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Advances in Optical Gas Sensors for Smart Food Biopackaging: Enhancing Freshness and Safety Monitoring

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Abstract: *This review focuses on gas sensors used in food packaging, highlighting their importance in limiting food deterioration through the detection of gases such as carbon dioxide, ammonia, and related compounds. When the concentration of these gases exceeds limits set by regulatory authorities, it signals the onset of spoilage, making such sensing systems essential components of smart packaging technologies. With increasing consumer demand for fresh, convenient, and cost-effective food products, the integration of sensors into packaging systems has become increasingly significant. These sensors enable early identification of spoilage, thereby reducing health hazards and minimizing economic losses. Among the different sensing approaches, colorimetric sensors have received considerable attention due to their simplicity and effectiveness. They operate by producing a visible colour change in the presence of target gases, allowing easy and reliable assessment of food quality and enhancing consumer confidence in food safety.*

Keywords: Food packaging, Gas sensors, Smart packaging, Food spoilage detection.

I. INTRODUCTION

Food is a potential source of risk to human health due to possible contamination by various pathogens (W. Cai et.al), including several bacteria, viruses, parasites, and fungi. Food infections may also occur due to improper handling and processing of food, further increasing the risk to public health and food safety (B.M. Oh et.al). Inadequate food management and treatment are critical factors contributing to these diseases, and strict hygiene practices must be adopted throughout the food production and distribution chain A. Altmann. Further significant risks arise from food deterioration and oxidation. Inadequate storage temperature, for example, can accelerate food spoilage, increasing the risk of microbiological contamination and chemical alteration. Recently, food producers, retailers and consumers have paid increasing attention to food safety N. (Sohrabi et.al). Users constantly demand innovative and creative food packaging that guarantees safety, quality, and traceability. It is important to remember that consumers also play a crucial role in reducing food waste. Making informed choices, such as proper food storage and/or reuse of leftovers, can significantly reduce the amount of food in the trash. Waste is often caused by overbuying, failure to pay attention to expiration dates, or poor portion management. Consumers also have the power to influence the market by favoring the purchase of products with packaging that promotes sustainability or by preferring local and seasonal foods. When consumers support companies that adopt responsible production and distribution practices, they help create a demand for solutions that reduce waste throughout the food chain.

However, cost remains a significant limit because biodegradable materials are often more expensive than conventional plastics (S. Siciliano et. al). Intelligent food packaging, a concept that allows for real-time communication on the state of a food product, assists in food defense and ensures consumers receive food products of the highest quality, is gaining traction (S. Siciliano et. al). The European Food Safety Authority defines intelligent food packaging as "materials and articles that monitor the condition of packaged food or the environment surrounding the food" (H. Cheng, et.al). Intelligent or smart food packaging utilizes sensors and indicators that are attached as labels, incorporated into, or

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printed onto regular food packaging materials to report on product freshness and package integrity by monitoring changes in package environment and ambient conditions, as well as electronic tags to track products from point-of-origin to point-of-use (C.T. Tracey et. al). Unlike traditional labels with fixed expiration dates, "smart expiration dates" can use built-in sensors, visual indicators or QR codes to provide real-time information on the freshness status of the product.

These technologies can monitor variables such as temperature, humidity and food deterioration, providing a more accurate assessment of its actual shelf life. The adoption of such smart labels can lead to a significant reduction in food waste (P. Shao et. al.), as consumers would be able to make better informed decisions, avoiding throwing away food that is still edible. At the same time, it could improve food safety as these technologies help prevent the consumption of spoiled foods.

More precisely, sensors are devices that sense the information of a measured object through a sensitive element and then convert the information into a usable signal by a conversion element (M. Soltani Firouz et. al.). Generally, sensors consist of three functional parts (E. Osm´olska et.al.):
1. the sensing unit or receptor, detecting the physical or chemical properties and converting them to an electrical, thermal, optical or other signal;
2. the signal conditioning unit, processing the generated signal;
3. the interface unit, by an adapter, a simple mechanical connector, a wireless sensor, etc.

Although some literature makes a distinction between sensors and indicators, the present review will include indicators (which have only the sensing part) in the broad group of sensors, considering them as synonyms as in most literature about intelligent food packaging.

Food traceability through such sensors is crucial to ensure the safety and quality of products by constantly monitoring the condition of food and detecting critical environmental parameters that can affect the freshness and safety of products. In the context of increasing attention to quality and food safety, the integration of traceability sensors has become crucial for companies that aim to stand out and offer their customers high standards of monitoring and transparency.

However, it is essential to invest in developing reliable and cost-effective sensors and ensure proper interpretation and management of the collected data. This work underscores the importance of gas sensors, detecting different gases produced when food deteriorates, depending on the decomposition processes and the microorganisms involved. It proceeds with an in-depth study of the literature on the last decade, from 2014 to 2024, highlighting the significant role these sensors can play in ensuring food safety.

II. GAS SENSORS

Several changes can occur in packaged food due to metabolism or microbial growth over time. For instance, variations in gas evolution can provide insights into the food's status, such as freshness or degradation.
Sensors capable of measuring these changes could comprehensively assess food quality. Integrating gas sensors into food packaging presents an advanced solution for monitoring and controlling the atmosphere within the package. These sensors can detect the presence and concentration of oxygen, carbon dioxide, ammonia, and other gases (e.g., hydrogen sulphide, dimethyl sulphide, methane, hydrogen, organic acids and volatile organic compounds) produced during food deterioration. In addition, gas sensors can detect packaging leakage, promptly signalling the need for corrective action to avoid external contamination and prolong the product's shelf life. Among all existing sensor types optical sensors are becoming increasingly frequent research subject due to their great potential for use in food packaging. Gas

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colourimetric indicators applied to food packaging are visual sensors that change colour in response to specific environmental or process conditions. These labels are designed to provide an immediate visual indication of any changes in conditions within the packaging or in the product, such as temperature, humidity, pH, or the presence of specific gases, indicating to consumers whether the product has been exposed to high temperatures, deteriorated, or otherwise compromised.

There is an increasing interest in developing colourimetric pH-sensitive sensors intended for utilisation in intelligent packaging systems that monitor the freshness of food products. They are generally produced by incorporating pH-sensitive dyes in biodegradable polymers and exhibit a colour change in response to pH fluctuations within the food items. The polymers utilised include polysaccharides, gums, proteins, gelatin, and polyvinyl alcohol, as they are recyclable, decompose rapidly, are non-toxic, and environmentally benign. Nevertheless, the employment of synthetic dyes as pH indicators is constrained due to apprehensions regarding toxicity and mutagenicity. As a result, contemporary research is directed towards utilising natural pigments derived from plants and food waste, as these meet the safety standards for packaging materials and potentially offer bioactive functions. Natural pigments comprise anthocyanins, curcumin, betalains, chlorophyll, and carotenoids. Therefore, pH-sensitive gas sensors are usually composed of a solid matrix (typically films, hydrogels, fibers) and a dye sensitive to pH changes, usually extracted from plants.

III. LIMITATIONS AND CHALLENGES OF OPTICAL SENSORS

While optical sensors have been one of the most promising technologies for intelligent food monitoring, especially in applications related to the detection of volatile compounds, colour changes, or spoilage-related fluorescence, they still present several critical limitations, including low sensitivity and selectivity and often unsatisfactory levels of automation, that hinder their large-scale deployment in the food packaging industry. Then, despite the progress, some challenges remain in optimising sensors, particularly regarding reproducibility and understanding how they work. When using colourants to monitor food freshness, it is essential to choose natural ones. Natural colourants, instead of synthetic ones, align with the current consumer trend towards more sustainable, natural, and healthy alternatives. In recent years, consistent with green chemistry and sustainable practices, natural colourants have progressively replaced synthetic options, which are often toxic and harmful to the environment. Derived from fruits, vegetables, or plants, they are non-toxic, biodegradable, safe for the body, and easily extractable, while offering a good chromatic variety. Embedded in smart sensors, these dyes, such as curcumin or betalains react to variations in acidity through colour changes, allowing the detection of the release of substances linked to food spoilage and thus facilitating effective freshness monitoring. However, their effectiveness can be limited by environmental factors such as light, temperature, and humidity, which affect the stability of the colour signal and compromise its reliability over time. One of the main problems is the possibility of false positives or negatives. Sensors may detect a colour change that does not correspond to actual product deterioration (false positive) or fail to identify a problem that risks food safety on time (false negative). This could undermine consumer and producer confidence in the system. In addition, the presence of other gases in the packaged environment influences the response. For example, to better understand the combined effects of multiple analytes, the response of an array indicator was evaluated by exposing the indicator to air with different ratios of NH_3 and CO_2, which are usually produced during the spoilage of fresh meat products. Compared to individual test gases, the responses of indicators to NH_3/CO_2 mixtures exhibit a greater complexity due to interactions among analytes, dopants, and dyes. For instance, it is well established that ammonia reacts with CO_2 in the presence of water to produce NH_4HCO_3. It is plausible that competitive reactions may have occurred between NH_3 and the indicator dyes in the presence of dissolved CO_2.

Additionally, the effects of temperature differed when compared to individual gas analytes, which can be explained by the higher solubility in water at lower temperatures of NH_3 compared to CO_2. In addition, changes in CO_2 and NH_3 permeability in ethyl cellulose matrix and the reaction of NH_3 with the HCl dopant would have also affected the enthalpy profiles of the array indicator [30]. Further investigation is necessary, particularly with more intricate headspace model gases and actual food systems. While this study utilized a capillary spotting technique to prepare the indicator prototypes, it is conceivable that other, more efficient manufacturing processes, such as ink-jet printing on alternative substrates like paper and porous nonwovens, could produce cost-effective single-use indicator labels. The ink-jet printing method enables multiplexing several dyes within a single element, which helps reduce the size of the array. With the rise of high-resolution cameras in mobile phones, it is possible to integrate the indicator into smart packaging systems, allowing consumers to analyse the captured array pattern using their phone's camera and an app to assess the real-time freshness of food items. Although the hydrophobic ethyl cellulose matrix is beneficial for encapsulating dye components, further prevention of unwanted mass transfer can be achieved by laminating or coating the indicator array with a polymer overlay like polyethylene or polypropylene. This feature will also improve the storage stability of the indicator, which is crucial for commercial use.

IV. CONCLUSION

Intelligent packaging is an emerging technology within the food packaging field. Sensors for food packaging are essential in many respects. They improve food safety by allowing continuous monitoring of food conditions and rapid identification of any abnormalities that could compromise food safety, thus ensuring quality and maximum integrity. The ability to quickly detect the possible deterioration of food allows companies and consumers to intervene promptly to avoid the loss of the product. This helps ensure the quality and safety of food that reaches consumers and contributes significantly to reducing food waste. Minimizing waste positively impacts companies' economies and promotes more sustainable management of global food resources. Then, the sensors allow consumers to access detailed information on the freshness and quality of food, mainly thanks to visual indicators. This will enable consumers to make more informed purchasing decisions, giving them access to safer, higher-quality food.

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