**Smart packaging materials: A review of existing and emerging packaging technologies and their applications**

**ABSTRACT**

Packaging of food plays a crucial role in the enhancement of shelf-life of the food products, by acting as a barrier between the food inside the packaging and the outside environmental conditions. This provides unfavourable conditions for the microbes to grow and thus food remains in consumable form for a longer period of time. Several types of packaging materials have been used till date such as LDPE, HDPE, PET etc. Oxygen scavenger, antimicrobial films and taste modifiers are examples of active packaging technologies that directly interact with food or its surroundings to prevent spoilage and increases its shelf-life. Informed decisions can be made at every stage of the supply chain due to real-time information about food condition given by intelligent packaging, which is made up of indicators, sensors and data carriers. The integration of these technologies, termed as “smart packaging” represents a significant advancement, combing preservation with improved communication. From early oxygen absorber to modern bio-based antimicrobial films, this study charts the evolution of active packaging over time. It also examines several kinds of active systems, like flavour control, CO2 and ethylene scavengers and antioxidant packaging. The rising demand to reduce food wastage and guarantee food safety underlines the necessity for continued advancements in active and intelligent packaging. This review discusses the present market trends, future research areas and challenges linked with application of these technologies and how food packaging has changed over time, focusing on intelligent and active packaging technologies that improve food quality, safety and shelf-life.

*Keywords: Active packaging, Intelligent packaging, Food safety, Food quality and smart packaging.*

1. **INTRODUCTION**

Packaging is essential to guarantee food safety and quality to enable efficient distribution and marketing across the supply chain. Packaging acts as barrier to protect food products from chemical deterioration, microbial spoilage and physical damage which is caused by external environment conditions. In addition to providing protection, it also serves a very crucial communication tool providing customers with important information through labels, brands and graphics. Packaging has another function of promotion of consumer convenience by addressing current lifestyles with features such as easy opening, reseal-ability and microwave compatibility (Yam and Lee, 2012). Effective packaging design also plays a crucial function of safeguarding the food products by keeping them safe and fresh. It facilitates in effective handling and transportation, which reduces the expenses and maximizes logistics. The primary aim of packaging is to ensure safe transportation and preserve food quality from the point of production to consumption. Despite its protective function, food quality can still be risked throughout the distribution and storage due to variety of biological, physical and chemical deterioration processes. Maintenance of food quality is not only a business concern but it is fundamentally related to improving overall quality of life (Sandulescu et al., 2011). Effective food quality control is essential for protecting users from foodborne diseases and boosting the food industry’s efficiency by reducing spoilage losses, particularly microbial spoilage of perishable goods.

After the industrial revolution packaging industry get well established. Active packaging comes under smart packaging and it has been introduced in 1970. In this mode of packaging package, food and outside product environment interact together to extend shelf life of product mainly and not to effect quality of good. Japan is leading in active packaging technology. First rules and regulations were set in Europe in Iceland (Day and Potter, 2011). There are different types of active packaging technology like Oxygen scavenging technology, in which oxidation is prevented by various methods like iron based, enzymatic, photosensitive dyes, micro-organism, platinum scavengers etc. (Yildirim et al., 2018). Carbon dioxide prevents respiration in food and has some antimicrobial properties so carbon dioxide sources are used along with sorbents (Lee, 2016). Ethylene scavengers are of two types physical and chemical. Antimicrobial agents i.e. petroleum and bio-based are used to kill microbes (Gaikwad et al., 2020). Ethanol has germicidal properties that kill microbes (Vanmathi & Anandakumar, 2022). Antioxidant are released into food at controlled rate and nowadays many natural antioxidants such as catechin, quercetin, cavacrol and many others are being used. Polymeric packaging absorbs unwanted odour and flavour from the food. Amine odour and citrus bitterness can be removed from food products. Fig. 1. Shows functions of packaging (Active and Intelligent).



**Fig. 1. Functions of packaging**

Intelligent packaging system observes material and resources in food. Intelligent packaging performs various smart functions like sensing, recording, tracing and other. Indicators tells about presence or absence of particular thing. Time and temperature indicators are important for packed food products because after certain temperature many physical and chemical changes can occur in food (Tsironi et al., 2017). Freshness indicator can detect the attack of microbes and spoilage of food products (Lee and Rahaman, 2014). With the time many food products like fruits respire which release gases and these gases can improve the microbial activity. Gas indicators should be in direct contact with food. MAP replaces O2 with some other gas mixture (Kuswandi et al., 2011). Leak indicators can check efficiency of oxygen absorbers by using water vapour, ethanol, hydrogen sulphide and other gases. With the increasing denaturation in food material humans are becoming more dependent on active and intelligent packaging and also for demand for fresh food products (Shinde et al., 2018). These technologies are for humankind and have promising future.

1. **TYPES OF ACTIVE PACKAGING**
	1. **O2 SCAVENGING TECHNOLOGY**

Oxygen causes food spoilage through oxidation (leading to rancidity, discoloration, and flavour loss), microbial growth (aerobic bacteria and moulds), and nutrient degradation (loss of vitamins and other essentials). While Modified Atmosphere Packaging (MAP) and vacuum packaging can reduce oxygen levels, they don't eliminate it entirely. Oxygen can also permeate through packaging films. Oxygen scavengers are used to absorb this residual oxygen and minimize food quality degradation in oxygen-sensitive products (Yildirim et al., 2018). To avoid metallic taints in food non-metallic oxygen scavengers’ have been created. These also prevent accidental triggering of metal detectors, although some detectors can now ignore the scavenger signal. Non-metallic options use organic reducing agents like ascorbic acid or catechol, or enzymes like glucose oxidase or ethanol oxidase. These can be put in sachets, labels, or directly on the packaging film (Dey and Neogi, 2019). First marketing of oxygen scavengers was done in Japan by the Mitsubishi Gas Chemical Co. Ltd under the trade name Ageless in 1976. Table 1 shows various methods of oxygen scavengers.

**Table 1. Various methods of oxygen scavengers**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Methods | Working | Examples | Prevalence | Applications | References |
| Iron - Based | Iron powder oxidizes in the presence of oxygen and moisture. | Ageless, ATCO, Freshilizer, Vitalon, Sanso-cut, Freshpax | Most Common | Iron sachets are used along with vacuum technology for preservation of also used pasta, sausage. Polymeric films and iron nano-particles are also used. | (Dey and Neogi, 2019) |
| Enzymatic | Enzymes (e.g., glucose oxidase, ethanol oxidase) react with substrates to consume oxygen.  | Bioka | Less Common (due to environmental sensitivity), Slow | Bottled beer and wine | (Dey and Neogi, 2019) |
| Ascorbic Acid | Ascorbic acid oxidizes to dehydroascorbic acid. | Solgar | Used in specific applications | Multi- polycaprolactone layer (Crown caps, closures) | (Lee, 2016) |
| Photosensitive Dyes | Dyes are activated by light, creating singlet oxygen that reacts with an acceptor | Zero2™, OS1000 | Less Common | Coffee and tea (to preserve aroma) | (Bilgin and Backhaus, 2019) |
| Incorporated into Pack | Oxygen scavengers are incorporated directly into the packaging material. | Oxyguard, Oxbar, Amosorb | Alternative to sachets, Common | Baking goods, snack foods, coffee, meat, cheese. | (Yildirim et al., 2018) |
| Micro-organisms based scavenging systems | Dried yeast when comes in contact with water and ascorbic acid get activated. | Poly (ethylene terephthalate, 1,4-cyclohexane dimethanol) (PETG) | Less common | *Bacillus amyloliquefaciens, Kocuria varians* and *Pichia subpelliculosa* has been used for oxygen scavenging purposes in meats and baked goods | (Anthierens et al., 2011) |
| αTocopherol based scavenging systems | α- Tocopherol is typically paired with a catalyst that boosts its scavenging activity by facilitating a non-enzymatic reaction between oxygen and the transition metal, which is then followed by free radical scavenging. | Methylcellulose α-tocopherol,α-tocopherol + PLA films | Less common | Used in food oils. | (Byun et al., 2011) |

* 1. **CARBON DIOXIDE SOURCES AND SORBENTS**

In some food like meat and poultry some amount of CO2 is beneficial. CO2 has antimicrobial effect on food due to its high solubility in food products. CO2 prevents food from oxidation. CO2 reduces the activity of ethylene and prevents respiration. This should be kept in check that higher concentration of CO2 above tolerance limit causes physiological injury to the produce (Lee, 2016). Fig.2 depicts CO2 absorbers and emitters.

CO2 is formed by respiration in food and it has to be removed from food from food to prevent deterioration. CO2 absorbing sachets should be used like Fresh Lock and Ageless E (Lee, 2016). The CO2- absorbing sachet consist Calcium oxide (CaO) and a hydrating agent like silica which absorbs water. The reaction that takes place:

* $CaO+H2O \rightarrow Ca\left(OH\right)2$
* $Ca\left(OH\right)2+CO2 \rightarrow CaCO3+H2O$

**(a)**

**(b)**

**Fig. 2. (a) CO2 absorbers**

**(b) CO2 emitters**

* 1. **ETHYLENE SCAVANGERS**

Ethylene (C2H4), volatile unsaturated hydrocarbon promotes growth and ripening, and triggers softening, colour changes and eventually decay. Scavengers react by physical and chemical adsorption. Due to presence of double bond ethylene is very reactive in nature. In ethylene scavenging reaction for example in presence of potassium permanganate (KMnO4) ethylene initially oxidize to acetaldehyde, then to acetic acid and then further to carbon dioxide and water (Gaikwad et al., 2020). The Fig. 3 depicts the process:



**Fig. 3. Ethylene scavenging process**

Ethylene-scavenging materials are important for reducing food waste, especially of fruits and vegetables, which account for roughly half of all wasted food. Studies have shown that the ethylene concentration inside fresh produce packaging typically ranges from 0.017 to 0.035μL L−1. These materials can extend the shelf life of fresh produce (Sadeghi et al., 2021). For packaging of food, especially for climacteric food ethylene scavengers are required as they produce ethylene gas during respiration. Ethylene scavengers can be categorised on the basis of their mode of action into two categories:

1. Chemically Reacting Scavengers: They react with the ethylene gas produced by the food products. Potassium permanganate (KMnO4), an inorganic compound used in sachet and it react with ethylene, oxidizing it to water and carbon dioxide. Chemical scavengers are also called absorbents and they are loaded with some carrier and inert material like alumina or clay (Ebrahimi et al., 2022).
2. Physical Binding Scavengers: These scavengers simply work on having large surface and the mechanism of adsorption of gases on their outer surface. Activated carbon is a cheap method of trapping ethylene gas. Zeolites can be used as films, coating and sachets, but this can be more expensive method. Clays like bentonite or montmorillonite can also be used. Physical binding is different from chemical binding in way that in physical binding weak Van der Waals forces are there between gas and surface which form hydrogen bonds, but in case of chemical binding sharing and transferring of electrons take place (Sadeghi et al., 2021).
	1. **ANTIMICROBIAL PACKAGING**

Microbes are found all around and microbial contamination is very common due to pathogen attack owing to less processing of food products, rupturing of seal or high temperature. We already use traditional methods that prevent food from pathogen like freezing, adding oil, spices, organic acids, pasteurization etc. But these methods have effect on taste, some physical properties and chemical properties (Prasad and Kochhar, 2014). The use of antimicrobial active packaging utilizes multiple inventive methods that prolong food shelf life by preventing harmful microorganism growth. Sachets or pads filled with volatile antimicrobial materials such as oxygen and moisture absorbers serve as a common preservation method by being placed inside food packages. The substances work by absorbing oxygen and moisture from their surroundings to create conditions that bacteria and mould cannot thrive in. Some natural extracts can also be used that are extracted from plants, herbs, spices and microflora called polyphenols. Another approach is incorporating antimicrobial agents directly into packaging materials, such as bio-polymers, during the manufacturing process (Deshmukh and Gaikwad, 2024). For example, compounds like sorbic acid or essential oils (example oregano oil) can be added to polymers like PLA to enhance their antimicrobial properties, while still preserving the material's physical qualities. In addition, antimicrobial agents can be coated or adsorbed onto the surfaces of polymers, often using natural substances like proteins or fats, which offer the added benefits of biodegradability and good barrier properties. Another strategy involves immobilizing antimicrobials onto polymers through electrostatic or covalent bonds. This method ensures that the active agents remain effective while minimizing loss during packaging processes. Some materials, like chitosan, are inherently antimicrobial. Chitosan, for example, can naturally protect fruits and vegetables from fungal degradation by interacting with microbial cell membranes, making it a valuable material for food packaging (Contreras et al., 2017). The antimicrobial activity is based on disruption of various proteins. Some antimicrobial compound modifies cell permeability causing interference in cell membrane and DNA production (Deshmukh and Gaikwad, 2024).

* 1. **ETHANOL EMITTERS**

Ethanol is well known for germicidal properties. It is proven to destroy cell wall and cell membrane and coagulation of vital proteins (Vanmathi and Anandakumar, 2022). Ethanol emitters come in form of sachet and they are subset of preservative releasing films. They key difference is that preservative releasing films are directly incorporated into the food products (Kumar et al., 2018). They are particularly effective against moulds but can also be effective in case of yeast and bacteria. Specifically, in case of bread ethanol emitters are combined with oxygen absorbers (Latou et al., 2010). Many ethanol emitting sachets have been patented by Japanese companies like EthicapTM, Antimould102TM, OitechTM and many more. Ethanol emitters are composed of Ethanol, H2O and S2O2. Protein and carbohydrate content of food reduces with increase in ethanol concentration. During the process ethanol vapours are diffused into head of packed food material (Vanmathi & Anandakumar, 2022) Ethanol in combination with methyl jasmonate gives more suppressing effect to microbial population than the individual (Lucera et al., 2016). Ethanol pad can be placed on lid of container of food. Earlier ethanol used to be sprayed on food but now sachets are more common. Sachets are less expensive way of preservation, Ethicap is example of ethanol emitter, a heat- sealed sachet that contains food grade alcohol with silica powder (Kusuma et al., 2024). The size and capacity of ethanol releasing sachets depends on factor like weight of the food, its water activity, and the desired shelf-life. The Japanese are using this technology on high scale in bakery products like cake and improving their mold free storage upto 2000%. Ethanol sachets are also proven to improve shelf life of semi moist products like the sea-food. Ethanol releasing sachets are more expensive than other active packaging method so they are primarily used in premium food products (Day and Potter, 2011).

* 1. **ANTIOXIDANT PACKAGING**

Antioxidant are added to packaging films with purpose of oxygen removing and chemical stability. There are two types type of antioxidants: synthetic and natural. The antioxidants are released into food at controlled rate. The antioxidant compound should be compatible with food for homogenous distribution. Antioxidant packaging material are developed by incorporating active compounds in polymer matrix. When an active material functions as an antioxidant release system, the release of the agent is regulated through a mix of mass transport processes. These processes include the equilibrium of the agents between different layers or surfaces, along with the kinetic factors that influence how the agent moves and interacts within the food. This makes sure that the antioxidant releases in a controlled manner to help preserve the food. Synthetic antioxidants including polyphenols along with organophosphate and thioester compounds served as standard options. Some questions about the future use of these synthetic antioxidants have emerged because of worries about their potential toxicity through migration into food products.

Due to many advantages of natural antioxidants over synthetic its demand has been increasing in the market. Recently many antioxidants such as: caffeic acid, catechin, quercetin, carvacrol, α-tocopherol, rosemary extract (plant extract) have been used. α-tocopherol, one of most used AOs. Rosemary extract is one of the plant-based ingredients already used in food packaging. The food packaging industry currently uses rosemary extract as one of its plant-derived components. People have traditionally appreciated rosemary for its delicious taste and medicinal benefits in both culinary and medicinal applications. The effectiveness of antioxidants depends on the the release rate of antioxidants and food oxidation. If antioxidants are released too quickly or slowly, they cannot maintain the optimal quantity needed to prevent oxidative rancidity (Lee, 2014). Active packaging systems involve the interaction between the active substance, packaging material, and food, with two main types: package-food and package-headspace-food systems. The release of antioxidants follows diffusion principles, and their transfer is influenced by partition coefficients between the packaging, food, and headspace. Diffusion rate determines how antioxidants are released, ensuring effective food protection (Kuai et al., 2021). There are two types of contact of antioxidant molecule with food one is direct contact and other is indirect contact, when in direct food contact AO material release molecules and they pierce inside food whereas in indirect contact molecules are attached on food surface (Lee, 2014) Fig. 4 depicts both processes.

 

**Fig. 4. Direct and Indirect contact of antioxidant molecule with food**

* 1. **FLAVOUR AND ODOUR ABSORBERS AND EMITTERS**

Flavour scalping occurs when polymeric packaging materials absorb food flavours resulting in diminished flavour intensity and altered taste profiles. Flavour scalping typically damages food quality but can serve a useful purpose by selectively removing unwanted odours or flavours from food products. An active cellulose acetate (CA) layer present in the packaging transforms the bitter compound naringin from fresh citrus fruits into non-bitter compounds. This enzyme hydrolyses naringin to naringenin and prunin, reducing bitterness. In a study, CA films with immobilized naringinase showed a 60% hydrolysis of naringin in grapefruit juice within 15 days at 7°C, alongside a reduction in limonin content (Tran et al., 2020).

Amine odour resulting from protein breakdown and aldehyde formed during oxidation of fats can be removed by dupont polymers and blended pet films (Day and Potter, 2011). Odour and flavour scavengers like cellulose acetate can be used in debittering citrus juices like orange juice. Esters are volatile compounds and produce fruity and flavoury aroma in wine and beer. Esters such as isoamyl acetate and phenyl ethyl acetate provide fruity and floral aromas (Olaniran et al., 2017). Microencapsulation of aroma and flavour releasing compounds was used in past. Nowadays, a step forward technology nanoencapsulation is used. Some flavour encapsulations like limonene are highly aromatic and its thermal stability is now maintained from room temperature to 170°C. Cinnamaldehyde is one of the most used aromas releasing active compound constituting main component of cinnamon (Burgos et al., 2017).

1. **FUTURE OF ACTIVE PACKAGING**

The market of active packaging works on consumer demand for fresher and long-lasting food. Active packaging can see good growth in future (Wyrwa et al., 2017). Future trends emphasize sustainability, incorporating biodegradable and bio-based polymers to address environmental concerns (Azeredo et al., 2017). India being a diverse country needs to focus on ways to improve shelf life of goods and quality. The demand for fast foods is also driving innovation in modified atmosphere packaging and edible coatings (Han, 2014). However, challenges remain, including cost, government frameworks, and acceptance by people. Research that focuses more on local use of active packaging is important. Furthermore, educating consumers about the benefits and safety of active packaging is essential for market exploration. The use of nanotechnology is improving safety of products and extending shelf life (Qian et al., 2021). Stimuli responsive polymer material offers innovative approach by releasing molecules in response to external stimuli. As a consequence, to retain biological function and provide particular chemical function, selectively designed molecular assemblies which allow release of active ingredients only when required by the system have been recently designed. These stimuli-responsive macromolecular nanostructures are tailored to bring about conformational as well as chemical changes as a reaction to external stimuli such as change in chemical composition, temperature or pH (Majid et al., 2018). As the technology matures, the next generation of active packaging will likely focus on more effective and reliable methods to preserve food quality and safety while making the packaging systems more affordable for commercial use. One field on which active packaging can develop is detection of toxins in food. Some researchers are working on this technology (Han et al., 2018). Focus on using less plastic material and harmful polymers should also be focused. Awareness through news and social media should be spread on ill effect of plastic. In some developed countries there is list of positive materials that should be used but not followed in many other countries (Handa et al., 2021).

Using renewable resources for active packaging is crucial for addressing future climate change challenges. Another promising area of research would be how storage and transport condition can be improved with active and intelligent packaging. Natural plant extract of ayurvedic and medicinal plants can be used in near future (Ahmed et al., 2017). Essential oils can be used in active packaging rather than directly incorporating them into the food. Essential oils have gained popularity as natural alternative to synthetic preservatives due to their numerous bioactive properties (Ribeiro-Santos et al., 2017). CO2 scavengers haven't received as much attention. They have primarily been utilized in packaging for foods that generate high levels of CO2, but the methods have often relied on trial-and-error, lacking a systematic design that considers factors such as CO2 production by the food, package permeability, and the scavenger’s capacity. CO2 production is not a constant process; it can fluctuate over time and under different conditions, such as temperature changes in the supply chain. Moreover, consumers may have preferences that necessitate more customized packaging atmospheres, including specific CO2 levels. The interplay between CO2, moisture, and other gases within the package can further complicate the situation. In future bio based antimicrobial films, self-sterilizing sachets in packaging can be used or integration of sensors for intelligent packaging.

1. **INTELLIGENT PACKAGING**

Intelligent packaging can be defined in various ways such as “materials and resources that observe the state of the packed food or the surrounding of the food”. The main purpose is to examine the product and transfer the information to the users which can include details like state of the product, contents, time of manufacturing and storage details. It can also be defined as a system of packaging which can perform smart functions like sensing, detecting, recording, tracing, documenting and utilizing scientific logics to enable effective decision making to extend shelf life, improve safety, enhance quality and to provide information to the users regarding the potential problems and issues (Yam et al., 2005). These devices can be put in three kinds of categories. First category is external indicators which are attached outside the packaging and it comprises time temperature indicators and physical shock indicators. The second one is internal indicators which are positioned within the container. For example, oxygen leak, carbon dioxide, microbial and pathogen indicators are either placed within the package’s headspace or attached to the lid (Irkin and Esmer, 2015). The third type in the category is the indicators that improve the effectiveness of information flow and communication between the user and the packed product, they comprise of special bar codes that have food information like usage and expiration dates. It also includes product traceability, anti-theft and anti- counterfeiting. Fig. 5 depicts concepts of Intelligent packaging.

**Fig. 5. Concepts of Intelligent packaging**

Intelligent packaging application systems are those that offer greater ease in terms of quality, delivery and preparation techniques, those which enhance packed product quality and value such as quality indicators, temperature and time temperature indicators and gas concentration indicators. And the ones that offers defense against tampering, theft and counterfeiting (Fang et al., 2017). These packaging systems must be user friendly, economical and able to perform multiple tasks in order to be practical and useful like color indicating labels must feature irreversible color changes which are easy to understood by the users (Fang et al., 2017). From the perspective of food safety and quality, IP is greatly beneficial to both the industry and consumers by providing them timely information of the status of the packed food through systemic changes. Few intelligent packaging systems can communicate the whole history of the packed food product to the consumers (Sohail et al., 2018). Table 2 shows different types of indicators used in intelligent packaging.

* 1. **TIME - TEMPERATURE INDICATORS (TTIS)**

Temperature plays a very critical role when determining how long a food product can be stored. Variation in the temperature during storage raises concern about the quality of the processed food products. History of temperature of food product from production to consumption have a significant impact on the quality of the food product. Hence, temperature is an important component of cold chain management systems (Tsironi et al., 2017). Food processors and suppliers are now monitoring the temperature of food ingredients from the point of harvesting to the point of consumption, in order to ensure food safety and quality (Sohail et al., 2018). Loss of hygienic, nutritional and sensory properties of perishable foods is caused due to time and temperature both.

A time-temperature indicator is a measuring instrument which indicates an irreversible change that is time and temperature dependent and can be easily, precisely and accurately measured. This change imitates the changes of a target attribute which is undergoing the same variables in terms of time and temperature. Most of the TTI’s operational principle depend on chemical, enzymatic, mechanical, electrochemical, or microbiological reactions which shows the outcomes through color change. Pereira et al (2015) developed an inexpensive, precise time-temperature indicator using natural materials. They used chitosan, polyvinyl alcohol (PVA) and red cabbage anthocyanin (a natural pH indicator) to create a labeling film. The TTI can indirectly track food quality because anthocyanin’s color changes with pH and food spoilage often changes food pH (like milk). Application of these indicators are majorly in temperature-sensitive foods like chilled and frozen food products (Dutra Resem Brizio, 2016). TTIs tracks the accumulative effect of temperature on food quality. They are affixed to the exterior of the food packages and integrate the temperature exposure of the packaged food by aggregating the impacts of these exposures along the cold chain (Firouz et al., 2021). Storage conditions can be continuously monitored by using these indicators. Therefore, they can serve as indirect shelf-life indicators and can tell about cold chain disruption. Diffusion based and microbial based TTI are used widely in food applications. To enhance their functionalities, they need to be accurately responded to temperature variations and align with models that map these changes to soilage kinetics. However, research in this field is very less. Developing user-friendly tools that integrate such models could help provide real time information on corrective actions for temperature fluctuations (Firouz et al., 2021).

**Table 2. Types of indicators used in intelligent packaging.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| S.No. | Type of indicator | Function | Examples | References |
|  | Time-temperature indicator (TTIs) | Monitors time and temperature of the food product.Tracks the history of the food products. | Colour changing labels, pH sensitive films. | (Tsironi et al., 2017) (Sohail et al., 2018) |
|  | Freshness indicators | Detect spoilage and microbial growth. | pH sensitive films, gas indicators. | (Lee and Rahaman, 2014)(Kalpana et al., 2019) |
|  | Gas indicators | Monitors changes in O2 and CO2 levels. | O2 and CO2 sensitive labels. | (Kuswandi et al., 2011) |
|  | Leak indicators | Monitors gas leakage and identify package integrity issues. | O2 leak detection in MAP. | (Wilson et al., 2019) |

* 1. **FRESHNESS AND SPOILAGE INDICATORS**

It was recorded that one third of the world’s food production is wasted due to microbial spoilage yearly. Consumers typically assess food quality using colour, odour and texture but packaging can mask these qualities. Since microbial contamination reduces shelf life and increases the risk of foodborne illness, stakeholders of the food industry are eager to developing reliable, cost-effective, and non-invasive freshness detection methods. Freshness indicators are packaging systems that can assess product’s real-time quality by detecting microbial growth metabolites instead of relying solely on temperature changes or leaks. These indicators use microbial metabolites such as glucose, organic acids (acetic acidor lactic acid), ethanol, volatile, nitrogen compounds, biogenic amines, carbon dioxide, ATP degradation products and sulfuric compounds to estimate quality of the product (Kuswandi and Nurfawaidi, 2017). These indicators track the quality of the food products during transportation and storage. Freshness indicators, in contrast to temperature indicators, are direct indicators of food quality, analyse the chemical interactions of target bacteria and their metabolites that lead to food decomposition. The concept is that the target microbes which proliferate result in permanent alterations like pH variations, which indirectly result in a colour change ensuring a direct indication of the food product quality inside the container (Dutra Resem Brizio, 2016). They have application in many products such as fresh foods, fruits and seafood. Table 3 depicts different indicators which are used in the food industry. Besides, these indicators can be used for the estimation of shelf life of perishable food products (Kuswandi et al., 2011).

**Table 3. Application and working mechanism of different types of indicators.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| INDICATOR | INDICATOR TYPE | WORKING MECHANISM | APPLICATION | REFERENCE |
| Time-temperature indicators (TTIs) | Enzymatic TTI (Alkaline lipase, PVA gel) | Monitors enzyme diffusion and freshness. | Liquid products like milk. | (Lu et al., 2013) |
|  | Plasmonic TTI (Silver/Gold Nano crystals) | Chronochromic colour change from red to green. | Foods which are highly perishable such as milk. | (Yan et al., 2013) |
|  | Biopolymer TTI (red cabbage, chitosan, PVA) | Variation in pH through natural extract incorporation and colour change. | Pasteurized milk. | (Pereira et al., 2015) |
|  | Air activated TTI (Leuco methylene blue, AC) | Monitors shelf-life through redox reaction with oxygen. | Chilled storage food like sandwich. | (Lee et al., 2019) |
|  | OnVu® TTI | Commercial TTI, Effective supply chain tool. | Chilled boneless chicken breast. | (Brizio and Prentice, 2014) |
| Freshness indicators | Curcumin, Grape peel, Beetroot extracts | pH indication based on natural dye, colour change. | Cod fish | (Tichoniuk et al., 2017) |
|  | Bromocresol purple (PVA immobilized) | Variation in pH, indicator of freshness and shelf-life, direct contact type. | Chicken breasts | (Kim et al., 2017) |
|  | Bromothymol blue/ Methyl red (2:3) | Real time freshness indicator, pH and CO2 concentration indication | Green bell pepper | (Chen et al., 2018) |
|  | Methyl red/Bromocresol purple (dual sensor) | Indicates pH, detect freshness. | Beef products | (Kuswandi and Nurfawaidi, 2017) |
|  | Triple layer indicator (Tyvek®, bromocresol green) | Digital image processing, pH indicator, volatile amines, bacteria. | Chicken spoilage | (Lee et al., 2019) |
| Gas indicators | Bromocresol purple/Methyl red (polymeric films) | Show spoilage, tracks CO2 and monitors pH dependent colour change. | Intermediate moisture desserts | (Nopwinyuwong et al., 2010) |
|  | Luminescence based oxygen sensors (OxySense™) | Luminescence intensity/lifetime measurement, high sensitivity. | Sealed package | (Jung et al., 2012) |
| Leak indicators | **Nanoparticle-Based Oxygen Indicator** | Oxygen sensitivity, colour change, photoactivity. | MAP, sealed packaging | (Mills et al., 2012) |
|  | **UV-Activated Oxygen Indicator** | Colour change by utilizing a special dye. | Monitors quality during storage and transport. | (Vu and Won, 2013) |
|  | Pressure-operated compartmented oxygen indicator | Detects oxygen concentration change. | MAP | (Jang and Won, 2014) |
|  | Colorimetric CO2 indicator from natural extracts | Detect pH change. | Poultry meat (azure to intense purple) | (Saliu and Della Pergola, 2018) |

* 1. **GAS INDICATORS**

Maintenance of food quality within the packaging is quite challenging due to various factors such as respiration of fresh fruits and vegetables, changing gas concentration, gas leakage and microbial activity (Lang and Hübert, 2012). To provide solution to these issues, gas indicators have been introduced. They can detect oxygen or carbon dioxide levels within the packaging by undergoing a colour change through a specific chemical or enzymatic reactions. Gas indicators are in the form of labels, tablets, printed layer or laminated polymer films (Kuswandi et al., 2011). Vu and Won (2013) created an enhanced and user-friendly oxygen gas indicators to detect O2 gas and the prevention of dyes from leaching out of the package. The gas composition in the headspace of the packaging can be affected by the activity of the food product, the type of packaging or the surrounding conditions. Gas indicators which can be printed on packaging films or in the form of a package label can be used to monitor the food product’s quality and safety.

These indicators should be in direct and permanent contact with the food and the surrounding atmosphere inside the food package. The production of CO2-sensitive smart packaging films has been the subject of the recent studies (Firouz et al., 2021). As the CO2 gas percentage in the headspace of the package increases, the change of the colour of the films would give a visual index of the packed food product. These indicators monitor the quality changes in food that are initially invisible to users, ultimately leading to a visible change. Gas indicators can track alterations of metabolites including carbon dioxide (CO2), ammonia (NH3), hydrogen sulfide (H2S), dimethylamine ((CH3)2NH) and trimethylamine (C3H9N) as quality indices (Lee et al., 2019). Gas indicators find application in controlled and modified atmosphere packaging (MAP) to help in maintaining food quality. MAP involves replacement of air in the packaging with a fixed gas mixture, while controlled atmosphere packaging regulates gas composition during the time of storage. O2 and CO2 are the primary gases in MAP, though other gases like carbon monoxide, sulfide dioxide, nitrous oxide, ozone and chlorine are also used in specific industries (Lee and Rahaman, 2014).

**4.4 LEAK INDICATORS**

The gas composition in the headspace of the package gets affected due to the activity of the food product, leaks, the type of package or surrounding conditions. Oxygen and carbon dioxide gases can be employed to check the efficacy of the oxygen absorber or to assess the quality of the food or as seal indicators (leaks) (Pereira et al., 2012). Water vapour, ethanol, hydrogen sulphide and other gases can also be used for tracking. A leak indicator provides details on the package integrity along the entire chain of distribution that is attached to it. It can be developed as a label, printed layer or tablet or it can be laminated in a polymer film. To extend the shelf-life of the food product, the concentration levels of the internal gas in the package needs to be fixed (Kalpana et al., 2019). Although, the internal gas can change due to food respiration, metabolism of spoilage bacteria, permeation by the packaging ingredient or the package leakage. Oxygen indicators are utilized to detect leaks in food packaging (Fang et al., 2017).

Modified atmosphere packaging (MAP) extends the shelf-life by altering gas concentration levels inside the package. Although, leaks or distortions in package integrity can compromise optimal gas levels, significantly affects food quality including taste, nutrition and texture. To solve these concerns, leak indicators are used used to monitor and maintain package integrity. These indicators are utilized in modified atmosphere packaging (MAP) a type of active packaging technique (Wilson et al., 2019). In these cases, the atmosphere has a low concentration of oxygen and a higher concentration of carbon dioxide. When there is a leak in MAP, the concentration of oxygen increases and carbon dioxide concentration decreases which enables aerobic microbial growth to occur.

1. **CONCLUSION**

Food packaging has evolved from basic containment to sophisticated systems that actively and intelligently protect and inform. This review tells us about overview of active and intelligent packaging, how it extends shelf life of food, maintain quality and enhance flavour. There are various methods of smart packaging which includes oxygen scavenging, emitters, absorber and indicators. Active packaging methods like carbon dioxide emitters and sorbents are used to prevent respiration and have antimicrobial properties. Ethylene scavengers like potassium permanganate are important to extend shelf-life of food. Antimicrobial packaging is used to prevent food from pathogens. Petroleum based antimicrobial packaging is used but currently scientists are focusing more on natural antioxidant. Ethanol removing sachets are used less because they are very expensive. Flavour scalping and odour emitters remove bitterness, sourness from food. In contrast, intelligent packaging provides consumers with the real-time information about the food condition throughout the supply chain. Time - temperature indicators use chemical or enzymatic reactions to change colour over time. Freshness indicator tells us about the microbial growth in the food product. Gas indicators tell about oxygen, carbon dioxide or ethylene within the package. Active and intelligent packaging focus more on reducing food wastage and improves the after-life of the food product after being packed. The smart packaging has reportedly no ill effect on humans and nature. Active and intelligent packaging with time is focusing to revolutionize food industry and is now focusing on developing nation. For broad adoption of these technologies, factors like user acceptance, regulatory compliance and the cost effectiveness of these packaging solutions are important. Researchers are focusing on enhancing local use of these packaging. Active and intelligent packaging have potential advantages for economy and environment as it promotes food safety and enhance product value. These recent researches can help industries to know about various new technologies.

Disclaimer (Artificial intelligence)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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