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REVIEW

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Advancements in food packaging strategies with a focus on antimicrobials and sensor technologies: a comprehensive review

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Food that is fresh, healthy, and readily available is in high consumer demand due to busy lifestyles and the growing population; accordingly, strict rules to prevent food-borne infectious diseases have clearly increased over time. In order to provide wholesome and risk-free food without any contamination, food packaging is important. Several studies have been conducted on innovative packaging technologies, and antimicrobial food packaging technology is one of them. Antimicrobial food packaging is a potential approach that successfully incorporates antimicrobials into food packaging films. In the form of a thorough review, this work provides a brief introduction to all the innovative food packaging technologies, focusing on an overview of the contemporary antimicrobial agent research targeted at prolonging the storage life of food to enhance its quality and safety *via* suppressing pathogen development. This study addresses the various types of antimicrobial agents and novel techniques, which are currently in use and those that are still being researched, giving importance to their usage in food packaging. Emerging novel technologies such as active, bioactive, smart and intelligent packaging are considered suitable alternatives to combat the increasingly harmful effects of plastics, not only on consumers but also on the environment. This review gives a brief discussion on the combination of natural and technological approaches for enhancing food packaging strategies. Technology plays a critical role in the discovery of different types of packaging materials, which include biosensors, edible sensors, optical sensors and various kinds of indicators to detect changes in the food's quality. However, while outlining their applications, the challenges and disadvantages associated with antimicrobials are highlighted for future research to be in an appropriate path.

Sustainability spotlight

The dark reality of microbial resistance and its effects on food safety should be taken into account when choosing and integrating antimicrobials into food packaging materials. Sensor technologies are known to be a promising approach as an alternative food packaging method, as well as minimizing the harmful effects of plastic on the environment. Different types of sensors, such as optical-, edible-, chemical-, and bio-sensors, are used, depending on the type of food being packaged. Thus, sensor technologies will help us to monitor the quality of food in real-time. In order to create a bright and sustainable future, we require a multidisciplinary strategy that brings together professionals from all biotechnology domains, in particular engineering, food technology, microbiology, and materials sciences. These novel strategies should be further studied for taking complete advantage of their benefits while overcoming the challenges associated with them. Further research becomes pivotal, taking into consideration that food should not be contaminated and should be maintained in an efficient manner. Sustainable and environment-friendly food packaging systems are essential for a sustainable future.

1 Introduction

The production, processing, shipping, and storage of food present considerable challenges, requiring adherence to regulations pertaining to human health, environmental safety, and financial viability.[1] Over 1.3 billion metric tons of usable food are wasted annually.[2] The global demand for diverse food products necessitates extensive transportation, highlighting the critical role of proper food packaging in ensuring safety and

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minimizing waste.[1] Food packaging generally needs to fulfil four primary objectives: protection, communication, convenience, and containment;[3–5] with its most vital function being the preservation of food quality and safety through the prevention of spoilage and contamination and extension of shelf life.[1,6] Materials such as glass, polymers/plastics, metals, and paper are commonly used, often in composite forms.[7] Polymers/plastics constitute the largest segment of the food packaging market (37%) (Fig. 1), followed by paper and board (34%).[8] The main function of traditional food packaging materials like polyethylene terephthalate (PET), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) is to operate as physical barriers that shield food from outside environmental elements, including light, air, and moisture. These films have some degree of success in maintaining food quality, but they do not have any sensing or active features, including the capacity to stop microbiological growth or track the freshness of food in real-time. These restrictions have prompted the creation of active and intelligent packaging technologies, which use sensors, indications, or antimicrobial agents to improve food safety and shelf life above and beyond what is possible with traditional materials.[9,10] Sustainability is a key component of these developments, since smart packaging solutions use breakthroughs like biodegradable materials and

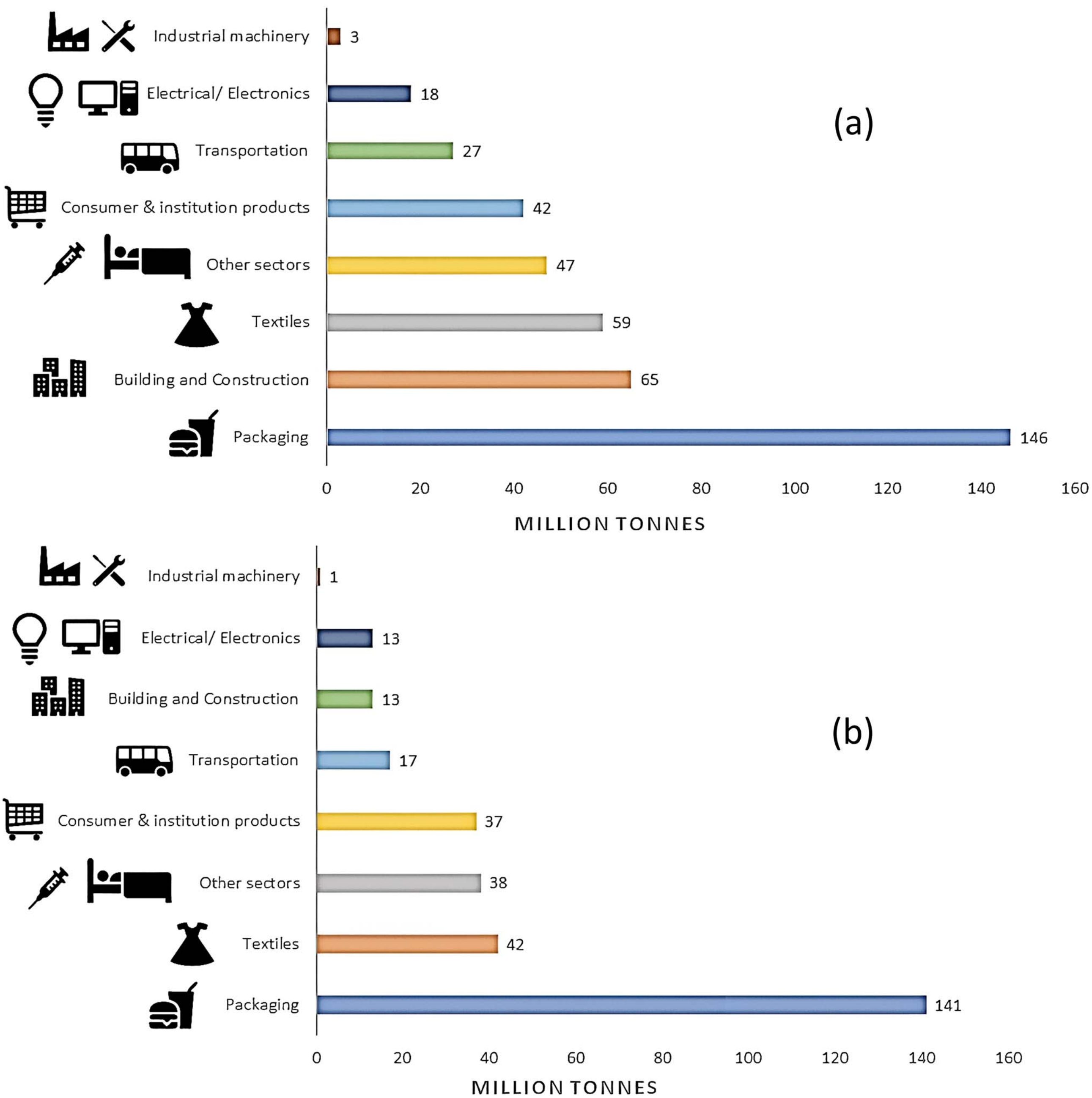

Fig. 1 Primary plastic production by the industrial sector in 2015 (a), and plastic waste generation by the industrial sector in 2015 (b).

improved packaging designs to limit waste and reduce their negative effects on the environment.[11]

Antimicrobial food packaging tackles microbiological infection without chemical preservatives, whereas antioxidant food packaging reduces oxidation-related degradation, which is especially advantageous for oils, fats, and processed foods.[12] This review article discusses advanced packaging technologies, emphasizing antimicrobial packaging and sensor technologies along with their applications.

2 Active food packaging

Active packaging technology includes components that are purposefully placed in or on the packing material or in the headspace of the container so that they can release or absorb substances into or from the surrounding environment of the food product.[13] Using active packaging for perishable items reduces the amount of active chemicals used, reduces localized activity and particle transfer from film to food, and avoids needless industrial processes that could contaminate the product, among other advantages.[14] As a result, the primary goal of active packaging is to avoid microbiological and chemical contamination while preserving the food's visual and organoleptic features.[15] Ethylene scavengers, oxygen scavengers, antimicrobials, preservative releasers, antioxidants and flavour and odour absorbers/releasers are all commonly employed in active packaging technologies.[16] Moisture absorbers are non-migratory active packaging that absorb excess moisture by utilizing hygroscopic substrates or substances (*e.g.* cellulose or silica gel) to establish an atmosphere less conducive to the growth of microorganisms and deterioration.[15] Ethylene removal systems aid in the reduction of ethylene (which accelerates the ripening process) in the packaging atmosphere, thereby reducing unwanted impacts on the products.[17] Ethylene can be removed using ethylene absorbents (*e.g.* silica or activated carbon), which act by physically absorbing and holding the molecules,[15] and ethylene scavengers (*i.e.* potassium permanganate, 4–6%)[18] anchored on an inert matrix, such as alumina or silica gel,[19] which act chemically. Carbon dioxide scavengers (CO_2 absorbers comprising calcium, sodium, and potassium hydroxides) remove excess CO_2 from food, preventing discolouration, off-flavor development, and tissue destruction[15,17,20] as shown in Fig. 2. Similarly, oxygen scavengers (*i.e.* iron-based scavengers) remove oxygen, which causes unwanted organoleptic changes like colour changes, off-flavor development, and the degradation of nutritional characteristics, as well as supporting microbial growth.[19,21] Phenolic chemicals (such as butylated hydroxytoluene) are commonly employed synthetic antioxidants that inhibit lipid oxidation in fat-containing foods, and also have antimicrobial properties.[19,20] Paraffin waxes, fatty acids, sugar alcohols, glycols, metallics, salt hydrates, and eutectics may be used in food packaging in the future.[15] Different kinds of active packaging materials and their functions are listed in Table 1.

Sustainable active packaging that incorporates antimicrobial packaging solutions can meet industry standards for safety, quality, and longer shelf life.[22] The active and intelligent packaging solutions work as a protective barrier, shielding the food item from numerous physical, chemical, and biological risks. They also act to indicate the freshness and quality of the food product while continuously monitoring the time and temperature of the contents, ensuring the overall safety and quality of the items. Both active and intelligent packaging systems strive to improve food safety and quality by delivering safe and nutritious food to customers, but their responsibilities in achieving this goal differ. The similarities and differences of intelligent and active packaging systems are shown in Fig. 3.[23]

2.1 Food packaging with antimicrobials

One of the more promising methods for eradicating pathogenic microbes that harm food items is antimicrobial packaging, which is a subtype of controlled-release packaging and active

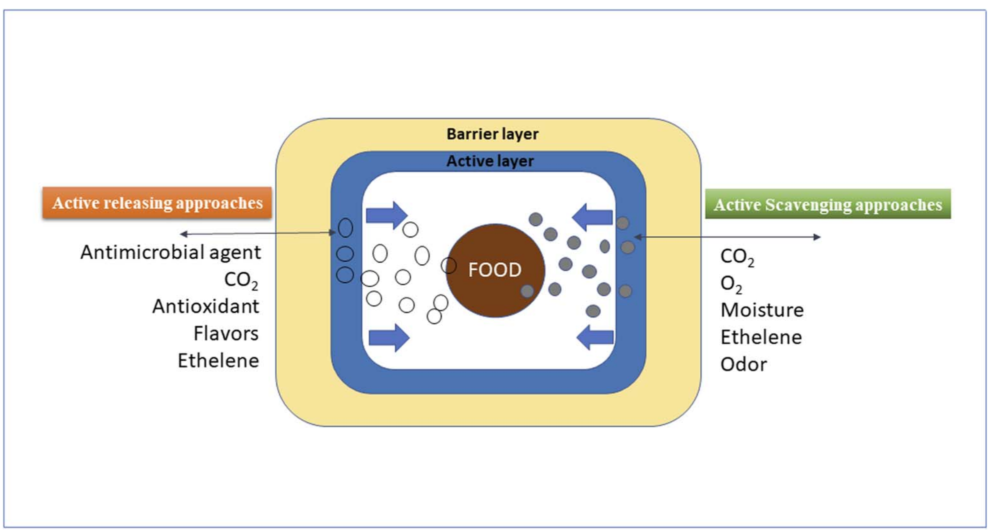

Fig. 2 Active scavenging and releasing approaches in food packaging.

Table 1 Various materials and their functions involved in active food packaging

Active packaging method	Materials	Functions	Foods which can be packaged	References
Moisture absorbers	Starch copolymers, silica gel	Reduce food water activity	Meats, fruits, fish and vegetables	24
O_2 scavengers	Ethanol oxidase, ascorbic acid, glucose oxidase	Inhibits growth of microorganisms and prevents food alterations	Juices (brewing industry), wines, sauces *etc.*	25
Desiccants	Calcium oxide, natural clay	Control moisture content	Chips, spices, candies, nuts, gums*etc.*	25
Antioxidants	Alpha tocopherol, rosemary extract	Oxidation of food due to the formation of radicals can be avoided	Butter, nuts, fresh meat, bakery products, oils, meat derivatives, vegetables and fruits	26
Ethylene scavengers	Potassium permanganate, zeolites, activated carbon, metal oxides, nanoparticles	Control the amount of ethylene (a growth hormone) and prevent early ripeness of vegetables and fruits	Ethylene sensitive vegetables and fruits, banana, carrots, mangoes, onions, and tomatoes	19 and 27
Humectants	NaCl	Absorbs moisture from the surroundings of food	Tomatoes	25
Ethanol emitters	Ethanol is present in encapsulated forms	Antimicrobial agent reduces oxidative changes; food preservative	Dried fish, bakery products	28 and 29
Antimicrobials	Plant extracts, chlorine dioxide, essential oils	Inhibits the growth of bacteria, fungi and viruses	Fish, meat, poultry, dairy and baked products	26

packaging. It effectively incorporates the antimicrobial agent into the polymeric film used for packaging and then releases it over a predetermined duration of time, thereby expanding the shelf life many times. Antimicrobial agents have been identified that provide longer effectiveness, broader coverage, greater controllability, and improved environmental performance. One innovative approach to antimicrobial packaging is to develop functional meals through the introduction of bioactive packaging, a technology by which packaging or coatings can actively improve the health of consumers.[30] Barriers in food packaging can be removed through methods like microencapsulation and nanoencapsulation, providing a sustainable solution for food packaging technologies.[31] Log-reduction curves or minimum inhibitory concentration (MIC) values acquired at fixed concentrations are frequently used to quantify antimicrobial efficacy *in vitro*. These ideals, however, hardly ever correspond to actual food systems.[32] The apparent dose needed to accomplish the same microbial decrease in complicated matrices is

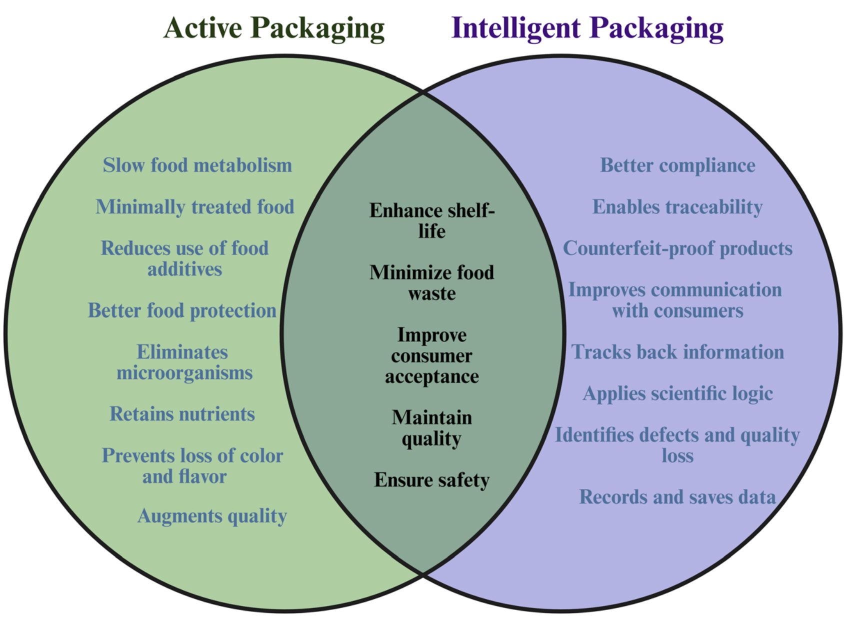

Fig. 3 Similarities and differences between active and intelligent food packaging systems.

usually more than that found in straightforward laboratory conditions.[33] Antimicrobial sorption onto dietary ingredients, chemical inactivation, decreased solubility, and limited mass transfer within heterogeneous structures are some of the causes of this disparity. As a result, in contrast to those in broth media, dose–response curves in meals typically show a tilt to the right.[33] To enable a realistic assessment of efficacy, it is crucial to examine antimicrobial performance in both relevant food matrices and standardized model systems.[32]

A number of variables, including pH, water activity (a_w), lipid and protein content, and temperature, affect how effective antimicrobial drugs are.[26,34,35] Antimicrobial activity increases in acidic conditions and decreases at very low pH.[36–38] While fat and protein content can lower bioavailability, water activity (a_w) can protect against microorganisms by lowering metabolism and diffusion rates.[26,39,40] Antimicrobial stability can also be impacted by temperature; at refrigeration temperatures, certain antimicrobials exhibit decreased solubility or diffusion.[41–43] Therefore, in order to properly evaluate antimicrobial medicines, real-world testing circumstances are crucial.[26,35,44]

Encapsulation and nanocarrier designs (*e.g.* liposomes, polymeric nanoparticles, and cyclodextrins) are examples of controlled-release systems, and nanocarriers that adjust release rates ensure that antibiotics act when needed, thereby lowering chronic low-dose exposure that leads to resistance.[45] Immobilization/surface-anchored antimicrobials (*e.g.* layer-by-layer immobilization or covalent anchoring) lower exposure and regulate migration risk by reducing migration into food while maintaining contact activity.[46] Although regulatory frameworks are changing, the use of biological agents (*e.g.* bacteriophages, bacteriocins and tailored peptides) with narrow specificity can reduce off-target selection pressure and is being assessed for safe packaging applications.[47] Encapsulation of natural antimicrobials and essential oils using microencapsulation, biopolymer inclusion systems, and nanoemulsions enhances stability, regulates sensory impact, and reduces resistance pressure by decreasing the required dosage.[48] In order to prevent continuous release and reduce resistance selection, materials that release antimicrobials in response to pH, moisture, or microbial enzymes have been developed that are known as stimuli-responsive and intelligent release (on-demand activation) materials.[49] Standardization of safety and migration testing, along with improved analytical methods and regulatory guidance for migrants (*e.g.*, plasticizers, nanoparticles, and additives), is essential for generating robust dossiers required by the Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA), thereby facilitating faster regulatory approvals.[50] In this regard, bio-based and sustainable polymer platforms, shifting to food-grade and biodegradable polymer carriers that reduce long-term environmental contamination, are simpler to defend under safety regulations.[51]

2.1.1 Principles and mechanisms of antimicrobial action. Antimicrobial activity can be accomplished in the packaging system by limiting microbial development by lengthening the lag period and lowering microorganism live counts by slowing down the growth rate.[52] Antimicrobial packaging systems have been developed to manage germs that compromise foods' quality, safety, and shelf life, as food security is currently a major concern. Microorganisms' characteristics can be quite useful in determining which antimicrobial agents to use. Antioxidants, natural antimicrobials, essential oils, antimicrobial polymers, biotechnology products, and other substances are commonly used antimicrobial agents.[53]

Packaging materials can be surface-modified, integrated, coated, or immobilized with antimicrobial chemicals to provide antimicrobial activity.[25] Antimicrobial films are divided into two categories: those that inhibit surface microbe growth without migration and those that come with an antimicrobial that penetrates into the food's surface.[25] The antimicrobial agent may not migrate at all, only becoming active when the food or target microorganisms come into direct contact with it. Alternatively, it may gradually diffuse partially or completely into the headspace or food, where it provides its protective effect, as shown in Table 2.[54,55] Bioactive packaging aims to extend food shelf-life and quality by incorporating antimicrobials and antioxidants, often derived from plant-based secondary metabolites, into the packaging materials. These compounds can migrate into food, becoming constituents and offering antimicrobial and antioxidant properties. They can also function as plasticizers, enhancing the mechanical properties of biofilms and packaging.[56]

2.1.2 Types of antimicrobial agents in food packaging. The food industry is increasingly focusing on maintaining the quality and safety of food goods as consumers become more health-conscious and want fresh, minimally processed foods.[22] Due to their distinct physiologies, different harmful microorganisms respond differently to antimicrobial treatments. To ensure the quality of food and its safety, antimicrobial agents are mixed into food particles or packaging materials and released gradually, resulting in a prolonged shelf life. Microbicidal and microbistatic effects are thus two essential activities of antimicrobial agents. For the duration of the storage period, the antimicrobial agent must actively work in order to keep the concentration above the minimal inhibitory levels to prevent the development of microbial species.[53] Antimicrobial agents are chemically manufactured or drawn from the biomass of living things, including animals, plants and microbes for food preservation. The functional properties of antimicrobial packaging films made of biopolymers like polylactic acid (PLA) and fossil-derived polymers like LDPE have been thoroughly studied, but most studies do not use life cycle assessment (LCA) to compare their environmental impacts, particularly carbon footprints. Such comparisons are essential since PLA's supposed sustainability over LDPE is not always clear-cut; LCA studies have demonstrated that, although PLA may occasionally lower greenhouse gas emissions, these benefits can be countered by its production and end-of-life management.[62–64] Claims of antimicrobial PLA films' superiority in terms of the environment are still up for debate in the absence of systematic LCA-based assessments. Thus, various antimicrobial agents are discussed in the following (Table 3).

Table 2 Mechanism of action of various antimicrobial agents in food packaging

Antimicrobial agent	Mechanism of action	Packaging application	References
Silver nanoparticles (AgNPs)	Releases Ag^+ ions → bind thiol groups of enzymes/proteins; generate ROS; disrupt DNA/protein replication; membrane leakage	Incorporated in biopolymer films (*e.g.* chitosan and PLA) for meat, dairy	57
Zinc oxide nanoparticles (ZnONPs)	ROS production (H_2O_2, $^{\bullet}OH$, O_2^-); Zn^{2+} release damages membranes and proteins	Active coatings/films for fruits, cheese	58
Essential oils (*e.g.* thymol, carvacrol, eugenol, and cinnamaldehyde)	Hydrophobic molecules integrate into lipid bilayers → membrane disruption, ion leakage, protein denaturation	Electrospun films and vapor-phase active packaging	59
Bacteriocins (*e.g.* nisin and pediocin)	Bind lipid II in bacterial membrane → pore formation → leakage of ions/metabolites; bactericidal against gram+	Biodegradable films and coatings for cheese, meat	33
Chitosan	Cationic groups bind to negatively charged microbial cell walls → leakage of proteins/ions; chelates metals → enzyme inhibition	Stand-alone antimicrobial film or nanocomposite with AgNPs	60
Enzymes (*e.g.* lysozyme, glucose and oxidase)	Lysozyme: hydrolyzes β-(1,4) glycosidic bonds in peptidoglycan; Glucose oxidase: Generates H_2O_2 → oxidative stress	Immobilized in protein/polysaccharide films	61
Organic acids (*e.g.* lactic acid, sorbic acid, and acetic acid)	Undissociated acids diffuse into cell → dissociate → intracellular acidification, enzyme inhibition	Coated films, edible coatings for fruits/vegetables	52

2.1.3 Incorporation strategies for antimicrobial agents. There are various ways to include antimicrobial agents in food packaging materials, and each has advantages and disadvantages. Direct integration, in which the antimicrobial component is mixed into the polymer matrix during extrusion, casting, or molding, is one of the most common techniques.

Table 3 Different antimicrobial agents and their applications in food packaging

Category	Origin	Examples	Applications in food packaging	References
Organic acids and salts	Natural (fermentation) and synthetic	Lactic, acetic, propionic acids; salts: sodium lactate, potassium lactate, sodium acetate, sodium benzoate, potassium sorbate	Active films (*e.g.*, EVOH + sorbic acid-chitosan microcapsules), dipping (*e.g.* salmon, trout fillets), PE films with salts	65
Antimicrobial peptides (AMPs) and Bacteriocins	Microbial origin (*e.g.* bacteriocins) and animal peptides	Nisin, pediocin, enterocin, leucocin, cathelicidins, defensins	Direct incorporation in polymer (*e.g.* soy, zein, and PLA), surface coating, nanoencapsulation	66
Antioxidants and polyphenols	Plant origin (*e.g.* fruits, herbs, spices)	Phenolic acids, flavonoids, stilbenes, lignans, tannins (*e.g.*, caffeic acid, quercetin, and xanthohumol)	Films with grape seed, green tea, hops extracts; active coatings with antioxidant + antimicrobial dual activity	19
Essential oils (EOs)	Plant metabolites (*e.g.* herbs, spices, citrus)	Carvacrol, thymol, eugenol, cinnamaldehyde, citral, and limonene	Active starch films, encapsulation in chitosan/PLA, coatings for cheese, meat, fish	65 and 67
Plant extracts (mixtures)	Plant secondary metabolites (*e.g.* polyphenols, terpenoids, and glucosinolates)	Oregano, rosemary, clove, garlic, onion, mustard extracts	Extract-incorporated films/coatings for meat, fish, cheese, fruits, vegetables	68
Enzymes	Microbial/animal proteins	Lysozyme, dispersin B, alginate lyase, DNase I, proteinase K, lysostaphin	Edible films (*e.g.* chitosan + lysozyme), enzyme coatings for cheese/meat/fish, combinations with chito-oligosaccharides	69

Controlled release is made possible by this method's homogeneous distribution of the active agent, scalability, and relative simplicity. However, sensitive bioactives like peptides, enzymes, or essential oils may be degraded by high processing temperatures, which could lessen their antibacterial efficacy,[66,67] as illustrated in Fig. 4.

Another method is coating, which involves applying the antimicrobial agent in layers, sprays, or dips onto the packing film's surface. Higher surface concentrations can be attained, and the agent's activity is maintained since it is not exposed to high processing temperatures. This is beneficial because microbial development usually takes place on the food-package interface. However, during storage, this approach could lead to poor adhesion, uneven release, and limited durability.[65]

Immobilization is a more sophisticated technique that uses nanocarriers like cyclodextrins or nanoparticles to covalently bind, crosslink, or entrap antimicrobial compounds on the packing surface. Immobilization increases stability, decreases migration into food, and extends antibacterial activity. But it is more expensive and complicated, and sometimes the compound's bioactivity can be changed by chemical alteration.[69,70]

Finally, a new generation of packaging systems is represented by multilayer structures. This technique confines antimicrobial substances to a particular active layer, which is subsequently joined by lamination or layer-by-layer assembly with additional functional layers (such as barrier or mechanical reinforcement layers). This structure enables the creation of multipurpose packaging with integrated barrier, mechanical, and antibacterial qualities while shielding delicate agents from deterioration during processing. Higher manufacturing costs and the requirement for sophisticated processing technologies are the primary obstacles.[19] A complete overview of antimicrobial packaging is illustrated in Fig. 5.

3. Intelligent food packaging

Although the terms "smart", "active", and "intelligent" packaging technologies are interchangeable, they refer to distinct ideas. While active packaging extends the shelf life of food by influencing the environment, intelligent packages keep an eye on the condition of food goods. Smart packaging is frequently utilized in commercial items and expands on conventional food packaging techniques. Using a variety of signals, including pH, humidity, temperature, and chemicals, intelligent packaging seeks to assess the quality of food. However, because of the high prices, complex equipment needs, and challenging integration with current packaging materials, real-time monitoring on

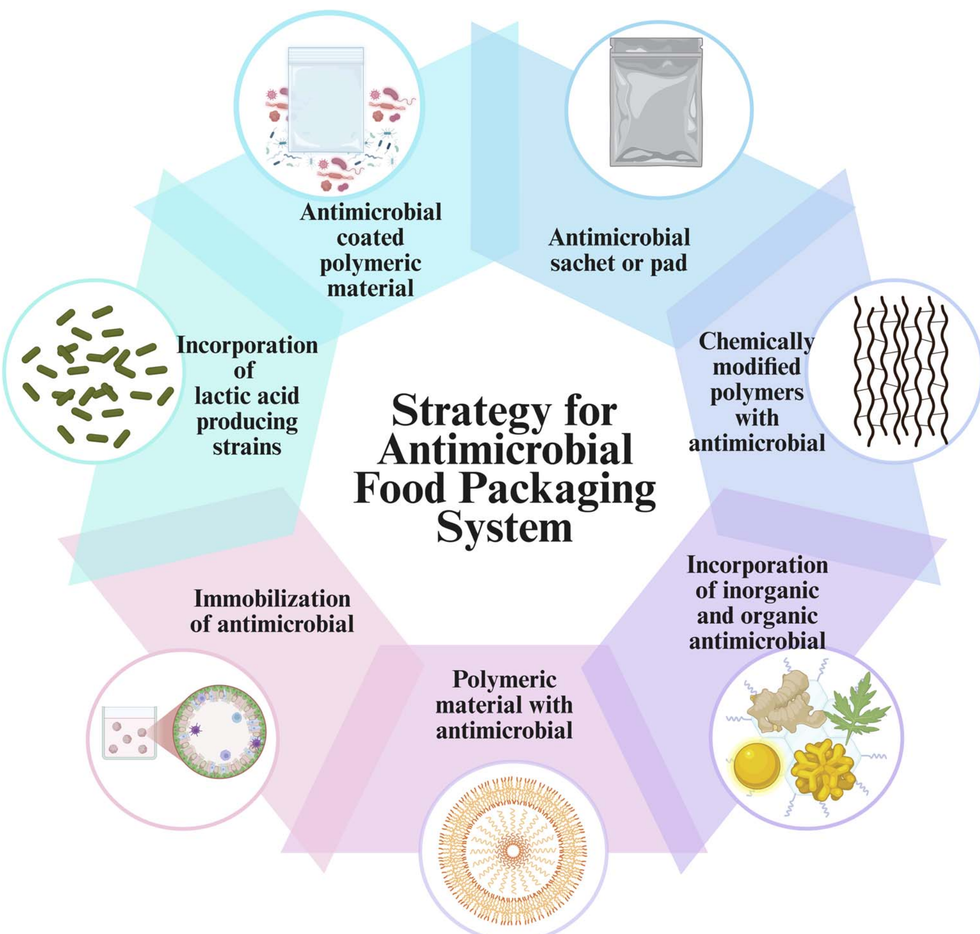

Fig. 4 Development of antimicrobial food packaging systems.

Fig. 5 Overview of antimicrobial packaging in food packaging systems.

a broad commercial scale is still a long way off.[71] Intelligent packaging has the ability to enhance product safety, lessen its negative effects on the environment, and make packaged goods and food companies more appealing. "Materials and articles that monitor the condition of packaged food or the environment surrounding the food" is how the EFSA defines intelligent packaging products. Despite not interacting with the goods, they can convey the circumstances of the packaged product. Their mission is to keep an eye on the goods and provide customers with information. This may include details like the manufacturing period, storage conditions, or the state of a package and its contents. These can be positioned on the primary (inside or exterior), secondary, or tertiary packaging, depending on whether it is a reactive or simple intelligent package.[72] By identifying and sensing changes in the food, intelligent packaging is a communication-integrated system that monitors and improves the quality of packaged food. By lowering food waste, reducing the chance of illnesses, enhancing environmental controls, and giving real-time information on product location and condition, this technology can increase supply chain efficiency. Additionally, it helps customers improve their shopping experience and make well-informed purchases. There are two categories of applications for intelligent packaging systems: quantitative sensors and qualitative sensors. When choosing and creating intelligent packaging solutions for meat quality monitoring, it is essential to understand the parameters and mechanisms. Sensors give quick, accurate, and reliable information regarding the safety and quality of products. Cost-effective information about freshness, temperature history, and package integrity can be obtained *via* indicators, including time–temperature, pH, and gas indicators. For industrial packaging applications, sensors and indicators need to be accurate, biocompatible, mass-producible, economical, reusable, and user-friendly.[73] Various devices included under intelligent packaging are illustrated in Fig. 6.

3.1 Sensor technologies in food packaging

A sensor is an apparatus used to identify, locate, or measure matter or energy by emitting signals in a continuous stream for detecting or quantifying a chemical or physical property. A receptor and a transducer are the two major functional pieces of most sensors.[74–76] For instance, along with pathogen-specific fluorescence, the N-CD-CS-CMC (novel nitrogen-doped carbon dots cellulose sulfate-carboxymethyl cellulose composite) film demonstrated potent antibacterial action against *S. aureus*, *C. albicans*, and *E. coli.* It became pH-responsive when beetroot was added, changing colour in response to acidity. It increased the shelf life of tomatoes from four to ten days when they were wrapped. Additionally, the film identified chromium by changing colour, demonstrating its multipurpose use in food safety and quality control.[77] When the film, which is composed of sulfur-/nitrogen-modified carbon dots (S,N-CQDs) and hydroxyethyl cellulose (HEC), comes into contact with Salmonella, it changes from red to light red, signifying that the chicken meat has spoiled. The film's sensitivity to pH changes associated with meat decomposition is seen in this colour shift. Additionally, the S,N-CQDs have antibacterial qualities that

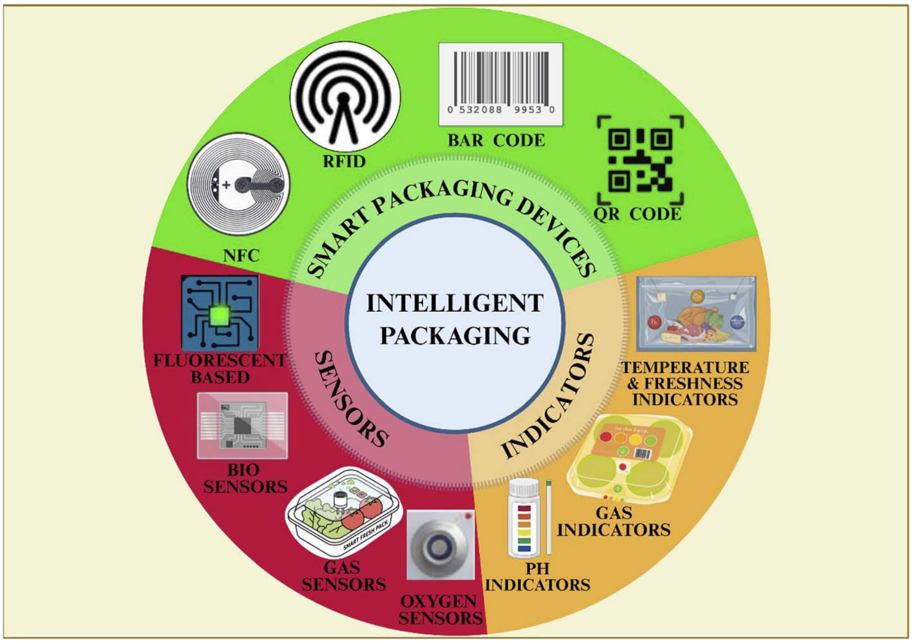

Fig. 6 Devices involved in intelligent packaging.

allow them to prolong the shelf life of packaged meat by 12 days, which is longer than the 3 day extension offered by the film that does not contain S,N-CQDs.[78] The carboxymethyl cellulose–N-fullerene–g-poly(co-acrylamido-2-methyl-1-propane sulfonic acid) (CMC–N-fullerene–AMPS) hydrogel was created in this study. The hydrogel's antibacterial qualities were greatly enhanced by the addition of N-fullerenes. Furthermore, when the hydrogel came into contact with *E. coli*, it changed from dark red to brilliant orange-red, displaying a characteristic "turn-on" fluorescence.[79] Types of sensors are as follows:

3.1.1 Biosensors. Biosensors are devices that sense, record, and send data regarding biological reactions.[80] Bioreceptors and transducers are employed in biosensors.[81] The transducer translates biological signals into measurable electronic responses after the bioreceptor detects the analyte of interest.[80] Enzymes, microorganisms, nucleic acids, hormones and antigens are examples of bio-receptors that are either organic or biological. Electrochemical, optical, or calorimetric transducers are available and are system-dependent.[74] ToxinGuard® (Toxin Alert, Canada) is an example of a biosensor where this visual diagnostic device detects pathogens such as *E. coli*, *Listeria* sp., *Salmonella* sp., and *Campylobacter* sp. by employing printed antibodies on PE-based packaging material.[82] There have been biosensors designed to detect xanthine and biogenic amines. The colorimetric analyte detection is used in the majority of bio-based substances in food packaging sensors.[1] Because decaying proteins release alkaline volatile compounds containing nitrogen (*e.g.* cadaverine, histamine, putrescine, and ammonia), colorimetric pH-sensitive sensors are often enough to assess food quality based on pH changes.[83,84] Because the structures of natural dyes, such as β-carotene, curcumin and chlorophyll, are particularly sensitive to oxidative radicals, they could be useful for sensing.[1]

The creation of biosensors using carbon dots (CDs) has shown great promise because of their high surface-to-volume ratio, variable fluorescence, outstanding biocompatibility, and simplicity of functionalization with biomolecules.[85,86] Enzymes, antibodies, nucleic acids, and aptamers can be used to modify their surfaces, allowing sensitive and selective detection of biological targets like infections, proteins, DNA, and glucose.[87,88] In biosensing platforms based on Förster resonance energy transfer (FRET), CDs frequently function as either fluorescent probes or energy donors/acceptors.[85] The basis for detection is frequently the quenching or increase of CD fluorescence in response to particular analytes.[86,87] CDs are especially helpful in non-invasive biosensing and real-time monitoring applications, such as medical diagnostics and point-of-care systems, due to their stability in physiological and aquatic settings.[86,88]

Although biodegradable sensors are being marketed as environmentally friendly options for smart food packaging, scaling issues have prevented their widespread use.[89] The main challenges are obtaining specialized materials, high production costs, and poor compatibility with industrial processes. Non-biodegradable conductive components are a source of e-waste issues. Compostable printed sensors are now being investigated by researchers employing water-based printing formulations, bio-based inks, and natural polymers; however, industrial adoption of these methods is still restricted, and most of the research is conducted at the laboratory level.

3.1.2 Chemical sensors. Chemical sensing in food packaging could potentially benefit from synthetic dyes based on diverse polydiacetylenes and azo-compounds. Enzymatic activities, wherein a change in color is often a function of temperature and time, can also be used to create colorimetric indicators and sensors.[1] Gaseous analytes present in food packages can be detected by gas sensors, which include sensors for oxygen, water vapour, carbon dioxide, and ethanol, as well as by piezoelectric crystal sensors, metal oxides, organic conducting polymers, and semiconductor field effect transistors.[75,76] The chemical sensor, also known as a chemical receptor, is a coating that is unique to a certain chemical and is used to detect the presence, make-up, activity, and concentration of that chemical or gas by surface adsorption. The presence of specific compounds is detected and transformed into signals by a transducer.[74] An electrode represents the transduction element in electrochemical sensors. Reference, counter, and working electrodes are linked to a potentiostat in a conventional electrochemical sensor. At the interface of electrode/analyte, a redox reaction takes place when a voltage is applied *via* the potentiostat, causing electrons to flow between the electroactive species and the electrode, resulting in a current proportional to the analyte concentration.[90] Inhibition zones and molecular docking simulations demonstrating robust binding interactions with bacterial proteins support the substantial antibacterial activity of betalains-N-CQDs (betalains-nitrogen-doped carbon dots) film against common foodborne pathogens such as *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans.* Additionally, the film serves as a fluorescence sensor, displaying clear colour changes in response to various microbes and Pb(II) heavy metals, allowing for quick, visual detection. Because of the betalains, the film also functions as a pH sensor, showing colour changes (yellow in acidic, brown in alkaline) that are helpful for tracking food degradation.[91] For instance, in order to identify tomato spoilage, a very recent study conducted by Tohamy[92] created pH-sensitive colorimetric sensors using carboxymethyl cellulose (CMC) sheets embedded with sulfur and nitrogen-doped carbon dots (SN-CDs), which were made from leftover red onion peel. The films allowed for naked-eye monitoring due to their intense fluorescence, antibacterial activity, and noticeable color changes (*i.e.* yellow in acidic and red in alkaline conditions) that corresponded to spoilage-induced pH shifts. Computational research and structural analyses provided additional evidence of these films' efficacy as environmentally friendly smart packaging materials.[92] By tracking variations in fluorescence intensity, wavelength shift, or lifetime, CDs in optical sensors can be used to identify metal ions (such as Fe^{3+}, Hg^{2+}, and Pb^{2+}), small molecules (such as dopamine and ascorbic acid), or environmental contaminants (such as pesticides and antibiotics).[85,87]

3.1.3 Optical sensors. Optical sensors either provide an optical signal (such as color, chemiluminescence or fluorescence) or alter the system's optical characteristics. The resulting optical signal is visible to the unaided eye or quantified with a photodetector, which transforms optical signals into electrical impulses that can be quantified.[15] Analytical electrochemical sensors and the selectivity of biological recognition methods are combined in electrochemical biosensors. Carbon dots' potent and adjustable photoluminescence, upconversion fluorescence, and photostability are the main components of optical sensing.[85,87] Excitation-dependent emission from CDs makes multiplexed sensing possible with a single probe.[93] Their distinct optical response is frequently brought on by interactions between the analyte and CD's surface functional groups, electron/energy transfer, or surface passivation processes.[88,93] Moreover, CDs can be incorporated into films or optical fibers, or field-use portable devices.[87] They are appealing for environmental monitoring, food safety analysis, and biological imaging-based sensing due to their low toxicity and straightforward production.[86,88]

3.1.4 Edible sensors. Edible sensors are made of biodegradable, consumable materials and make use of intelligent packaging technology. They offer up-to-date details on food product contamination, nutrition, and deterioration. Researchers recently created a proof-of-concept sensor for frozen meals that monitors temperature variations during shipping and storage by changing color when internal temperatures rise beyond a predetermined threshold, indicating possible contamination. This breakthrough, which ensures safety and freshness without changing the food itself, is essential for the future of food monitoring.[94] Edible sensors constructed entirely of natural and biodegradable ingredients that have no negative or severe long-term impacts on human health are used for detecting food spoilage.[15] Other technologies, such as electronic noses, replicate the human olfactory system in devices developed to acquire reproducible data, enabling detection and characterization of aroma combinations contained in odours. Each smell, flavour, or savour elicits a distinct response.[74] Food-based edible films were successfully created, and when exposed to specific gaseous amines, they dramatically changed color from purple to yellow. When the sensor film was exposed to the headspace above meat and fish products throughout their degradation at 21 °C and 4 °C, colorimetric alterations were also noticeable.[95] Various types of sensors are presented in Table 4.

3.1.5 Printed sensors. Printed sensors are a new development in packaging technology that allows organizations to collect real-time data without the need for bulky electronics. These sensors are thin, sticky strips integrated with electronics that measure temperature, humidity, and vibrations. This technology is especially beneficial for monitoring perishable foods, as it allows real-time tracking of conditions during transportation and storage. Businesses can use printed sensors to improve product quality control while lowering packaging space and material costs.[96] In addition to protecting food from environmental contamination, the synergistic integration of intelligent food packaging (IFP) with PE (printed electronics) technologies—which has moved from science fiction to a field of study—also actively contributes to food safety and quality. By evaluating the freshness of food, the legitimacy of medications, the environmental conditions (temperature, humidity, light, *etc.*) in circulation, and other elements, it extends the shelf life in ways that standard packaging cannot provide.[97] Flexible printed sensors and radio-frequency identification systems are two examples of specific products that have been successfully developed based on flexible printed electronics. These products are excitingly able to meet various requirements for food safety, including ingredient detection, environmental monitoring, logistics tracking, and anti-counterfeiting and anti-theft measures.[98] Dairy product spoilage may be detected using 3D-

Table 4 Various devices and their functions involved in intelligent food packaging

Intelligent packaging device		Example	Function	References
1. Indicators	Freshness and ripeness indicators	Sensor label from FQSI (food quality sensor international Inc)	Used to detect biogenic amines	72
	Time–temperature indicators	Visual indicators TTI/RFID tag Fresh check	Detect any internal and external changes in the food's temperature and also carries data for product identification	72
	Gas indicators	Water vapour indicators, CO_2 indicators, O_2 indicators	Detect any kind of changes in the internal atmosphere of packages Monitor changes in gas composition	112
	pH indicator	pH sensitive dyes	Make food safer for customers by indicating its quality	113
2. Sensors	Fluorescence-based oxygen sensors	O_2xyDot®	Detects changes in the concentration of oxygen in the package	114
	Biosensors	Toxin guard	Can detect pathogens	72
	Gas sensors	Potentiometric CO_2 sensors	The most sophisticated method available for measuring O_2 in package headspace	112
	Oxygen sensors	Piezoelectric crystal sensors	These sensors are utilized to know the amount of O_2 in modified atmosphere packaging	114
3. Smart packaging devices	a. Barcodes	UPC (Universal product code)	These are three common types of data carriers which encode larger data in reduced forms	112
		RSS expand barcode	Carry information about the product	
		RSS-14 stacked omni-directional barcode. PDF 417		
	b. RFID (radio frequency identification tags)		Traceability, product identification, promotion, security	72
	NFC chips (near field communication)		Anti-counterfeiting, cold-chain tracking, consumer engagement Freshness monitoring Authentication	100,106–108

printed sensors, tackling the serious problem of foodborne illnesses that impact one in six Americans. Colorimetric indicators in packaging are crucial for consumer safety and reducing the risk of food poisoning, because contamination in fresh items is frequently undetectable. In addition to improving quality evaluation and encouraging functional integration within autonomous systems, these technologies can be scaled for industrial food processing and agricultural applications.[99]

3.1.6 Humidity sensors. One of the most significant environmental elements affecting food items' quality, safety, and shelf life is humidity. While insufficient humidity may result in texture loss, staling, or a decrease in product weight, excessive moisture within packing can encourage mold growth, microbial growth, and biochemical deterioration.[100,101] As a result, one of the main functions of intelligent and active packaging technologies is the monitoring and regulation of humidity within food packages. Water vapor in the air or within packaging can be detected and measured using humidity sensors. They primarily function according to three principles: (i) capacitive sensors track variations in hygroscopic materials' dielectric constant;[102] (ii) resistive sensors identify changes in resistance brought on by water molecules that have been absorbed;[103] and (iii) colorimetric indicators generate an obvious color shift of materials or dyes that are sensitive to humidity.[104]

Recent innovations that enable real-time remote monitoring of humidity in packaged foods include wireless RFID-enabled devices and sensors based on nanomaterials (*e.g.* graphene oxide, carbon nanotubes, and MXenes).[90,105] Additionally, humidity sensors that are printable and biodegradable are becoming available, which means they can be used with environmentally friendly packaging materials.[106] Producers may improve quality control, increase shelf life, and decrease food waste by incorporating humidity sensors into food packaging. This will also give customers and supply chain stakeholders more information.

3.2 Near-field communication (NFC) chips

With its ability to facilitate wireless data interchange between consumer smartphones and NFC chips embedded in labels or films, NFC technology is quickly becoming a crucial element in intelligent food packaging. This makes packaging more secure, traceable, and interactive. Product authentication and anti-counterfeiting are two of NFC's main uses in food packaging, especially for expensive goods like wine, dairy powders, olive oil, and infant formula. Customers may rapidly confirm authenticity by scanning the NFC tag, which lowers the dangers associated with fake goods.[107] By recording and transmitting data regarding product origin, transportation, and storage conditions, NFC also facilitates supply chain traceability, increasing compliance and transparency.[106] NFC chips improve customer engagement in addition to safety. To increase trust and brand loyalty, a quick scan can provide recipes, nutritional information, promotions, or sustainability features.[104] Additionally, NFC packaging can offer real-time food freshness monitoring when combined with sensors, such as those for temperature, humidity, or gas. This is crucial for cold-chain logistics and perishable goods.[108] Large-scale food applications can benefit from NFC's advantages over classic RFID, which include smartphone compatibility, affordability, and flexibility. Big data analytics and cloud-based monitoring are also made possible *via* its internet of things (IoT) connection. Many sensors, indicators, and data carriers have played a major role in understanding the properties of food related to its quality. They provide information on the product's freshness by monitoring chemical changes in the food, its texture, or any pH changes in the surroundings of the product, to avoid microbial contamination. They also track the product while it is being transported from the provider to the consumer.[109] Because these advanced packaging technologies incorporate biodegradable substances into the packaging materials, they are environmentally friendly. They also prevent food contamination and food loss.[110] Due to these technologies, the consumption, storage and transportation have been efficiently increased, thereby meeting the consumer expectations.[111]

4 Challenges

While novel packaging holds great promise for increasing traceability, safety, and sustainability, it also confronts significant challenges that must be solved. In order to improve food quality, nutrition, and shelf life while reducing environmental effects, it is crucial to include a variety of biomaterials, sensors, biodegradable materials, nanotechnology, essential oils, and plant extracts when developing novel food packaging (NFP) systems. NFP represents the future of packaging technology and includes smart, green, and active technologies that enhance food longevity and consumer health.[115]

4.1 Integration challenges and synergistic potential of smart systems

It becomes economically untenable for low-margin items to integrate technology like sensors, RFID tags, and indicators, since they dramatically increase packing costs, frequently surpassing the traditional threshold of 10% of the whole product value and occasionally accounting for 50% to 100% of the product cost.[11] Particularly in fragmented supply chains, many intelligent technologies struggle to seamlessly interface with traditional IT, manufacturing, or logistical systems.[116] Including sensors, batteries, and electronic parts makes recycling more difficult and can increase packaging waste, which goes against sustainability objectives.[72] By providing precise information on product quality that can deter theft and minimise food waste, smart packaging technologies improve supply chain systems through real-time monitoring and traceability. Experts from a variety of disciplines must work together in a multidisciplinary manner to integrate them into conventional packaging. The successful use of technology can be facilitated by the application of supply chain management principles.[117]

4.2 Functionality: designing integrated antimicrobial-sensor platforms

When microbial activity is still low, some antimicrobial drugs are released too soon, wasting their effectiveness during the crucial later stages of storage or spoiling.[118] In order for packaging to both detect deterioration or risk and take action to stop spoiling or pathogen growth, integrated antimicrobial–sensor platforms combine real-time sensing of the package/food environment (temperature, gases, pH, metabolites, or microbial markers) with active antimicrobial responses (controlled release, contact-killing surfaces, or triggering preservative delivery). By focusing treatments just where necessary, this hybrid "sense-and-respond" strategy can decrease waste, increase safety, and prolong shelf life.[119]

Among the integration strategies are:

1. Films with passive antimicrobials (contact-killing/constant release).

2. Controlled-release, stimuli-responsive systems, which only release antimicrobials in response to sensor-detected conditions (such as a temperature increase, pH change, or gas signature), minimizing needless exposure to active agents and increasing their efficacy.[120]

4.3 Regulatory and safety considerations for smart materials

Strict regulatory scrutiny is triggered when active agents, particularly nanomaterials or novel chemicals, are used in packaging (*e.g.*, FDA in the U.S., Novel Food Laws in the EU). Prior to commercialization, extensive safety testing and compliance are necessary.[121] Smart packaging must be evaluated for chemical and microbiological risks (including nanomaterials and antimicrobials), obtain the proper pre-market authorizations or notifications, adhere to food-contact regulations (safety, migration, labeling, and traceability), and meet standards for recyclability, occupational safety, and data/privacy when devices gather information[122]

4.4 Economic feasibility and consumer acceptance

The creation of environmentally friendly smart packaging, such as biodegradable sensors, is still in its infancy and is not yet generally accessible. A key factor in determining market success is consumer perception. According to studies, perceived safety, affordability, usefulness, trust, and environmental impact all influence how widely smart packaging is used.[123] Customers may discard perfectly safe food due to misinterpretations of color-changing freshness indications, eroding brand credibility and increasing waste.[11] A number of variables, including production cost, scalability, material availability, and market value, affect the economic viability of smart packaging technologies, such as active, intelligent, and antimicrobial-sensor systems. Although these technologies have the potential to decrease food waste, increase shelf life, and improve supply-chain transparency, their uptake is frequently hindered by the high cost of materials and manufacturing, as well as difficulties integrating with current packaging systems.[5,124]

Another important consideration is scalability. Through mass printing methods, technologies such as printed electronics and biodegradable biopolymer sensors are demonstrating promise in reducing production costs. For smart packaging to be commercially successful, cooperation between material scientists, food producers, and technology suppliers is essential.[125]

5 Applications

Chitosan and zinc oxide (ZnO) nanocomposites have demonstrated encouraging outcomes; for example, coatings containing chitosan-ZnO nanoparticles significantly decreased *E. coli* in cheeses, while ZnO-based pad absorbents eradicated *Campylobacter jejuni* from raw chicken meat.[126] These packaging types release antimicrobial compounds (such as organic acids or essential oils) in response to microbial development, particularly for meat products. Optimizing release kinetics-based activation of antimicrobial drugs at the appropriate time to maximize efficacy remains a challenge. The development of intelligent systems, such as time–temperature indicators (TTIs), gas sensors, RFID, and colorimetric indicators for food safety, was examined in this article. It emphasizes antibacterial methods and chromogenic indicators based on natural compounds.[118] The biosensors use enzymes, antibodies, antigens, phages, or nucleic acids to detect volatile substances, such as H_2S, NH_3, and CO_2, with excellent selectivity. Examples from the commercial world include "Toxin GuardTM" and "Flex Alert" for infections such as *Salmonella*, *Listeria*, and *E. coli*.[127] Optical sensors are used to detect colour changes, temperature variations, or gases to keep an eye on spoilage. Examples of technologies used in production include "Fresh Tag®", "Sensor QTM", and "Food Sentinel System".[127] Electrochemical sensors are used to monitor the pH, oxygen content, and chemical composition of meat and dairy products. For example, they can identify trace amounts of gases or additives by monitoring changes in electrode signals.[127] Bio-based solutions, which are mostly used for perishable goods like meat, fish, and shellfish, give information on how fresh a product is. The most researched choices for creating bio-based sensors are the pigments betalains, curcumin, and anthocyanins, which are typically derived from fruits and plants and their waste. When combined with a package, these pigments can provide the biopolymer with some activity, extending the shelf life of the goods being packaged. They also have antibacterial and antioxidant qualities.[128] Because of their antibacterial qualities, chemically produced nanoparticles such as nano-Ag, ZnONPs, TiO_2NPs, and CuONPs are utilized in coatings and packaging films. For safety and environmental considerations, green synthesis techniques are becoming increasingly popular. Superior mechanical, barrier, and antibacterial qualities are provided by complex composites, gold nanoparticles, and nanocrystalline cellulose.[129] The inclusion of sensors, nanomaterials, and other intelligent elements into active and intelligent packaging systems has demonstrated great promise in prolonging food products' shelf lives while preserving their quality and safety. By enabling the real-time monitoring of crucial parameters like temperature, humidity, and gas composition, the integration of artificial intelligence (AI) and the internet of things (IoT) into packaging systems holds revolutionary promise. Supply chains may cut down food waste, enhance storage conditions, and guarantee fresher items by using predictive AI algorithms to evaluate this data and forecast shelf life, detect quality degradation, and predict spoilage. Furthermore, by offering real-time lifecycle data, improving recycling efficiency, and lowering contamination in waste streams, sustainable solutions like recyclable, sensor-embedded materials, RFID tags on biodegradable substrates can completely transform waste management.[11]

By keeping an eye on and preserving ideal circumstances, intelligent packaging plays a critical role in increasing the shelf life of perishable goods. To keep a constant temperature and prevent spoiling, gas-regulation modified atmosphere packaging (MAP), active cooling systems, and humidity control desiccants have been used. By identifying anomalies early, this technology also improves food safety by avoiding the consumption of spoiled or dangerous goods. By guaranteeing the safety and freshness of perishable goods, intelligent packaging increases consumer trust and saves money for manufacturers, retailers, and customers. Additionally, it uses sophisticated sensors for real-time monitoring and early problem detection, and it displays the product's freshness visually. Reducing food waste and satisfying the rising demand for perishable items that are safe, fresh, and of excellent quality depend on this creative strategy.[130] A brief overview of applications of active and intelligent packaging is illustrated in Fig. 7.

Eco-friendly packaging options are being adopted by businesses in an effort to reduce their carbon footprint. Among the environmentally friendly choices are temperature-sensitive packaging, NFC tags, QR codes, biodegradable materials, and compostable film. In addition to improving sustainability and convenience,

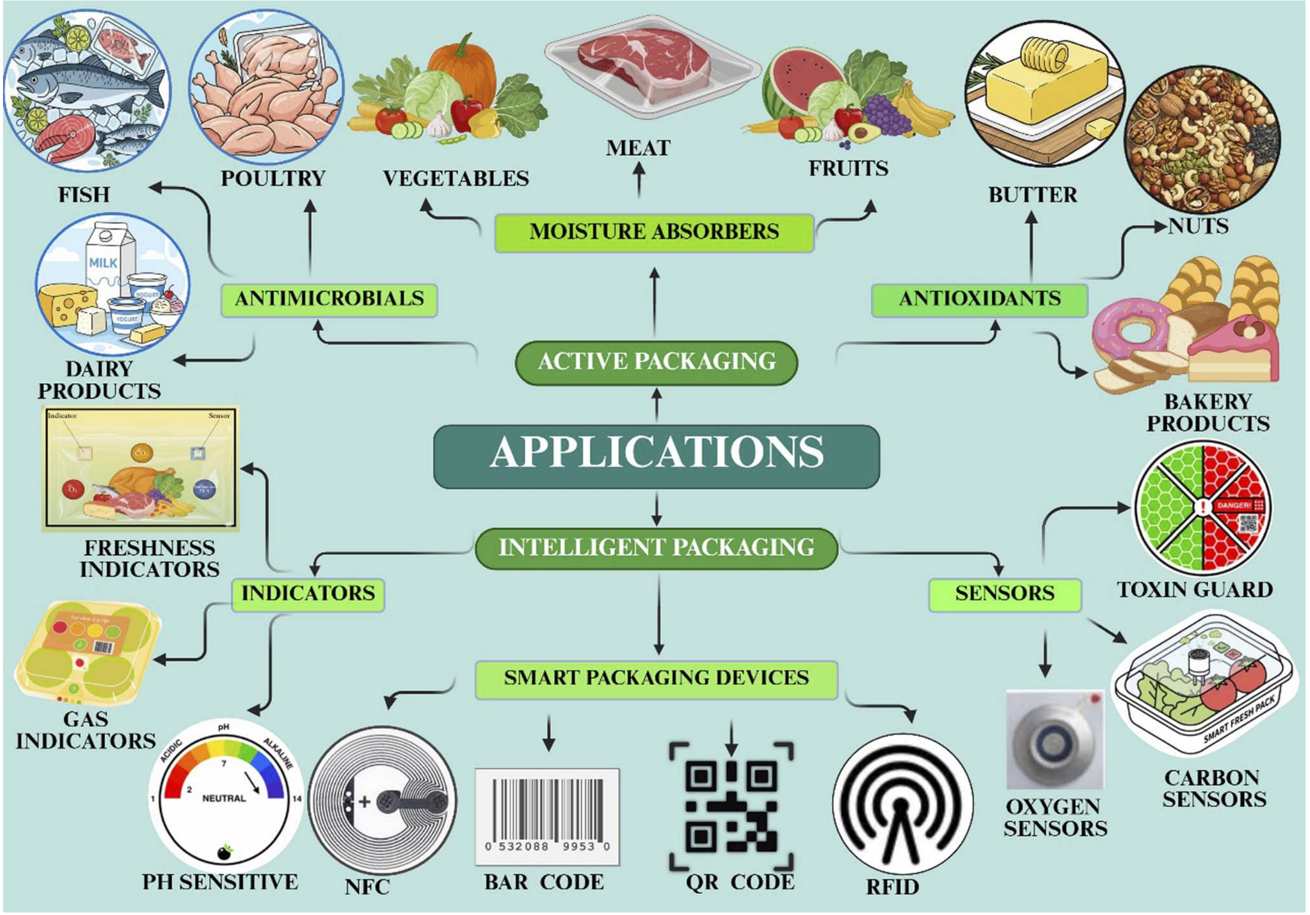

Fig. 7 Overview of the applications of active and intelligent packaging technologies (Created by Biorender).

these solutions close the gap between technology and customer demands, spurring innovation in this dynamic market.[130]

7 Conclusions

Passive containment solutions have gradually given way to active, intelligent platforms that combine antimicrobial agents and sensor technology in food packaging advancements. Foodborne pathogens can be decreased, shelf life can be increased, and chemical preservatives can be reduced with antimicrobial packaging. In the meantime, real-time food safety, quality, and storage condition monitoring is made possible by sensor-integrated packaging. Despite these encouraging advancements, large-scale commercialization is still hampered by issues including consumer acceptance, cost-effectiveness, material compatibility, regulatory approval, and environmental sustainability. To further the field of antimicrobial chemicals and nanosensors in food, future research should concentrate on standardization, safety evaluations, scalability, sustainability, circular economy strategies, intelligent data integration, and consumer-centric research. This entails creating standardized testing procedures, developing affordable, environmentally friendly materials, fusing sensing technology with digital platforms, and understanding customer attitudes. The next generation of sensor-enabled and antimicrobial packaging can go from lab prototypes to commercially feasible, environmentally friendly solutions by tackling these research priorities. In addition to improving food safety and quality, these developments will support international initiatives to cut down on food waste and guarantee a robust food supply chain. Sustainable and environmentally friendly food packaging systems are essential.

Author contributions

PR, KVR: conceptualization, writing – original draft, software; BMV, AA, PPV, GGDDSV: formal analysis, investigation, data curation; NRM, RP: writing – original draft, writing – review and editing, formal analysis, methodology.

Conflicts of interest

The authors declare that they have no conflict of interest.

Data availability

All the data are presented within the manuscript.

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