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Recent Trends in Smart Packaging

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Abstract: Recent advances in packaging technology have given rise to the concept of intelligent packaging, which incorporates various sensing and communication capabilities to enhance product safety, quality, and consumer engagement. This paper reviews the latest trends in intelligent packaging, focusing on innovations that improve shelf-life monitoring, provide real-time information to consumers, and contribute to sustainability. One prominent trend involves the integration of sensors and indicators that can monitor environment conditions such as temperature, humidity, and gas composition within packaging. These smart sensors offer real-time insights into product freshness and quality, enabling timely interventions to reduce food waste and ensure consumer safety. Most of the biosensors can detect spoilage or contamination, providing visual or digital alerts to consumers. Another significant approach is QR codes, where consumer can access detailed product information through their smartphones. These methods improve the transparency and trust between the manufacturers and consumers. Sustainability has also become a crucial focus within intelligent packaging trends. The development of biodegradable materials, coupled with intelligent features, promotes environmentally friendly practices while meeting consumer demand. Smart packaging solutions are now being designed not only to reduce waste but also facilitate recycling and reusability, thus enhancing the overall lifecycle of packaging materials. Furthermore, the integration of artificial intelligence and machine learning is revolutionizing the customization of packaging solutions, allowing manufacturers to optimize designs based on consumer behavior and preferences. As the market for intelligent packaging expands, these technological advancements will play a vital role in shaping the future of packaging practices across various industries, including food, pharmaceuticals, and consumer goods.

Index Terms: Intelligent Packaging, Packaging technologies, Smart sensors, Sustainability

1 INTRODUCTION

Packaging is very important in the product supply chain. Its main jobs are to hold and protect the product, ensure safe transportation, prevent damage, and stop tampering. Packaging also helps maintain the product's quality and safety from production to consumption by acting as a barrier against outside elements like oxygen, moisture, dust, gases, and pests. Most packaging provides basic protection by keeping the product safe from its surroundings. However, some packaging materials allow gases to pass through, which can help keep fresh products alive for a short time. Today, consumers are concerned about additives in products and prefer items with minimal processing and fewer or no additives. This has increased the importance of packaging in protecting products. To enhance protection, new packaging technologies are being developed, such as modified atmosphere packaging, active packaging, smart and intelligent packaging, and the use of nanomaterials. Over the past years, plastic packaging has become popular due to its low cost, light weight, ease of production, and compatibility with products [1,2]. However, many plastics are made from petroleum, which raises concerns because they take a long time to break down, can create microplastics, and contribute to pollution and energy use during their lifecycle. To address these issues, the packaging industry is focusing more on biodegradable bioplastics made from natural materials.

Innovative packaging solutions are being developed in response to a growing population, consumer demand for eco-friendly products, decreasing resources, and increased environmental awareness. Trends in packaging now include smart, active, and sustainable options that improve efficiency in the supply chain, ensure product safety, reduce waste, and enhance communication with consumers [3,4].

Intelligent packaging technology is most promising for protecting products, facilitating transportation and storage, enhancing sales, and improving consumer experience. It can increase product value and extend shelf life, leading to better economic benefits [5]. As technology and social conditions evolve, intelligent packaging is becoming more common in the market. This type of packaging combines modern materials, electronic information, sensors, and advanced technologies like the internet. It uses electronic technology to control and manage packaged products, helping to maintain their quality and prolong shelf life. Intelligent packaging creates business opportunities in the digital economy and is suitable for various sectors within industry. It involves multiple disciplines, including material science, information technology, microelectronics, and communication technology. The primary functions of intelligent packaging include protecting products, monitoring quality and safety, identifying and preventing counterfeiting, ensuring product safety, tracking items, and automating production processes. In the meantime, intelligent packaging acts as a quality control system, aimed at improving product safety and reliability. The relationship between intelligent packaging and intelligent products is complementary and any intelligent packaging relies on the appropriate underlying technology to function effectively [6]. Also, it allow to real-time tracking of products, easy information sharing, quick detection of food freshness, and has a wide range of uses. It can improve the safety and healthiness of food. Advanced techniques like pattern recognition and deep learning help to detect freshness of food accurately [7].

Active packaging is another new technology that can help extend the shelf life of meat and poultry products. One common type of active packaging in the meat industry uses oxygen scavengers made from iron powder mixed with acids or salts, which helps prevent spoilage. The advantage of active packaging is that it can maintain the preservative effects of various compounds, like anti-microbial, antifungal, or antioxidant agents, without coming into direct contact with the food. This is important because consumers prefer foods with clean labels and want to limit the use of food additives. Active packaging is defined as materials that do more than just act as a barrier to the outside environment. To meet consumer demand for preservative free foods, some manufacturers are now using natural antimicrobials to help preserve and extend the shelf life of products. The goal of active packaging is to keep the quality, safety, and freshness of the products while avoiding the direct addition of active agents to the food [8,9].

The goal is this review is to summarize the latest advancements in artificial intelligence (AI) technology for intelligent packaging, especially in detecting food freshness. The paper gives an overview of current research and suggests future directions for using AI in freshness detection.

2. Core Technologies of Intelligent Packaging

There are three main technologies used for intelligent packaging systems, including carriers, indicators, and sensors.

Indicators can be used to monitor the environmental conditions, where these conditions can affect food quality, such as time, temperature, gas leaks, and humidity. They can be placed inside or outside of the package. To check the quality of the packaged item, sensors can be used directly, like biosensors and freshness indicators. These devices are usually found inside the package. Data carriers store and transfer data, while indicators and sensors monitor the environment and show the information later [8,10] [11]. Fig.1 indicates the main technologies used in intelligent packaging.

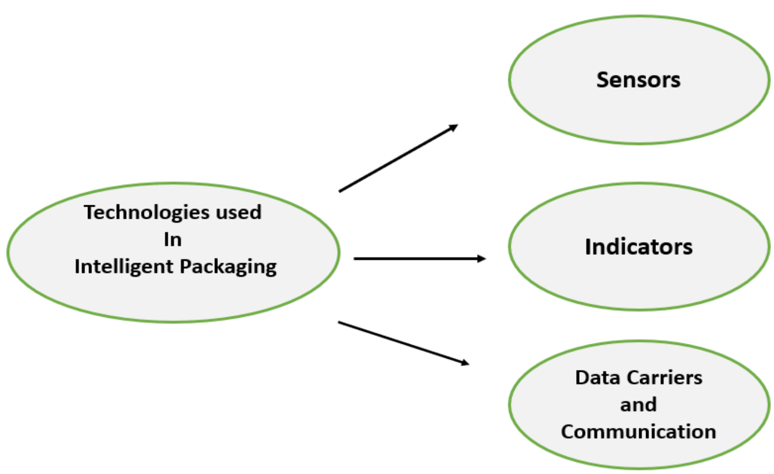

Fig. 1. Technological aspects of Intelligent Packaging

Indicators

Indicators are a type of smart food packaging that provides real-time information about product quality, helping to improve consumer satisfaction and make the food supply chain safer and more efficient. When food starts to spoil, it releases volatile compounds, which indicators can detect. These indicators change colour or emit odours, making spoilage visible. Some sensors can also measure the presence and amounts of gases that indicate spoilage in fruit and vegetables. Indicators can show whether a substance is present, how strong a reaction is between substances, or the concentration of a particular substance [12]. These changes are often shown through visible signs, like different colour intensities [13]. Depending on the type of indicator, they can be placed inside or outside the packaging [10].

Time Temperature Indicators (TTIs)

Temperature changes in food products can affect their safety and quality. A time temperature indicator is a simple and inexpensive device that shows how temperature has changed over time for a food product to which is attached. TTI works based on different principles, including mechanical, chemical, enzymatic, or microbiological changes. These changes are usually visible, such as through colour changes or physical deformation [14,15]. TTIs are small, self-adhesive, and easy to use. They provide clear information to consumers, helping them decide whether to buy a product based on its quality. These indicators keep track of the temperature history of food, especially perishable and frozen items, over a specific period [5]. Chemical or physical responses occur due to reactions that happen over time and temperature, like acid-base reactions or melting. Biological responses are based on the changes in the activity of microorganisms, spores, or enzymes in response to time or temperature. The rate at which these changes happen depends on temperature, increasing at higher temperatures, similar to how food quality deteriorates. Therefore, the visible changes in TTI reflect the temperature history of the product. TTIs should be easy to activate and show a clear, measurable change over time and temperature. This change must be irreversible and should relate to the food's deterioration and remaining shelf life. TTIs can be classified as three main groups: critical temperature indicators (CTI), critical temperature/time integrators (CTTI), and time temperature integrators or indicators (TTI) [16,17]. Temperature is a key factor in how long food lasts before it spoils. If the temperature changes too much, it can allow harmful microorganisms to grow, leading to spoilage. Even a small increase in temperature, just 1 °C, can raise water actively, change the internal structure of food, and cause loss of nutrients [18]. TTIs help to inform consumers whether a product has been kept at the right temperature during transport and storage. Additionally, freezing food incorrectly can damage the proteins in meat and other products. To ensure that the right temperatures are maintained during the food supply chain [19,20].

TTI works by detecting changes in food based on time and temperature. These changes can be mechanical, chemical, enzymatic, or biological [15]. For example, chemical changes can occur through reactions like acid-base reactions, while biological changes involve microorganisms or enzymes reacting to temperature and time. The results are usually shown as visible changes [21], such as colour shifts or physical changes. Because TTIs are easy to use, they are popular among consumers (23). One example is the FreshCheck from Lifeline Technologies. This TTI changes color based on a chemical reaction. A clear center means the food is fresh, while if the center colour matches the outer ring, the product should be eaten soon. A dark center indicates that the product is not fresh (24).

Several companies produce TTIs, including Monitor Mark^{TM} by 3M is a TTI developed in the USA. on the molecular diffusion principle, and it shows a color change as colorless to blue, Fresh-Check by Lifelines Technology is another commercially available TTI, which uses polymeric changes to change the colorless to blue [21]. Another commercially available TTI is Checkpoint by Vistab International AB, which works with an enzymatic principle where Tricolor green changes into yellow and then to red. OnVu by Freshpoint works with a photochemical scenario and ith shows color ranges from dark blue to colorless. eO TT indicator works with microbiological principles and changes their color from green to red [22-24]. TTIs have applied in food processing industry, such as monitoring and assessing the pasteurization and sterilization processes of milk. Diffusion-based TTI, can be used to food products like milk powder, coffee, and tea powder where it rates of diffusion of a substance by reflecting temperature history and potential quality degradation [24]. Thermochromic labels are another type of TTI which can use to milk product and it change the color at specific temperatures [25]. Bimetallic type TTIs are made with expansion of metal alloys mechanism to use in ice cream products (30). Another example is using anthocyanins extracted from red cabbage in a film made with chitosan and PVA to detect milk spoilage. When the temperature changes over time, the milk spoils, causing a visible color change in the TTI 50.

This indicator can detect the processing conditions and spoilage parameters. Most of the TTIs can determine the heating and freezing temperatures of meat and meat related items. TTIs have been made from using laccase, enzymes that is attached to electrospun chitosan fibers to monitor food quality. Laccase helps oxidize certain compounds, causing color changes from transparent to deep brown or purple-brown when the temperature fluctuates [26]. Some studies indicate that, color-changing TTIs use for meat products especially for fish and it indicate the cumulative temperature exposure over time [18]. Enzymatic TTI which use enzymatic reactions as main mechanism of operation used beef products [26]. TTI have also been created using lactic acid as the main ingredients, which changes color based on how much lactic acid diffuses. When lactic acid vapor diffuses, it causes a permanent color change in a chemical indicator from green to red due to a decrease in pH. In addition, lipase enzymes from various sources, such as Burkholderia cepacian and Aspergillus niger, have been combined with calcium alginate microplarticles and glycerol tributyrate to monitor the quality of ground meat, beef, and fish over time based on temperature changes [25,27].

Electronic monitoring is another advanced mechanism use Radio-frequency identification tags with TTIs This type of indicators especially use in tomato packages because it provides real-time temperature data through RFID technology [28]. Melting point indicators are another promising type TTI, which indicates melting of a substance. This type of TTIs can be used in mango and papaya packages to show cumulative temperature exposure and potential issues [29].

Freshness Indicators

Freshness indicators help monitor the quality of food during storage and transportation. Food can lose freshness due to poor conditions or exceeding its shelf life. These indicators provide information about the growth of microorganisms, the presence of their byproducts, or chemical changes in the products

[30,31]. Some examples of quality-related compounds that freshness indicators can detect include glucose, organic acids, ethanol, volatile nitrogen compounds, biogenic amines, carbon dioxide, breakdown product of ATP, and sulfur compounds [32,33]. To effectively monitor these compounds, freshness indicators need to be placed inside the packaging. Different methods can be used to detect this information, depending on the type of freshness indicator. They provide real-time information about food quality during production, packaging, and distribution, benefiting both producers and consumers. The effectiveness of freshness indicators is based on the spoilage compounds in food, such as volatile sulfides and amines. Over the last 20 years, the development of these indicators has become increasingly important. They also rely on measuring the total volatile basic nitrogen content produced from the food sample [10,18].

One example of a freshness indicator is a sensor label from FQSI (Food Quality Sensor International) that can detect biogenic amines. This SensorQ™ sticker is placed on the inside of food packaging and changes color from orange to brown when a critical level of bacterial growth has been reached [34]. The way biogenic amine sensors work is based on enzymes called amines oxidases or transglutaminase. Lactic acid sensors use the activities of lactate oxidase and peroxidase to function [23]. For glucose sensors, glucose oxidases are immobilized on the surface of electrodes. Glucose oxidase is an enzyme that helps oxidize glucose [35].

Freshness indicators react specially with the volatile compounds in the air inside the food package and show a visible color change. The effectiveness of these freshness indicators is often measured using three main methods. The first method is color response to different pH levels; this test checks how the color of the indicator changes with acidity or basicity inside the package. For example, a study in 2019 looked at freshness indicators for milk and fish and found that the indicator changed from orange-red to yellow when pH levels varied between 2 and 12 [36]. Another study developed an indicator for meat spoilage that changed color from brownish violet to light yellowish-brown when exposed to ammonia gas, within a pH range of 7 to 11 [37]. The second method is color response to target analytes in a liquid. In this method, a specific amount of a substance is placed directly on the indicator label, and any color changes are recorded. A study created a freshness indicator for monitoring shrimp spoilage and found it reacted to liquid ammonia when placed on various pH buffer solutions, changing color depending on the pH level [38]. Next method is color response to gaseous target analytes, this method involves exposing the freshness indicators to a known concentration of gas inside a sealed glass vial, allowing researchers to measure the color changes based on the concentration of the gas. For example, a study looked at a freshness indicator for a Thai dessert called golden drop and observed a bright color change in the label due to exposure to different levels of CO_2 [33].

Silver and copper ions are applied to thin films, around 1 to 10 nm thick. When food starts to spoil, it releases amine compounds, causing the color of the film to change to dark red [39]. Polythiophene in the packaging film also contributes to color changes during tuna fish spoilage [40]. Food quality sensors that can be placed inside the packaging to check the freshness of meat products. E-noses have been created to detecttimethylamine in raw food, helping to determine how fresh it is [41]. Curcumin, a natural compound, is added to various polymer films like chitosan and starch to create a color-changing pH sensor that indicates food freshness. Carbon nanotubes are used to detect CO_2, amines, and volatile sulfides in packaged food [40]. Hydrogen sulfide indicators are implemented to assess the freshness of meat, as the meat ages, hydrogen sulfide reacts with myoglobin, changing the color of the indicator. A fish freshness indicator was developed using cresol red bromocresol purple dyes in the packaging. It changes color from yellow to black to purple based on the concentration of ammonia, which indicates spoilage. Fish samples stored at different temperatures for a week showed that this indicator effectively tracked spoilage without damaging the fish [42,43]. Some indicators change color based on pH, the release of volatile nitrogen compounds, hydrogen sulfide, and enzymes produced by these microorganisms [44].

Leakage Indicators

The gas composition in the air inside food packages often changes due to the activity of the food, leaks, the type of packaging, or environmental conditions. Oxygen and carbon dioxide can be used to check food quality, detect leaks, or verify how well oxygen absorbers are working. Most O_2 and CO_2 indicators change color due to chemical or enzymatic reactions [9]. A color change shows when the oxygen level in a sealed food package goes above a certain limit. The respiration of food, the type of packaging materials, and changes in the environment can alter the gases in food packaging. These changes are directly related to the quality, safety, and durability of the packaging [45]. Oxygen indicators are commonly used to find leaks in food packaging. For example, ne oxygen indicator uses a UV activation method with alginate as a coating to measure thionine leakage. Another oxygen indicator is made by covering electrospun polystyrene fibers with a special polyvinyl alcohol nanofiber base using 3D-printing technology.

In tests, the time took for the color to change in the oxygen indicator without the polystyrene coating ranged from 1.8 to 189.4 seconds, with a leakage rate of 1.85 to 29.6%. In tests, the time it took for the color to change in the oxygen indicator without the polystyrene coating ranged from 1.8 to 189.4 seconds, with a leakage rate of 1.85 to 29.6%. In contrast, the color recovery time for the electrospun polystyrene fiber layer was between 38.2 and 240 seconds, with a much lower leakage rate of 0.02 to 0.3% [46].

Changes in oxygen levels in packaged food can lead to poor quality, and fluctuations in CO_2 levels can harm some internal microbes in the food. Therefore, CO_2 indicators could also help detect leaks. Similar to oxygen indicators, natural substances like lysine and anthocyanins have been used to create color-changing CO_2 indicators to measure pH changes. In experiments with poultry meat, both water-type and label-type indicators were tested at different CO_2 levels, showing a color change from sky blue to dark purple [47].

pH Indicators

Smart packaging with a pH indicator is a growing innovation in food packaging. pH indicators typically have two components, a solid base and a dye that changes color when the pH level changes according to how acidic or alkaline their environment is. These dyes are often made from fruits and vegetables [23]. When food starts to spoil, the pH level changes, which serves as an indicator of the food's quality. As the deterioration process begins, the color of the indicator or packaging changes. Therefore, a package that shows the pH level of food before it is bought or consumed helps ensure the product's quality and safety for consumers [48].

One example is a pH sensitive film made from chitosan dyed with extracts from the Bauhinia Dunn flower. This film can be used as a sticker sensor on fish packaging to monitor freshness and pH changes. When fish releases volatile amines during storage, the pH changes and the film color shifts from purple to green [49]. Another study involved a chitosan and polyvinyl alcohol film infused with anthocyanins from red cabbage, which was used to wrap pork belly slices. This thin film changes color from pale green to yellowish as it detects spoilage [50]. Additionally, a film made with anthocyanins from fruit and sweet potatoes was tested on meat stored at three different temperatures: -20 ℃, 4 ℃, and 20 ℃ for 72 hours. The film changed color from red to blue, indicating that meat stored at 4 ℃ and 20 ℃ became contaminated after 72 hours and 24 hours respectively [51]. When alizarin was added to the chitosan-based film, it also showed a color change from yellow to purple, indicating spoilage in fish based on pH changes [52].

Some studies show that using smart packaging as a pH indicator for pasteurized milk, they have tested the packaging at room temperature for 48 hours with film placed in milk. The film showed a color change, indicating that the milk was deteriorating and the pH dropped from 7 to 6. Other food tested with pH indicator packaging included pork, chicken breast, and fish fillets. [53] Choi et al, 2016 has created a color-changing pH indicator film using agar, potato starch, and anthocyanins from sweet red potatoes. When placed on pork, the film changed color from red to green as the pH changed and the meat spoiled. Additionally, a chemical barcode was developed for real-time monitoring of chilled, skinless chicken breast spoilage. This barcode used filter paper and two groups of pH- sensitive dyes. The results showed that the indicators responded to changes in microbial growth and pH levels, allowing for quicker and more sensitive detection of spoilage [54].

Black pulp peel waste was used to extract anthocyanins, which were then added to chitosan-based films along with titanium oxide NPs. This combination indicated spoilage when the pH shifted from acidic to basic. Also, extracts from black and purple rice were incorporated into chitosan films to test the pH levels of pork samples [38,55]. Titanium oxide NPs were also used as pH indicators in chitosan films to monitor salmon meat storage. Additionally, anthocyanins from purple potatoes were utilized to assess fish spoilage in both acidic and alkaline environments from butterfly pea flowers combined with titanium oxide NPs in starch-based films [56].

Humidity Indicators

Moisture levels play a crucial role in how quickly microbes grow. In low-moisture foods, higher humidy can actually speed up microbial growth, which creates a need for humidity sensors to help keep moisture levels in check [57]. Researchers are developing special film that change color to show humidity levels, using technology that interacts with electromagnetic fields from humidity sensors attached to packaging. One approach involves using a photonic crystal hydrogel, which is made by coating small spheres with a special polymer to create a humidity sensor [58] . Wheat gluten protein has also been studied as a way to monitor humidity. Scientists looked at how different amounts of water interact with wheat gluten at low, medium, and high hydration levels, focusing on the types of water molecules present. By using styrene and methacrylic, like special monomers in a process called radial copolymerization, different colours can be achieved based on the moisture content. Humidity sensors have been created using chitosan and a type of nanopowder called $CuMn_2O_4$, which work by measuring changes in electrical resistance [58]. The sensor's resistance decreases as humidity increases because more charge carriers are generated with temperature changes. ZnO nanoparticles, along with films made from glycerol and gelatin, have also been used to measure humidity at room temperature. Another type of humidity sensor uses a quartz crystal microbalance coated with chitosan and carbon nanotubes. This optimized sensor is very sensitive, has minimal errors, responds quickly, and maintains stability and reliability over time [57]. Other humidity sensors have been made with chitosan combined with zinc oxide or single-walled carbon nanotubes. In these cases, the sensor works by the swelling of chitosan, which creates the path for electrical conduction between the nanotubes [55].

Sensors

A sensor is a device that detects or measures energy or matter, providing signals to indicate physical or chemical properties. Most sensors have two main parts: a receptor and a transducer. Receptor detects certain chemicals or physical things, like their presence, while another part takes the information from the receptor and changes it into a different form [59,60].

Biosensors

Biosensors consist of biological material receptors, such as antigens, enzymes, nucleic acids, or hormones [61]. Also, the biosensors can detect light, pH, temperature, mechanical force, and solvent compositions. They work by using materials that can attract or repel water. Biosensors are quite similar to chemical sensors, but they are focused on finding biological compounds such as cells, antibodies, and bacteria. They can also detect gases and other chemicals accurately, including substances like hydrogen, carbon dioxide, methane, and more [10,62].

The "Toxin Guard" is a biosensor developed to detect harmful germs like Campylobacter, E. coli, Listeria, and Salmonella in meat, fruits, and vegetables. When spoilage bacteria stick to antibodies in the packaging, it causes a change in colours on the polyethylene films that show quality loss. This colour change signals a positive result [63,64]. Another company, "Flex Alert", has created biosensors that can detect pathogens like E. coli and Salmonella in finished foods, as well as aflatoxin in food items such as coffee beans, nuts, seeds, wine barrels, and fresh fruits. This product is now available for commercial use [65,66]. Another biosensor can detect xanthine, which is a breakdown product of adenine

nucleotides found in animal tissues. It does this by using xanthine oxidase, and enzyme, that is attached to electrodes made of platinum, silver, or pencil graphite [67].
“Food Sentinel”, another biosensor developed from SIRTA Technologies, used to detect pathogens in food packages, including fish, meat, poultry, and liquid packages [68]. Another study from Mirza et al 2022, shows “LactoSens” can determine lactose content in milk and other dairy products [69].

Chemical Sensors
Chemical sensors are different from others due to their working principle. They can categorized into optical and electrochemical sensors [12]. Chemical sensors are ideal for creating smart food packaging because they can detect specific chemical molecules, such as volatile organic compounds and gases like hydrogen, carbon monoxide, nitrogen dioxide, and hydrogen sulfide. These substances are mainly responsible for food spoilage, particularly in meat, fish, fruits, and vegetables [66].

Optical sensors play a crucial role in the food industry by enabling non-invasive, real-time monitoring of food quality and safety. They can be used to detect changes in the food environment, such as gas composition, pH level, temperature, freshness, microbial spoilage, and oxygen levels [10]. For example, optical sensors can measure infrared absorption to assess moisture content or detect specific compounds associated with spoilage, providing visual or colour changes to users [70]. Optical sensors are utilized as freshness indicators that respond to the production of gases like CO_2 during microbial activity, resulting in color changes within the packaging. They can also be integrated with digital systems to automatically alert stakeholders about lowering food quality, helping in early intervention to prevent spoilage and reduce waste. Additionally, natural colour makers embedded in packaging materials allow consumers to visually assess freshness based on pH or bacterial growth, enhancing transparency and trust [71].

According to Alfei et al 2020, pH sensors monitor the acidity or alkalinity of food products, especially tomatoes [72]. pH sensors can signal spoilage by detecting increases in acidity due to microbial growth or the fermentation process. When bacteria proliferate, they often alter the pH of the food, and the sensor can translate this into a visual cue, changing green (fresh) to red (spoiled). In products like meat, dairy, or seafood, pH sensors help ensure quality by tracking pH fluctuations that correlate with deterioration, thereby extending shelf life and reducing waste [73].
A digital oxygen indicator is a type of optical sensor used to check for leaks in modified atmosphere packaging (MAP) [74]. Also, metal oxide sensors can easily interact with specific gases and detect the volatile compounds that are in contact with food quality. These sensors can be used in packed foods [75]. Some specific gas sensors to detect ammonia and ethylene, which are caused by spoilage or

ripening processes, can be easily detected in chicken and other meat foods [76]. Not only the gases, moisture content in meat products be detected by using moisture sensors, but it also gives accurate data while monitoring and controlling moisture levels in packed meat items. Sweden has developed an optical sensor called “Bioett” to measure the temperature of products, while Canada created a flex alert optical sensor, detects volatile compounds by changing their electrical properties [77]. Some commercially available optical sensors are used to analyze vegetables, such as “Fresh Tag”, “Sensor QTM”, and “ Toxin Guard” [77].

Electrochemical-based sensors in food packaging work by detecting specific chemicals in food through interactions between the sensor’s electrode and the target substances. These sensors produce electrical signals that help assess food quality and safety. Common methods include potentiometric, voltametric, and conductivity measurements [78]. The main goal of these sensors is to monitor oxygen levels, detect pH changes, and identify chemicals related to food quality and safety, especially in the meat and dairy industries. The sensors use electrodes that are especially designed to interact with the chemicals of interest. When the target analyte comes into contact with the working electrode, it undergoes a redox reaction, producing an electrical current or voltage corresponding to the analyte's concentration. Electrochemical sensors can also measure colours in food products. For example, a sensor was created using a modified glassy carbon electrode to detect sunset yellow dye in beverages, showing high sensitivity at very low concentrations [79].

Materials like carbon nanotubes and graphene are promising for gas sensors because they change resistivity based on gas molecule adsorption. Their two-dimensional structure allows for increased detection capacity. Fullerenes are strong molecules that can withstand high pressure, making them suitable as receptors, while carbon nanofibers are pure and strong, ideal for sensor use [66,80].

Gas Leakage Sensors

Gas leakage sensors are designed to be water-insoluble and non-toxic, allowing them to detect gas leaks in food packaging. They can easily identify leaks or breaches in packaging seals and ensure the real-time quality of the package. By detecting unwanted gas leaks early, manufacturers can implement timely interventions or remove compromised products, while extending the shelf life and maintaining freshness [81]. These sensors change colour and produce a fluorescent signal when gas is detected [82]. They are often made from metal oxides and can identify gases like carbon dioxide, ammonia, hydrogen sulfide, and others, leading to food spoilage. These sensors use various methods to monitor food quality, including chemical reactions, gas detection, electrical signals, and light analysis [83]. They can also track temperature changes and radiation to ensure food safety.

Zhu et al 2023 show that ammonia gas sensors can monitor gas leaks or spoilages in meat and seafood packages. [84]. Yousefi et al, 2019, determine that SO_2 gas sensors can detect spoilage and prevent the growth of bacterial organisms [85]. This type of sensor can detect volatile compounds like trimethylamine, volatile fatty acids, biogenic amines, alcohols, ammonia, and carbon dioxide, which are released during meat and aquatic products spoilage. For example, a nanoporous colorimetric sensor array has been developed to monitor trimethylamine production in meat and aquatic products [86,87]. Additionally, they can monitor the quality and freshness of fruit by detecting alkenes, esters, aldehydes, and alcohols released during decay. Sanaeifar et al and Beniwal et al have conducted studies and shown that metal oxide sensors can detect ethylene gas leakages during the ripening of banana and apple, respectively [88,89]. Gas leakage sensors in dairy products can monitor the quality of raw milk by observing VOCs like ethanol, acetaldehyde, dimethyl sulfide, and acetic acid, which are released due to microbial contamination, chemical reactions, and genetic factors [90]. These sensors can be used to assess beer quality by predicting changes in aroma compositions due to the release of VOCs [91]. The same theory can apply to rice-like grains to detect unnecessary gases due to the storage conditions [92].

Oxygen Sensors

Oxygen inside packaging affects food quality and shelf life. While modified atmospheric packaging (MAP) and controlled atmospheric packaging (CAP) help reduce oxygen's negative effects, they don't show how much oxygen is present or how spoiled the food is. Oxygen sensors address this issue by detecting the level of oxygen inside the package. These sensors can come in different forms, including labels, tablets, printed layers, or as a coating on packaging materials [93,94]. For instance, a special colour-changing oxygen sensor can be activated by UV light. This sensor is initially blue but turns colorless when activated by UV light. When it comes into contact with oxygen, it reverts to blue. The sensors, like TiO_2 and methylene blue, work by changing colour based on the amount of oxygen present [95,96]. TiO_2 particles can be activated with UV light, which helps indicate the oxygen level by changing the sensor's appearance [97]. Another type of oxygen sensor uses graphene oxide to show changes in oxygen levels through its chemical reactions [85].

Data Carriers and Communication

Traditional packaging has been important for distributing products, but it often doesn't meet the current market demands. To address this, we need to explore new technologies and innovations in packaging that help to improve customer satisfaction. This includes ensuring safety, reducing waste, improving shelf life, and providing real-time monitoring of products. Smart packaging includes various data carriers that help with tracking products, ensuring their authenticity, and engaging with consumers.

Barcode & QR Scanners

Barcodes are an affordable and easy way to help manage inventory, track stocks, and process payments. They come in two main types: 1-dimensional and 2-dimensional barcodes, which have different storage capacities [10,98]. A barcode consists of parallel lines and spaces that encode 12-digit numerical data. An optical barcode scanner reads these codes and sends the information to a system for storage and analysis. The barcode is low-cost and widely used in large retail stores, allowing manufacturers to monitor stock levels and record supplies throughout the supply chain [98]. 1D barcodes are simple and commonly used to encode food information, integrating well with various software systems in the packaging industry. Later, 2D barcodes were developed to store more data in a smaller space. In the past decades, application of barcode systems has been investigated in smart packaging. For example, special printing inks that change with pH levels have been made for barcodes. These inks cause the dark lines on the barcode to either get darker or lighter when the pH changes. This change can be read by a barcode scanner to check the freshness of meat and milk products [99]. Another study from Chen et al have developed a mobile application using 2D barcode technology for trace pig meat products [100].

A quick response (QR) code is a type of barcode with a grid of dots that can hold information. Although they aren't widely used in the food industry, QR codes are becoming more popular in food packaging. They provide consumers with important details about the food, such as nutritional information, potential health effects, and allergens [101]. They are made up of small black and white squares, called cells or modules. Each cell represents a bit of information; these cells are arranged in columns and rows, creating a rectangular or square pattern that makes QR codes recognizable [102]. QR codes help keep track of food safety by showing critical information for recalls. They allow for traceability, helping to track the food's source and production. When consumers scan QR codes with their mobile devices, they can also log their food intake and understand their eating habits better. Many studies have stated the importance of traceability of foods, aquatic products like fish and tuna, dairy products like cheese, fruit yoghurt, and milk, horticultural products like apples, buckwheat, grains, olive , rice, wheat, and vegetables, meat products like beef and pork, and other products like egg, using QR codes [103]. Also, QR codes have become a popular tool for digital marketing in retail, especially among food manufacturers. They can help boost sales by building brand images, offering fun services, and giving rewards [103]. For instance, Chef's Basket, which is a famous pasta company, allow customers to get recipe videos for their customers simply by scanning the QR code. Emmi milk company allow to consumers to take discounts and raffle entries by QR code [103]. The Coca-Cola company provide entertainment services with interesting face filters while scanning the QR codes [104].

Radio Frequency Identification

Radio Frequency Identification (RFID) systems use tags or chips to collect real-time information about temperature, humidity, shelf life, and nutritional details of food products. These tags are attached to food items and raw materials, allowing them to send accurate information to a reader connected to a user's system. RFID is part of a group of technologies that can help improve production, distribution, inventory and supply chain management [10]. In retail, RFID can enhance processes like shipping, receiving, and storing products. It helps track the movement of items, making it easier to manage recalls by quickly identifying where affected products came from. While RFID itself is not considered intelligent packaging, it acts as an intelligent part of packaging by transmitting product information through digital signals [105]. The main components of an RFID system include a reader, a recording unit, and a tag

which work together using electromagnetic signals. These tags monitor the quality of food products and track their location, time and temperature changes, especially for items that need to be kept cold [106]. RFID has advantages over other data carriers, such as storing large amounts of data, fast communication, and sending signals over long distances. Researchers are also developing RFID tags that can check the freshness of fish by monitoring temperature and gas concentrations [107].

RFID systems are used to manage the logistics of products and generate a large amount of valuable data. For instance, a supermarket using RFID technology can produce around 12.6 GB of data every second, totalling about 544 terabytes of data each day. Because of this, there is a need for effective ways to control, assess, and extract information from RFID systems [108].

Variable shelf life, which changes based on the food's condition, has advantages over fixed shelf life, such as helping to reduce food waste and ensuring better food safety. This approach relies on real-time information from RFID sensors to monitor food quality. Combining variable shelf life with discount strategies can lead to more efficient reduction of food waste [109]. There is ongoing research into using nanoparticles and nanomaterials in RFID sensors and other tags. Moreover, to address electronic waste, some researchers are creating "Green RFID devices", including biodegradable tags made from materials like paper and wood that break down easily in the environment, as edible RFID that can be absorbed during digestion[110]. Not only that, this technique can be used to package applications in healthcare to monitor product quality, collect real-time data from patients, track the product journey from production to patients, and sterilisation and waste reduction sections [102].

Near Field Communication

Near field communication (NFC) uses wireless sensors that communicate through inductive coupling. NFC tags and labels can help prevent the consumption of soiled food by alerting buyers or suppliers. NFC is often seen as an extension of near-field RFID technology. Unlike RFID, where one device act as a reader, NFC devices can interact with each other [111]. Durdevic et al explained that NFC is a technology for short-range wireless interactions. It is similar to mobile technologies like 3G, 4G and Wi-Fi, but uses different frequencies and power supplies for communication. NFC operates over very short distances, making it effective for enhancing communication in everyday life [112,113]. NFC sensors are commonly embedded in packaging to monitor temperature changes during the transport and storage of perishable items. They ensure that food is kept in the right conditions to maintain its quality. NFC also protects digital certifications, quality assurance documents, and compliance data, allowing for quick access to important information [114]. By using NFC tags, the risk of counterfeit products is reduced, and regulatory compliance is ensured. This technology benefits everyone in the supply chain by providing traceability, real-time evaluations, and improved communication in food quality management systems [115].

A whisky brand utilises NFC tags to verify the authenticity of its products and enhance customer satisfaction. The tag is hidden in the bottle label, allowing customers to scan it with their smartphones to access detailed information about the item and brand [116].

3. Application by Industry Sectors

Smart packaging uses advanced technology to improve packaging in different industries, making products safer, better quality, and more engaging for consumers. Fig.2 defines about the recent industrial applications of smart packaging in important industries, including food & beverages, Pharmaceutical & health care, and other main industries.

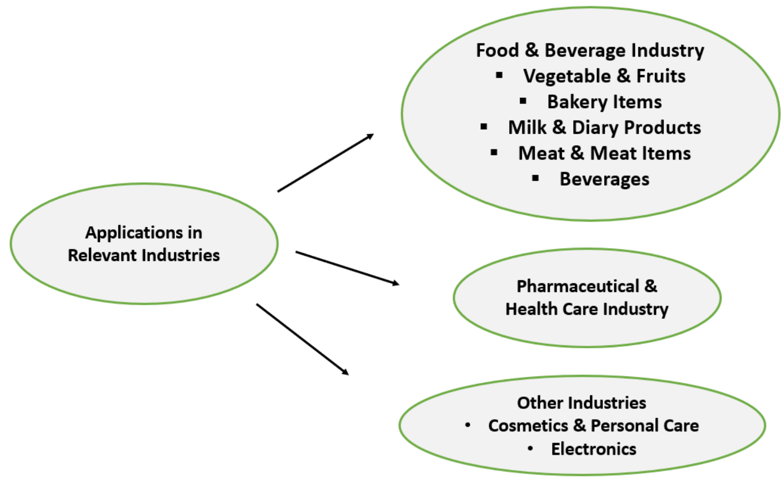

Fig. 2. Applications of Smart Packaging in different industries.

Food and Beverage Industry

Active packaging enhances the performance of food packages by adding extra features that help keep food fresh, prevent contamination, and extend shelf life. This system helps monitor food quality and alerts users to potential issues. Smart packaging improves communication about changes in the food inside, providing information on factors like time, temperature, freshness, or volatile substances [117]. Intelligent packaging can also lower energy use in the cold chain, reduce the need for preservatives, and minimize food waste [118].

Vegetables and Fruits

India is a significant exporter of fresh fruits and vegetables, with exports valued at 750 million for fruits and 767 million for vegetables, approximately. Since fruits and vegetables spoil quickly, they need careful management of temperature, gas levels, and humidity [59]. Common bacteria that can affect these products include E. coli, Listeria, Salmonella, Shigella, Bacillus cereus, and Vibrio cholerae. Microbial contamination often happens due to improper handling during transportation [119]. To ensure quality, it's important to control postharvest processes like respiration, ripening, and ageing. Packaging materials should allow for gas exchange, and active packaging can help manage oxygen, ethylene, and moisture while preventing bacterial growth [120]. Temperature plays a critical role, as higher temperatures increase rates and speed up spoilage. However, fruits like bananas and mangoes can also be harmed by low temperatures [121].

Labels can be attached to food packages to show temperature-based changes, such as how microbes survive, how proteins break down, and other chemical changes [122]. Enzymatic reactions on the packed fruits and vegetables caused pH changes and colour changes, by using pH indicators manufactures can easily monitor the food spoilage conditions [10]. These are very useful for fresh and minimally processed fruits and vegetables. Ethylene scavengers can be used to enhance the shelf life of climacteric fruits, including apples, kiwifruit, apricot, banana, mango, and vegetables like carrots, potatoes, and asparagus [123]. Moreover, these scavengers can improve the shelf life of mangoes up to one and a half months and other fruit packages, by reducing ripeness and weight loss [124]. Another study showed that the use of oxygen absorbers in dried sweet potato flakes and tomatoes prevents oxidation and microbial growth and maintain the quality level [125]. Lastly, antimicrobial packages that consist of natural compounds to fight harmful bacteria, and keep minimally processed foods like papaya, tomatoes, and spinach safe for consumption [126]. Sweetness and aroma are two important factors for the shelf life of fruits like melons and oranges. As fruits degrade, they release bad odors that can affect the quality of fruits. To minimize this, ordor sensors or ordor proof packaging can be used, that includes the qbility to absorb unpleasant smells [127,128]. Additionally, ripness sensors can detect when fruits are ripe by changing color due to the gases they release. As example, packaging that uses methyl red can indicate when strawberries are ripe by changing color as the pH level increase [129,130].

Bakery Items

Bakery products are an important food, and they take 4 to 10 days to spoil due to their low water content [131]. Refrigerating baked goods isn't practical because it changes their texture and taste, so modern packaging solutions are used to extend their shelf life and prevent consumer spoilage. Baked goods are vulnerable to yeast and mold contamination, which can survive baking or happen during cooling and packaging [132]. Products with low to moderate moisture can spoil due to moisture loss but these products are generally less prone to microbial spoilage [133].

Factors that contribute to spoilage include oxygen-permeable packaging, poor sealing, and trapped air, and molds can still grow in low oxygen. It's hard to remove oxygen from packaging completely. Although oxygen sensors can help to extend shelf life, especially for humidity-sensitive items like cakes [133]. Ethanol is another option for extending shelf life, as its vapor can kill bacteria and molds, it's often used in Japan for this purpose [134].

Milk and dairy products

Dairy products are nutritious, but they spoil quickly due to their high-water content and nutrient composition, which supports microbial growth. Spoilage is mainly caused due to the presence of lactic acid bacteria and harmful pathogens [135]. Dairy products need packaging that limits oxygen exposure, as excess oxygen promotes spoilage and affects flavor and nutrition [136]. Packaging additives like pectin and essential oils can improve shelf life and indicate expiration. Color indicates that reduction of beta carotene by changing the colour from orange to light yellow [137]. Carbon dioxide gas can enhance milk quality, but it must be monitored to prevent the growth of harmful bacteria [138].

Meat and meat products

Meat products are highly perishable and can quickly develop spoilage due to microorganisms like bacteria, yeast, and molds, including harmful pathogens [139]. These factors can lead to a decline in quality and safety. Some factors, like pH, moisture content, and nutritional composition, influence how quickly meat spoils [140]. Oxygen helps aerobic organisms thrive, causing off flavors, odour changes, colour shifts, and nutritional losses, which all shorten the shelf life of meat. For instance, when meat is exposed to air, deoxy myoglobin turns into oxymyoglobin, giving the meat a bright red colour. When oxymyoglobin oxidizes, it turns brown, indicating the meat is less fresh [141]. The material's oxygen transmission rate, storage temperature, and exposure to light. Natural antioxidants like vitamin C and E can be included in packaging films to help prevent oxidation [142] . Active packaging technologies can include coatings or edible films designed to reduce spoilage and contamination [143]. Additionally, tools like the "SensorQ" stick-on indicator label can be used to detect freshness by changing colour when bacteria start to grow, helping consumers assess the quality of the meat [144].

Beverages

In beverages, the aromatic profile can be altered due to oxidation or acid reactions, and vitamin C can degrade when exposed to oxygen [145]. Glass bottles have the lowest oxygen permeability, which helps preserve freshness. At the same time, other materials, such as multilayer plastic, also provide decent protection against the packed beverages. Oxygen-absorbing materials can further reduce oxygen levels to very low percentages, helping to maintain beverage quality [145]. Sensors and indicators can be incorporated into packaging to minimise surface contamination and slow the growth of harmful microorganisms. Some innovative packages, such as self-heating and self-cooling cans, are now available, and temperature indicators can be used to indicate if drinks are at the correct serving temperature [16].

Pharmaceuticals and Healthcare Industry

Smart packaging in the pharmaceutical industry uses modern technologies to improve the safety, quality and tracking of medicines throughout their life cycle, from the production process to delivery. It includes tools like temperature and humidity sensors, RFID tags, and time indicators that help monitor storage and transportation conditions [146,147]. This technology not only ensures that medicines remain safe and effective but also meets the growing demand for transparency and compliance with regulations. As consumers seek reliable information about their medications, smart packaging has become essential for pharmaceutical companies to stay competitive. This section discuss the importance of integrating these smart technologies to meet international quality standards [148].

There are two types of sensors that are used in smart packaging for pharmaceuticals. Bluetooth Low Energy (BLE) sensors can use real-time data about storage conditions to mobile devices or the cloud. Some packages also have single use indicators that change color to show if temperature or humidity levels are harmful to the product. Some sensors give real time information about the temperature and humidity changes of pharmaceutical products during transportation by changing their color or any visual signal. Sensirion SHT35-DIS-B and Maxim Integrated DSI1923 iButton sensors help to real-time monitoring and help with products which require constant monitoring of storage conditions. The second sensor can store a lot of data and works independently for a long time [148].

RFID and NFC technologies are the most significant technologies, making up 30% of usage after the sensors, as they help with tracking products and managing the supply chain. Time and temperature indicators account for 20% contribution and are important for alerting users to any temperature changes that could harm products. Smart labels and tags make less contribution to the applications but still add value by providing extra product information and enhancing consumer experience. This integration of advanced technologies also helps make operations more efficient and supports sustainability by reducing waste and ensuring products are stored and transported properly [148].

Smart packaging is used in blister pack systems, and these systems can record when a pill is taken out of the packaging and can send audio and visual alerts. Topcryo is a thermal indicator that changes colour from green to red to show if a product has been exposed to high temperatures, making it easy to track temperature issues [149]. ColdMark indicator is another application which can monitor whether the product has been frozen or exposed to low temperatures. They are used for sensitive items like vaccines. There are different types of indicators for various temperature limits [149]. Smart packaging is also used in blood storage and transportation. Using packages with temperature indicators helps to ensure that blood stays at the right temperature, which should not exceed 6 or 10℃. These indicators show if the temperature has been maintained properly, which is crucial for blood transfusions. This type of packaging is valuable because it can reduce costs associated with lost blood products and prevent risks to patients' lives. Some indicators change colour from white to red if the temperature exceeds 10℃. If the indicator stays white, the blood can still be used. This helps ensure constant monitoring of temperature for sensitive blood samples [149].

<u>Cosmetics and Personal Care Industry</u>

Smart packaging for the cosmetics and personal care sectors is transforming the way products are presented, interacted with, and utilized by consumers. One prominent approach involves embedding NFC technology or QR codes in packaging, allowing customers to access detailed product information, including ingredients, user instructions, country of origin, and tutorials by simply scanning the packaging with their smartphones. This also promotes brand loyalty through interactive experiences [150].

Moreover, smart packaging can incorporate sensors that monitor environmental conditions, such as temperature and humidity, ensuring that products maintain their quality and effectiveness throughout their shelf life. For instance, certain skincare products may feature packaging that changes colour if exposed to harmful environmental factors, alerting consumers to potential degradation. Another innovative approach is that these technologies enable consumers to visualize how a product will look or perform before making a purchase, thereby enhancing the shopping experience [151]. Furthermore, some cosmetics brands are exploring sustainable smart packaging solutions that incorporate biodegradable materials and refillable designs, appealing to environmentally conscious consumers.

Overall, these smart packaging approaches not only enhance product safety and user experience but also align with the evolving trends toward personalization and sustainability in the cosmetics and personal care industry.

<u>Electronics</u>

Smart packaging in the electronics industry is revolutionizing how products are packaged, transported, and utilized, enhancing both functionality and user experience. One of the key applications is the integration of RFID tags and QR codes into product packaging, allowing for real-time tracking and inventory management throughout the supply chain [152] . These technologies help manufacturers monitor the location and condition of sensitive components during shipping, ensuring they are safeguarded from environmental factors like humidity and temperature fluctuations. Additionally, smart packaging can feature built-in sensors that provide alerts to users regarding the product's operational status, such as battery levels or system performance, enhancing functionality and user convenience [5]. Furthermore, this innovative approach can also facilitate product authentication, reducing the risk of counterfeits in the market. With the rise of IoT, smart packaging enables seamless connectivity, allowing devices to interact with consumers via mobile applications for easier setup and troubleshooting. These technologies not only improve logistics and quality control but also elevate the overall consumer experience by providing valuable information and capabilities directly through the packaging.

4. Challenges and Limitations

Smart packaging presents several challenges and limitations that can hinder its widespread adoption. The biggest problem with adding electronic devices to packaging is the creation of electronic waste and materials that do not break down in the environment. This is a significant environmental concern. Researchers are working on solutions like sustainable electronic and bio-sensors, but they have some limitations, such as short shelf life, manufacturing issues, and specific environmental conditions like specific temperatures and pH levels needed for optimal use [153]. Plastics are commonly used in food packaging because they are versatile, but their non-biodegradable nature and potential toxicity raise environmental concerns. Despite growing awareness, the use of single-use plastics in food packaging continues to rise [154]. Technical limitations also pose challenges, as smart packaging may have limited shelf life and be sensitive to environmental conditions like temperature and humidity.

Research is being done on eco-friendly packaging made from agricultural waste; leftover crops can be transformed into useful materials for making biopolymers and biocomposites, which can then be used for sustainable food packaging. [155]. However, turning agricultural waste into useful products can be

more expensive and affect the feasibility of these projects. Many agricultural wastes like rice straw, corn straw, and sawdust have high moisture content and contain sugars and proteins, making them prone to spoilage and contamination, which shortens their shelf life. To create sustainable packaging, it's important to focus on research and development that can improve production processes, find affordable production methods, and secure financial support for bio-based packaging projects. [156].

A study in China found that most consumers were neutral about traditional packaging, with a small number preferring it. Surprisingly, many showed a stronger interest in intelligent packaging compared to active packaging [157]. While sensors in smart packaging are placed outside and do not touch food, there is a risk of chemicals leaking into the food over time. Additionally, food packaging regulations differ by country, making it important for intelligent packaging to meet various food safety standards [158]. Finally, reliance on battery power for certain smart functionalities can limit the technology's effectiveness due to the battery lifespan constraints. Addressing these challenges requires ongoing innovation, research, and collaboration within the industry.

5. FUTURE TRENDS AND PERSPECTIVES

The future of smart packaging is shifting towards “green electronic”, which focus on using eco-friendly Technologies. These devices are made from safe, biodegradable materials and include sensors that use low power, helping to address environmental issues. However, the colour changes in these devices can be hard for some users to see. To make the information clearer, a digital display is suggested to provide precise updates. Additionally, to help visually impaired individuals, packaging with voice output could be introduced, offering support in multiple languages and allowing for hands-free alerts. The use of internet (IoT) and artificial intelligence is also expected to expand, allowing for real-time monitoring and enhanced supply chain transparency. Overall, the future of smart packaging will likely focus on creating user-friendly, sustainable solutions that not only address environmental challenges but also enhance the overall consumer experience.

6. CONCLUSION

In conclusion, smart packaging represents an innovative evolution in the packaging applications in different industries, combining advanced technologies with practical applications to enhance food safety, extend shelf life, and improve consumer engagement. As the demand for sustainability grows, smart packaging is increasingly incorporating eco-friendly materials and low-power electronics, aligning with environmental goals. The features of smart packaging make more valuable tools for both consumers and manufacturers. However, challenges such as high costs, regulatory framework, and consumer acceptance must be addressed to fully realize its potential. As technology continues to advance, the future of smart packaging looks promising, with the opportunity to significantly impact food safety, sustainability, and the overall consumer experience in positive ways.

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