Biological Forum – An International Journal **16(4): 33-45(2024)**

ISSN No. (Print): 0975-1130
ISSN No. (Online): 2249-3239

From Farm to Table: Advancements in Smart Packaging for Dairy and Food Products

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(Received: 04 February 2024; Revised: 20 February 2024; Accepted: 06 March 2024; Published: 15 April 2024)
(Published by Research Trend)

ABSTRACT: Food contamination can happen at any point, from the farm to when it reaches your table, potentially leading to different diseases ranging from mild to severe. Traditional packaging methods primarily focus on environmental protection, but there's a rising demand for more advanced systems that offer improved communication capabilities. Enter smart packaging: a solution that not only protects but also communicates and ensures food safety. In response to shifting consumer preferences towards safer food options, packaging technologies have undergone significant innovations. This article delves into various smart packaging systems and their applications within the realm of food packaging, exploring the latest advancements in packaging research. Active and intelligent packaging are two such technologies that promise to deliver enhanced safety and quality in food products. Active packaging involves the incorporation of additives into the packaging material, aimed at preserving or extending the product's quality and shelf life. On the other hand, intelligent systems are capable of monitoring the condition of packaged food, providing valuable information on its quality throughout transportation and storage. These innovative solutions are tailored to meet the growing demand for safer foods with extended shelf life. The market for active and intelligent packaging systems is poised for substantial growth, driven by their integration into packaging materials and systems.

Keywords: Active packaging, Intelligent packaging, Indicator, Oxygen scavengers and Sensors.

INTRODUCTION

Food packaging systems aim at preserving the freshness and structural integrity of the food product thereby preserving the food for long-term storage. Food packaging encompasses a multifaceted design process, encompassing the creation, evaluation, and construction of packages within the food production system. Its primary role is to safeguard food quality and safety from producer to consumer by serving as a protective barrier against external elements. Beyond preservation, packaging also serves to convey vital information such as composition, storage guidelines, expiration dates, and producer details. Key functions include containment, protection, communication, and convenience (Ghaani *et al*., 2016; Kuswandi *et al*., 2011; Mangaraj *et al.,* 2012; Mangaraj *et al.,* 2012; Yam *et al*., 2005). Moreover, packaging condition can serve as an indicator of food status, encompassing physiological, physical, infestation, microbial, and chemical parameters Traditional food packaging is meant for protection, communication, convenience and containment (Paine, 1991; Robertson, 2006). The package is used to protect the product from the deteriorative effects of external environmental conditions like heat, light, the presence or absence of moisture, pressure, microorganisms, gaseous emissions and so on. The key safety objective for traditional packaging materials that come in to contact with food is to be as inert as possible. While the smart packaging systems like active and intelligent packaging concepts are based on the useful interaction between the packaging environment and the food to provide active protection to the food. Advancements in food packaging have led to the emergence of innovative smart packaging technologies designed to precisely monitor internal changes within food products. Given the complexity of food systems, packaging must be customized to meet their distinct physical, chemical, and physicochemical requirements. This review evaluates the effectiveness of various smart packaging techniques across diverse food systems, providing insights into the underlying mechanisms employed for different categories of food products. However, traditional packaging is no longer sufficient due to continuously increasing customer experience expectations, increasing product complexity, and, most recently, national and international initiatives towards fostering a circular economy and minimising the carbon footprint of manufactured products (Cheung *et al*., 2017). Novel packaging solutions are emerging, including intelligent, active, and smart packaging. Intelligent packaging integrates indicators, sensors, and data carriers to monitor food freshness, CO_2 levels, oxygen, and temperature (Guo *et al.,* 2023). Active packaging incorporates active compounds to extend food shelf life by inhibiting bacterial growth and absorbing oxygen and water vapor (Ahvenainen and Hurme 1997; Amin *et al*., 2022; Dirpan and Hidayat 2023). Smart packaging combines the features of both intelligent and active packaging. Furthermore, smart packaging plays a pivotal role in extending market reach within the global landscape. It facilitates compliance with increasingly stringent food safety standards on both national and international levels. Moreover, it acts as a safeguard against potential risks posed by food bioterrorism (Yam *et al*., 2005). The smart packaging system encompasses two main categories: Intelligent packaging merges traditional packaging with advanced electronic sensors, such as those detecting changes in food quality, ensuring consumer safety. On the other hand, active packaging incorporates compounds like antioxidants into standard packaging materials, bolstering food stability and quality over its shelf life (Drago *et al*., 2020). Both active and intelligent packaging act as shields, safeguarding food against physical, chemical, and biological threats. Additionally, they play crucial roles in signalling freshness, quality, and continuously monitoring factors like time and temperature, ultimately ensuring the safety and excellence of food products.

DECODING SMART PACKAGING: AN EXAMINATION OF FRAMEWORKS AND CLASSIFICATIONS

Packaging has long been an essential component of product delivery, serving as a protective barrier and a medium for branding and communication. However, with the advancement of technology, packaging is undergoing a profound transformation, evolving into what is now known as "smart packaging." Smart packaging integrates sensors, actuators, and other technologies to enhance product safety, improve shelf life, and provide consumers with valuable information. Food degradation primarily stems from oxidation and microbial growth, leading to freshness loss and food deterioration (Guillard *et al*., 2009; Kuswandi *et al.,* 2012). Additionally, enzymatic activity, nonoxidative reactions, moisture changes, light exposure, etc., contribute to this process (Brody *et al.,* 2001; Mangaraj & Goswami 2009a, 2009b; Mangaraj *et al*., 2011). Factors such as transportation, handling, and storage conditions influence food quality during packaging, impacting consumer satisfaction (Ghaani *et al.,* 2016; Realini & Marcos 2014).Smart packaging presents an innovative solution to address numerous challenges in the food industry. By integrating both active and intelligent systems, it has the potential to extend shelf-life significantly and provide continuous monitoring of food quality from production to consumption. This technology not only enhances the efficiency of distribution and supply chains but also facilitates direct communication with consumers regarding the freshness and safety of the products. According to Vanderroost *et al.* (2014) "smart packaging provides a total packaging solution that on the one hand monitors changes in a product or its environment (intelligent) and on the other hand acts upon these changes (active)". Smart packaging is broadly classified as active packaging and intelligent packaging.

A. Active Packaging

Active packaging stands out as a pioneering departure from conventional packaging practices. Labuza (1987) was the first to introduce the term "active packaging" in the realm of food packaging development. Today, it is widely employed in packaging research and studies. Active packaging represents an innovative approach to packaging, aimed at enhancing the longevity and preserving the quality of perishable items. By leveraging mechanisms such as emission or absorption of specific compounds within the packaged goods, it effectively retards microbial proliferation, mitigates moisture fluctuations, and curtails oxygen-related reactions. This results in a prolonged shelf life and heightened product freshness, ensuring optimal consumer satisfaction. It represents a progressive approach to food packaging, designed in direct response to evolving consumer preferences and market dynamics. Active packaging technology integrates elements within the packaging itself, enabling the release or absorption of substances into the stored food or its surroundings. This innovative strategy aims to uphold quality standards and extend the shelf life of products (Arvanitoyannis, *et al*., 2012). Active packaging goes beyond merely acting as a passive barrier to the external environment, as stated by Rooney (1995). It entails a dynamic interaction among the product, packaging, and surrounding environment to enhance shelf life or achieve specific characteristics, according to Miltz *et al*. (1995). Another perspective, provided by Ahvenainen (2003), describes active packaging as a form of packaging that alters its conditions to prolong shelf life, enhance safety, or improve sensory properties without compromising the quality of the packaged food. Various researchers have offered different interpretations of active packaging, including Brody *et al*. (2001); Kerry *et al.* (2006); Robertson (2006); Rooney (1995b); Yam *et al.* (2005). Nonetheless, the fundamental idea behind active packaging is the incorporation of specific substances into food packaging to regulate or prolong quality and enhance food shelf-life. Active packaging systems operate on the basis of the physicochemical properties of the polymer material used in packaging, whether it's the material itself or its surface in multilayer structures, or associated with specific components like labels, pads, sachets, or bottle caps (Gontard, 2007; Gumiero, 2009). These systems employ various compounds capable of absorbing oxygen, carbon dioxide, ethylene, Flavours, Odours, moisture, or releasing and emitting carbon dioxide, antioxidants, flavours, and antimicrobial agents (Biji *et al.,* 2015; Realini & Marcos 2014; Suppakul *et al*., 2003). Active packaging can be categorized into four main classes, each serving distinct functions:

Active Scavenging or Absorber Agent (Nonmigratory): This type of packaging includes agents like moisture absorbers, which induce a specific response in the packaged food without transferring their active components into the food itself (Dainelli *et al*., 2008). Some applications of active scavengers and absorbents are described as follows:

a) **Oxygen scavengers:** These components remove oxygen from the package, which helps prevent the oxidation and spoilage of oxygen-sensitive products such as meat, poultry, and certain snacks. In most cases, food spoilage is caused by oxidation or microorganism spoilage in the oxygen present inside food packaging (Cruz *et al*., 2012). Therefore, Modified Atmosphere Packaging (MAP) can be used as a partial solution to this oxidation problem inside the food package due to the oxygen present. Even though oxygen sensitive foods can be packed in modified atmosphere packaging (MAP) or vacuum packaging, but it does not remove oxygen completely. Oxygen, which permeates through the packaging film, cannot be removed through the system. The presence of oxygen in a package accelerates the oxidative deterioration of food. Oxygen facilitates the growth of aerobic microbes, off flavour and odour development, colour changes and nutritional losses, and the overall shelf-life stability of muscle foods (Hogan and Kerry 2008). By using oxygen scavengers, which absorb the residual oxygen after packaging, quality changes in oxygen sensitive foods can be minimized (Vermerien *et al.,* 1999; Kerry *et al.,* 2006). The commercially available oxygen scavengers utilize one or more of the following technologies: iron powder oxidation, ascorbic acid oxidation, photosensitive dye oxidation, enzyme oxidation, saturated fatty acid oxidation, immobilized yeast on solid material etc. (Floros, 1997; Vermeiren *et al*., 1999). These agents can be used individually or in a combination of two or more agents in order to increase their effectiveness as oxygen scavengers (Cruz *et al.,* 2012). Ferrous oxide is the most commonly employed oxygen scavenger in the dairy industry (Haghighi-Manesh & Azizi 2017). The incorporation of pectin, essential oils, and beta-carotene in packaging films, elevates the shelf life of butter as well as indicates the expiration time of butter. Due to the oxidation reaction, the number of β-carotene drastically reduces and there is a colour change from orange to light yellow observed in the packaging film (Asdagh & Pirsa 2020). The use of an oxygen scavenger in food packaging materials involves a chemical reaction between the OS and the oxygen contained in the food packaging (Buckner *et al.,* 2018). When an OS reacts with oxygen, there will be changes in the structure and composition of the compounds involved in the reaction. This reaction produces compounds that are more stable and do not produce oxygen, so the oxygen in the food packaging will be reduced or eliminated (Gaikwad *et al*., 2022; Johnson *et al*., 2018). Examples of commercially active oxygen scavengers packaging are Ageless (Mitsubishi Gas Chemical), Keplon (Keplon), Freshilizer (Toppan), Secule (Oxy Sorb) (Nippon Soda), etc.

b) **CO_2 scavenger:** Certain foods produce carbon dioxide (CO_2) as a byproduct of deterioration and respiration processes. This CO_2 accumulation must be mitigated to prevent food spoilage and potential packaging damage. For example, roasted coffee emits significant CO_2 due to Strecker degradation, a reaction involving sugars and amines. Failure to remove this CO_2 can lead to packaging ruptures from increased internal pressure. Similarly, kimchi, a fermented vegetable product, generates CO_2 during fermentation. Since pasteurization compromises kimchi's sensory quality, fermentation continues, resulting in CO_2 buildup within the packaging. To address this, scavengers like calcium hydroxide are commonly used. In this process, calcium hydroxide reacts with CO_2 in the presence of sufficient water activity to form calcium carbonate according to the equation: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$ (Altaf *et al.,* 2018). Some examples of commercial active CO_2 scavengers are Freshock, Ageless E (Mitsubishi Gas Chemical Co. Inc.), Evert-fresh United States (Ever-fresh type G),Evert-fresh green bags (Evert-fresh Corp) etc.

c) Ethylene scavenger: Ethylene gas, both naturally occurring and man-made, is a colourless and odourless substance found in various environments. When fruits, vegetables, and flowers reach maturity, they emit ethylene gas, which can affect surrounding perishable items. Some of these products are particularly sensitive to ethylene exposure, leading to accelerated ripening or maturation (Gaikwad *et al*., 2017). Certain fruits and vegetables are also significant producers of ethylene gas, necessitating segregation during transportation and storage based on their ethylene emissions. Additionally, ethylene expedites the breakdown of chlorophyll in leafy greens and fruits. Therefore, eliminating ethylene gas from the packaging environment can decelerate the ageing process and extend the shelf life of these items (Vermeiren *et al.,* 2003). Therefore, packaging materials have been designed to scavenge ethylene from the internal environment by introducing ethylene absorbers such as potassium permanganate, alumina, and silica in the form of sachets (Wei *et al.,* 2021). Ethylene absorbers are employed in improving the shelf life of climacteric fruits such as apples, kiwifruit, apricot, banana, mango, tomato, and avocado as well as vegetables such as carrots, potatoes, and asparagus (Soleimani & Zarrinbal 2022). To preserve the freshness and extend the shelf life of fruits and vegetables, it's crucial to prevent the buildup of ethylene gas within their packaging. Commonly utilized for this purpose are ethylene adsorbers based on potassium permanganate. The process involves two steps of oxidation: initially, ethylene is converted to acetaldehyde, which then progresses to acetic acid. Subsequently, acetic acid can be further oxidized to carbon dioxide and water. These potassium permanganate adsorbers undergo a visible colour change from purple to brown as the MnO^{4-} is reduced to MnO^{2}, indicating the remaining adsorption capacity. The primary goal of employing these adsorbers is to curb excessive ripening and softening of fruits and vegetables. They find widespread usage across various produce types, including apples, apricots, mangoes, tomatoes, avocados, carrots, potatoes, and Brussels sprouts. Examples of ethylene adsorbers encompass sachets containing a blend of aluminium oxide and potassium permanganate, activated carbon coupled with a metal catalyst, and clay-based materials. These adsorbers play a pivotal role in regulating ethylene levels and upholding the quality of fruits and vegetables throughout their storage period (Altaf *et al.,* 2018). Some examples of commercialiy active ethylene scavengers are Purafil (Purafil), Air Repair (Delta trak), BO Films (Odja Shoji Co.) etc.

D.) Moisture absorber: Moisture plays an important role in determining shelf life of a stored product. In high moisture food packages, there is a chance of liquid water accumulation on the package due to temperature fluctuations which can lead to spoilage due to mold and bacteria or deterioration of quality in the package. Moisture content in the pack causes softening of dry crispy products, and caking of hygroscopic products like milk powder, instant coffee powder, sweets, etc. (Anon., 1995; Vermeiren *et al*., 1999). Moisture absorbent pads, sheets and blankets are used for controlling liquid from foods like fish, meat, poultry, fruits and vegetables. Large sheets and blankets are used for absorbing melted ice during the air freight transportation of chilled fish (Day, 1998). Silica gel, molecular sieves, natural clay, calcium oxide, calcium chloride and modified starch can act as moisture absorber (Suppakul *et al.,* 2003). Placing humectants between two layers of a plastic film that is highly permeable to water vapour can be done to control excess water. Controlling relative humidity (RH) using deliquescent salts (such as $CaCl_2$, and $MgCl_2$) in packaging materials can regulate moisture (Mohan *et al*., 2010).

Active Releasing or Emitter Agent: Here, either non-volatile compounds or volatile agents are released or migrate at a controlled rate within the packaging environment (Dainelli *et al.,* 2008).

a) **CO_2 emitter:** Perishable foods like fresh meat, poultry, fish, and certain fruits benefit from high concentrations of carbon dioxide to prevent microbial growth on their surfaces. Carbon dioxide not only directly inhibits microorganisms but also prolongs the lag phase and slows down the logarithmic growth phase of these organisms (Coma, 2008). Hence, the market offers various commercial CO_2 emitters to extend the shelf life of such foods. Additionally, carbon dioxide is generated within packages through reactions between food, sodium carbonate, and citric acid mixtures in drip pads (Bjerkeng *et al*., 1995). Studies have shown that pure CO_2 is more effective in controlling microbial growth during Modified Atmosphere Packaging (MAP) of Mozzarella cheese at 7°C compared to gas mixtures like 50% N_2 and 50% CO_2, or pure nitrogen gas (Alam & Goyal 2011). Carrots exhibit reduced respiration rates in environments with 10% CO_2 (Pal & Buescher 1993). Similarly, fruits and vegetables such as ripening bananas, tomatoes, and pickling cucumbers respond favourably to higher CO_2 concentrations within packaging. Therefore, it is advisable to tailor CO_2 concentrations to accommodate the specific carbon dioxide tolerance levels of different fruits and vegetables.

b) **SO_2 emitters:** SO_2 emitters function through the metabisulfite hydrolysis mechanism and the reaction of calcium sulphite with moisture. They are employed in packaging grapes to prevent mold growth (Suppakul *et al.,* 2003). Different sheets of SO_2 release were utilized for packaging white and purple grapes to assess their impact on decay and grape quality (Christie *et al.,* 1997). Following 4 days of storage at 21°C, it was observed that sulphite levels were lower in purple grapes compared to white grapes, despite higher levels of SO_2. To achieve fungal inactivation without adverse effects on food, a polymer must be applied for controlled SO_2 release.

c) Ethanol emitters: Ethanol, known for its antimicrobial properties, can effectively hinder the growth of yeast, bacteria, and mold. Its ability to extend the shelf life of bakery products through direct spraying has been extensively proven. The concentration of ethanol added is approximately 0.5%–1.5% (w/w) of the product (Mexis & Kontominas 2014). This concentration of ethanol is sufficient enough to inhibit the growth of all yeasts. To produce as microbial free shelf life, ethanol may be sprayed on the surface or packed inside without direct contact with the commodity. Japan, extensively employs ethanol emitters to enhance the shelf life of cakes and other bakery products (Lucera *et al*., 2016). Utilizing sachets or films infused with food-grade ethanol allows for the exchange of ethanol with water vapor in the headspace of packaging. To mitigate the odour of ethanol, flavourings are occasionally incorporated into these sachets. The speed at which ethanol is released is influenced by several factors, including the permeability of the carrier water, the initial amount of ethanol in the sachet, the water activity of the food, and the ability of ethanol to pass through the film material. When using ethanol-infused films, additional layers are often necessary to ensure a sustained release. A recent approach by Mu *et al.* (2017) involved creating an ethanol gel through a reaction between ethanol and sodium stearate, which was then adsorbed onto diatomite to improve ethanol emission. However, a notable drawback of ethanol emitters is their tendency to be absorbed by food, although this can be mitigated by heating or microwaving the product. Nevertheless, food items consumed without heating may retain residual ethanol, potentially leading to regulatory concerns (Day, 2008; Ozdemir *et al*., 2004).

d) Antioxidant release: Antioxidants are widely used in food to improve the oxidation stability of the food and prolong its shelf life. Antioxidants are often incorporated into food packaging films or applied as coatings on packaging materials to prevent oxidation of fats and pigments (Vermeiren *et al*., 1999). Additionally, edible films can be coated with antimicrobials or antioxidants and utilized to directly treat meat surfaces (Kerry *et al.,* 2006). Frequently, plastic films like polyolefins are infused with antioxidants to enhance polymer stability and shield against oxidation (Robertson, 2006). Researchers have suggested cellulose acetate films with various morphological characteristics to regulate the release rate of natural antioxidants such as L-ascorbic acid and L-tyrosine (Gemili *et al.,* 2010). Antioxidants may be employed in the packaging to prevent the oxidation of milk. Raw milk contains low concentrations of natural antioxidants such as vitamin E is largely destroyed during the processing and storage of milk (Van Aardt *et al.*, 2007). Incorporating natural antioxidants like vitamins C and E in packaging films reduces oxidative reactions such as the development of rancid odour and colour changes in fatty fish (Biji *et al.*, 2015). Vitamin E is also safe and effective for low to medium water activity cereal and snack food products (Labusa and Breene 1989; Day, 2003) and proved to be stable under processing conditions with excellent solubility in polyole fins (Wessling *et al.,* 1998; Vermeiren *et al.,* 1999). The incorporation of active components in the form of the coating into packaging material or edible films reduces the rate of rancidity caused by lipid oxidation, myoglobin oxidation, moisture loss, moisture accumulation, and pathogenic microorganisms on the surface of coated meats (Kerry, 2012).

Blocking or Barrier agent. These agents create a barrier that prevents certain substances from permeating through the packaging material, thereby exhibiting antimicrobial properties.

a) **antimicrobial agent:** Active packaging with antimicrobial properties serves to hinder microbial growth within food packaging through two primary mechanisms: blocking and barrier functions. These functions effectively impede the proliferation of microbes, thereby ensuring the preservation and safety of packaged food products. Active packaging incorporating antimicrobial properties serves to hinder the growth of microorganisms within both the packaged food and the packaging material itself (Appendini and Hotchkiss 2002). This proactive approach to controlling undesirable microorganisms involves the integration or coating of antimicrobial substances onto food packaging materials (Labuza and Breene 1989). Natural sources such as spices (e.g., cinnamon, allspice, clove, thyme, rosemary, and oregano) and plant extracts (e.g., onion, garlic, radish, mustard, and horseradish) are commonly utilized as antimicrobial agents. Additionally, substances produced from fungal and bacterial action, such as polypeptide nisin, natamycin, pediocin, and various bacteriocins, contribute to the arsenal of natural antimicrobials (Nicholson, 1997). Antimicrobial packaging materials can be categorized into two main types: those that release antimicrobial agents to the surface of the packaging material and those that inhibit surface microbes without transferring the active agent to the food products (Han, 2000). Antimicrobials in beverage packaging are used to enhance quality and safety by reducing surface contamination of processed food, reducing the growth rate, and maximum population of microorganisms either by extending the lag phase of microbes or inactivating the microbes (Sofi *et al.*, 2018). Advancements in packaging technology have led to the creation of materials capable of releasing silver ion nanoparticles in a controlled manner. This innovation has proven effective in extending the shelf-life of apple juice by inhibiting microbial growth (Sportelli *et al.,* 2021). Yam starch-based film incorporated with eugenol possesses antibacterial activity against *E. coli, S. aureus,* and *L. monocytogenes* in pork which improves the shelf-life beyond 50% (Cheng *et al.*, 2019). A chitosan film infused with grape seed extract and Origanum vulgare essential oil demonstrates strong antibacterial effects against a range of microorganisms, including *Enterobacteriaceae*, *Pseudomonas* spp., lactic acid bacteria, and yeast Mold throughout a 20-day storage period (Mojaddar Langroodi *et al*., 2021). Nano fibre-based film embedded with cinnamon nano-phytosomes shows a strong antibacterial effect and extends the shelf life of shrimp to 12 days (Nazari *et al*. (2019). Incorporating of Sulphur dioxide into the packaging of wine acts as an oxidizing agent that prevents discoloration and inhibits the growth of Pseudomonas tolaasi (Ghoshal*,* 2018).

Regulating or Buffering Agent. This category involves substances that regulate conditions within the packaging, such as maintaining a specific relative humidity level. For instance, a desiccant introduced into the packaging absorbs moisture once the relative humidity reaches a certain threshold. In the realm of food packaging for distribution, storage, and eventual consumption, there exists an opportunity to address issues related to flavour and odour absorption or release, as well as moisture control. These functions, which contribute to regulating and buffering the environment within the packaging, play a crucial role in maintaining the quality of the enclosed food products.

a) **Release or Absorption of flavour and odour:** Controlling the aroma within the packaging of foods like fruits and vegetables is crucial for consumer acceptance. Volatile compounds produced during food degradation, such as aldehydes, amines, and sulfides, can be effectively absorbed through the use of flavour scavengers (Day 2008). These scavengers play a crucial role in preventing the spread of pungent Odors, particularly during the transportation of mixed loads. Morris (1999) pioneered the development of Odor-proof packaging specifically designed for transporting durian fruit, ensuring its distinct aroma remains contained. One approach involves actively managing the headspace by adding fragrances or sensitive ingredients to the packaging material. The choice of packaging material significantly impacts food quality, especially regarding vapor transfer and potential migration of organic compounds into the food (Frank *et al*., 2001; Huber *et al*., 2002; Strathmann *et al*., 2005). While this can enrich the food's flavour, it may also lead to undesired odour or flavour absorption, necessitating scalping to remove them. Although flavour scalping can compromise food quality, it can be strategically utilized to selectively absorb unwanted Odors or flavours (Hotchkiss, 1997; Van *et al*, 2002).

b) **Temperature control packaging:** It is also known as thermal packaging or cold chain packaging, is designed to maintain specific temperature ranges for products that are sensitive to temperature variations during storage and transportation. This type of packaging is crucial for preserving the quality, safety, and efficacy of temperature-sensitive items such as pharmaceuticals, vaccines, food, and biologics. It often utilizes insulated materials, phase change materials, and temperature-monitoring devices to ensure that the desired temperature is maintained throughout the entire distribution process. Temperature control packaging plays a vital role in preventing spoilage, degradation, or loss of potency, thereby safeguarding product integrity and consumer health. These are usually used in ready to eat meat, fish, meat, poultry, and beverages (Day, 2003). Moreover, these classifications can also be based on the mode of action and their specific roles in food packaging (Floros *et al.,* 1997).

B. Intelligent packaging

Intelligent packaging systems serve to monitor various aspects of food products and relay essential information to consumers. EC/450/2009 defines intelligent materials and articles as those capable of monitoring the state of packaged food or the surrounding environment. Intelligent packaging provides a direct indication of the quality by providing a signal that is a reaction between the indicator and the specific chemical compounds or metabolites produced by the deteriorative mechanism in beverages (Taoukis & Tsironi 2016). Intelligent packaging systems offer users insights into food conditions or environmental factors such as temperature and pH. Unlike active components, intelligent components focus on detecting, sensing, and recording changes in the product's environment rather than releasing constituents into the food. Intelligent packaging materials are "materials and articles that monitor the condition of packaged food or the environment surrounding the food" (European Commission, 2004). This extends the traditional packaging's communication function, providing consumers with valuable information. These systems aim to enhance product quality, convenience, and security, including tamper resistance. They can either report external conditions or directly assess the quality of the food inside the package. To measure product quality within the package, direct contact between the food product or headspace and quality markers is necessary. Ultimately, these intelligent systems aid consumers in decision-making processes by extending shelf life, enhancing safety, improving quality, providing information, and alerting to potential issues. They are invaluable tools for detecting potential abuse during the food supply chain and can even notify consumers of tampering events through innovative labels or seals that undergo colour changes upon opening, ensuring consumer safety. Three main technologies drive intelligent packaging systems: indicators, sensors, and data carriers (Ghaani *et al*., 2016). While indicators and sensors primarily offer insights into product quality, data carriers focus on supply chain logistics management. These systems can be integrated into various packaging layers, including primary, secondary, or tertiary packaging (Han *et al*., 2005).

Indicator. Indicators serve the primary function of conveying information to consumers regarding the presence or absence of specific substances, the occurrence of reactions between components, or the monitoring of substance concentrations. Typically, this information is translated into an immediate visual cue, such as varying colour intensities or dye diffusion along a defined path, offering qualitative or semi-quantitative insights (Yam, 2005). A fundamental requirement for indicators is that these colour or intensity changes are irreversible in most cases (Dutra Resem Brizio, 2016). They represent a vital category within intelligent packaging, commonly classified based on the controlled variable, including time-temperature, freshness, and gas indicators. Alternatively, indicators can be categorized as external or internal depending on their placement on the packaging (Kalpana *et al*., 2019).

Freshness Indicator. Freshness indicators offer valuable insights into the quality of a product, particularly concerning microbial growth or chemical alterations. By interacting with integrated indicators within the packaging, these indicators visually signal information about the microbial condition of the product, reflecting its overall freshness and safety (Kerry *et al.,* 2006; Kuswandi *et al.,* 2013). Freshness indicators are sophisticated devices utilized for monitoring the quality of food items throughout storage and transportation. The degradation of freshness can result from exposure to adverse conditions or surpassing the established shelf-life. Metabolite concentration alterations, such as glucose, organic acids, ethanol, carbon dioxide, biogenic amines, volatile nitrogen compounds, or sulphur derivatives, serve as indicators of microbial growth, thus being leveraged in freshness indicators (Poyatos-Racionero *et al*., 2018). Typically, these indicators rely on pH-sensitive dyes, reacting to product deterioration and manifesting visible colour changes. While finding application across various products like fresh food, fruit, and seafood, the market penetration of freshness indicators remains limited (Dutra Resem Brizio 2016). Freshness indicators are typically either printed on the packaging film or included as labels within it, reacting with storage-produced agents (Rawdkuen *et al*., 2020). However, these indicators can pose challenges, such as false negatives and positives. False negatives can lead to unsafe products being perceived as safe, risking consumer health. Conversely, false positives may result in unnecessary food waste by indicating spoilage or damage when the product is actually safe to consume. To address these issues, standardized protocols for the accelerated development of freshness indicators, especially on an industrial scale, are imperative (Poyatos-Racionero *et al.,* 2018). The starch-based film incorporated with anthocyanins from butterfly pea flower and TiO_2 is used as a pH indicator to monitor the freshness of the prawn (Mary *et al.,* 2020). The development of pH-sensitive packaging films using cassava starch and *L. ruthenicum* anthocyanins to monitor the freshness of pork (Qin *et al.,* 2019). A freshness-indicating sensor was developed by incorporating the anthocyanins of black carrot into a starch matrix to monitor the freshness of the milk and differentiate fresh milk from spoiled milk using an indicator (Goodarzi *et al*., 2020). The agarose matrix developed with anthocyanins from red cabbage indicates the microbial spoilage of milk by measuring the pH change of the milk (Weston *et al.,* 2020).

Time-Temperature Indicator. Temperature plays a crucial role in determining the rate of physical, chemical, and microbial spoilage in food items. As outlined in EC/450/2009, Time temperature indicators (TTIs) serve to indicate whether a specific temperature threshold has been surpassed over time and/or estimate the duration a product has been exposed to temperatures exceeding that threshold (time-temperature history). These labels offer visual cues regarding temperature variations throughout distribution and storage, particularly highlighting instances of temperature abuse in chilled or frozen products. TTIs are categorized into three main types: critical temperature indicators, partial history indicators, and full history indicators (Singh, 2000). Altaf *et al*. (2018) highlight the importance of visual or electronic indicators to signal when food has encountered unfavourable temperature conditions. Time–temperature indicators monitor temperatures under the hazard analysis and critical control points to prevent unsafe bacteria growth (Chowdhury and Morey 2019). This indication serves as a warning for potential microbial growth or quality deterioration. By providing this information, both consumers and suppliers are empowered to make educated choices regarding the safety and freshness of the food. Time–temperature indicators are commonly used in the transportation of vaccines, pharmaceuticals, and perishable food items like seafood to ensure that temperature-sensitive products are kept within safe temperature ranges. In conclusion, time-temperature indicators are essential tools for ensuring food safety and quality control. They provide real-time monitoring of temperature fluctuations, helping to maintain product integrity during transportation and storage. While they have limitations, such as focusing primarily on temperature-related issues and potentially increasing packaging costs, their benefits in reducing the risk of distributing or consuming spoiled products far outweigh these drawbacks. Time-temperature indicators are instrumental in safeguarding consumer health and confidence in the food supply chain.

Integrity Indicator. Damage to the integrity of flexible plastic packaging often stems from faulty seals, as noted by Hurme (2003). Traditional methods for testing food package and seal integrity, such as biotesting, dye penetration, electrolytic, and bubble tests, are destructive and labour-intensive, limiting their application to food sampling rather than individual package inspection (Kerry *et al*., 2006). In response, time and gas indicators have emerged as key integrity indicators, offering continuous monitoring throughout the production and distribution process (Biji *et al.,* 2015). One notable example is the Ageless Eye indicator developed by Mitsubishi Gas Chemicals Company, which serves as an oxygen indicator. This indicator undergoes a colour change, shifting from pink to blue in the presence of oxygen and reverting to pink when oxygen is absent. However, its reversible nature poses a significant drawback.

Sensor. A sensor serves as a device that reacts to various properties, whether chemical, biological, or physical, by generating a measurable signal in proportion to the parameter being measured (Ghaani *et al.,* 2016). Commonly used traditional sensors are tailored for gauging temperature, humidity, pH levels, and light exposure (Vanderroost *et al*., 2014). However, with the increasing demand for monitoring food quality and packaging integrity, there's a rising interest in deploying disposable and sophisticated sensors, including edible ones, for smart packaging applications. Typically, a sensor comprises four primary components: a receptor, which acts as the sensitive element, often featuring a selective coating capable of detecting specific chemical analytes through surface adsorption; a transducer, responsible for converting the detected signal change into an output signal, categorized as "active" if requiring external power and "passive" if not; (Vanderroost *et al.,* 2014; Siracusa *et al*., 2019) and finally, the inclusion of electronic components for signal processing and display (Ghaani *et al*., 2016). In the realm of food packaging, sensors can broadly be categorized into chemical and biosensors, further divided based on the method of signal transduction, encompassing electrochemical, optical, mechanical, magnetic, thermometric, and microgravimetric approaches.

Chemical Sensor. The chemical sensor, also known as the receptor, comprises a chemical-selective coating designed to detect specific chemicals or gases by adsorbing them onto its surface. It discerns the presence, activity, composition, and concentration of these substances. Upon detection, the sensor converts this information into signals through a transducer. Transducers come in two types: active and passive, depending on whether they require external power for measurement, as outlined by Vanderroost *et al*. (2014). Chemical sensors play a pivotal role in advancing intelligent food packaging systems by utilizing receptors with the capability to detect specific chemical molecules. These receptors are adept at identifying the presence, activity, composition, and concentration of various substances such as volatile organic compounds (VOCs) and gases like H_2, CO, NO_2, CO_2, and H_2S, which are chiefly responsible for food spoilage, particularly in meat, fish, fruit, and vegetable products (Vanderroost *et al*., 2014; Siracusa *et al*., 2019). The gas composition within food packaging undergoes alterations due to the food products' activity, the packaging material's gas permeability, and environmental conditions. These changes directly impact the shelf life, quality, and safety of packaged food items (Lamba, *et al*., 2019). Chicken breast packaged with polyamide bags integrated with intelligent labels monitors the increase in CO_2 that correlates well with the colour change (Obaidi *et al*. (2022). Carbon nanomaterials such as nanoparticles, graphene, graphite, nanofibers, and nanotubes find application in chemical sensors due to their exceptional electrical and mechanical properties, as well as their high specific surface area (Vanderroost *et al.,* 2014). Nano-based sensors offer versatile capabilities, including the detection of pathogens, chemical contaminants, spoilage, product tampering, and ingredient tracking throughout the processing chain (Nachay, 2007; De-Azeredo, 2009; Liu *et al.,* 2007). A recent advancement in sensor technology involves the use of optical transducers, eliminating the need for electrical power and enabling readings from a distance using UV, visible, or IR light. Silicon-based optical transducers consist of integrated optical circuits within semiconductor materials (Yebo *et al.,* 2012).

Biosensor. In contrast to chemical sensors, biosensors utilize organic or biological materials as receptors, including DNA, RNA, enzymes, antibodies, antigens, microbes, hormones, and nucleic acids (Yam *et al.,* 2005;Vanderroost *et al*., 2014; Ghaani *et al.,* 2016). They serve to detect, monitor, and quantify various substances such as allergens, sugars, amino acids, alcohols, lipids, pathogens, and metabolites produced during food degradation processes (Vanderroost *et al*., 2014; Siracusa *et al*., 2019). The primary hurdles facing biosensors lie in effectively immobilizing biological components within the receptor. This entails employing robust attachment techniques like electro-deposition to prevent the denaturation or degradation of these components. Of utmost importance is mitigating any potential risks associated with biological component migration onto food products (Vanderroost *et al.,* 2014; Siracusa *et al.*, 2019). Commercial biosensors primarily find applications in clinical diagnostics rather than in the food industry, including food packaging (Kerry *et al.,* 2006). However, enzymes or microbes, are utilized in time-temperature indicators (TTI) for intelligent food packaging (Kuswandi, 2018). Despite this, several laboratory-scale prototypes have been developed. For instance, SIRA Technologies (Pasadena, California, United States) created the Food Sentinel System, a barcode-based biosensor designed to detect pathogens in food (Ayala & Park 2000). In this system, a specific-pathogen antibody is affixed to a membrane, forming part of the barcode. When contaminating bacteria are present, they cause the formation of dark bars within the barcode, rendering it unreadable to a barcode scanning reader. Numerous studies have focused on utilizing natural substances in intelligent food packaging, particularly in the preservation of fish, meat, and seafood to mitigate economic losses due to quality degradation. These biosensors are, sensitive to pH changes in the environment, offer a dual function by not only detecting pH shifts but also possessing bioactive properties such as antibacterial characteristics, thereby enhancing the packaging material's preservation capabilities. However, integrating these substances into the biopolymer matrix can impact the mechanical, barrier, and optical properties of the films. Hence, there's a need to strike a balance between the advantageous pH-sensing activity and potential adverse effects on the mechanical qualities of the biopolymer, depending on the specific application (Salgado *et al*., 2021). Biosensors, vital components of intelligent food packaging systems, offer significant potential but pose integration challenges within packaging materials. Critical factors for biosensors encompass their microstructure, sensitivity, specificity, and detection limits. Despite manufacturers' keen interest in biosensors to uphold product quality, the commercialization of this technology remains nascent. Progressing global smart food packaging technology hinges on tackling biosensor-related issues in packaging. Suggestions for biosensor advancement involve attaining compact size and effortless assimilation into packaging materials, maintaining consistent sensitivity over time, and managing costs for consumers.

Edible Sensors. Edible sensors crafted from natural and biodegradable materials hold promise for revolutionizing intelligent food packaging. One such innovation involves a sensor composed of a pectin matrix infused with red cabbage extract, known for its colorimetric indicator properties. Anthocyanins, abundant in red cabbage extract, react to pH changes and can detect amines, making them invaluable for discerning food deterioration (Dudnyk *et al.,* 2018). Another advancement features an edible film comprising gelatin, gellan gum, and red radish anthocyanin extract. This film exhibits sensitivity to gases, undergoing a colour shift from orange-red to yellow within a pH range of 2–12. It has been successfully employed for real-time detection of milk and fish spoilage, identifying gases emitted by bacteria and enzymes during decomposition (Kalpana *et al.,* 2019). Additionally, genipin, a natural iridoid, has shown promise as a dual colorimetric sensor for oxygen and biogenic amines. By immobilizing genipin within edible calcium alginate microspheres, researchers have expanded the realm of natural compound-based sensors, offering biodegradable, non-toxic, and food-compatible solutions for detecting common analytes in food products (Mallov *et al.,* 2020). These breakthroughs are paving the way for a new era in food safety and quality assurance.

Data Carriers. Data carrier devices in food packaging serve distinct functions compared to those previously discussed. Rather than conveying information on food quality, they serve purposes such as automated traceability, theft prevention, and counterfeit protection (Müller *et al*., 2019). Traceability, specifically, enhances food safety and consumer confidence by enabling the tracking of a package's entire history (Kalpana *et al*., 2019). Barcode labels and radio frequency identification systems (RFID tags) are key examples of such devices, typically affixed to tertiary packaging like containers and pallets to remain readable throughout the supply chain.

Barcodes. Barcodes have been integral to large-scale retail trade from the outset, streamlining inventory control, restocking, and checkout processes (Manthou *et al*., 2001). Initially, one-dimensional barcodes emerged, offering limited data storage capacity (Robertson *et al*., 2013). Subsequently, Reduced Space Symbology (RSS) barcodes were introduced to pack more data into a smaller area. The latest advancement, Quick Response (QR) 2-D barcodes, can store even more data, utilizing four encoding modes: numeric, alphanumeric, byte/binary, and kanji (logographic Chinese characters). Reading 2-D barcodes require scanning devices capable of simultaneously capturing data in two dimensions, vertically and horizontally (Ghaani *et al*., 2016). Compared to conventional barcode data matrix codes exhibit significantly higher data density. This feature enhances their space efficiency, facilitating the encoding of greater amounts of information within a smaller area. Data Matrix codes are two-dimensional barcodes that can store a large amount of data in a small space. They consist of black and white squares arranged in a square or rectangular pattern. Data matrix codes are commonly used in industries such as healthcare and automotive for tracking and traceability purposes.

RFID Tags. Radio Frequency Identification (RFID) tags use radio waves to transmit data wirelessly. These tags can be embedded in or attached to packaging and products, allowing for automated tracking and inventory management. RFID tags can store more data than barcodes and can be read without line-of-sight. An RFID setup comprises three primary components: a tag, which integrates a microchip and a compact antenna; a reader, responsible for transmitting radio signals and capturing responses from the tag; and middleware, serving as the bridge between RFID hardware and enterprise applications (Kumar *et al.*, 2009; Sarac *et al.,* 2010). RFID technology stands out due to its capacity to store numerous codes within the tag and facilitate information exchange across considerable distances, thereby enhancing the efficiency of automated product identification and traceability processes (Plessky, 2009). RFID technology encompasses two distinct tag types: active and passive. Active tags are powered by their own internal batteries, boasting transmission ranges of 20 to 100 meters and the ability to engage with readers at any moment. However, they come at a higher cost and are larger in size compared to passive tags. In contrast, passive tags draw power from external radio frequency signals, offering transmission distances ranging from a few centimeters to 10 meters. They spring to life when in proximity to an RFID reader, are more cost-effective, and boast a smaller form factor (Ghaani *et al*., 2016). While RFID shouldn't replace barcodes entirely, the two technologies can synergize effectively.

FUTURE SCOPE

Intelligent packaging revolutionizes how we track and maintain product quality, providing real-time information crucial for consumer safety. Studies consistently demonstrate its efficacy in monitoring and extending the shelf life of perishable goods. Incorporating natural dyes as indicators not only enhances safety but also promotes environmental sustainability. Moving forward, research must prioritize establishing precise guidelines and evaluating the safety of smart packaging to mitigate potential toxicity from environmental exposure. Additionally, understanding how the concentration of active components affects the sensory qualities of packaged products is vital. Future advancements should focus on developing intelligent and active packaging with superior physical, mechanical, and barrier properties, while also exploring biodegradable options and optimizing production costs for widespread adoption. Moreover, exploring innovative features like interactive labels or personalized information delivery could further enhance the functionality and appeal of smart packaging in the marketplace.

CONCLUSIONS

This review highlights the game-changing impact of active and intelligent packaging, supported by a plethora of scientific studies. The promise of smart packaging goes beyond mere functionality, offering immense benefits in terms of safety, logistics, and marketability. It's poised to not just integrate into the industry but potentially revolutionize it in the coming years. Yet, there remains a crucial gap between theoretical research and practical market implementation. Tailored solutions are essential, considering the intricate nature of food products and their unique packaging needs. Bridging this divide demands a concerted effort, with a focus on custom solutions for specific product categories. Collaboration between research entities and industry players is paramount, encompassing development, regulatory, and commercial aspects. Such synergy holds the key to expediting the adoption of these groundbreaking packaging solutions.

In essence, smart food packaging represents a paradigm shift in the food industry, elevating standards of safety, quality, and sustainability. Through real-time monitoring, innovative sensors, and advanced tracking mechanisms, it has not only curbed food waste but also enhanced the overall consumer experience. The future promises even more remarkable advancements, with sensors and data analytics poised to offer unparalleled insights into food quality and nutritional value. Integration with IoT platforms will revolutionize supply chain management, bolstering traceability and efficiency. Sustainability remains a driving force, with a concerted research focus on eco-friendly materials and strategies to minimize food losses. Smart packaging, with its ability to extend shelf life and maintain optimal conditions during storage and transit, holds the key to a more efficient, sustainable, and consumer-centric food industry. Embracing these innovations is not just prudent but imperative for the industry's evolution and prosperity.

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How to cite this article: Namita Shukla, A.K. Tripathi, Ashutosh Tiwari, Sarang Pophaly, Kranti Sharma and Shivani Sahu (2024). From Farm to Table: Advancements in Smart Packaging for Dairy and Food Products. *Biological Forum – An International Journal, 16*(4): 33-45.