Communicative Packaging Systems for Safety of Food Products

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Abstract

The packaging system protects the food content from moisture, oxidation, biological deterioration, and physical damage and facilitates product distribution throughout the supply chain. It is of the utmost importance to select the suitable packaging material, right packaging technique, and distribution system to meet the consumer demand. The traditional packaging system facilitates the distribution system by performing the basic function of containment, protection, preservation, and communication. Nowadays food industry and consumers are more concerned about the product's freshness and safety apart from containment and protection. This chapter entails that a communication-based packaging system is an important technique that improves or indicates product safety in the supply chain using smart devices in the packaging system. It monitors the changes in the environments and communicates the condition of food products throughout the supply chain. Smart devices may include various indicators, sensors, Radio frequency identification tags, bar codes and other techniques that improve food safety and quality. These devices establish a chain of responsibility throughout the food supply chain and build a more transparent distribution system and transmit information, rectifying the existing challenges and improving food safety.

Keywords: Communicative packaging, Smart packaging indicator, Food safety, Sensors, RFID

Introduction

There are four primary functions of a packaging system involving containment, protection, convenience and communication. Protection of the food materials is one of the primary functions of packaging materials. In general, all the packaging materials protect the food material from the external environment to ensure that the food product is safe and fit for consumption and is not contaminated by external materials (Roberson, 2016). Moreover, these functions are connected; the food packaging industry has sought additional functions to raise the regulatory body's concern and meet the consumer demands for food safety in the supply chain and storage. Food business operators implement GAP & HACCP to ensure that these hazards do not occur in any processing stages (Kleter & Marvin, 2009). Once the product leaves the processing site, there are possibilities that these hazards will occur in food from the environment, but most of the time, these are not monitored as the facility lacks to check them. The possible safety concerns may be contamination with physical hazards, chemical changes in food, migration from the packaging materials, and the rise of microbial load. A Communicative-based packaging system can play an important role in achieving a safe food supply chain. A communicative-based packaging system monitors the condition of packaged food, carries basic information during distribution, and can convey information about its quality. It has functions like sensing, recording, detecting, tracking and communicating to facilitate decision making to extend shelf life and warn about possible problems. This chapter entails various communicative-based smart packaging systems, smart packaging devices, data layers, data processing and wireless communication network, highlighting the research involved in food product safety. These smart package devices may be attached to primary packaging or secondary packaging to communicate throughout the supply chain.

Packaging system for microorganisms and toxins detector

Foodborne diseases generally occur due to contamination of food with microorganisms and are a major threat to consumers. These microorganisms produce toxins or ill effects if ingested by consumers. It requires strict monitoring of food products in the supply chain and storage. Therefore, many modifications in the packaging have taken place to identify the growth of microorganisms. The potential target molecules for microorganisms and toxins covers organic acids (lactic and acetic acids), glucose, ethanol, volatile nitrogen compounds (ammonia, dimethylamine, trimethylamine), biogenic compounds (histamine, carbon dioxide, ATP-degradation products), and sulfuric compounds, etc. The decrease or increase of the target compounds is used as an indication of the quality of food. Most of the spoilage indicators are based on color changes due to microbial metabolites produced from spoilage. Packaging systems that indicate a clear visible readout can be employed in such cased for warning the consumer about safety. The pH dyes-based indicators are frequently used in the food packaging industry to detect spoilage of food products. A typical example is a colorimetric mixed-pH dye-based indicator developed by Rukchon et al. (2014) to monitor skinless chicken breast spoilage on the package. The amount of CO2 and total color difference of the indicators correlate with the spoilage of chicken. The pH dye reagents include bromothymol blue, methyl red, bromocresol green, xylenol blue, bromocresol purple, cresol red, phenol red, and alizarin are generally used for indicators. Gas sensors may also be used for the indication of the quality of food products. The various indicators are studied for gases, but gas sensors employ changes in the sensor's electrical properties for changes in food to correlate the decay process better. A paper-based electrical gas sensor (PEGS) was developed in a study by Barandun et al. (2019) for sensing water-soluble gases using cellulose paper and carbon ink. The maximum sensitivity of PEGS was for NH_3 followed by trimethylamine and CO_2, while CO and H_2S were least detectable. There was an increase in the conductance of PEGS when the concentration of NH_3 was increased. The sensor's sensitivity was affected by environmental RH. The sensor's increased conductance is attributed to an increase in the concentration of NH_3, trimethylamine, and dimethylamine, which correlated with the microbial load of the meat. The electronic nose and biosensor also can communicate the quality of food products during the supply chain.

Packaging system for tampering

Tampering can be defined as the change in the package condition from external forces, which may be intentional or unintentional. In general, it is the question of integrity and safety of the package. Food products are carefully sealed in packaging material before dispatching them from the company. During transit, the package may get damaged from a pointed object, or a person opens it and closes it back. If a person intentionally opens a package, it would help to acknowledge that it has tampered and might not be safe. Due to these reasons, there is a need for a packaging system to detect tampering. It will ensure that the food is safe and has not been contaminated intentionally or unintentionally from the external environment. It has a wide application for MAP and other packaged food.

For advanced packaging systems, there is continuous development in this category of packaging. Gas indicators are used to detect package leaks, sealing integrity and quality of food products. Most of the gas indicators are based on colour change, transparency and pH change. The most widely used oxygen indicator is composed of redox dyes and strong reducing agents- the conventional oxygen indicator films based on synthetic and artificial components. A two-compartment arrangement was used by Won et al. (2016) for developing a tampering indicator using natural compounds (laccase, guaiacol and cysteine). Laccase in one compartment and guaiacol & cysteine was kept in wells of the indicator. The indicator containing laccase (1 U/mL), guaiacol (5 mM) and cysteine (5mM) was evaluated at different concentrations of oxygen (1, 10 and 21), which showed a maximum color difference at 21% oxygen after 2 hrs of tampering. The rate of color change increased with increasing oxygen concentration. Vu & Won (2014) made a colorimetric oxygen indicator film with carrageenan and redox dyes to reduce dye leakage with water. Carrageenan was employed at 0.2, 0.3, 0.4 and 0.5% in the films using dip coating. Three different redox dyes, methylene blue (MB), azure A (AA) and thionine (Th), were used for indicator films. Leaching studies of the film indicate that the dye leaching from the carrageenan films was very low compared to zein-based reference films subjected to electrostatic bonding between carrageenan (anionic) and dye (cationic). Upon UV irradiation, MB/TiO_2/glycerol/carrageenan-based films were completely bleached in 4 minutes with a decreased rate for films with higher concentration. The film with 0.2% carrageenan recovered in 8 hrs in the presence of the oxygen at ambient condition. These Carrageenan-based colorimetric oxygen indicator films can be utilized in the MAP products to maintain low oxygen levels, indicating the package's poor seal or tampering. Furthermore, the kinetic indicator study is needed to understand the effect of oxygen level on the indicator recovery.

CO_2 concentration also gives an idea about the tampering or package leak. Choi & Han (2018) developed a CO_2 indicator utilizing sodium caseinate and pectin solution for real-time monitoring of food quality based on transparency and pH. Sodium caseinate tends to agglomerate at lower pH, which changes its transparency. Pectin further lowers the agglomeration point as their zeta-potential and isoelectric point is changed. In the presence of

CO_2, there is a reduction in the solution's pH, which can be inferred from the solution transparency. As most of the deterioration process is assisted by microbial growth in the substrate, which increases the CO_2 concentration, this solution can potentially detect the CO_2. The indicator was used to determine the quality of the kimchi at room temperature for five days. As there was the growth of *Lactic acid bacteria* during storage, the pH changed and subsequently, the transparency altered due to a rise in CO_2 concentration. In many cases, CO_2 rise also occurs due to overripe products or fermentation. A similar principle for developing CO_2 indicator was utilized by Lee & Ko (2014) with whey protein isolate. Whey protein isolate solution tends to alter its turbidity due to aggregation upon a change in pH below 6.0 due to transition at isoelectric point. A lower concentration of the whey protein isolates favored a steep decrease in the pH and turbidity in a 100% CO_2 environment. A 0.3% whey protein isolate solution used in the sachet showed a pH transition from 7.05 to 5.50 and transparency from 71.1 to 12.6% in 100 minutes under a 100% CO_2 environment. Jung et al. (2013) indicated that the pH decreased due to reaction with the CO_2 into the headspace for the solution transparency. Chitosan-based CO_2 indicator includes, which is turbid at pH 7.0 and changes to transparent at low pH due to chitosan dissolution. 2-amino 2-methyl 1-propanol (AMP) was incorporated in an indicator to control the rate of transition of chitosan dissolution. The indicator behaves significantly different at different temperatures. At 10°C, Lactic acid bacteria's growth during storage was delayed, which took 9 days to reach pH 4.0 compared to 10°C storage. Optimum ripening of kimchi (pH 4.0-4.2 and titrable acidity 0.4-0.8%) was achieved in 1 day and 5 days at 20 and 10°C, which directly correlated with the transparency of the indicator solution. These indicators are not exhaustively studied, but their study for different temperatures and CO_2 levels improve these indicators' functionality. Furthermore, these have a great potential to be used as an indicator to communicate about the package tempering.

a. Time-Temperature Indicator based packaging system

The temperature has a significant effect on the quality and shelf life of the food product. A Time-Temperature Indicator (TTI) is a device that is intended to record the temperature history of the product after production (Giannakourou et al., 2005). TTI devices are small adhesive labels integrated onto food containers or individual packages to monitor food product quality during distribution and storage. The most common TTI is based on deformation, colour movement or colour development with temperature change in the supply chain. TTI generally reflects partial or complete temperature history, which can also reflect on food product safety. An elevation in the temperature during transportation accelerates the growth of microorganisms in the food product. These microorganisms pose a threat to human safety as many of them are responsible for foodborne illnesses. TTI can be classified into six categories based on their mechanism (Dan et al., 2014):

1. Diffusion based TTI
2. Microbial TTI
3. Enzymatic TTI
4. Polymer based TTI
5. Photochemical TTI
6. Electronic TTI

TTI are dependent on temperature and its indication changes upon temperature change. Hence, it becomes an important aspect to calculate the activation energy of these TTI to implement with the type of food that matches TTI. Furthermore, there should be alignment in the endpoint of TTI with the end of food product shelf life (Wanihsuksombat et al., 2010).

Diffusion-based TTI incorporates material that flows depending on the temperature of the storage. During distribution and storage of perishable food products, diffusion-based TTI systems can be an important tool for monitoring microbial quality and temperature abuse. A diffusion-based TTI with isopropyl palmitate (IPP) was studied by Kim et al. (2016) for the microbiological quality of non-pasteurized angelica juice during storage. The diffusion of IPP in mm was studied and modeled isothermally over a range on temperature (15, 20, 25, 30, 35ºC) and verified at 13, 23 and 33 ºC. This TTI was used at non-pasteurized angelica juice at 5, 15 and 25 ºC for 48hrs. Microbial growth was not favored at 5 ºC. 6 log cgu/ml was taken as critical and for 15 ºC, 9.7 mm was covered in 36.6 hrs and for 25 ºC, 7.2mm was covered in 12.5 hrs by TTI to reach critical growth. Dynamic temperature storage study showed a distance of 7.6 mm in 27.4 hr. Hence, IPP diffusion of 7 mm is set for the threshold for microbial spoilage Isopropyl palmitate diffusion showed similar increases in microbial growth after 12 h.

Microbial-based TTI prevails over other TTI as these give more accurate results. Kim et al. (2012) optimized pH-indicator to be used with lactic acid bacteria-based TTI. Out of 5 pH indicators, bromocresol green was the best based on maximum colour change, ΔE and response function F(x) when tested at 37 ºC followed by bromocresol purple, bromophenol blue, chlorophenol red and congo red. The TTI exhibited activation energy for 4 microbial strains of lactobacillus between 103.88-116.35 kJ/mol indicated that it could be used for various food depend on their spoilage characteristics.

Enzymatic TTI utilizes enzymes that react with a substrate at a temperature-dependent rate. An enzymatic TTI was developed by Brizio & Prentice (2015) based on the activity of α-amylase. Starch and iodine form a dark blue color complex. This was utilized to verify that the ham was properly pasteurized or not. When starch is heated, it is converted into maltose by the activity of α-amylase and as the concentration of the starch depletes, the dark blue complex turns whitish-yellow. Hence, heating the ham for the desired time was analogous to the complex color degradation, a suitable enzymatic TTI to ensure ham's pasteurization. A concentration of 6.5% of α-amylase was optimum for use as it coincides with the ham pasteurization and even after 4 months, this TTI works fine if stored in refrigerated condition. In a recent study, Wu et al. (2013) developed a TTI in which urease reacts with carbamide to produce carbamic acid and ammonia. This results in increased solution pH and phenol red, a pH-dependent dye, and its color changes from yellow to red. TTI has activation energy (Ea) of 23.05±1.15 kJ/mol for a temperature range (5, 10, 15, 20, 25 and 30 ºC), which can be used with foods that exhibit similar spoilage characteristics.

A polymer-based TTI employs a polymer matrix for making TTI. Lee & Shin (2012) studied the polymer-based TTI to determine activation energy. The TTI was prepared from 4,4’-bis(2-benzoxazolyl) stilbene (BBS) chromophores and commercial polymer TOPAS 5013, a copolymer of ethylene and norborene. Beyond the polymer's glass transition temperature, irreversible phase separation occurs, which aggregates the dye resulting in the change in color of TTI. 1 and 2% BBS exhibited noticeable color change above the 140 ºC. Kinetic modeling of the TTI gave activation energy of 185.67 and 179.29 kJ/mol. The TTI is suitable to use for retort processing, baking and confectionery processing purposes.

An electrical-based TTI measures electric properties such as conductivity, resistance, etc. of substances that vary with time and temperature. Wan & Knoll (2016) fabricated and investigated an electrochemical TTI. This contains a conductive activation layer and hydrophilic migration layer. TTI can be activated with the help of 0.5M NaOH filled in the temperature-sensitive film that migrates from the doping front of TTI. The length of migration fits with the conductance, which depends on the storage temperature. This can avoid the food from temperature abuses by indicating the end of shelf life upon storage.

b. Bar codes for packaging system

Bar codes are intended to deliver the information when scanned. Novel barcodes are introduced in the food packaging to promote the quality of food. It incorporates using chemical or enzymes which react and change its appearance concerning the reference barcode. The code change is always subject to chemical or microbiological alterations in the food. This is emerging as a promising visual indicator that can be utilized to indicate the food safety. A US patent provides innovation that a dual barcode was made to detect toxic contamination (Goldsmith et al., 2002). The bar code is prepared with labeled antibodies and printed on the substrate formed with antigens. As the toxins are produced upon the product storage, the toxin binds with the substrate antigens. This leads to changes in the binding with the antibodies and the barcode changes, indicating toxins or contamination that occurs upon scan. Different antigens can be employed depending on the toxin or contaminant that is to be identified. A barcode for sensing the volatile organic compounds (VOCs) in the food sample was also developed recently. A filter paper-based colorimetric sensor array was developed by Chen et al. (2017), which use a mobile phone to diagnose chicken samples' freshness and safety at different temperature ranges. Barcode sensor fabricated in square shape contains Nile red (rectangle), zinc-tetraphenylporphyrin (triangle) and methyl red (circle). These three dyes change optical readout concerning emanating VOCs and pH change for the chicken meat upon storage. The picture was taken from the phone and processed in MATLAB for R, G, and B values. The intensity of the R was analyzed in the principal component analysis because of its maximum sensitivity. A significant daily and hourly change in the PCA was observed, which was distinguishable, and it can be used to predict the freshness and aging at different temperatures. This barcode sensor can be a very promising alternative for consumers as it does not require expertise to evaluate the parameters. Further development for this sensor can be employed by developing mobile software with the database in cloud storage for different temperatures for different products. The development of novel barcodes (such as toxins and metabolites-based) can further strengthen the application of intelligent food packaging. Though there is continuous development for food product safety, more novel barcodes with a wide application should be developed. Their easy interface would help consumers read out the status of safety.

c. Radio Frequency Identification based packaging system

Radio Frequency Identification (RFID) deals with many existing food industry problems such as waste in the supply chain, empty shelves at retail outlets, temperature, theft, and recall of dangerous products subjected to foodborne illnesses (Harrop, 2012). Every food business operator should adopt product recall to ensure that safe food is delivering to consumers. In case of emergencies, these affected foods can be recalled and outbreaks can be stopped. The tags implemented may be active, semi-passive, or passive. These devices operate in low frequency (125-134 KHz), high frequency (13.56 MHz), ultrahigh-frequency (860-960 MHz) and super high frequency (2.45-5.8 GHz), but most of the time, high and ultra-high frequencies are employed (Bibi et al., 2017). An active RFID continuously sends the information rather than the passive. RFID employing temperature is useful in conforming to HACCP requirements (Kumar et al., 2009).

RFID is meant to deliver the information from a distance irrespective of the barcodes, giving information upon scanning. In development by Nambi et al. (2003), an RFID named Auburn University Detection and Food Safety (AUDFS) was made using a biosensor interface operating at 13.56 MHz. This biosensor interface was capable of identifying pathogens like *Salmonella* and *E. coli* in the food. This can be used widely in the food chains to minimize foodborne illness risk due to pathogens. Hence, it may serve to deliver safe food to the consumers. RFID technology is widely used in integration with the TTI, humidity sensors, etc., directly telling about the food package's current situation. It will reduce the consumption of spoiled food and waste and better control the supply chain by monitoring and rectifying the existing challenges towards food safety and security. Huang et al. (2006) conceptualized using mobile diagnosis on RFID for food product safety. RFID operating at 13.56 MHz was employed with PDA in the mobile server with remote monitoring and diagnosis server. The remote diagnosis sensor records the food product storage temperature changes using an X-chart and statistical process control. The abnormality in the temperature was communicated and classified for its severity by transmitting data between RFID and PDA attached to the phone. Various data can be fused at a time to provide the severity of the abuse. The emergence of this concept in RFID can help the various parties in the food supply chain monitor the food status with temperature abuse.

In a recent development of critical temperature indicators (CTI), integrated RFID tag microfluidics technology is used (Lorite et al., 2017). The indicator functionality depends upon a solvent melting point. Dimethyl sulfoxide with erythrosine B is employed for horizontal and vertical CTI to understand the working of solvent-based indicators. Microfluidic technology-based CTI, when integrated with passive RFID tag operating at 13.56 MHz with a reading range of 10cm, using hexadecane as solvent (critical temperature 19°C), sends a signal to the attached PC/tablet interface as the critical temperature is reached with the help of the reader. The RFID signal is based on the change in the system's resistance from 1 kΩ to 8 kΩ as hexadecane melts. This microfluidic CTI integrated RFID can be utilized for the supply chains with different critical temperatures using different solvents. Another temperature and humidity measurement-based passive RFID was developed by Le et al. (2016) for analyzing the freshness of the packaged vegetables. The reader can read the tag from a distance of 30cm for temperature and humidity values. This can help determine the freshness of the packaged vegetables. RFID employed in the food system can be very helpful in continuously providing information at the interface. This can be used to assess the food products' quality and safety in the food supply chain. Moreover, various losses concerning quality and microbial growth can be controlled with conveyed information.

Conclusion

The food industry, consumers and regulatory bodies are concerned about the safe food and transparent supply chain system for food products. In this sense, a new packaging system based on smart devices will continue to evolve to improve product traceability and reduce food waste. The current chapter entails a communicative-based packaging system that has evolved to provide enhanced communication and better information at an optimized cost in the food supply chain and storage. In this packaging system, inexpensive labels or tags of smart devices are attached to the packaging to monitor changes in food packages and communicate the food product conditions throughout the supply chain. It is concluded that smart devices-based food packaging is gaining importance for consumers, industry and researchers due to its potential to provide information to achieve the desired benefit in food quality and safety enhancement. Various indicators, sensors, tags, and bar codes are developing in recent years, which are being integrated into the packaging systems to improve the food supply chain management. This type of packaging could add several benefits to the system by enabling real-time monitoring, integrity, and traceability of the products while moving along the supply chain. Future research should direct on the manufacturing and deployment of smart devices in packaging systems to enable a wider application to improve the food supply chain.

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