Sustainable Food Technology

Accepted Manuscript

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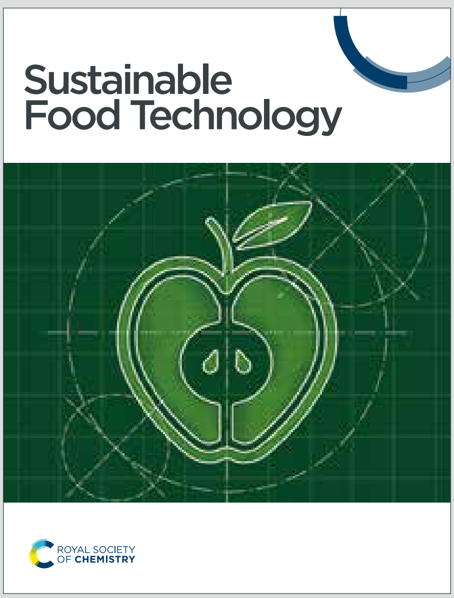

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DOI: 10.1039/D5FB00303B

Sustainability Spotlight Statement

The dark reality of microbial resistance and all 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 kinds of sensors, such as optical, edible, chemical, and biosensors, are used depending on the type of food being packaged. Thus, this technology 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 material sciences. These novel strategies should be further studied to taking the complete advantage of these while overcoming the challenges associated with them. Further research becomes pivotal, taking into consideration that the food should not be contaminated and should be maintained in an efficient manner. Sustainable and environment-friendly food packaging systems are absolutely essential for a sustainable future.

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Advancements in food packaging strategies with a focus on Antimicrobials and Sensor Technologies: A comprehensive review

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Highlights

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- Food packaging with healthful, risk-free food without contamination is essential.
- Antimicrobial food packaging brings antimicrobials into the food packaging films.
- Active, bioactive, smart, and intelligent food packaging techniques are innovative in food safety, quality and shelf life.
- Bio-, edible-, optical sensors-based packaging materials can detect changes in food quality.
- The food packaging industry is facing environmental, technical, and regulatory issues.

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Abstract

Food that is fresh, healthy, quick, and fast is in higher consumer demand with strict rules to prevent food-borne infectious diseases has clearly increased over time due to busy lifestyles and world's growing population. In order to provide the wholesome and risk-free food without any contamination, food packing is important. Several studies have been going on innovative packaging technologies, among which antimicrobial food packaging technology is one. Antimicrobial food packaging is a potential approach that successfully incorporates the antimicrobials into the film of the food packaging. In the form of a thorough review, this paper provides a brief introduction to all the innovative food packaging technologies focusing on the overview of 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 kinds of antimicrobial agents and novel techniques that are in use at present as well as 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 to be a suitable alternative to combat increasing harmful plastic effects on not only consumers but also the environment. This review gives a brief information about the combination of natural and technological strategies for enhancing the food packaging strategies. Technology plays a critical role in the discovery of different types of packaging materials which include bio-sensors, edible sensors, optical sensors and various kinds of indicators to detect the changes in the food's quality. However, while outlining their applications, challenges/disadvantages associated with antimicrobials are also highlighted for the future research to be in an appropriate path.

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Keywords: food packaging; antimicrobial packaging; antimicrobials; sensor technologies.

1. Introduction

The production, processing, shipping, and storage of food present considerable challenges, requiring adherence to regulations for 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 minimizing waste.[1] Food packaging generally fulfils four primary objectives: protection, communication, convenience, and containment;[3-5] with its most vital function being the preservation of food quality and safety through 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%), 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 don't have any cognitive 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

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smart packaging solutions use breakthroughs like biodegradable materials and improved packaging designs to limit waste and their negative effects on the environment. [11]

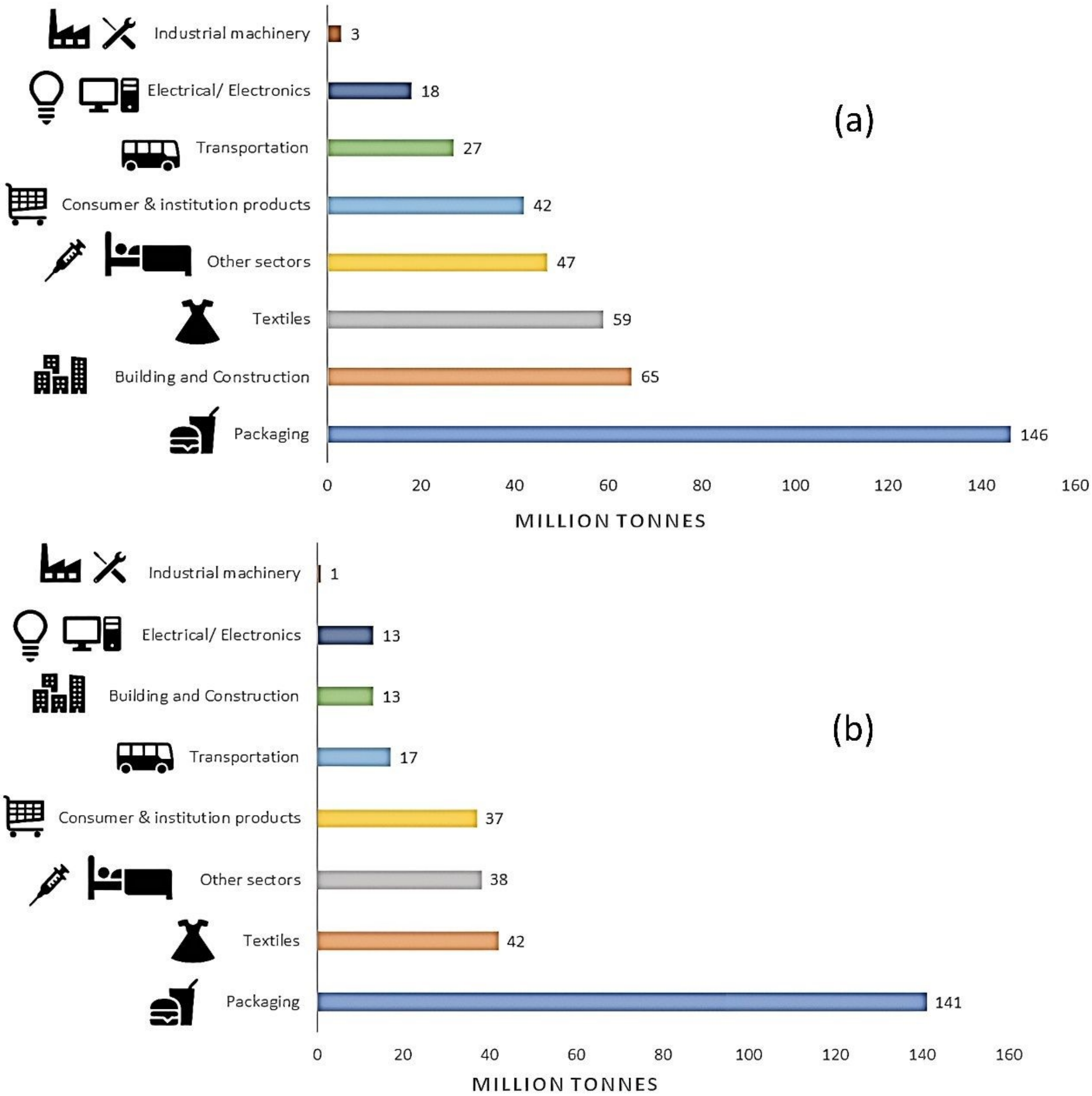

Figure 1. Primary plastic production by industrial sector 2015 (a), and Plastic waste generation by industrial sector, 2015 (b).

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 about advanced packaging technologies giving special

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importance to 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 the headspace of the container so that they can release or absorb substances into 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 gets rid of 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 still preserving food's visual and organoleptic features.[15] Ethylene scavengers, oxygen scavengers, antimicrobials, preservative releasers, antioxidants and flavour and odour absorber/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, silica gel) 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, hence reducing unwanted impacts on the products.[17] Ethylene can be removed using ethylene absorbents (e.g. Silica, activated carbon), which act physically by absorbing and holding its 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 **Figure 2**. Similarly, oxygen

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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 properties of antimicrobials.[19,20] Paraffin waxes, fatty acids, sugar alcohols, glycols, metallics, salt hydrates and eutectics may be used in future in food packaging.[15] Different kinds of active packaging materials and their functions were shown in **Table 1**.

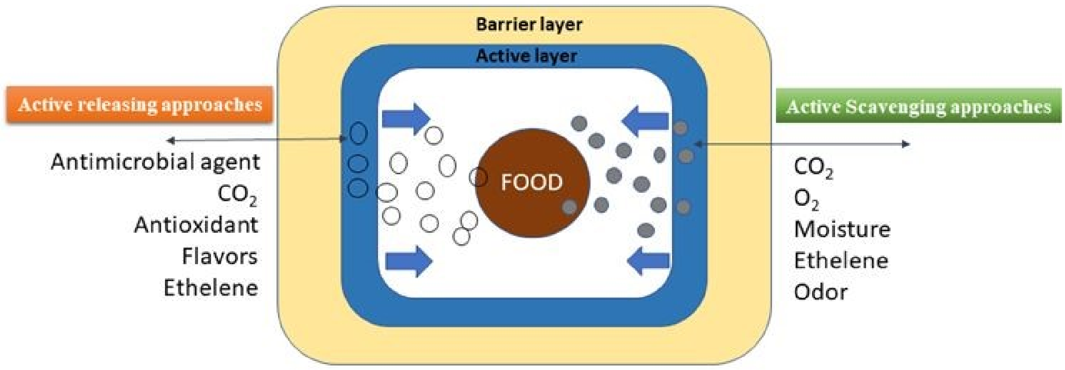

Figure 2. Various active scavenging approaches in food packaging.

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 food product, 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 were shown in **Figure 3**.[23]

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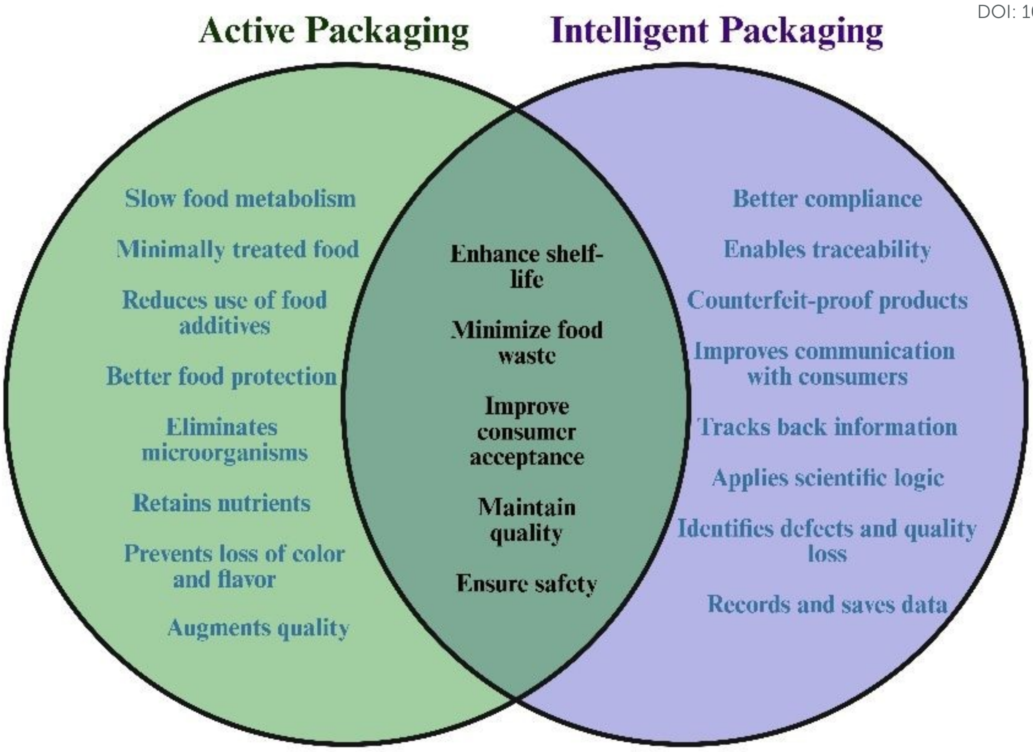

139

140 **Figure 3.** The similarities and differences of active and intelligent food packaging
141 systems.

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

Active packaging method	Materials	Functions	Foods which can be packaged	Reference
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.	19,27
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	28,29

Antimicrobials	Plant extracts, chlorine dioxide, essential oils	Inhibits the growth of bacteria, fungi and virus	Fish, meat, poultry, dairy and baked products	26

2.1 Food packaging with antimicrobials

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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 packaging. It effectively incorporates the antimicrobial agent into the polymeric film used for packaging and then releases it over a predetermined duration of time, hence expanding the shelf life by many times. Antimicrobial agents have arisen provides longer effectiveness, broader coverage, greater controllability, and improved environmental performance. One of the innovative approaches under antimicrobial packing is to developing functional meals and introduces bioactive packaging, a technology where packaging or coatings actively improve consumer health.[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 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 as pH, water activity (a_w), lipid and protein content, and temperature, affect how effective antimicrobial drugs are.[26,34,35] Antimicrobial

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activity is increased in acidic environments and decreased in low pH environments.[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 refrigerated 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, cyclodextrins) are examples of controlled-release systems and nanocarriers that adjust release rates to 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) lowering the exposure and regulates 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 reduces off-target selection pressure and are being assessed for safe packaging applications.[47] Natural antimicrobials and essential oils can be encapsulated via microencapsulation, inclusion biopolymer matrices, and nano emulsions, which increase stability, regulate sensory impact, and lessen resistance pressure by requiring fewer dosages.[48] In order to prevent continuous release and reduce resistance selection, materials that release antimicrobials in reaction to pH, moisture, or microbial enzymes are known as stimuli-responsive and intelligent release (on-demand activation).[49] Standardizing safety and migration testing, better analytical techniques and regulatory advice for migrants (plasticizers, nanoparticles, and additives) to create strong dossiers that the Food and Drug Administration (FDA) and European Food Safety Authority

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(EFSA) need and speed up approvals.[50] Bio-based and sustainable polymer platforms shifting to food-grade and biodegradable polymer carriers that reduce long-term environmental contamination and 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 the microbial development by lengthening the lag period and lowering microorganism live counts by slowing down the growth rate.[52] Antimicrobial packaging systems are particularly developed to manage germs that compromise foods' quality, safety, and shelf life, as food security is a major concern nowadays. 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 common antimicrobial agents used.[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 inhibits 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 touch with it. Alternatively, it may gradually diffuse partially or completely into the headspace or food, where it demonstrates 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 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]

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

Antimicrobial agent	Mechanism of action	Packaging application	Reference
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, PLA) for meat, dairy	57
Zinc oxide nanoparticles (ZnONPs)	ROS production (H_2O_2, •OH, O_2^-); Zn^{2+} release damages membranes and proteins	Active coatings/films for fruits, cheese	58
Essential oils (e.g. Thymol, Carvacrol, Eugenol, 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, 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 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, acetic acid)	Undissociated acids diffuse into cell → dissociate → intracellular acidification, enzyme inhibition	Coated films, edible coatings for fruits/vegetables	52

2.1.2 Types of antimicrobial agents in food packaging

The food business is increasingly focusing on maintaining the quality and safety of food goods as consumers become more health conscious and want fresh, minimally

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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 for preventing the development of microbiological 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 3. Different antimicrobial agents and their applications in food packaging.

Category	Origin	Examples	Applications in Packaging / Food	Reference
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

Category	Origin	Examples	Applications in Packaging / Food	Reference
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, 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, 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, limonene	Active starch films, encapsulation in chitosan/PLA, coatings for cheese, meat, fish	67,65
Plant extracts (mixtures)	Plant secondary metabolites (e.g. polyphenols, terpenoids, 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

2.1.3 Incorporation strategies for antimicrobial agents

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

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be degraded by high processing temperatures, which could lessen their antibacterial efficacy [66,67] as illustrated in **Figure 4**.

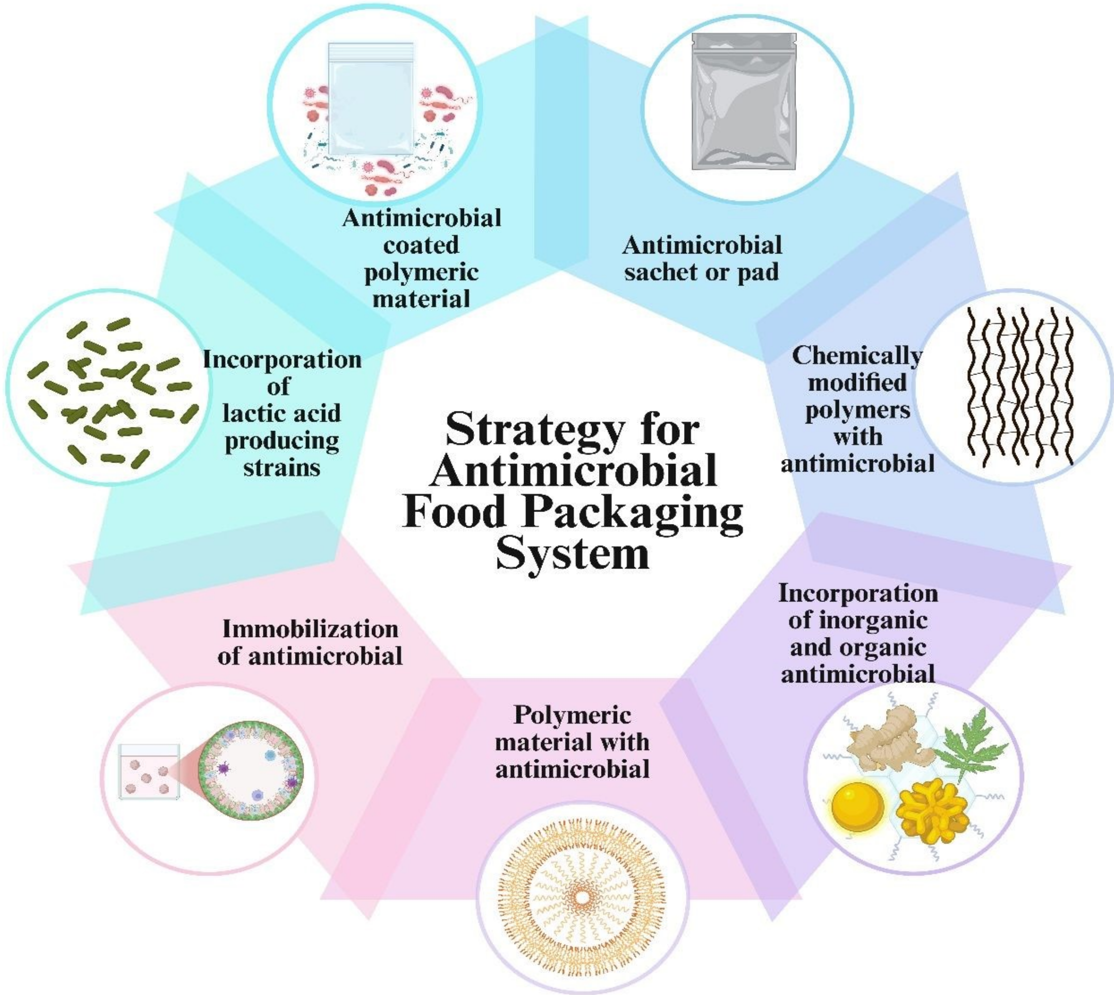

Figure 4. The development of antimicrobial food packaging systems

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 tactic could have poor adhesion, uneven release, and limited durability.[65]

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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 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] Complete overview of antimicrobial packaging was illustrated in the **Figure 5**.

Figure 5. Overview of antimicrobial packaging in food packing systems

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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 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, which is a communication-integrated system that monitors and improves the quality of packaged food. By lowering food waste and illnesses, enhancing environmental controls, and giving real-time information about 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

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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 comprehend parameters and mechanisms. Sensors give quick, accurate, and trustworthy 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 has been illustrated in the **Figure 6.**

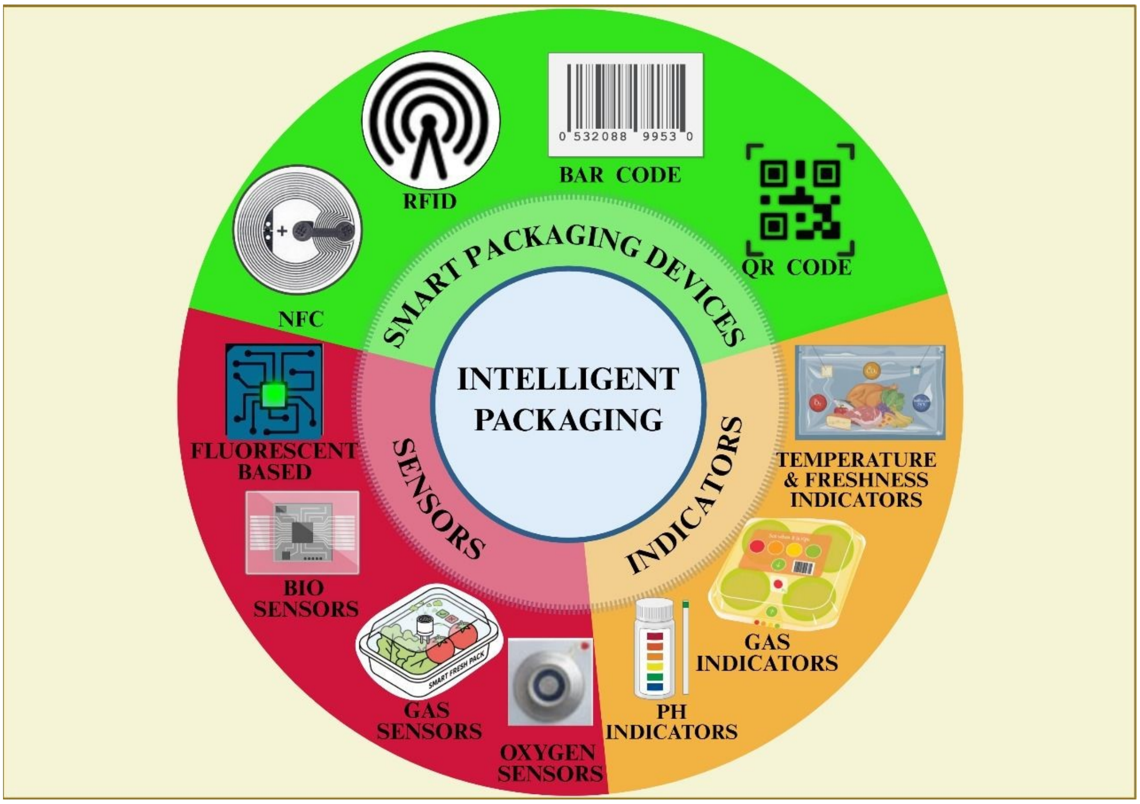

Figure 6. Devices involved in Intelligent Packaging

3.1 Sensor technologies in food packaging

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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–CDs-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 touch with Salmonella, it turns from red to light red, signifying that the chicken meat has spoilt. 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 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:

i) Biosensors

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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 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 -carotene, curcumin and chlorophyll are particularly sensitive to oxidative radicals, they could be useful for sensing.[1]

The creation of biosensors has shown great promise for carbon dots (CDs) because of their high surface-to-volume ratio, variable fluorescence, outstanding biocompatibility, and simplicity of functionalization with biomolecules.[85,86] Enzymes, antibodies, nucleic acids, or aptamers can be used to modify their surfaces, allowing for the 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-

DOI: 10.1039/D5FB00303B

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 prevent 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 the 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.

ii) Chemical sensors

Chemical sensing in food packaging could potentially benefit from synthetic dyes based on diverse polydiacetylenes and azo-compounds. Enzymatic activities, wherein the change in color is often a function of temperature and time, can also be used to create colorimetric indicators and sensors.[1] The food package containing a gaseous analyte, is detected by gas sensors which include sensors for oxygen, water vapour, carbon dioxide, and ethanol, as well as piezoelectric crystal sensors, metal oxides, organic conducting polymers, 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 voltage is applied via the

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potentiostat, causing electrons to flow between the electroactive species and the electrode, resulting in a current proportionate 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-CQD (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, 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 identify metal ions (such as Fe^{3+}, Hg^{2+}, and Pb^{2+}), tiny compounds (such as dopamine and ascorbic acid), or environmental contaminants (such as pesticides and antibiotics).[85,87]

iii) 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

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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 surface functional groups, electron/energy transfer, or surface passivation processes.[88,93] Moreover, CDs can be incorporated into films, 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]

iv) 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 inside 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 humans, are used for detecting food spoilage.[15] Other technologies that replicate the human olfactory system in a device developed to acquire reproducible data enabling detection and characterization of aroma combinations contained in the odour include electronic noses. 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 fisheries products

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throughout their degradation at 21°C and 4°C, colorimetric alterations were also noticeable.[95] Various types of sensors were presented in the **Table 4**.

v) 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 for real-time condition tracking 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 is quite difficult.[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 spoiling may be detected using 3D 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 lowering food poisoning cases because contamination in fresh items is frequently undetectable. In addition to improving quality evaluation and encouraging functional integration within

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autonomous systems, these technologies can be scaled for industrial food processing and agricultural applications.[99]

vi) 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 (ii) Colorimetric indicators are based on the 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

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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 benefits 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 about the product's freshness by observing any chemical changes in the food, its texture or any pH changes in the surroundings of the product to avoid any microbial contamination. They also trace the product while it is being transported from provider to consumer.[109] These advanced packaging technologies are incorporating biodegradable substances into the packaging materials which results in the sustainable conservation of environment. They also prevent food contamination and food loss.[110] Due to these

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technologies the consumption, storage and transportation has been efficiently increased thereby reaching the consumer expectations.[111]

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

Intelligent packaging devices		Examples	Functions	Reference
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 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 any changes in the concentration of oxygen in the packages.	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	Barcodes	UPC (Universal product code). RSS expand barcode. RSS-14 stacked omni-directional barcode. PDF 417	These are three common type of data carriers which encode larger data in reduced forms. Carry information about the product.	112
	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

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4. Challenges

While novel packaging has 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 effect, 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 supply chains that are fragmented, 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

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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- that only release antimicrobials in response to sensor-detected conditions (such as a temperature increase, pH change, or gas signature) minimize needless exposure to active agents and increase 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

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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.[124,5]

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

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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 with excellent selectivity, such as H_2S, NH_3, and CO_2. 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 gas to keep an eye on spoiling. Examples of technologies used in produce 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 were 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 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 more and more popular. Superior mechanical, barrier, and antibacterial qualities are provided by complex composites, gold nanoparticles, and nanocrystalline cellulose.[129] The use of sensors, nanomaterials, and other intelligent elements into active and intelligent packaging systems has demonstrated great promise in prolonging food products' shelf lives while

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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 on 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, such 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 stop spoiling, it uses Gas Regulation Modified Atmosphere Packaging (MAP), active cooling systems, and humidity control desiccants. By identifying anomalies early, this technology also improves food safety by avoiding the consumption of spoilt 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 has been demonstrated in the **Figure 7.**

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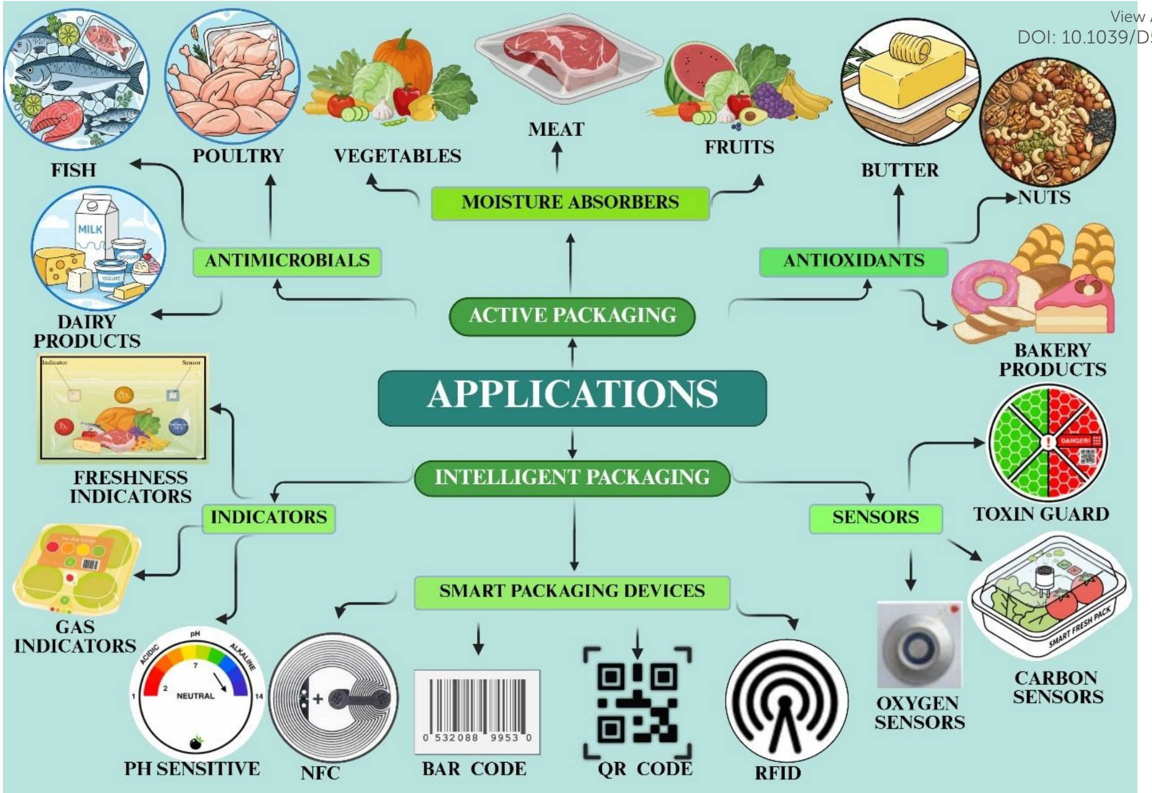

Figure 7: Overview of applications of active and intelligent packaging technologies (Created by Biorender).

Eco-friendly packaging options are being adopted by businesses in an effort to lessen 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, these solutions close the gap between technology and customer demands, spurring innovation in the dynamic market.[130]

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,

DOI: 10.1039/D5FB00303B

real-time food safety, quality, and storage condition monitoring is made possible by sensor-integrated packaging. Large-scale commercialization is still hampered by issues including consumer acceptance, cost-effectiveness, material compatibility, regulatory approval, and environmental sustainability, despite these encouraging advancements. 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, creating affordable, environmentally friendly materials, fusing sensing technology with digital platforms, and comprehending 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.

Authors' contribution

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 is presented within the manuscript itself.

Acknowledgements

DOI: 10.1039/D5FB00303B

PR, KVR, BMV, AA, PPV, and GGDDSV are thankful to Jawaharlal Nehru Technological University of Hyderabad (Kukatpally, Hyderabad, India) for encouraging throughout this work.

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Data availability

All the data is presented within the manuscript itself.