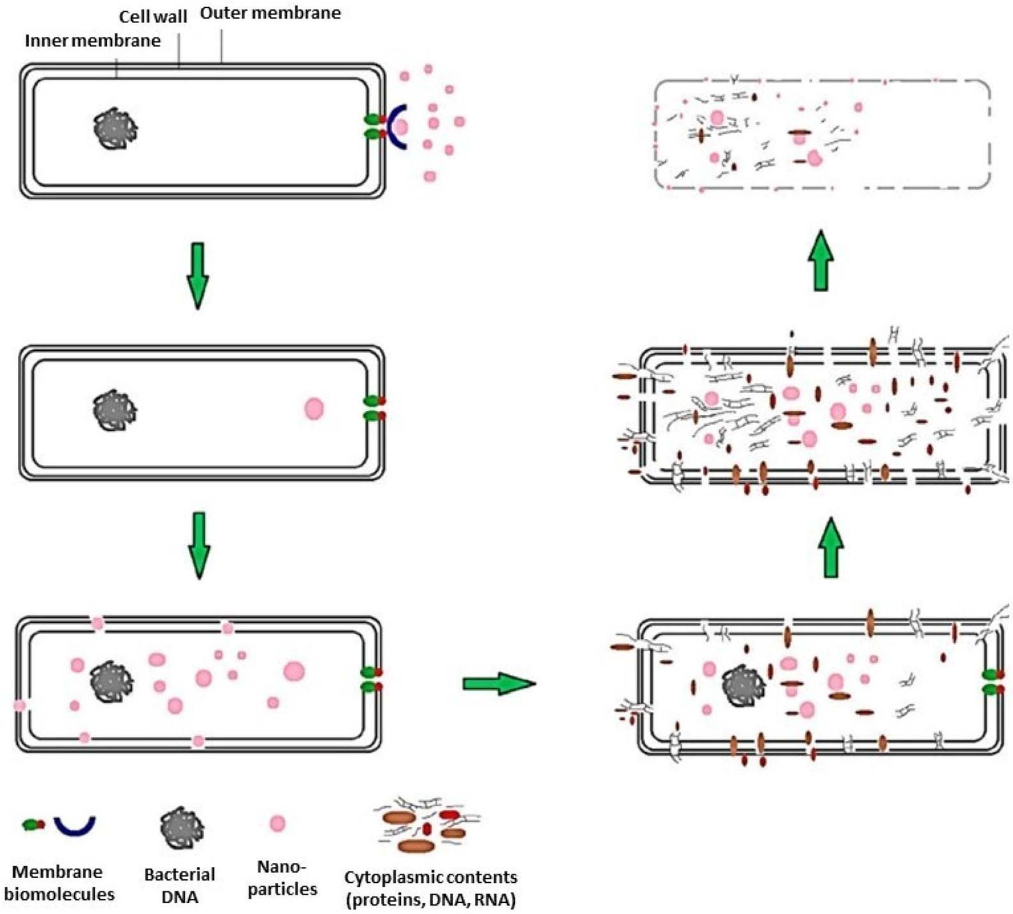


Fig. 3 Antimicrobial mechanisms of nanoparticles. Schematic illustration showing the interaction of nanoparticles with microbial cells, including membrane adhesion, membrane disruption, intracellular penetration, interference with metabolic processes, leakage of cellular contents, and eventual cell death.

the layers of sugars, proteins and lipids, get destroyed as a result of attachment of Zn^{2+} ions released from ZnONPs. The small size of ZnONPs allows them to penetrate the wall of bacterial cell, weaken the cell membrane and disrupt the cell's DNA.[42] ZnONPs also produce H_2O_2 or ROS upon exposure to UV which combine and destroy the protein and lipids bilayer of the microbial cell.[43] The surface area to volume ratio of silicon dioxide nano particles is quite high and this enables the absorptivity of this nanoparticle onto bacterial and viral cells' surfaces as well as destroy the integrity of their cell membranes. SiO_2 nanoparticles have the ability to produce reactive oxygen species (ROS) when exposure to light or heat, and this triggers oxidative stress as well as destruction to the microbial cells.[44]

The chitosan nano particles act through the reaction of the amino groups of chitosan that are positively charged with that of the negatively charged groups on the microbial cells surface, which retards the mRNA as well as the protein synthesis, and so create a boundary that restricts the availability of nutrients that are essential for the microbial cell's growth.[45] The chitosan nano particles also inhibit the DNA replication and with time cause the death of the microbial cell by binding to the cell's DNA.[46] Polylactic acid nano particles, especially when incorporated with other antimicrobial agents like essential oil and metal nanoparticles, may interact with the membrane of bacterial cells, increase its permeability, and cause the cell's content to leak out.[47] PLA nano particles, can also generate ROS when exposed to certain conditions like light, which cause the destruction of the microbial cell's proteins, lipids and even the DNA, and this further destabilize the cellular functions of the cell and eventually lead to cell death.[48]

In food packaging, nano sensors perform both detection and antimicrobial functions. Nanomaterials like carbon nanotubes are used by nano sensors to detect microbial metabolites like pH changes and volatile organic compounds. Antimicrobial agents such as AgNPs embedded in the packaging matrix are triggered and released, upon detection. Nano sensors generate reactive oxygen species by photocatalytic nanoparticles such as titanium dioxide, which oxidizes the microbial cell components. They also disrupt cellular activities like DNA replication and enzyme activities by releasing metal ions like Ag^+. It can be noted that nano sensors only release antimicrobials when microbial activity is detected. Though, these pathways are common in nanotoxicology, their relevance in food packaging arises when nanoparticles migrate or dissolve from packaging films into food matrices.

2.4 Mechanistic chemistry of antimicrobial nanomaterials

2.4.1 Cell wall disruption by nanoparticles. Nanoparticles disrupt bacterial cell walls and membranes primarily by adhering to the surface and increasing membrane tension. This mechanical interaction causes stretching and deformation of the bacterial membrane, leading to increased permeability, membrane rupture, and ultimately cell lysis.[49] The process involves nanoparticles binding electrostatically to the negatively charged bacterial surface due to their own positive charge, which enhances their affinity and effect.[50] The mechanical stress from nanoparticles adsorbing to the membrane causes the lipid bilayer to stretch and collapse, damaging the cell wall and membrane integrity. This disruption allows leakage of cellular contents, penetration of molecules that can damage intracellular components like proteins and DNA, and effectively kills the bacteria.[51] Different nanoparticle shapes (spherical, star-shaped) and surface properties impact the degree of membrane disruption and bactericidal activity. Some nanoparticles also form pores or ion channels on bacterial membranes, further increasing permeability and leading to cell death. The bactericidal action occurs without nanoparticles necessarily entering the cell, relying on external mechanical damage to the cell wall and membranes.[52]

2.4.2 Intracellular penetration. Nanoparticles penetrate cells primarily through various endocytosis pathways including clathrin-dependent, caveolin-dependent, and lipid raft-mediated endocytosis.[53] After binding to the cell surface, nanoparticles are engulfed into membrane-bound vesicles such as endosomes or phagosomes. Some nanoparticles can also directly translocate across the plasma membrane by disrupting the lipid bilayer or fuse with the membrane to release their cargo directly into the cytoplasm, bypassing endosomal entrapment.[54] Once inside, nanoparticles interfere with internal cellular structures and metabolic processes by generating reactive oxygen species, damaging organelles like mitochondria, disrupting protein function, and interacting with.[55] This intracellular damage can lead to impaired cell metabolism, apoptosis, or cell death. The mechanism and extent of intracellular penetration and damage depend on nanoparticle size, shape, surface chemistry, and cellular uptake pathways.[56]

2.4.3 Oxidative stress. Oxidative stress induced by nanoparticles occurs through the generation of ROS such as superoxide anions, hydroxyl radicals, and hydrogen peroxide.[55] Nanoparticles have unique physicochemical properties, including high surface area-to-volume ratio, surface reactivity, and sometimes the presence of transition metals, that catalyze ROS formation on their surfaces.[57] These ROS cause oxidative damage to essential cellular components like proteins, lipids, and DNA, disrupting their normal functions. Mechanistically, ROS are generated both extracellularly on the nanoparticle surface and intracellularly after nanoparticle uptake, especially within mitochondria where nanoparticles impair the electron transport chain and induce mitochondrial damage peroxide.[55] The oxidative stress response can trigger cell signalling pathways leading to inflammation, genotoxicity, apoptosis, or fibrosis. The extent of oxidative damage depends on nanoparticle size, surface characteristics, and cellular interactions. For example, smaller nanoparticles and those with positive surface charge tend to induce higher ROS levels and oxidative damage.[58]

2.4.4 Signal transduction modulation. Nanoparticles can modulate bacterial signalling pathways primarily by interfering with quorum sensing (QS), a key cell-to-cell communication mechanism bacteria use to coordinate group behaviours like virulence factor expression and biofilm formation.[59] Engineered nanoparticles, such as silica nanoparticles functionalized with β-cyclodextrin, bind and sequester signalling molecules like acylhomoserine lactones (HSLs) in Gram-negative bacteria.[60] This binding prevents the signalling molecules from reaching their receptors, effectively silencing quorum sensing and disrupting bacterial communication. By blocking QS, nanoparticles inhibit bacterial communication critical for growth regulation and biofilm development, weakening bacterial virulence and resistance.[61] This pathway modulation offers a promising alternative to traditional antibiotics by targeting bacterial behaviour rather than killing cells directly, potentially reducing the pressure for resistance development.[62] Functionalized nanoparticles can penetrate biofilms and reduce bacterial virulence by chemically quenching signals and downregulating QS-regulated genes.[63]

2.4.5 Ion release and synergistic effects. Some nanomaterials such as silver ions (Ag^+), molybdenum-based compounds, and cerium oxide (CeO_2) nanoparticles release ions that enhance their antimicrobial activity. The released metal ions contribute to microbial killing by interacting with cellular components, disrupting enzymatic functions, and damaging nucleic acids and proteins.[11] These ions can also catalyze reactions, including enzyme-like catalysis and photo-induced effects, which generate ROS that further damage bacterial cells.[64] For example, silver nanoparticles (AgNPs) release Ag^+ ions that penetrate bacterial cells, interacting with intracellular structures and causing oxidative stress by generating ROS (Fig. 4). Similarly, Mo-based and CeO_2 nanoparticles act as catalysts for redox reactions, mimicking enzyme activities such as oxidase and peroxidase, which promote ROS production and bacterial membrane damage.[65] This ion release and catalytic activity often act synergistically with other mechanisms like membrane disruption and signal interference to significantly enhance the overall antimicrobial efficacy.[66]

2.4.6 Direct nano-bio interactions. Nanoparticles may interact directly with microbial cells to induce functional and structural disruptions.[70] These interactions are mediated typically by electrostatic force of attraction, where positively

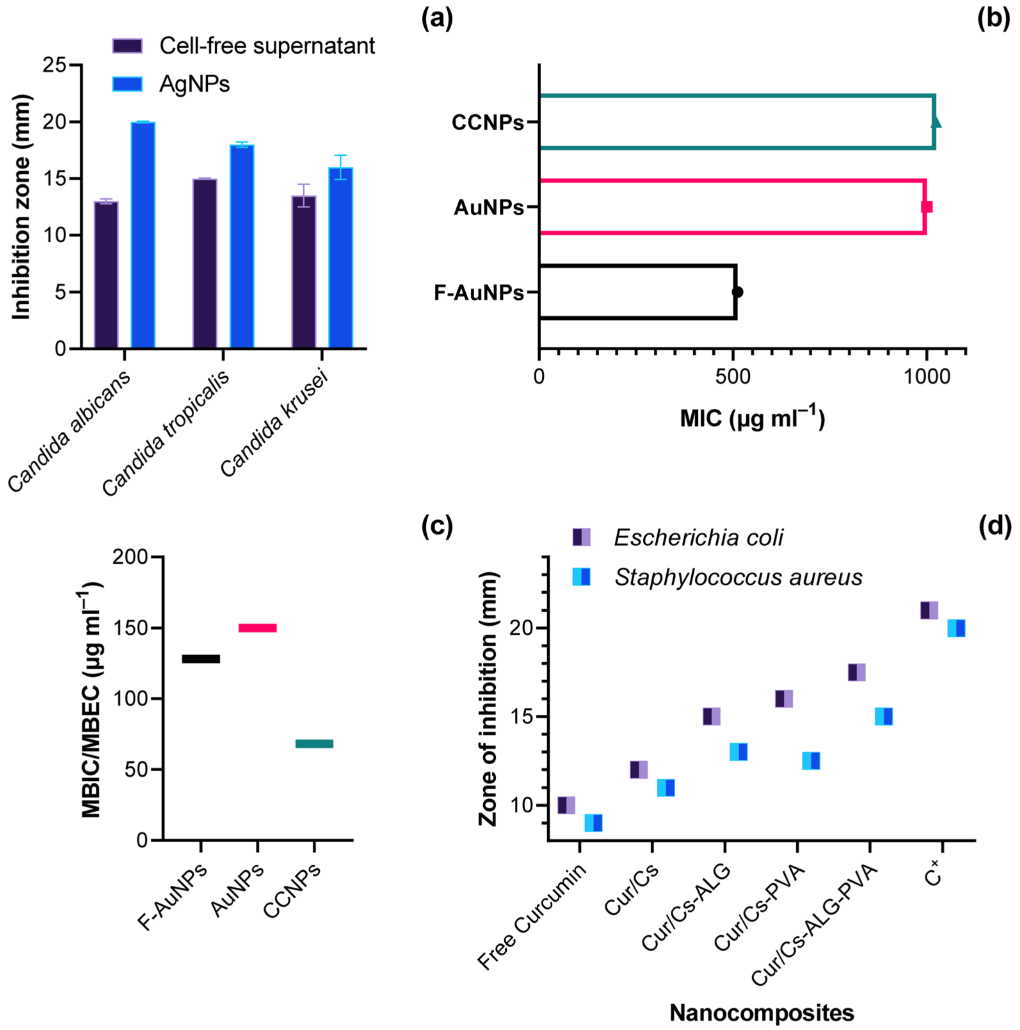


Fig. 4 Antimicrobial functions of nanomaterials and nanocomposites: anticandidal activity of silver nanoparticles (synthesized from *Streptomyces* sp. VITPK1).[67] (a), MIC (b) and MBIC/MBEC (c) of selected nanoparticles,[68] and antibacterial effects of nano-composites based on curcumin/chitosan-PVA-alginate (d)[69] [MIC; minimum inhibitory concentration. MBIC/MBEC; minimum biofilm inhibitory/eradication concentrations].

charged nanoparticles bind to negatively charged bacterial cell walls, resulting to the destabilization of membrane, increased permeability and the leakage of intracellular contents.[71] Nanoparticles may also bind to proteins and nucleic acids, resulting to inhibited enzyme activity or replication inference.[72] Factors such as nanoparticle size, zeta potential, surface functional groups and aggregation state which is influenced by the packaging film and surrounding food components controls the extent of these interactions.

2.5 Advantages over traditional antimicrobials

Nanotechnology based packaging provides great advantages over traditional antimicrobials such as chemical preservatives like sodium benzoate and the use of natural extracts. Some of these advantages are: firstly, the improved barrier properties of packaging materials. This improved barrier capabilities enables the protection of food products from environmental conditions like moisture and oxygen, thereby extending shelf life can be produced using nanotechnology.[20] Secondly, nanomaterials *e.g.* the use of nano sensors, AgNPs, possess the ability to detect and inhibit microorganisms that can cause food spoilage, which ensures the safety of food and also reduce the risk of food-borne illnesses.[73] Nanotechnology based packaging materials are also often more lightweight and compact than traditional antimicrobials, which reduces the amount of packaging materials needed for food products, reduce packaging costs and improve the overall efficiency of the packaging process.[74] Nanotechnology based packaging materials are overall more sustainable and eco-friendlier than traditional antimicrobials which promotes the production of sustainable food and limits the negative impacts of packaging on the environment.[20] Through nanotechnology smart labels could be created which would provide consumers with more information such as nutritional value of the food, its origin and other useful information about the food they are buying and detect spoilage pathogens.[74]

3 Types of nano-packaging

Nano-packaging involves the utilization of nanomaterials to improve the preservation of food products. There are basically four types of nano-packaging. They are improved packaging, active packaging, intelligent packaging, and the bio-based system packaging. The improved packaging requires embedding nanomaterials such as AgNPs or SiO_2, into polymer matrices of the packaging material to enhance the properties of the matrices. Incorporating nanomaterials enhances polymer strength, flexibility, and resistance to temperature, gas, humidity and pH.[75] The reinforcement of polymer matrices with nanomaterials also improves the physiochemical characteristics like structural strength, durability, flexibility and barrier capabilities of the matrix of the polymer. This implies that the wear loss and friction coefficient of the material is enhanced, lower flammability and higher heat resistance of the polymer, encouraged use of thinner films which reduces the cost of recycling and raw material consumption as a result of enhanced mechanical properties.[76]

The active packaging systems allows the food product and the packaging material to interact, and this helps to promote food safety and provide other features such as protection against microbial contamination (antibacterial properties), prevention of food oxidation caused by UV exposure (UV blocker), and improved barrier properties (gas absorber, odor absorber and flavor releasers), through the use of nanomaterials.[77] Active packaging was defined by the Commission Regulation (EC), as the intentional incorporation into or from the packaged food or food environment, components that would absorb or emit substances. This implies that active packaging maintains the parallel relationship between the food and its surrounding through the emitters (release substances) and scavengers (absorb substances), while simultaneously preserving the food product.[78,79] The emitters release antimicrobials, antioxidants, ethanol (C_2H_5OH) or ethylene (C_2H_4), carbon dioxide (CO_2), and flavors, which helps maintain the food quality, extend its freshness, and also maintain its flavorable condition, while the scavengers on the other hand, remove unwanted substances such as moisture, oxygen, CO_2 and odor from the packaged food environment.[80]

Intelligent packaging as defined by the European Food Safety Authority (EFSA), refers to materials and articles that regulate the conditions of packaged food or its environment.[79] Through the means of nanomaterials, particularly the nano sensors, intelligent packaging aid in the monitoring of temperature, time, freshness, moisture, gas or environment of the packaged food product and conditions that facilitate spoilage, which ensures the safety of the packaged food.[76] Nano sensors regulate the both the inside and outside environments of packaged food. This type of packaging also offers to producers, retailers, and those consuming the food product real-time information on the condition of the product.[76] Other types of intelligent packaging systems that are utilized in the food industry aside the nano sensors (sensors), include: indicators, time–temperature indicators, freshness indicators, data carriers, barcode, radio-frequency identification, biosensors, and gas sensors.[80] Sensor capped with AgNPs indicated spoilage in chicken breast and silver carp.[19] In similar manner,[81] explained that freshness sensors and indicators are incorporated into polymer-based matrices including cellulose and chitosan to form biodegradable, sustainable films for the packaging of meat. These nano-enabled systems in addition to providing real-time monitoring also enhance the functionality and integrity of packaging throughout handling and storage, reducing the effects of external environmental and mechanical stress factors while simultaneously improving food safety and reducing food waste.

Bio-based packaging involves the use of materials or polymers obtained from bio-sources for packaging food products. These bio-based materials are obtained from materials that are renewable or non-renewable but are biodegradable. Bio-based packaging films are generated from natural sources like proteins, polysaccharides, polynucleotides, directly, also through synthesis chemically from bio-based monomers like the bio-polyesters, polylactic acid, and can as well be obtained from microorganisms or organisms that are genetically modified like the bacterial cellulose, and polyhydroxyalkanoates.[82]

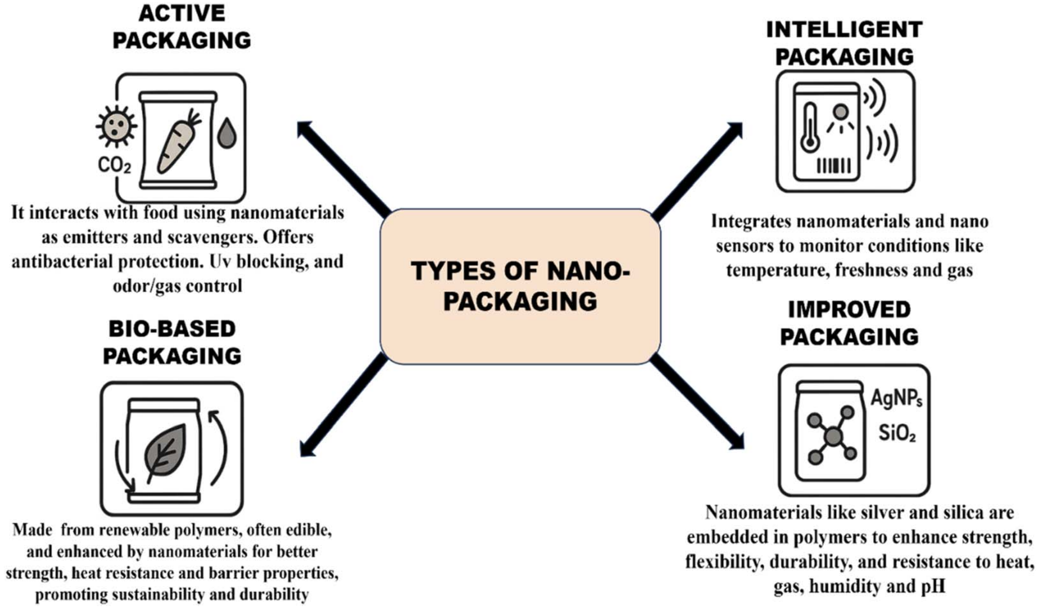


Fig. 5 Types of nano-packaging. Overview of the four major nano-packaging categories: improved packaging, active packaging, intelligent packaging, and bio-based nano-packaging.

Bio-based packaging is made up of edible films and coatings that comprises of proteins, lipids, and polysaccharides in either single or multiple layers. The low structural as well as thermal resistance, low gas and water barrier properties, of biodegradable materials are enhanced with nanomaterials to enforce their functionality. Nanomaterials are used to fill the spaces between molecules of the polymer and this increase the feasibility and strength of the packaging material.[83] Nanomaterials when incorporated in bio-polymer restrict the movement of the matrix of the polymer and that increases the structural strength, thermal properties and barrier capabilities of the packaging. The types of nano-packaging are shown in Fig. 5.

3.1 Methods of incorporation into packaging materials

There are several methods of incorporating nanomaterials into packaging materials. The first method is the direct incorporation into the food packaging films. During manufacturing, the nanomaterials and active agents are mixed directly into the food packaging films, either by melt-blending the nanoparticles and the film together or by dispersing the nanoparticles and the film in a solvent, thereby forming a nanocomposite film. This aids the enhancement of the structural strength, barrier and antimicrobial capabilities of the packaging material. For instance, AgNPs are incorporated into PLA for antimicrobial packaging.[84]

Another method is the coating or surface application. In the coating or surface application, the nanomaterials are applied as coatings on packaging materials that are not fully formed or pre-formed. Nanomaterials such as TiO_2 nanoparticles, silver nanoparticles, are embedded into a coating solution (*e.g.* biopolymers), and applied either by spraying, dipping or layer-by-layer deposition. This minimizes the use of nanomaterial and preserves the effectiveness of the bulk material. For instance,[85] in their study highlighted that the coating of PLA films with AgNPs and graphene oxide, improves the barrier and antimicrobial properties for active packaging.

Electrospinning is another method of incorporating nanomaterials into packaging materials.[85] Here, a polymer solution (*e.g.* PLA) containing nanomaterials, is expelled through a needle under a high voltage electric field, as a result forming nanofibers which are collected as a film or mat. This provides a high encapsulation efficiency, controlled release for active properties and enhanced sensitivity for intelligent functions.[86]

Another method is the printing technologies. Nanomaterials such as nano sensors or carbon nanotubes are incorporated into functional inks for printing and are applied using screen, inkjet or gravure printing to create smart labels or sensors. The printing of nano sensors onto biopolymer films for intelligent packaging which enables real-time spoilage monitoring.[87] This method also give room for high precision and is cost-effective for mass production. In addition, another method is the advanced fabrication techniques, 3D printing and microfluidics, which incorporate nanomaterials into packaging with precise sensing capabilities and structures. While 3D printing embed the nanomaterials into the biopolymer structures, microfluidics integrates the nanochannels with nano sensors for real-time monitoring. 3D printing of nanomaterial-based sensors into PLA packaging, which enhances its active and intelligent functionalities.[88] The methods of nanoparticle incorporation into packaging materials is shown in Fig. 6.

3.1.1 Role of polymeric packaging matrices. The polymeric packaging matrix plays significant role in determining the safety, performance and durability of antimicrobial nano-packaging systems.[89] Antimicrobial efficacy and migratory behavior are influenced by polymer chemistry, which also controls nanoparticle dispersion, interfacial interactions and retention within the matrix.[90] For instance, biodegradable

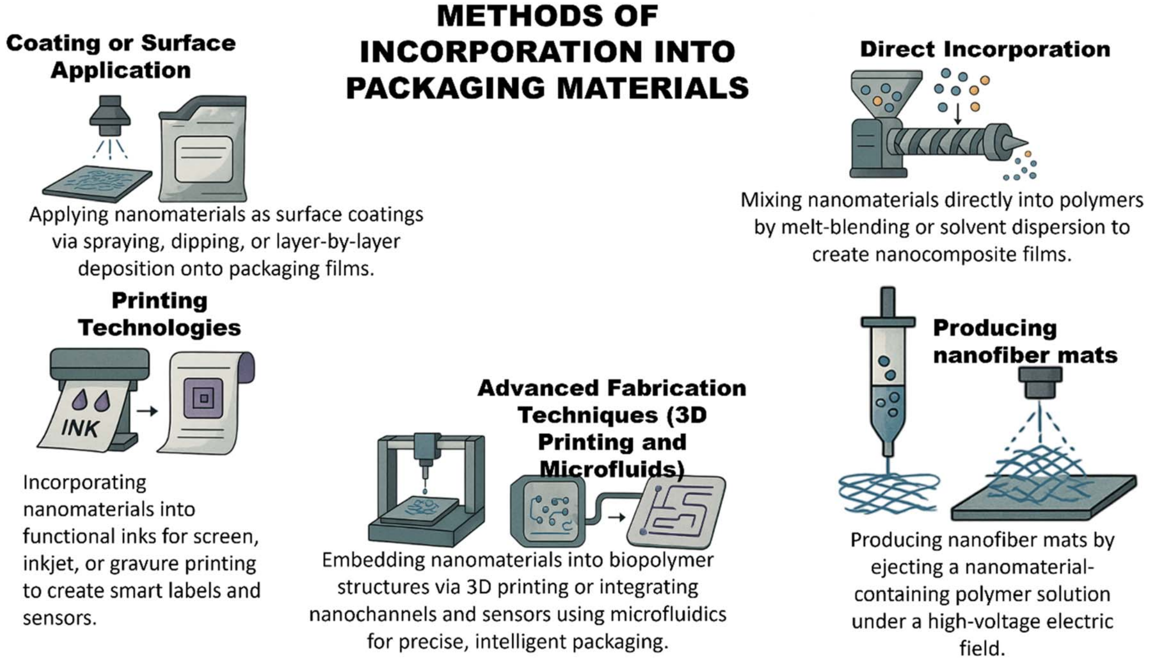


Fig. 6 Methods of nanoparticle incorporation into packaging materials. Common techniques for embedding nanomaterials into food packaging films, including direct incorporation, coating or surface application, printing technologies, producing nanofiber mats, and advanced fabrication techniques such as 3D printing and microfluidics.

polymers like PLA offer functional groups that interact with nanoparticles to enhance dispersion and prolong antimicrobial activity.[91] Inorganic nanomaterials usually need surface modification or compatibilizers in order to obtain uniform nanoparticle distribution and long-tern stability.[92] Cellulose-based matrices also offer high mechanical strength and barrier properties while also promoting the development of sustainable and biodegradable packaging material.[93] Crucially, the polymer matrix influences both antimicrobial efficacy and adherence to food-contact safety requirements by acting as a diffusion barrier that regulates nanoparticle and ion release.

3.2 Migration and transformation pathways of nanomaterials in real matrices

3.2.1 Migration behaviour in food packaging. Migration depends on nanoparticle diffusion within the polymer matrix, partitioning between polymer and food simulant, NP size, surface functionalization, and matrix compatibility; reported migration from antimicrobial films is often low but depends on polymer type and processing conditions.[94] Factors reducing migration include strong particle–polymer binding, surface functionalization, and immobilization within crosslinked matrices, whereas poor compatibility and high food fat content can increase apparent transfer into foods.[95] Specific diffusion coefficients and partition coefficients vary by system and are not universally reported; reported migration studies often use food simulants and report negligible or low migration under tested conditions, but data are material and test condition specific.[96] In addition to general mitigation trends, polymer chemistry plays a decisive role in controlling release from food packaging systems.[97,98] A quantitative comparison of reported migration and antimicrobial performance across representative nanomaterial-polymer systems is summarized in Table 2.

Nanomaterials including AgNPs, ZnONPs and TiO_2NPs are typically embedded within the polymer matrix of biodegradable polymers such as PLA, rather than dispersed freely at the surface.[102] AgNPs incorporated into PLA, for instance, has been shown to release antimicrobial silver, predominantly Ag^+ ions, with its migration rates influenced by the nanoparticle loading, crystallinity of the polymer, and food stimulant composition.[103] Acidic food environments promote the higher release of ions due to the enhanced dissolution of nanoparticle and polymer swelling.[103] ZnO-based nanocomposites portray a similar migration behavior as zinc migration occurs significantly in the form of Zn^{2+} ions rather than particulate ZnO.[104] This migration extent is governed by the hydrophobicity of the polymer and the permeability of matrix. Migration of inorganic oxides such as TiO_2 and SiO_2 from polymer matrix is generally reported to be very low as they tend to strongly remain immobilized within PLA, PE or chitosan films, with their antimicrobial effects arising predominantly from surface-mediated ROS generation rather than the diffusion into the food matrix.[30,105] Food composition also plays critical role with fatty and acidic foods promoting higher migration levels than aqueous or neutral systems.[106] Overall, these observations highlight the importance of polymer-specific design strategies and safe-by-design approaches to balance antimicrobial performance with food safety requirements.

3.2.2 Transformation in food matrices. pH affects dissolution of metal oxides and ion release (*e.g.*, ZnO dissolution increases under acidic conditions), altering antimicrobial potency and speciation.[107] Ionic strength and presence of salts

Table 2 Comparison of migration and antimicrobial performance across nanomaterial-polymer systems

Nanomaterial	Polymer matrix	Reported quantitative performance	Food/simulant studied	References
AgNPs	PLA	Ag^+ migration 0.02 mg kg^{-1}; antimicrobial activity 2–5 log CFU g^{-1} reduction	Apple juice, acetic acid, distilled water and ethanol	Emelda *et al.*, (2019)[99]
ZnONPs	Chitosan	Zn^{2+} migration up to 50 mg kg^{-1} in acidic media, ∼2 log CFU g^{-1} reduction	Meat	100
TiO_2NPs	PLA	Up to 7.9 log CFU g^{-1} reduction under photoactivation	Tomatoes	25
Chitosan (nanostructured)	Chitosan films	1–2% weight loss reduction in fruits/vegetables, 2–4 log CFU g^{-1} reduction in fish	Fruits, vegetables, fish	101

modulate aggregation and corona formation, which can reduce free nanoparticle concentration and change bioavailability.[108] Proteins and lipids in foods bind to NP surfaces (protein corona, lipophilic adsorption), altering dispersion, suppressing direct surface reactivity, and modifying migration and antimicrobial activity.[109] High fat content can sequester hydrophobic coatings or change partitioning, sometimes reducing measured migration into aqueous simulants but promoting association with lipid phases.[110]

3.2.2.1 *Aggregation and agglomeration.* A common transformation process is the aggregation and agglomeration.[111] This process occurs when nanoparticles lose colloidal stability in complex food environments. Factors such as acidic conditions, high ionic strength or the presence of divalent cations such as Ca^{2+} can neutralize charges of the surface and promote particle–particle interactions[72,112] The aggregation process increases the particle size and causes a reduction in the surface area, resulting in the limited reactivity of the surface and the ion release of nanomaterials.[113] Simultaneously, large aggregates of nanoparticles may become entrapped within the matrix, reducing movement but also altering the contact of the surface with microorganisms.

3.2.2.2 *Dissolution and chemical speciation.* Another important transformation pathway especially in metal and metal-oxide nanoparticles such as AgNPs and ZnO is the dissolution and chemical alteration. Dissolution is accelerated by food matrices with low pH, organic acids or chloride ions, thus converting nanoparticles into bioactive ionic species.[114] For instance, Ag^+ is readily formed from AgNPs in acidic environments,[115] while ZN^{2+} is released from the dissolution of ZNO under similar conditions.[116] This dissolution process enhances the antimicrobial activity and affects the migration potential, as ions are smaller, more motile and easily diffuse through packaging materials or components of food. It may also result to redox reactions such as oxidation of metallic silver to silver oxide or the reduction of nanoparticles by the constituents of food, thus altering their catalytic behavior and reactivity.

3.2.2.3 *Protein corona and bio-molecular interactions.* Nanoparticles often undergo the formation of protein corona, that is, the adsorption of food proteins onto the surface, in protein-rich foods such as meat, milk and legumes.[117] This corona can modify the charge, hydrophobicity, dissolution rate, and biological interactions of the nanoparticle surface.[109] The corona in some cases causes the stability and reduction of ion release by the nanoparticle. In other cases, it masks the active sites and reduce the antimicrobial efficiency. The absorbed proteins may also act as carriers, facilitating the movement of nanoparticles within the food matrices. Since the composition of the corona depends on the temperature, presence of specific proteins and storage conditions, the behavior of the nanoparticles can vary greatly across the different food types.[117,118] Due to the adsorption of lipids, carbohydrates, polyphenols, or other food constituents, nanomaterials may also experience surface modification. In fatty foods such as oils and cheese, lipid adsorption can readily occur, forming a hydrophobic coating that reduces the reactivity as well as suppresses the formation of ROS. Polyphenols and antioxidants in fruits and beverages may also reduce and scavenge ROS, thus influencing further the antimicrobial capacity.[119]

3.2.2.4 *The role of environmental factors.* Environmental factors such as temperature, humidity, exposure to light and storage duration modulate further the transformation behavior. Increased temperatures can promote the rates of diffusion and dissolution,[85] while the exposure to UV or visible light can activate photocatalytic materials such as TiO_2, thus altering profiles for ROS generation.[120] Prolonged storage facilitates changes in structure, promotes aging processes and weakness of material in both the nanoparticles and the food-contact polymer.[85]

3.2.2.5 *Behaviour in biological fluids and tissues.* Biological fluids rich in proteins and salts rapidly form a biomolecular corona that alters surface charge, opsonization, cellular uptake, and dissolution rates; corona composition is dynamic and matrix specific. pH in different tissue compartments (*e.g.*, acidic phagosomes) can enhance metal ion release and ROS generation locally, modifying antimicrobial action and host toxicity.[109]

3.2.2.6 *Environmental transformations.* Aggregation/agglomeration driven by ionic strength, natural organic matter and aging reduces mobility and alters reactivity.[109] Dissolution releases bioactive ions (Zn^{2+}, Ag^+, Cu^{2+}), which can travel separately from particle cores and contribute to toxicity over different spatial and temporal scales.[121] Surface modifications (oxidation, sulfidation for Ag, carbonate formation) and corona formation with natural organic matter alter both antimicrobial potency and detectability.[122] Long term stability depends on environmental redox, light exposure (photocatalytic activation or photodegradation), and interactions with biota.[122]

3.2.2.7 Stability and degradation pathways by context. In polymeric packaging matrices, immobilized NPs are relatively stable, with low migration unless matrix integrity is compromised or processing produces loosely bound particles.[123] In physiological media, coronas and acidic microenvironments accelerate dissolution and transformation, often increasing short term bioactivity but also modulating toxicity.[109] In environmental waters and soils, sulfidation of Ag and complexation of Cu reduce free ion availability but may form persistent phases with altered bioavailability.[123]

3.3 Role of water vapor transmission rate on antimicrobial efficacy

3.3.1 Moisture as an activator for antimicrobial surfaces. A wide range of antimicrobial surfaces such as copper, silver, quaternary ammonium, triclosan, ionic liquids, and hydrogels show strong dependence on ambient humidity and wet-contact time. For copper and other metals, moisture is critical for ion release and transport.[124–126] Copper surfaces show progressively greater killing of *Staphylococcus aureus* as relative humidity (RH) increases from <30% to >60%; at low RH, log reductions can fall below 1, whereas at high RH they exceed 2 logs in 2 h.[126] Other antimicrobial surfaces likewise show RH-sensitive activity: triclosan-containing polyester is more bacteriostatic under dry than humid conditions but still depends on environmental moisture and loses efficacy with wear or washing,[127] humidity-responsive ionic-liquid copolymer membranes maintain high antibacterial efficacy while undergoing moisture-driven shape changes.[128]

Semi-interpenetrating hydrogels combining hygroscopic LiCl and antimicrobial nanoparticles leverage moisture uptake (0.6–5.1 g g^{-1} from 15–90% RH) to sustain broad-spectrum antibacterial action and humidity regulation. These observations support the general statement that local water availability such as thin films, droplets, and adsorbed water often gates antimicrobial function *via* ion release, ROS generation, diffusion of actives, or swelling of polymer matrices.[124–126,128]

3.3.2 Moisture dependent killing mechanisms. In humidity-responsive antimicrobial membranes based on poly (ionic liquids), the same polymer network acts both as humidity sensor and antimicrobial surface, with water uptake controlling chain mobility, ion exposure, and thus bactericidal actio.[128] A dry transfer method for MRSA showed copper surfaces require environmental moisture for strong antibacterial activity; log reductions increased markedly with RH, paralleling increased water availability at the surface.[126] Cinnamaldehyde released from β-cyclodextrin inclusion complexes in packaging is strongly RH-gated: higher RH increases weakly bound water, drives structural rearrangements, and competitively displaces cinnamaldehyde, boosting cumulative release and giving complete inhibition of *Staphylococcus aureus* and *Aspergillus niger* at 98% RH.[129]

3.4 Case studies

Two packaging materials, one with zinc oxide nanoparticles incorporated into pectin-based biodegradable films and the other with just the pectin-based film (control) was used to store chicken breast samples at 5 degrees Celsius for up to 15 days. The microbial counts in the pectin–ZnO packaged film was 6–7 log CFU g^{-1} after 15 days, which is below the spoilage thresholds, but the microbial counts in the control surpassed them all by day 10. The thiobarbituric acid reactive substances (TBARS) in the pectin–ZnO group increased very slowly which indicates the low levels of lipid peroxidation. The samples wrapped in the pectin–ZnO films-maintained freshness and color better than the control samples which showed pH shifts and discoloration due to microbial metabolism. The pectin–ZnO films prolong the freshness and color of the samples by 5–7 days.[130]

For second case study, Douaki,[131] integrated into packaging a combined near field communication (NFC) powered gas sensors with a system that triggers the release antioxidant or antibacterial agents when spoilage is detected in perishable foods like fish. They made use of a paper-based gas sensor (PEGS) that detects volatile spoilage compounds like ammonia, dimethylamine and trimethylamine (TMA), which are known gases produced by *Pseudomonas* and *Shewanella* species as they break down fish proteins. The integrated NFC antenna allows a wireless transfer of power from a smartphone or handheld reader. The smartphone powers the circuit briefly and long enough to activate the sensor once in close proximity (∼1–4cm), to measure the gas concentration and communicate the data back. If the sensor detects a gas concentration above threshold like for TMA > 10 ppm, it activates the antioxidants/antibacterial agents in the packaging. This allows the consumers and supply-chain managers to check the freshness status of the food product, as data showing whether the food is still safe or close to spoilage are relayed through a colorimetric display or app-based interface. This packaging helped to maintain the freshness of the fish samples to up to 14 days at 4 degrees Celsius, compared to 6–8 days for samples without the integrated sensors and triggering system.

For the third case study, native starch was dissolved and gelatinized with heat, and subsequently mix it with various concentrations of ZnO. The starch-ZnO composite films showed strong inhibition against harmful microbes like *Escherichia coli*, and *Staphylococcus aureus* with clear zones of 13–15 mm around the film discs, although higher concentrations of ZnO showed greater effects. It was observed that the films degraded completely within 7–10 days when buried in the soil. The starch-ZnO film protected the food from photooxidation, maintained strength and flexibility, also no ZnO migration beyond safety thresholds was observed in the food, which ensures the safety of consumer.[132]

For the fourth case study, Bafroee,[133] enhanced polylactic acid with natural nano-cellulose scaffolds and plant essential oils. The film greatly maintained the microbial load of minced lamb meat stored at the refrigerator below spoilage thresholds throughout storage, thereby increasing shelf life. The nanocellulose scaffolds improved the structure of the packaging film by hindering the movement of moisture and oxygen, while the plant essential oil, disrupt the membranes of microbial cells, thereby extending preservation of the minced lamb meats.

3.5 Impacts of antimicrobial nanomaterials

The impacts of antimicrobial nanomaterials on food packaging and preservation includes: Firstly, they are well-suited for active antimicrobial packaging.[20] Active antimicrobial packaging system incorporates antimicrobial agents into the polymer or packaging matrix.[134] Antimicrobial nanomaterials like AgNPs, ZnONPs when incorporated inhibit the proliferation of microbes from when they are transported even until when they are consumed, thereby prolonging the shelf life of the food product. Another impact of antimicrobial nanomaterials is the reduction of food waste.[8] The maintenance of quality by antimicrobial nanomaterials as greatly reduced the food spoilage and that as in turn reduced the quantity of loss of food. Due to the inability or growth of microorganisms, controlled moisture, oxygen, water vapor and carbon dioxide levels in the packaged material, the packaged food product tends to last longer, thereby minimizing the quantity lost.[135]

The third impact of antimicrobial nanomaterial is the enhancement of food safety. The risk of food-borne illnesses is reduced through the action of antimicrobial nanomaterials inhibiting the proliferation of pathogenic microbes like *Listeria monocytogenes*, *Streptococcus aureus*, as a result promoting food safety.[136] The growing threat of pathogens that cause foodborne illnesses like the *E. coli*, *Salmonella enterica* as well as *L. monocytogenes* developing resistance to the action of antimicrobials is overcome by antimicrobial nanomaterials such as AgNPs.[137]

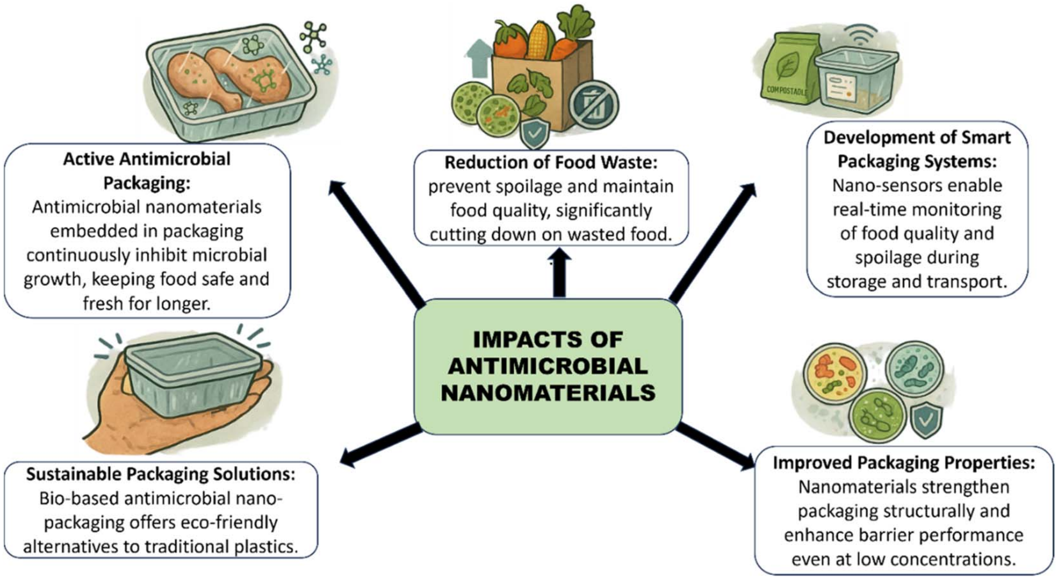
Antimicrobial nanomaterials have helped in the emergence of packaging materials with better and enhanced properties. Packaging materials with infused antimicrobial nanomaterials exhibit better structural, thermal and barrier capabilities, which enhances the overall performance of the food packaging.[138] They augment the interface surface area of the packaging material which enables the rigidity, reinforcement and gas absorption of the material even at low concentrations.

Sustainable packaging solutions is another impact of antimicrobial nanomaterials. Bio-based nano-packaging which contains antimicrobial nanomaterials gotten from renewable and compostable sources have contributed to more sustainable and environmental-friendly solutions, compared to the conventional packaging where petroleum-based, non-degradable materials and plastics, are used and this have a negative impact on the environment.[139,140]

The coupling of antimicrobial nanomaterials has promoted the development of smart systems of packaging that monitors food quality. The monitoring of food quality is part of the challenges of traditional packaging.[141] Nanomaterials such as the nanosensor allows the detection of spoilage and instantaneous monitoring of packaged products when transported and stored. Impact of antimicrobial nanomaterials are shown in Fig. 7.

3.6 Key approaches in quantitative benchmarking of antimicrobial nanomaterials

Life Cycle Assessment (LCA) and Comparative Toxicity Potentials (CTP) LCA frameworks, such as USEtox 2.0, are adapted to include Nanomaterials (NMs) specific fate and exposure models (*e.g.*, SimpleBox4Nano), enabling calculation of CTPs for NMs like TiO_2 across air, water, and soil compartments. These CTPs allow direct comparison with other chemicals and NMs, supporting robust environmental impact assessments.[142] LCA also



Active Antimicrobial Packaging: Antimicrobial nanomaterials embedded in packaging continuously inhibit microbial growth, keeping food safe and fresh for longer.

Reduction of Food Waste: prevent spoilage and maintain food quality, significantly cutting down on wasted food.

Development of Smart Packaging Systems: Nano-sensors enable real-time monitoring of food quality and spoilage during storage and transport.

IMPACTS OF ANTIMICROBIAL NANOMATERIALS

Sustainable Packaging Solutions: Bio-based antimicrobial nano-packaging offers eco-friendly alternatives to traditional plastics.

Improved Packaging Properties: Nanomaterials strengthen packaging structurally and enhance barrier performance even at low concentrations.

Fig. 7 Impacts of antimicrobial nanomaterials. Summary of major benefits provided by antimicrobial nanomaterials, including reduction of food waste, real-time monitoring, strengthen structural packaging, eco-friendly alternative, and extended shelf life.

quantifies the environmental footprint of NM synthesis, highlighting the dominant role of energy and raw material consumption in overall impacts.[143]

High-throughput and mechanistic toxicity screening high-throughput screening (HTS) platforms and advanced proteomics (*e.g.*, TMT labeling) enable simultaneous, sensitive, and reproducible assessment of multiple NMs, supporting prioritization, ranking, and grouping for hazard evaluation. Predictive toxicological approaches integrate *in vitro* HTS with limited *in vivo* validation to establish structure–activity relationships (SARs) and hazard rankings, expediting NM safety assessment.[144]

Quantitative Weight of Evidence (WoE) and Bayesian Models Quantitative WoE frameworks, often combined with multi-criteria decision analysis (MCDA), synthesize diverse lines of evidence (physicochemical, toxicological, and study quality data) to generate hazard scores for NMs, enabling direct comparison and ranking Bayesian networks (BN) offer probabilistic, self-learning models that integrate new data and provide stable hazard rankings. Combining WoE and BN approaches yields optimal frameworks for NM hazard assessment.[145]

Grouping, read-across, and machine learning computational similarity methods, including Bayesian and machine learning models, compare dose–response curves and physicochemical properties to group NMs with similar hazard profiles, reducing the need for exhaustive testing.[145] These models support safe-by-design strategies by predicting toxicity and guiding the synthesis of inherently safer NMs.[142]

3.7 Limitations and challenges of antimicrobial nanomaterials

Antimicrobial nanomaterials present several limitations and challenges despite their numerous benefits in food packaging and preservation. These limitations and challenges include: non-specific effects on microbiota.[146] Antimicrobial nanomaterials may not only inhibit pathogenic microorganisms, but might affect the proliferation of beneficial microorganisms.[147] The antimicrobials nanomaterials in an attempt to destroy pathogenic microbes that may cause spoilage or foodborne diseases, may also disrupt the proliferation of microbes which are beneficial to the body present in the food that was packaged such as lactic acid bacteria in milk. Another major limitation is the toxicity and safety concerns. Nanoparticles may potentially migrate into packaged food and this can negatively affect the human health and environment.[148] Nanoparticles incorporated in packaged food enters the body either by oral consumption, inhalation or dermal exposures. When these nanoparticles *e.g.* AgNPs, ZnONPs, enter the circulation, they aggregate in the body's organelles since they are insoluble in biological fluids.[7] Regulatory challenges is another major challenge of antimicrobial nanomaterials. Some regulations have been created by the government for embedding nanomaterials in the packaging of food, its migration into food packaged alongside its safety.[149] In few countries, specific nanomaterials have been permitted for use in food packaging, whereas other countries still believe that nanomaterials in small and large concentrations are toxic.[150]

Another challenge is the scalability and cost of nanomaterials.[151] The production cost of nanomaterials can be expensive as a result of the specialized materials and complex manufacturing processes involved in incorporating nanomaterials into food packaging materials and there are still issues such as the process optimization, safety considerations and cost-effectiveness, which affects the upscaling of the manufacturing processes of nanomaterials from lab-scale synthesis to industrial levels.[152,153] Also, the research and development investments required for the optimization of nanotechnology in the packaging and preservation of food is quite large.

During the utilization, disposal or production process of packaging material incorporated with nanomaterials, the discharge of these nanomaterials into the environment has raised concern as they could have unforeseen ecological consequences.[85] These nanomaterials are easily transported through water and soil systems, and could be easily ingested by organisms, enter the food chains and affect organisms at higher trophic levels, with high potential risks of affecting the human health as a result of their minute size and reactivity at a higher rate.[152]

4 Conclusion and future perspectives

Effective food preservation through advanced packaging technologies plays significant roles in enhancing food safety, maintaining food quality as well as reducing foodborne illnesses. Traditional packaging systems predominantly act as barriers against oxygen, moisture and environmental stress, but the integration of nanotechnology in food packaging has led to the development of intelligent, active and sustainable packaging systems with improved functionalities. Antimicrobial nanomaterials offer great benefits by improving the antimicrobial efficacy, structural performance and environmental sustainability in response to the growing demand for biodegradable and environmentally-friendly packaging solutions over conventional approaches.

Antimicrobial nanomaterials like the AgNPs, ZnONPs, TiO_2, chitosan, polylactic acid (PLA), and nanosensors, have demonstrated strong antimicrobial activity against a wide spectrum of pathogens while maintaining food quality. Incorporating these nanomaterials into polymeric packaging films, coatings and composites either through improved, active, intelligent or bio-based packaging ensures controlled antimicrobial action. The efficacy of these systems is also governed by their interactions with polymer matrices and the surrounding food environment.

As critically discussed in this review, the transformation process such as aggregation, dissolution and protein corona formation directly determines their antimicrobial potency, migration potential as well as overall safety, which are strongly influenced by polymer chemistry, food composition and nanomaterial surface properties. The successful application of nanopackaging therefore depends not only on the intrinsic properties of the nanomaterials but also on deep understanding of the chemistry of the interactions with polymer.

The potential challenges such as toxicity and safety concerns, regulatory approvals, scalability and cost, environmental impacts of nanomaterials must be addressed, to enable widespread adoption of nano-packaging. The development of safety-by-design nanocomposite system where antimicrobial activity is carefully balanced with controlled release, immobilization of polymer, and long-term stability in food contact applications is needed to address these challenges. Comprehensive regulatory frameworks and standardized safety assessment protocols is essential to support the deployment of safety-by-design nanocomposite systems commercially and build consumer trust, especially in emerging markets where improved preservation of food enhance food security significantly. Future research should also prioritize polymer-specific design strategies to optimize the dispersion, stability and antimicrobial performance of nanomaterials in both conventional (*e.g.* PE, PP) and biodegradable (PLA, chitosan) packaging systems. Great emphasis should be made on scalable and industry-relevant processing techniques such as electrospinning, coating, additive manufacturing and melt extrusion. The integration of nanotechnology with technologies that are emerging such as 3D printing and data-driven approaches further enables tailored and intelligent packaging solutions. Furthermore, continued research should be made to reduce the potential of unintended interactions of nanomaterials with food components which can in turn affect the human health to ensure long-term safety and environmental compatibility.

Consent to Publish

All authors provide consent for the publication of the manuscript and understand that this information will be freely available online and accessible to the general public.

Author contributions

Oluwafemi Adebayo Oyewole: conceptualization, supervision, Olayemi Felicia Amole: preparation of original draft, Majin Emmanuel Nmadu: design of figures, Naga Raju Maddela: review and editing.

Conflicts of interest

The authors have no relevant financial or non-financial interests to disclose.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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