Carbon dioxide sensors for intelligent food packaging applications

Pradeep Puligundla, Junho Jung, Sanghoon Ko*

Department of Food Science and Technology, Sejong University, 98 Gunja-dong, Gwangjin-gu, Seoul 143-747, South Korea

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A B S T R A C T
Recently, the demand for safe and high quality foods, as well as changes in consumer preferences have led to the development of innovative and novel approaches in food packaging technology. One such development is the smart or intelligent food packaging technology. Intelligent packaging has enabled to monitor and communicate information about food quality. This technology also helps to trace a product’s history through the critical points in the food supply chain. In general, occurrence of elevated CO2 gas level is the prime indicator of food spoilage in packed foods and also its maintenance at optimal levels is essential to avoid spoilage in foods packed under modified-atmosphere packaging (MAP) conditions. Hence, a CO2 sensor incorporated into food package can efficiently monitor product quality until it reaches the consumer. Although much progress has been made so far in the development of sensors monitoring CO2, most of them are not versatile for food packaging applications and suffers from limitations such as high equipment cost, bulkiness, and energy input requirement, including safety concerns. Therefore, the development of efficient CO2 sensors that can intelligently monitors the gas concentration changes inside a food package and specific to food packaging applications is essential. In the present review, progress on the development of different types of CO2 sensors such as optical sensors, polymer opal films, polymer hydrogels, etc., which can be readily applicable to food packaging applications, is discussed.

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References

* Corresponding author. Tel.: +82 2 3408 3260; fax: +82 2 3408 4319.
E-mail address: sanghoonko@sejong.ac.kr (S. Ko).

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1. Introduction

1.1. Novel food packaging techniques

Conventionally, a food package helps protect food from environmental influences, such as moisture, light, oxygen, microbes, mechanical stresses and dust. These factors lead to or enhance the deterioration of food or drink. An ideal food packaging material should be inert, not to allow the transfer, i.e. must have a perfect barrier property, and recyclable. Food package makes distribution easier. Apart from these, there are other important functions of packaging, including containment, convenience, marketing, and communication. However, in recent years, the area of active and intelligent packaging is becoming increasingly significant.

According to the definitions of the European ‘Actipak’ project, the active packaging changes the condition of the packed food to extend shelf life or to improve safety or sensory properties, while maintaining the quality of the packaged food. And, the intelligent packaging systems monitor the condition of packaged foods to give information about the quality of the packaged food during transport and storage (Ahvenainen, 2003). Active food packaging plays a dynamic role in food preservation and makes packages to interact with food and the environment. Active packaging technique enables the regulation of various aspects that may play a role in determining the shelf life of packaged foods, such as physiological (e.g., respiration of fresh fruit and vegetables), chemical (e.g., lipid oxidation), and physical (e.g., dehydration) processes as well as microbiological aspects. Other developments in packaging technologies include odor absorbers, ethylene removers, and carbon dioxide emitters/absorbers.

On the other hand, intelligent packaging systems attached as labels, incorporated into, or printed onto a food packaging material offer enhanced possibilities to monitor product quality, trace the critical points, and provide product information like product history (Han, Ho, & Rodrigues, 2005). The commonly used intelligent visual indicators are time/temperature indicators and leak detectors, and these are indirect indicators, based on polymerization rate, diffusion, chemical or enzymatic reaction. However, the direct indicators are preferred because of their ability to provide more precise and targeted information on quality attributes (Gontard, 2004).

1.2. Carbon dioxide (CO₂) as a direct indicator of food quality

To decrease microbial growth rate and subsequent spoilage, food products are often packed under modified-atmosphere packaging (MAP) conditions. The carbon dioxide (CO₂) gas can be solely (100%) or in different combinations with other gases such as nitrogen (N₂) and oxygen (O₂) is typically used (as flush gas) for creating protective atmosphere surrounding the food inside of a pack with an aim to exclude or minimize the oxygen content, thereby the shelf life of food can be extended through inhibiting the aerobic spoilage microbes. And also, oxygen has been suggested to be a major factor for deterioration of meat quality through lipid oxidation (Andersen & Skibsted, 1991). Carbon dioxide is considered as an active packaging gas because high levels reduce the metabolic rates of microbes even if oxygen is present (Wayne, 2000). Depending on the type of food and the delivery stage of food item, the composition of protective atmosphere varies (Mills, 1998). The quality of MAP-packed food ultimately depends on the integrity of package and, therefore, leakage detection is the essential part of MAP technology (Bultzingslöwen et al., 2002).

In modified-atmosphere food packages, freshness and safety of food can be assessed by determination of CO₂ concentrations (Smolander, Hurme, & Ahvenainen, 1997). A decrease in its original concentration could be a sign of leakage in a package (Neethirajan, Jayas, & Sadistap, 2009). Conventionally, package headspace gas analysis is generally carried out at various points of the food supply chain by using electrochemical fuel cell for oxygen analysis, and by infrared absorption spectrometry for carbon dioxide content measurement, to ensure package integrity. However, in this method, the food packs are sampled destructively by inserting a needle probe for gas collection (Smolander et al., 1997). A major disadvantage with this method is, if a package fails the leak test, a large number of packages before and after the tested one will have to be considered failed and need to be destroyed or repacked (Mills, 1998); sometimes may include food products of an entire batch also. Moreover, apart from destructive and time consuming nature of conventional method, trained technician and expensive analytical equipment is required to monitor the equality.

Under normal atmosphere packing conditions, when the food within a sealed container starts to spoil, several by-products are formed and they accumulate inside. Therefore, theoretically it is possible to detect spoilage by detecting one or more of these by-products. Production of heat, acidity, pressure, and carbon dioxide is commonly observed as by-products in food spoilage. Ideally, a spoilage detector should be useable with as many different food products as possible, without requiring different detectors for each different type of food material. As the small amounts of heat evolve during deterioration process, heat detection is not likely to be practical. And also, pH of the various foods varies widely and, therefore impractical. Pressure detection is also impractical.

Limited amount of published work is available regarding food spoilage indicators. Based on volatile compounds produced in microbial spoilage, indicators have been fabricated on a trial basis. A myoglobin-based indicator for modified-atmosphere-packed poultry meat has been developed, which can indicate spoilage by detecting presence of hydrogen sulfide (H₂S) formed upon spoilage (Smolander et al., 2002). For monitoring fish spoilage, Pacquit et al. (2006, 2007) developed a colorimetric dye-based sensor that detects the presence of total volatile basic nitrogen (TVB-N), a product of spoilage. Knowledge about the quality-indicating metabolites is an essential prerequisite for the development of food spoilage indicators. Under non-MAP or nitrogen-flushing conditions, aerobic and facultative anaerobic microbes thrive during storage of the food products and often resulted in the formation of lactic and acetic acids by lactic acid bacteria (LAB). However, carbon dioxide is generally known to be produced during any kind of bacterial, mold growth on foods. Therefore, to indicate deterioration of foods, simply detection of CO₂ levels is the ideal way, and such detectors would have to operate without interference of the other properties of food, such as pH, salt content (corrosiveness), pressure or vacuum etc (Eaton, Kilgore, & Livingston, 1977). A correlation between CO₂ concentration and the growth of microorganisms was made in pea or tomato soup that is packaged aseptically either in air or in a mixture of 5% oxygen and nitrogen (Mattila & Ahvenainen, 1989; Mattila, Tawast, & Ahvenainen, 1990); bromothymol blue, the pH-sensitive dye was used as indicator for detecting the formation of CO₂.

1.3. Driving force for innovation in food quality monitoring

The prime driving force is the growing consumer demand for mildly preserved, minimally processed, easily prepared and ready-to-eat fresher foods (Nopwinyuwong, Trevanich, & Suppakul, 2010). Also, the innovations are fueled by globalization of food business and, therefore, food products are needed to be kept fresh over long distances and time. Conventional packaging techniques are inadequate to meet this requirement. In addition, consumers’ complaints
over the reduction in shelf life of foods and an increase in the risk of food-borne illnesses from microorganisms reporting around the world in recent years are also an important issue. Food traceability throughout the food supply chain is increasingly becoming a necessary task, mandatory in European Union (EU) since 2005 (Giraud & Halawany, 2006). In the light of the above, to maintain safety and freshness and to evaluate real-time freshness of food products, there is a constant need to develop a cost-effective, accurate, rapid, reliable, non-invasive and non-destructive methods or devices. Therefore, in order to achieve these goals, a measurable technology, visually or instrumentally, should be developed which provide in-situ information about the gas composition and, therefore, information on food quality of packaged foods through any point of food supply chain until reaching the consumer.

Indicator should be very inexpensive, and not add significantly to the overall cost of the package. It should be non-toxic, and have non-water soluble nature. The sensor components should have approval for use in food-contact materials. Also, it should not require an expensive instrumentation for analysis and should be able to check it even by an untrained person. It also should exhibit an irreversible response toward analytes.

2. CO₂ sensors for intelligent food packaging applications

2.1. Conventional CO₂ sensors

Broadly, the CO₂ sensors can be divided into two types, optical and electrochemical, based on the type of transducer. The electrochemical CO₂ sensors are further sub-categorized into potentiometric, amperometric, and conductometric types. Non Distributive Infra Red (NDIR) and Severinghaus-type sensors are used conventionally, commercially for gaseous and dissolved CO₂ detection, respectively. However, the NDIR instrument is expensive, large in volume, vulnerable to contamination, and water vapor interference despite its high precision. Furthermore, the process requires the destruction of a sealed package for gas analysis, and not suitable for routine sample analysis. Therefore, compact and cheap sensors are in high demand.

Severinghaus CO₂ sensor consists of a bicarbonate solution filled glass electrode covered by a thin CO₂ permeable membrane. The membrane is impermeable to water and electrolytes. The sensor functions on principle that in an aqueous solution, CO₂ forms carbonic acid, which is then dissociates into a bicarbonate anion and a proton (Dieckmann & Buchholz, 1999). The proton-induced pH change in electrolyte solution can be measured by a pH probe. A CO₂ sensor principle that slightly differs from Severinghaus concept was presented by Varlan and Sansen (1997). The concept is based on conductivity change as a result of the reaction of carbon dioxide and bicarbonate solution inside a cavity covered with a gas permeable membrane. This kind of sensors can measure CO₂ concentrations between 0 and 11 kPa with a very fast response time. The advantage with this kind of sensors is that the use of a separate reference electrode is not required. Unfortunately, however, keeping the cavities clean is a major concern.

Electrochemical potentiometric CO₂ sensors using solid electrolytes are one among promising methods because of their compact structure, ability of continuous monitoring, high selectivity, and low cost (Hong, Kim, Jung, & Park, 2005). However, they require power for signal generation, and often require above 400 °C operating temperature and, therefore, are not suited for food packaging applications. The environmental factors such as temperature and humidity can affect the sensors performance, especially in the case of metal oxide sensors, by cross-sensitivity reactions.

2.2. Innovative optical CO₂ sensors

The concept of on-pack, continuous gas composition indicating optical sensors are attractive and have been developed, tested by many researchers for monitoring MAP package integrity. Optical CO₂ sensors can be classified into two types, namely, the sensors which function based on the color (colorimetric) change of a pH indicator dye, such as thymol blue, phenol red, cresol red, etc. (Kawabata, Kamichika, Imasaka, & Ishibashi, 1989; Mills, Chang, & McMurray, 1992, Mills, Lepre, & Wild, 1997); and those based on the CO₂-induced fluorescence change of a luminescent dye (Marazuela, Molenono-Bondi, & Orellana, 1995; Mills & Chang, 1993) such as ruthenium (II) complexes and 1-hydroxypropene trisulfonate.

2.2.1. Wet optical CO₂ indicators (pH-based)

All wet optical sensors function on the principle of Severinghaus carbon dioxide electrode, and therefore diffusion of CO₂ from the test medium (gaseous or aqueous) through a thin (ca. 10 μm) gas permeable membrane, and a quick establishment of equilibrium with the entrapped aqueous layer, which contains pH-sensitive dye, usually occurs in a typical wet optical sensor for CO₂ (Mills, 2005). The detection process involves mixing of gas to be tested with a chemical reagent/dye which results in a color change/shift of the chemicals. This change of color can be measured and compared to a standard. The usefulness of colorimetric analysis for CO₂ measurement has been shown (Hauser & Liang, 1997; Mills & Monaf, 1996; Uttamial & Walt, 1995). Tufflex GS pouches that contain a visible CO₂ indicator were developed by Sealed Air Limited. The pouches can be used to identify machine faults and gas supply problems, to indicate non-integrity of the package, and to check the presence of desired gas mixture in modified-atmosphere packaging. A reversible CO₂ indicator comprising five indicator strips for use in modified-atmosphere packages was fabricated and patented by Balderson and Whitwood (1995); the strips are coated with CO₂-sensitive indicator material, for instance, anion of an indicator and a lipophilic organic quaternary cation (Mills & McMurray, 1991), and each strip is designed in such a way that changes their color when the CO₂ level is below a certain limit (e.g., 25%, 20% or 15%). A mixed pH dye-based, on-package colorimetric indicator was developed for real-time monitoring of intermediate-moisture dessert spoilage (Nopwinyuwong et al., 2010). This indicator responds through visible color change to carbon dioxide (CO₂) as a spoilage metabolite; and the change correlates well with microbial growth patterns in dessert samples.

To sense ripeness of fermented vegetable foods such as kimchi several physical properties such as color, volume, turbidity; chemical properties such as pH, acidity, CO₂, sugars, salts, etc., and microbiological properties have been tested (Mheen & Kwon, 1984). However, commercial packed kimchi products generally undergone a continuous natural fermentation process even during storage and distribution. So, the ripeness/over-ripeness cannot be detected by general testing methods without destroying the packaging materials (Hong & Park, 1999). Therefore, a sensor which can monitor the CO₂ gas continuously, and indicate levels through exhibiting different colors accordingly, non-destructively, has been under development. Changes in CO₂ concentration within the kimchi package showed a sigmoid increase during fermentation. A color indicating sachet responding to CO₂ levels has been developed for application to kimchi packaging (Hong & Park, 1997). However, the technique suffered from disadvantages of inconvenience, handling difficulty and safety concerns for commercial products. The same research group had developed a color indicator film consisting of polypropylene (PP) resin, Ca(OH)₂ as a CO₂ absorbent and bromocresol purple or methyl red indicators, and the film was attached to the lid.
Majority of colorimetric CO₂ optical indicators are solvent-based (i.e. non-aqueous) systems, incorporating a phase transfer agent (PTA) to solubilize the usually lipophilic dye and base (Mills et al., 1992). However, poor shelf life stability of such systems is a major drawback when stored under dark and/or ambient conditions (Mills & Monaf, 1996; Weigl & Wolfbeis, 1995). Thus, the dye in such indicators changes irreversibly to its acidified form, rendering the indicator ineffective in short time. Therefore, usually an inert atmosphere is used in packaging, but with additional cost to production. Interestingly, water-based CO₂ indicators have shown markedly greater lifetimes, than their solvent-based counterparts. A water-based ink containing base-sodium hydrogen carbonate and plasticizer-glycerol, having improved operational lifetimes, quick response and recovery times (≤ 2 min), reversible color change on all tested surfaces, and works under ambient condition has been reported (Mills & Skinner, 2010). However, sensitivity to humidity and temperature is needed to be addressed before realizing potential usage for intelligent food packaging applications. But, luckily, a fixed temperature (chilled, 4 °C) and unchanged % RH is usually maintained for MAP food packages and, therefore, water-based CO₂ sensors could be used. The sensitivity of CO₂ sensor is linked to the equilibrium constant (pKa) of the pH indicator used and to the nature of surrounding buffer (Mills & Chang, 1994). An aqueous bicarbonate buffer usually contained in first generation optical carbon dioxide sensors. The aqueous buffer containing sensors have been replaced by quaternary ammonium hydroxide containing solid sensor membranes (Mills et al., 1992). Earlier, colorimetric leak indicators in the form of sachets and tablets have been used for sensors development in food packaging technology. Latest approaches, for more compatible with industrial demand, would consist of printable sensor membranes on the packaging material and should provide information about analytes at any given stage in the packaging and delivery process.

2.2.2. Principle in pH dye-based indicators

The carbon dioxide gas dissolves in the aqueous buffer or hydrophilic filter layer in strip or membrane type sensor and forms carbonic acid.

\[ \text{CO}_2(g) \rightleftharpoons \text{CO}_2(aq) \]

\[ \text{CO}_2(aq) + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3 \]

The two hydrogen atoms from the formed carbonic acid (diprotic) may dissociate to form hydrogen ions (H⁺) and bicarbonate ions (HCO³⁻) with pKₐ of 6.36 at 25 °C (Mook & de Vries, 2000).

\[ \text{H}_2\text{CO}_3 \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \]

Then, a hydrogen ion, as a proton, combines with a water molecule to form a hydronium ion, H₃O⁺

\[ \text{H}^+ + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ \]

Hydronium ions react with the basic (dissociated) form (In⁻) of the indicator dye, resulting in an acid (protonated) form (HIn) which in turn produces a color change of the indicator containing solution or label.

\[ \text{H}^+ + \text{In}^- \rightarrow \text{HIn} \]

There are certain drawbacks are associated with use of pH-based sensors that CO₂ levels cannot be measured directly, but in its ionic form and, therefore, the pH-value measurement could be impaired by other volatile acid or basic gases produced during spoilage. And also, maintenance costs are very high.

2.2.3. Fluorescent CO₂ sensors

Similar to the colorimetric method except that a fluorescent dye is used to generate its own radiant energy at a different wavelength to that of the excitation wavelength. The generated excitation spectra will depend on the sample gas concentration. CO₂ measuring instrumentation also fabricated using this principle (Choi & Hawkings, 1995a,b; Wolfbeis & Weis, 1998).

A printable oxygen and carbon dioxide sensors formulations have been developed for application in food packaging (McEvoy et al., 2003); the oxygen was measured by detecting the degree of quenching of a fluorescent ruthenium complex entrapped in a sol-gel matrix. For monitoring CO₂ gas, a fluorescence-based and pH-sensitive 8-hydroxyppyrene-1, 3, 6-trisulfinic acid (HPTS) indicator dye encapsulated in organically modified silica (ORMO Sil) glass matrix was used. In the context of in-situ monitoring of analytes, issues such as cross-reactivity, robustness, and humidity interference need to be addressed before realizing the full potential.

2.2.4. Dry optical CO₂ sensors

A novel plastic film incorporated with fluorescent dye HPTS was used to sense CO₂ gas with a 0–90% response and recovery times of the film when exposed to an alternating atmosphere of air and 5% CO₂ are typically 4.3 and 7.1 s, respectively (Mills & Chang, 1993). Phase transfer agent (PTA) such as tetroactyl ammonium hydroxide (TOAH) plays vital role in the fabrication of solid, dry CO₂ sensors. PTA agent in its general form, Q°OH°, can be used to dissolve the anionic form (D⁻) of a colorimetric pH indicator dye, such as m-cresol purple (MCP), in a hydrophobic solvent, such as toluene, that is mutually compatible with that of a water-insoluble polymer, such as ethyl cellulose (EC) or polyvinyl butyral (PVB) (Mills, 2009). Thus, it was found that mixing of pH-sensitive, hydrophilic indicator dye anion with phase transfer agent result in formation of ionic pairs, Q°D⁻, which can be dissolved in hydrophobic solvents. Therefore, a color-based dry CO₂ sensor comprises a pH-sensitive dye/phase transfer agent/polymer/solvent, which could be cast, by printing, spin-coating, to generate a range of thin, colored plastic films containing a pH-sensitive dye in its deprotonated anionic form, i.e. as Q°⁻. Carbon dioxide levels in dry and humid gases can be determined by using these types of solid dry sensors. The sensor sensitivity toward CO₂ decreased with increase of temperature. Also, acidic and oxidizing gases have a marked and irreversible deleterious effect on the response features. A luminescence intensity-based dry optical sensor film was designed using the luminescent dye, HPTS, the phase transfer agent, TOAH, the polymer, EC, and the plasticizer, tributyl phosphate (TBP) (Mills & Chang, 1993).

2.2.5. Sol-gel-based optical CO₂ sensor

An optical sol-gel-based CO₂ sensor strip was fabricated using a fluorescent pH indicator, 1-hydroxypyrene-3, 6, 8-trisulfonate (HPTS) (Bültzingslöwen et al., 2002). The sensor exhibited a fast and reversible response to carbon dioxide over a wide range of concentrations (0–100% CO₂) with sufficient resolution (±2%). The dye was immobilized in hydrophobic organically modified silica matrix. Cetyltrimethylammonium hydroxide (CTA-OH), a quaternary ammonium base, was used as an ion-pairing agent for a polar pH indicator in a non-polar gas permeable membrane, and also it functions as internal buffer. The Dual Luminophore Referencing (DLR) sensing method, an internal ratiometric method, is used for measuring the fluorescence. In which, the analyte-sensitive fluorescence intensity signal is converted into the phase domain by co-immobilizing an inert long-lifetime reference luminophore.
having similar spectral characteristics. Ruthenium complex and HPTS dye are the excellent candidates for a DLR-type CO$_2$ sensor because their excitation and emission wavelengths are well matched. Oxygen cross-sensitivity is minimal and compatible with established optical oxygen sensor technology.

2.2.6. Photonic crystal sensors

2.2.6.1. Polymer opal films. Color changing polymer opal films have been developed by various research groups and were initially developed at the University of Southampton in the United Kingdom and the Deutches Kunststoff-Institut (DKI) in Darmstadt, Germany. The polymer opals are a type of photonic crystal consisting of a 3D lattice of plastic spheres but have a large contrast in their components’ optical properties. This causes a range of frequencies to occur and, therefore, causes variations in the light that is reflected from these regions, also called photonic band gaps. Tiny carbon nanoparticles can be wedged between the crystalline spheres. Thus, incident light cannot reflect at the interfaces between the crystalline spheres and the surrounding materials, but scattering of light can occur. Due to a high surface to volume ratio of nanoparticles, an intense color is generally observed in produced opal films. The color depends on manner of arrangement of the spheres and the placement of the nanoparticles. Stretching of flexible films will cause orientation of the lattice structure and changes to the distance between the spheres. This will cause a change in color to appear.

2.2.6.2. Polymer hydrogel-based CO$_2$ sensor. In response to external stimuli, polymer hydrogels can exhibit large reversible change in their volume, and thus regarded as suitable materials for chemical sensors. These kinds of sensors are best suited for food packaging applications due to the fact that they don’t require sophisticated and expensive detection systems. They offer fast response times, and are robust. Also, sensors have a long lifetime (>6 months) without degradation of response time or reproducibility. Volume change in hydrogel is exerted by Donnan potential between the analyte ions and their receptor which is covalently bound to the hydrogel building block (Shin, Braun, & Lee, 2010). In order to compensate the local ion inhomogeneity, there is influx of water molecules to the hydrogel. Color change of sensor is observed due to volume change in periodic structure, known as photonic crystal. These hydrogels are imprinted with photonic crystal; such color is often called ‘structural color’. Relatively simple optical detection techniques are possible using hydrogel photonic crystal sensor, for a wide variety of analytes such as protons (Debord & Lyon, 2000; Xu, Goponenko, & Asher, 2008), metal ions, glucose, and volatile organic compounds (VOC). Therefore, a proton-based photonic crystal CO$_2$ gas sensor could be fabricated for use in food packaging.

2.2.7. Color changing metals

Recently, a research group identified the color changing nature of modified rhodium metal to different gases. The modified rhodium changes to yellow in the presence of nitrogen, deep blue in the presence of oxygen, and brown in the presence of carbon monoxide. According to head of the team, the gases bond to the compound’s central metal without disrupting the exact placement of each individual atom in the compound’s crystalline lattice in an unprecedented way (Queen’s University, 2011, July 21). This discovery could form the basis for development of early warning system if failure of MAP system occurs. However, this metal usage in food systems could be subject to food safety clearance.

3. Safety & regulatory aspects

Indicators or sensors are intended to be placed inside the packaging exposing to headspace atmosphere and, therefore, safety criteria have to be fulfilled. Often, packaging materials are in direct contact with food inside the pack, so the embedded or attached indicators to these packing materials must be suitable for direct food contact applications. A major role by nanotechnologies is expected in fulfilling the additional safety considerations and existing gap in knowledge (Danielli, Gontard, Syropoulos, Zonderwan Van Den Beuken, & Toback, 2008).

For innovative food packaging technologies to be successful, they must comply with strict regulations. Most of the active and intelligent agents are considered as food-contact material constituents, not as additives, and, therefore, food packaging systems must comply with the existing food-contact materials regulations. According to the EU framework directive, all the food-contact materials shall not be hazardous to human health and shall not affect the composition or sensory character of the packed foodstuff in an unacceptable way (De Kruifj et al., 2002).

4. Conclusions

It can be concluded that the optical carbon dioxide gas sensors are suitable for food package indicator applications. Especially, dry optical sensors containing pH-sensitive dye indicators are better suited for CO$_2$ monitoring and/or as spoilage indicators in food packaging application. However, issues such as humidity interference, lifetime, cost, safety, and proton generation during other oxidative reactions have to take into consideration before realizing the complete potential of pH-based sensors. Water-based, CO$_2$ indicator inks can be used potentially in food package applications. Although they are relatively less sensitive toward CO$_2$ than their solvent-based counterparts, possess more stable shelf life and quick response/recovery time. On the other hand, photonic crystal sensors are promising due to low cost, long lifetime, suitability to wide variety of analytes, and effective indication with quick response time. However, there is still more research efforts are necessary for the development of food application-specific sensors.

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