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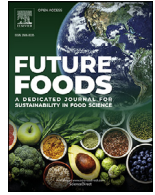
RFID-based sensing in smart packaging for food applications: A review

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ABSTRACT

The global pandemic COVID-19 has led to an increase in the number of people purchasing food online, which has brought to a higher demand on the food supply chain. Such as the need to collect more information related to food safety and quality in real-time. Strengthening management of food logistics information flow can reduce food loss and waste and bring better quality and safety of food to consumers. In this review, the importance and applicability of RFID (Radio Frequency Identification) technology to smart food packaging are described. This study emphasizes the recent advancement of the RFID tags in humidity, temperature, gas, pH, integrity, and traceability sensor applications in connection with food packaging. RFID sensors are more suitable for smart packaging both in terms of sensing ability and data transmission. A simpler, low-cost, more robust and less power-demanding sensors network is the development direction of smart packaging in the future. Chipless RFID sensors have the potential to achieve these functions. But it still faces many challenges to be overcome. For example, biocompatible, cost, reading range, multi-tag collision, multi-parameter sensors, recycling issues, security and privacy of RFID system should be solved.

1. Introduction

Recently, the spread of the COVID-19 pandemic has forced us to re-think the way we consume food, leading to a sharp increase in online trade, including an increase in the number of people purchasing food online(Dannenberg et al., 2020). Moreover, because of short shelf-life, the supply chain of fresh food should be regulated. Consumers also like to know information regarding product status through the entire supply chain, from the manufacture, distribution and storage processes. The following must be considered. Firstly, environmental factors, such as temperature and humidity will influence food quality and increase the risk of product deterioration (Vorst et al., 2009). Secondly, as food quality deteriorates, there is also an increased risk that contaminated goods will influence food safety (Akkerman et al., 2010). The food industry managers need to have more data about food safety and quality in real-time, such as temperature, humidity, and pH, etc. This way, they can ensure that various types of perishable products, such as fruit, vegetables, meats, and fish will remain fresh until they reach their destination.

Hence, the smart packaging is urgently required to collect effective information about the surrounding environment and transport process.

As a primary alternative to traditional packaging, smart packaging can interact with products in real-time and provides crucial data of food products. Yam et al. (2010) defined smart packaging as a packaging systems with a variety of intelligent functions such as detection, sensing, recording, tracking, communication, etc. This system can be used to facilitate decision-making, monitor and provide information on any changes in food quality and warn of possible problems (Wu et al., 2020). The ultimate purpose of smart packaging is to extend the shelf-life and maintain the high quality of food products, improve product's safety, provide information on quality to consumers, and improve traceability of the product along the supply chain (Chen et al., 2020a). Smart packaging to implement these functions normally depends on internal or external hardware, such as indicators, electronic sensors and RFID devices. The main function of indicators is to transmit crucial information about the quality of food to the consumer. Indicators usually provide qualitative or semi-quantitative information in the form of color

changes or color diffusions (Yam et al., 2010). According to the classi-fication of function, commonly the indicators can be divided into: time - temperature, freshness and gas, etc. Indicators can sense and inform on the status of food products to consumers, without any professional device. The color change or color diffusion of an indicator is hard to reverse, so they are difficult to reuse or provide quantitative informa-tion. But recent research shows that some temperature (Zhou et al., 2022) and pH (Ezati et al., 2020) responsive indicators can be reversible. Whereas, electronic sensors can give accurate data for different kinds of parameters observed in food products, for example, electronic nose and electronic tongue. These types of sensors can be both chemical and biosensors, which are mainly applied in food to fermentation monitoring (Buratti and Benedetti, 2016), process and storage evaluation (Gu et al., 2017), quality evaluation (Zhong, 2019), and ripening process tracing (Du et al., 2019). But their size and cost make it hard to embed them in packaging, compared with the ease and low-cost of a traditional bar-code.

RFID technology has progressed significantly in the past few years. Its capability for identification and traceability make a major contribu-tion to food safety and quality. Fig. 1 (a) shows the application architec-ture for food traceability using RFID-based blockchain technology. RFID is now considered to be a likely next generation successor to barcodes. Compared to barcodes, apart from the function of identification and traceability, RFID can read hundreds of tags simultaneously regardless of angle, as well as through the most packaging materials. For instance, an RFID reader can be placed at the entrance of a warehouse to be easily monitored inventory, as shown in Fig. 1 (b). Eventually, it can speed up the logistics processing of goods. RFID tags can also integrate multiple types of sensors that can provide identification and sensing capabili-ties in a wireless, contactless and non-visual way. These sensible RFID tags could detect changes in food properties, such as pH, conductivity, dielectric constant, humidity, temperature, gas, etc, and the recorded information be sent to the central control system (Vanderroost et al., 2014). Fig. 1 (c) shows which aspects of RFID technology can promote the intelligence of food packaging.

Most of the reviews in literature have discussed the application of RFID in different areas, such as (Athauda and Karmakar, 2019) focus-ing on food freshness monitoring; (Bibi et al., 2017) focusing on tracking and monitoring ability; (Landaluce et al., 2020) focusing on the differ-ences between RFID and wireless sensor networks, and the possibility of the integration of the two technologies; (Singh et al., 2017) focus-ing on smart materials; or (Raju et al., 2020) focusing on food quality monitoring. However, in this paper, we have made a detailed review of the potential applications of RFID sensors in intelligent food pack-aging, and explain the future development direction and challenges. In Section 2, we summarize the composition and characteristics of RFID. Section 3 investigates potential applications for food packaging based on RFID technology and RFID sensors. In Section 4, we summarize the challenge of RFID technology development. In Section 5, we discuss the future trend of smart packaging based on RFID. The conclusion of this review is in Section 6.

2. RFID technology

Radio Frequency Identification (RFID), as a non-contact technology that can recognize specific targets, read and write associated informa-tion by using radio waves(Want, 2006). It can communicate between two main types of devices: a reader, which controls the communication, and the tag, which has an associated electronic code, to be uniquely identified. According to a 2019 report by IDTechEx (Das, 2019), the RFID market will total $11.6 billion and grow to $13 billion by 2022. This includes passive and active RFID tags and the other components of RFID systems. Usage is particularly high among livestock and pets, with 580 million tags being used in these areas in 2019, mainly due to local legal requirements. IDTechEx estimates that there will be 20 billion tags
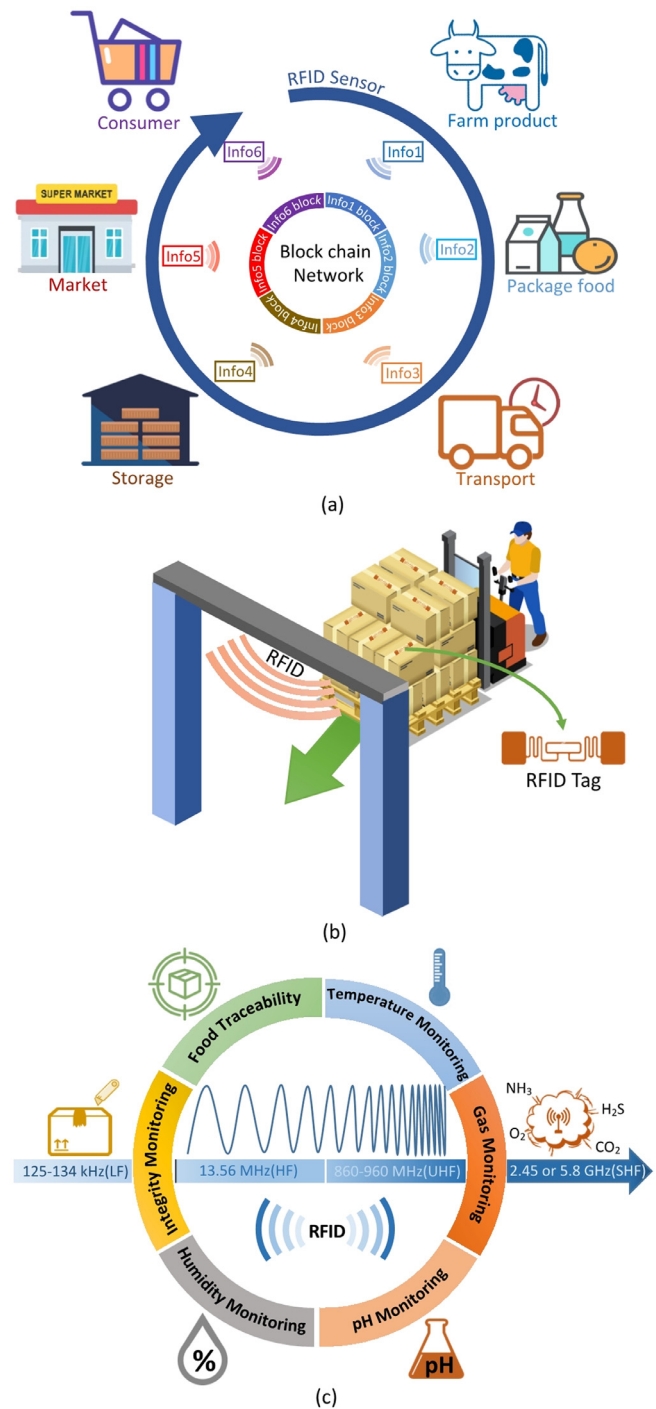

Fig. 1. (a) Architecture of food supply chain based on the block chain and RFID technology. (b) An RFID reader can read multiple tags in a single pass. (c) The framework of RFID for food packaging.

sold in 2019. Much of the growth comes from passive UHF (Ultra high frequency) RFID tags.

2.1. Components of an RFID system

Generally, the RFID system is composed of three parts: transponder (RFID tag), reader, and antenna with an application software system (Hsu et al., 2011). Fig. 2 (a) illustrates a monitoring system operation of livestock which is based on RFID. The tag is comprised of a cou-pling element and a chip for unique identification, the RFID reader can

Fig. 2. (a) The monitoring system of livestock which is based on RFID. (b) RFID tags applied in the food industry.
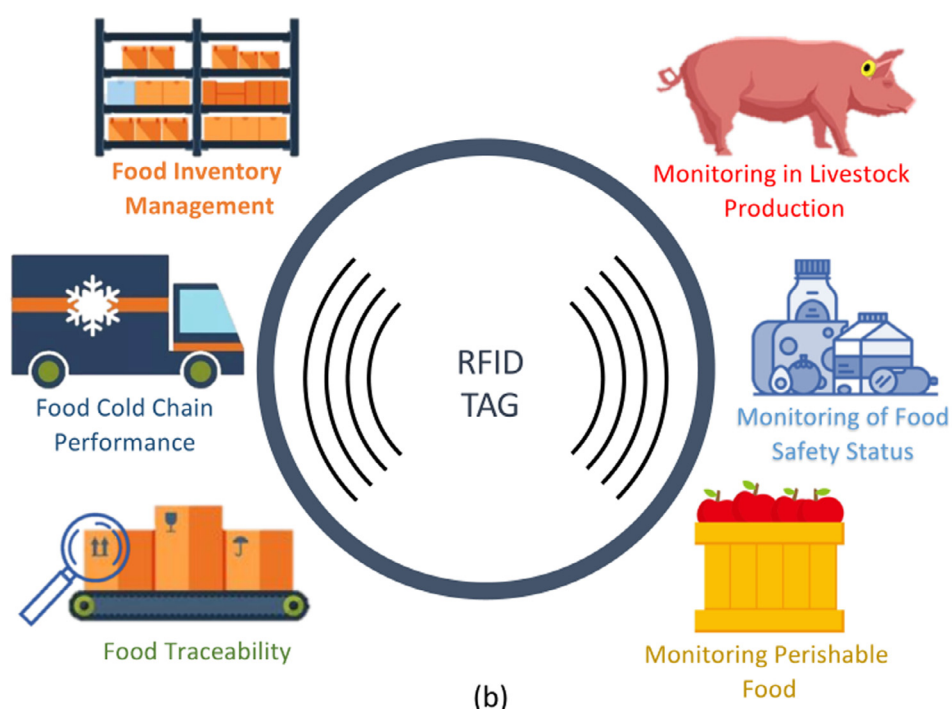
read the information stored in tags, and the antenna is used to transmit radio frequency impulses between the reader and the tag. The application software system includes hardware driver, database and control application for further processing, storage, and the management of data to control tag reading and writing(Harish, 2013). Compared with barcodes, RFID systems have larger operation ranges and can store more data (Kumar et al., 2009). Readers can interrogate faster and communicate with multiple RFID tags simultaneously, with more than 100 or more tags per second being possible. Furthermore, RFID tags do not require contact with scanners.

2.1.1. RFID tags

Currently, RFID tags have been used as a data carrier in many aspects of food industry, as shown in Fig. 2 (b). RFID tags could be categorized into three types based on power source: active tags, passive tags and semi active tags.

Active tags are embedded with a power source for the chip and emit signals via an active transmitter. The features of active tags can be described as following: The capability of the active tags is broader that of passive tags. Moreover, the rate of transmission is faster, and the number of tags being read simultaneously, can be increased. A multi-exchange of information on readings and writings could be done on the chips. Notwithstanding this, the negative points of the active tags are the high costs of the tag, and the relatively large dimensions of the tag. Besides, the tag life is related to the battery life.

Semi-active tags are battery-powered, with the battery only powering the chip, and thus still relying on readers to emit electromagnetic waves. The battery remains inactive most of the time, which can extend the tag life. Compared with passive tags, the energy provided by semi-passive tags can enhance the operating capacity. In certain circumstances, batteries on semi-passive tags can operate sensors connected to the chip and be used for sensors recording.

Passive tags do not include a built-in battery. Instead, they rely on the energy from the radio wave to operate the chip. The data confined in the chips could be read more than once (one writes and multiple reads). The characteristics of passive tags (smaller size, longer life, lower costs, and lightweight) allow them to be developed in a number of ways. Table 1 summarizes the benefits and disadvantages of the three types of tags.

Table 1
Features of three types of tags.

	Active tag	Semi-active tag	Passive tag
Advantage	wider capacity faster transmission rate the number of tags can be read at once multiple exchanges of information	increasing working life	one writes and multiple reads low cost long life small size lightweight
Disadvantage	high costs size of tag operational life relies on battery	complex design	read range single function

2.1.2. Reader

The reader is comprised of a Radiofrequency (RF) interface, a control unit, and an antenna. The RF interface produces power to trigger and run the tag, send data to the tag and receive data from the tag. The reader has one or multiple antennas, which emit radio waves and receive signals sent from the tags. Using a microprocessor, the communication with the tag is controlled by the control unit. This unit encodes and decodes the signals entertained from the tags. The performances of a reader is typically assessed by the rate and range at which the reader recognizes, reads, or writes markers (Kumar et al., 2009).

The device which reads and writes tag information is the information processing center of the RFID tool. It is generally comprised of a control system and a radio frequency interface and uses radio frequency signals to perform non-contact information transmission in a spatially coupled manner, in a range from several centimeters up to tens of meters. Coupling methods can either employ inductive coupling, or electromagnetic backscatter coupling.

The reader communicates with the tag through radio wave, and the back-end system controls or supports the behavior of the tag and the reader to achieve the purpose of the application (Ham et al., 2015). The technological process of RFID tags and the information exchange among tags, readers and communication networks is illustrated in Fig. 2 (a).

2.1.3. Antenna

An antenna is a component enabling the information to be transmitted between tag and RFID readers. The readers and tags of RFID systems have antenna to send and receive data respectively. The antenna of the reader is used to convert the electric energy generated by the reader into radio waves and then send them to the tag. The antenna on the tag receives radio waves and converts them into electrical energy to power the chip (Kumar et al., 2009), Fig. 3 illustrates commonly used RFID antennas.

Antennas can generally be divided into three categories: loop coil type, dipole, and slot (including microstrip patch) type(Zauind-Deen et al., 2011). Loop coil antennas are made by coiling a metal wire into a flat surface or winding a metal wire around a magnetic core. A dipole antenna is formed by two straight wires of the same thickness and equal length, arranged in a straight line. The signal is transmitted from two ends, with the frequency range being determined by the length of the antenna (Ying and Kildal, 1996; Youngbaek et al., 2008). Compared with looped coils, dipole antennas have greater reception sensitivity/transfer proficiency from a specified length (Raaijmakers et al., 2015). The microstrip patch antenna consists of a circuit board with a rectangular shape at the end. The frequency range depends on the width and length of the rectangular shape. Low-frequency and short-range RFID antennas with a recognition distance of fewer than 1m generally use coil-type antennas, because of their simple processes and low cost(Montgomery et al., 2019; Zhang et al., 2017); long-range application systems with high-frequency or microwave frequency bands above 1m require dipole and slot antennas.

2.2. Operating frequencies

Because of different working frequencies, the RFID system can be classified into four types: low-frequency (LF), high-frequency (HF), ultra-high-frequency (UHF), and supper-high-frequency (SHF) (Guizani, 2014b). The operating frequency change of RFID is shown in Fig. 4. The method of radiofrequency energy harvesting can be divided into inductive coupling and backscattering (Hemour and Wu, 2014). The HF RFID working at the carrier frequency of 13.56 MHz transmits and receives power through near-field inductive coupling (Zargham and Gulak, 2012) and the UHF working at the carrier frequency of 840∼960 MHz deals with power transmission and reception with far-field backscattering (Venuto and Rabaey, 2014)(Table 2).

Low-frequency RFID is typically operated at 125 kHz to 134 kHz. Through the inductive coupling method, the power of the tag is acquired from the radiation near the field of the reader's coupling coil. The distance between reading and writing is short, generally within 10 cm, and less than 1 meter. Its characteristics are energy saving, strong penetrating ability, and little interference from the outside world, particularly where the product has a high liquid content, or is contained in a metal package. There are also some disadvantages. For instance, the slow data transmission rate; the small amount of data; the poor flexibility; and only one-to-one electronic tags can be read at a time. Therefore, low-frequency tags are applied in animal tracking, low-speed and close-range object identification.

High-frequency RFID usually gets the working power from the radiation near the reader through inductive coupling method, and the working frequency is generally at 13.56 MHz (Guizani, 2014a), and read/write distance is usually less than 1 meter. Due to the read/write distance and multiple encryption protocols, HF is more focused on cold chain monitoring.

Ultra-high-frequency RFID usually works at 860 MHz∼960 MHz. The criteria of different countries are varied, as show in Table 2 (Rao et al., 2005). UHF has the characteristics of large reading range, fast data identification and transmission speed, and strong anti-collision ability. It has been widely used in supply chain distribution and logistics systems. But it is relatively energy-consuming and has weak penetrating power, mean that the interference should not be too high in the work area. In the areas of localization and of information capture, UHF RFID also has a promising potential, particularly concerning the information capture, such as temperature, humidity, gas, pH, etc.

Super-high-frequency RFID is either 2.45 GHz or 5.8 GHz. The SHF bands have wider bandwidths and more frequency hopping channels. However, there is a lot of interference in the microwave frequency band because so many ordinary household devices we use work at this frequency, such as cellphones and microwave ovens.

3. Application of RFID sensors in food packaging

In the age of the Internet of Things (IoT), the package is no longer just a piece of paper or a carrier for items, but an important part of the interconnection of all things. It is a communication channel between enterprises and users, which can provide essential information about food products. Although the traditional package made a huge contribution to the food supply chain before, it cannot meet the current market demand. We need to constantly look for innovative packages, with more functionality to satisfy consumer' requirements for low amount of preservatives in foods, increased regulatory requirements, globalized markets, concerns about food safety, and food loss and waste (Poças et al., 2008).

Although RFID technology has been developed for many years, RFID sensors are still in the early exploration stage (Athauda and Karmakar, 2019). Commercially used smart RFID tags are given in Table 3. A sensor is a device that responds to a chemical, biological, or physical property, by providing a quantifiable signal, proportional to the measurement (Ghaani et al., 2016). The integration of sensors with RFID tags is a huge advance, bringing more possibilities to RFID technology. Food
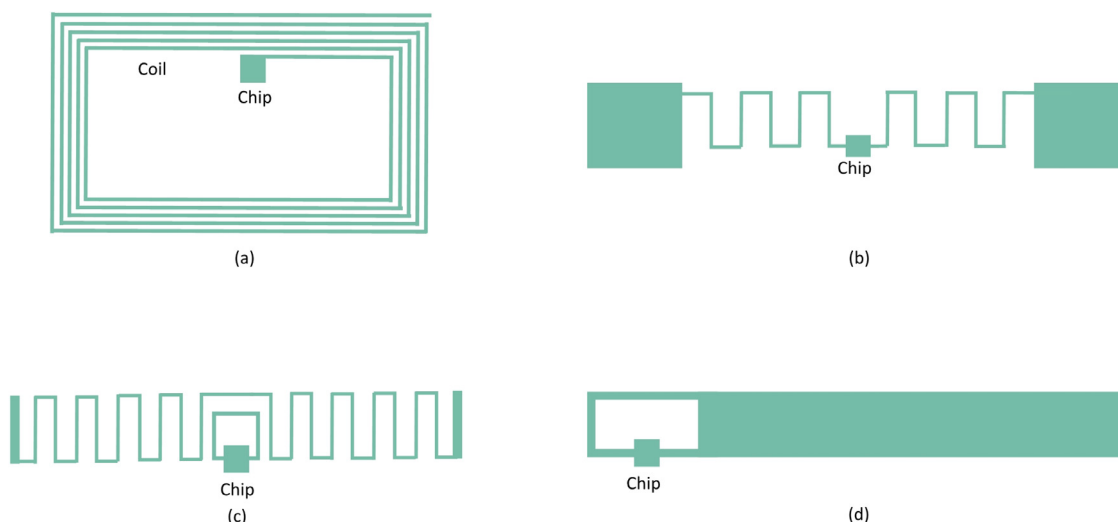
Fig. 3. Commonly Used RFID Antennas. (a) Typical planar disk antenna. (b) Bent dipole antenna. (c) Coupled antenna. (d) Single-ring monopole antenna(X. Y. Deng et al., 2016).
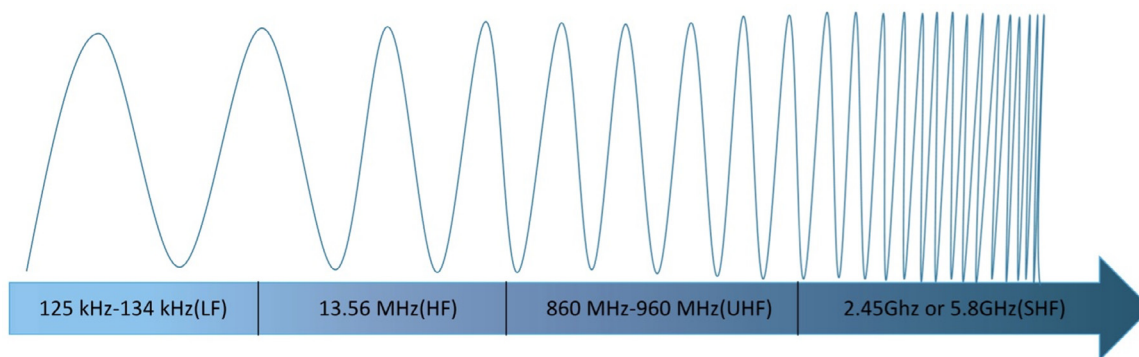

Fig. 4. Operating frequency of the RFID.

Table 2
The characteristics of different RFID operating frequencies.

	LF	HF	UHF	SHF
Frequency	125-134 kHz	13.56 MHz	860-960 MHz 865-868 MHz (EU) 902-928 MHz (US) 865-867 MHz (IND) 920-926 MHz (AUS) 952-954 MHz (JPN)	2.45 or 5.8 GHz
Coupling type	Inductive (near field)	Inductive (near field)	backscatter (far field)	backscatter (far field)
Communication speed	Few kb/s	~100 kb/s	Few hundreds of kb/s	Few hundreds of kb/s
Reading distance	20-100 cm	0.1-1.5 m	3-15 m	3-30 m

Table 3
Commercially used smart RFID tag.

Commercial Name	Frequency	Tag Type	Manufacture	Functionality description
DOGBONE S2	860–960 MHz	Passive	Smartac	Detects and measures moisture levels in the environment
DOGBONE S3	860–960 MHz	Passive	Smartrac	Detects and measures temperature and optionally moisture levels in the environment
CS8300	860–960 MHz	Passive	Ayma	Cold chain temperature monitoring
Ela Innovation Active	433 MHz	Active	Ela Innovation S.A	Temperature, Relative humidity monitoring
Savi	433 MHz	Active	Savi SmartChain	Temperature and humidity monitoring
AD TT Sensor Plus 2 BLE	860–960 MHz	Passive	Avery Dennison	Temperature recording
Circus™ Tamper Loop	860–960 MHz	Passive	Avery Dennison	Authentication Reordering, Expiration and Care, Integration into Label, Packaging
AD-327 FCC	860–960 MHz	Passive	Avery Dennison	Supply Chain Management, Inventory and Logistics.

packaging combined with RFID tags, and associated with the proper sensors, may provide a database of food products, which would carry all of the essential data that we need for the product. Sensing is done by two techniques: the first method is based on an internal or external digital sensor integrated into an RFID chip; the second method is based on antenna surface functionalization by a sensitive material (Saggin et al., 2019). These sensors, that are based on RFID technologies can provide accurate data on the condition of the products. Thus it can prevent theft, protect brands, and ensure compliance, as well as reduce food loss and waste (Chen et al., 2020b).

3.1. The Role of RFID-based Packaging in Reducing Food Waste

For food consumption in the United States, the top three in terms of the values of food waste are meat, poultry, and fish (41%); vegetables (17%); and dairy products (14%)(Buzby and Hyman, 2012). Freshness is one of the most critical reasons in determining food consumption behavior. The spoilage process is complex for each type of meat, but one common process is the production of catabolism products, which are also associated with variations in freshness. One of these catabolism products, the volatile organic compounds (VOCs), is commonly used as an important biomarker to assess the freshness of meat, such as hydrogen sulfide, ammonia, etc. In addition, common biomarkers for freshness assessment of dairy products and vegetables are pH and concentrations of oxygen and carbon dioxide in the package. RFID-based smart packaging can achieve effective management of perishable food by sensing changes in these biomarker values, thereby reducing food waste. In Muriana (2017) are summarized the main 11 causes of food loss and waste in the food supply chain. For example: supply chain information sharing, product recalls, shelf life control, inventory control, packaging and transportation mistakes and other reasons. Many of them can be improved by RIFD technology, for instance, "product recall" can take advantage of RFID traceability; "inventory management" can take advantage of RFID data transmission; and "shelf life control" and "transport mistakes" can be monitored by RFID sensors for pH, temperature, humidity and other data of products, as shown in Fig. 5.

A monitoring system capable of providing freshness and shelf life of meat is presented in Eom et al. (2014). They have integrated temperature, humidity and ammonia sensors in semi-active RFID tags. In this work, the food poisoning index was used as a criterion for judging the freshness of meat. The food poisoning index is determined only by temperature and humidity to indicate the growth rate of spoilage microorganisms under certain temperature and humidity conditions. In the experiments, data on ammonia concentrations in pork packages at different temperatures and humidity conditions were compared with the food poisoning index to determine freshness levels. Finally, the freshness of the meat is classified into four levels: high, medium, low and spoilage. In Eom et al. (2012), the authors use the respiration quotient (RQ) to indicate the freshness of vegetables, when the RQ is larger than 1, the freshness of the vegetables is reduced (Chan et al., 1999). And the value of RQ is highly correlated with the rate of oxygen consumption and the rate of carbon dioxide production. Vegetables in the package consume oxygen and emit carbon dioxide, which also changes the freshness of the vegetables, meaning that the freshness of the vegetables can be monitored by the concentration of oxygen and carbon dioxide. Therefore, they proposes an RFID tag with integrated oxygen and carbon dioxide sensors to enable monitoring of vegetable freshness. In Avery Dennison's report (studioID, 2021), they estimate that utilizing RFID technology could save 20% of food waste. In Nikolicic et al. (2021), by simulation modeling, the improvement effect of modern communication technology (such as RFID product tags) on retail supply chain is verified. The simulation results show that dairy product waste in supermarkets and production sites is reduced by 29.41% and 38.52%, respectively. This shows that the application of RFID technology for real-time synchronization of food data in the supply chain can effectively reduce expired food stocks. And in the following subsections we will summarize the

application of RFID technology in food packaging, looking at different characteristics.

3.2. Temperature monitoring

Temperature is a significant factor in guaranteeing the high quality of food, particularly for perishable foods. Therefore, the cold chain logistics system is mainly concerned with storage and transportation of these products (Chen et al., 2020). Lack of temperature monitoring can cause a large amount of food waste during the distribution chain. Studies show that poorly managed temperature in perishable food logistics can cause the loss of up to 35% of products (Göransson et al., 2018). Hence, food safety of supply chains could be maintained by effective temperature monitoring.

A Time–temperature indicator (TTI) device that can utilize an irreversible color change to indicate temperature change. TTI is widely used due to its simple structure and low cost, but its disadvantage is that it cannot perform continuous temperature measurement and data transmission. RFID technology has been considered to be an enhanced method for temperature monitoring because of its many benefits, such as offering real-time information for the product, allowing the capture of long-duration temperature profiles, and its ability to provide sensing functionality along with identification.

A novel smart material for temperature monitoring has been proposed in Shafiq et al. (2019). This smart material is 4-D-printed liquid crystal elastomer (LCE), which is sensitive to temperature (Ambulo et al., 2017). The unique property of LCE is that its shape changes with temperature. Place the LCE under the tag to adjust the height between the antenna and the ground plane, as shown in Fig. 6 (b). When the temperature changes, the height of the LCE will also alter, leading to the variety of the RFID tag's working frequency between 902 and 928mhz. The biggest advantage of this temperature sensor is that it can be reused, because it can go through multiple high/low temperature cycles and still work. But this paper only tested RFID tags at room temperature and 160°C. If this RFID sensor wants to be tested in the cold chain in the future, it needs to be replaced with a new material, such as shape-memory polymers or LCEs that react to lower temperatures (Liu et al., 2007).

The food product may be contaminated with various bacteria, which have different optimal temperature ranges for their growth. For example, some bacteria can spoil milk, even at temperatures below 7 °C. Therefore, it is really crucial for RFID sensor to customize the threshold temperature. When temperatures are lower than 100 °C, ionic liquids stay in liquid state, but their melting point can be altered by the doping of the cation/anion pair (Schäfer et al., 2007). In Vivaldi et al. (2020) the Ionic liquids doped with copper can be applied as smart materials for temperature monitoring due to its melting point characteristics. The Cu-IL was dropped between two pincer-shaped electrodes. When the room temperature rises above 8 °C, the ionic drops will melt and short-circuit the RFID tag circuit to achieve the purpose of temperature monitoring. And this material is not sensitive to relative humidity, so it is suitable for use in cold chains, but the temperature monitoring process is irreversible.

A battery-free RFID temperature sensor is proposed in Bhattacharyya et al. (2019), which can customizable the threshold in the 0–20 °C range. This RFID temperature sensor is made of an Asymmetric Circular Split Ring Resonator (ASCRR) as shown in Fig. 6 (c). The characteristics of the ASCRR change when the sensor is coated with coconut oil and grapeseed oil at the ratio of 1:4. At 4 °C there is a peak at 5.65 GHz, and the peak shifts left, due to the presence of the oil. Because at 4 °C the oil has just started to melt. When the oil melts, it will be a short circuit Resonator C, due to the slightly conductive nature of the oil, as shown in Fig. 6 (c). These two RFID sensors, described above, can have customizable temperature thresholds, but the sensing process is irreversible and as such, they cannot be reused.
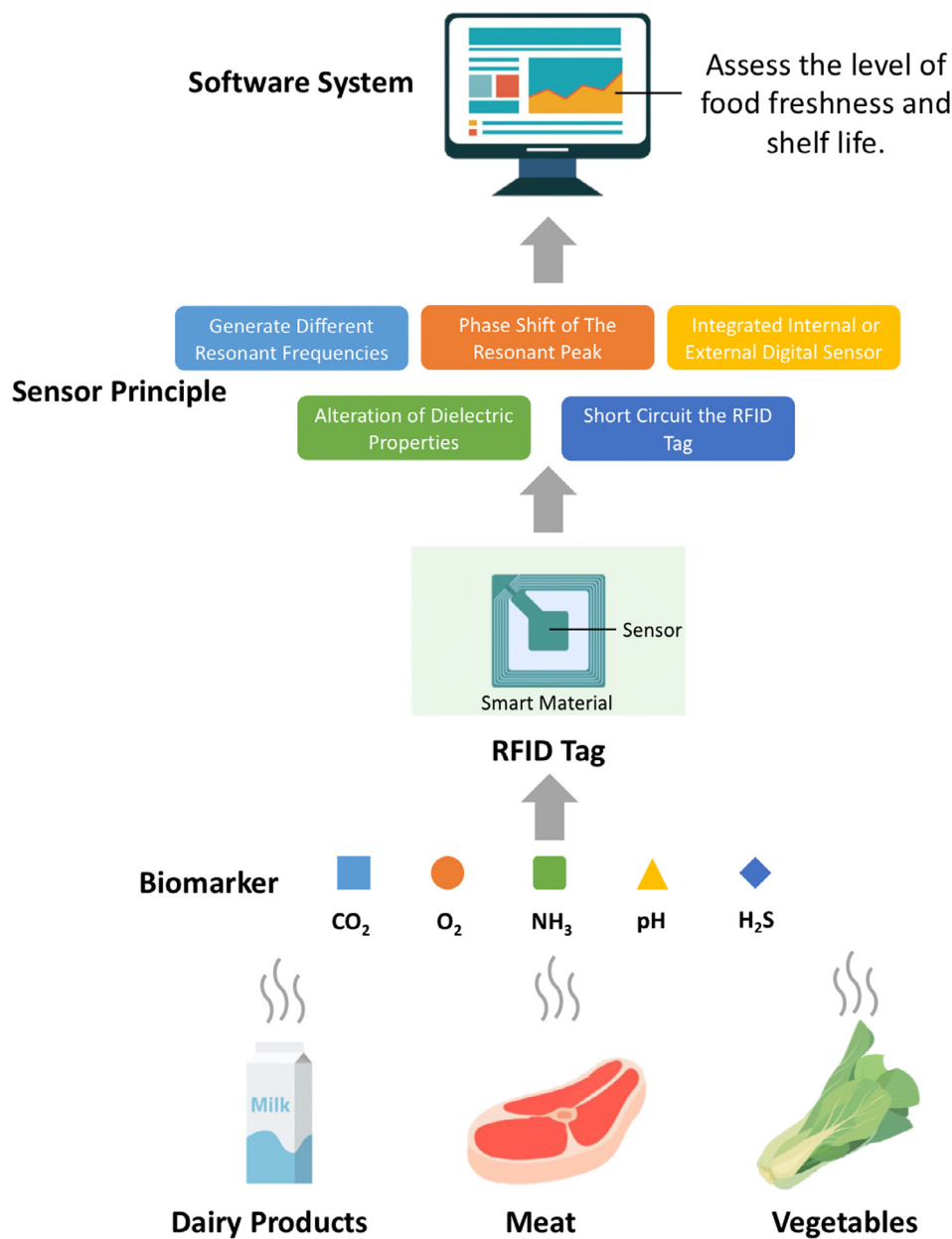
Fig. 5. Main process of RFID-based packaging system for food freshness assessment.

Passive RFID sensors are battery-free, low-cost and can be embedded in food packaging. This has been widely studied, due to the great potential of this application. An important direction in developing such sensors is to find a smart material that is biocompatible, food-safe and temperature-sensitive. There are not a lot of studies on this. Different categories of food have different requirements for shipping temperature, such as fresh fish at 0–4 °C or at -18 °C (frozen), meat at -25 °C, and fruits like bananas between 12 °C and 16 °C (Mercier et al., 2017). Hence, customizable temperature threshold RFID sensor development is also an important direction of study.

3.3. Gas monitoring

In general, a change of gas composition in food packaging also represents the variation of food quality and safety status. For instance, the concentration of carbon dioxide (CO_2) gas in food packages can reduce the metabolic rates of microbes. The concentration of ammonia (NH_3) in meat packaging presents a noticeable sign of food freshness and safety.

Carbon dioxide is a crucial part of gas detection in food packaging. As Emmental cheese wheels ripen, they will release huge amounts of gases (CO_2, H_2 or both) making the cheese wheels swell considerably. An RFID tag was proposed in Li et al. (2009), as shown in Fig. 7 (a). There is gas released during the ripening of cheese, which results in an increase of pressure. The level of pressure inside the cheese package increases from 275 mBar to around 1.1 Bar throughout the ripening process. The chip SL900A, with an integrated pressure sensor, can detect the variation of pressure, so it can be used to monitor the level of cheese maturation. The IC of the chip-based tag guarantees high accuracy sensor data. But it may increase the complexity and cost of the tag, and decrease its robustness. Therefore, the chipless tag which utilized smart materials, it offers a promising solution.

The ability of CNT to sense gas concentration has been proven in Yun and Yeow (2014). The conductivity of CNT changes a lot when subjected to gas, temperature change, as well as humidity. The physical explanation is that due to the absorption of certain molecules by CNT, it produces holes in the conductive band are created. A fully inkjet printed
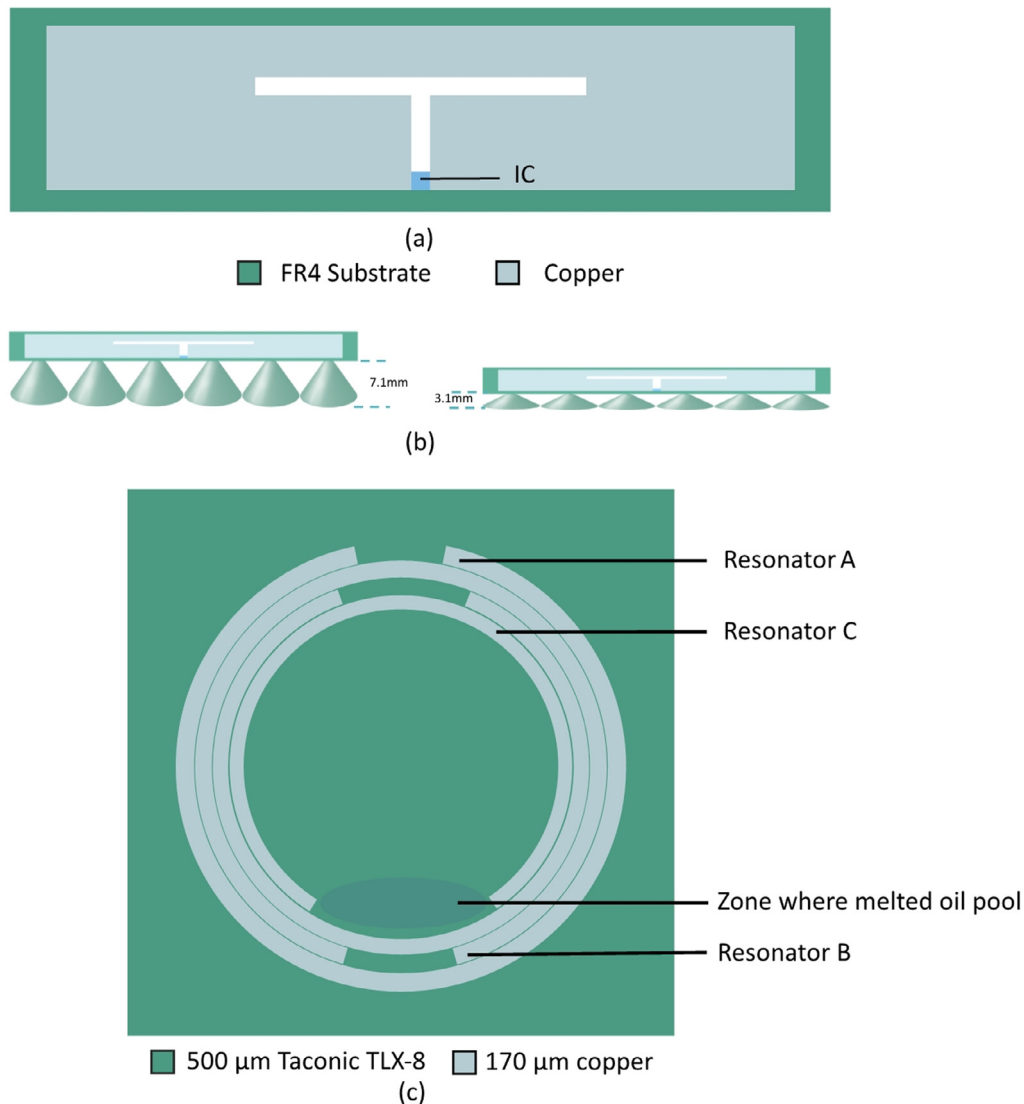
Fig. 6. (a) The tag is utilizes an integrated T-match network (ITMN). (b) The LCE array reaches a height of 7.1 mm above the ground plane at 160 °C. The LCE array returns to a height of 3.1 mm at room temperature (Shafiq et al., 2019). (c) Composition of ASCRR: Resonator A, B and C (Bhattacharyya et al., 2019).

chipless RFID sensor designed to detect the presence of carbon dioxide in the air is proposed in Vena et al. (2013). As illustrated in Fig. 7 (b), it consists of two split-ring resonators (SRRs) in different polarization directions. It uses CNT-based PEDOT-PSS ink to create a carbon dioxide sensor on the vertical-polarized resonator. In areas where CNTs are deposited, the conductivity of the structure is subjected to changes in CO_2 changes with the gas concentration. Consequently, it will shift the resonant frequency. The radar cross section (RCS) of the horizontally-polarized resonator barely changes. Thus, it has two purposes. First it can be used as a reference to increase sensing data accuracy, second it can transmit ID information. However, CNTs are known to not only be selective to CO_2. They can not work in a complex environment. There are several other materials that are sensitive to CO_2, such as graphene oxide (Andò et al., 2015) and wheat gluten (Bibi et al., 2017b) that can also be combined with RFID technology.

NH$_3$ is a kind of gas which is highly significant for food quality and safety. In literature, a number of materials applied in RFID tag sensors for detecting NH$_3$ have been extensively studied, such as carboxylated polypyrrole nanoparticles (C-PPy NPs) (Jun et al., 2016), a Hydrogel-coated pH-electrode (Bhadra et al., 2015), ruthenium doped zinc oxide (Ali et al., 2020), and Silver/Reduced Graphene Oxide (Zhang et al., 2019). Polyaniline (PANi) has a high affinity towards NH$_3$, such that

the sensor coated with a thin-film of PANi on the surface could trap the NH$_3$ molecules. The conductivity of the film will vary with absorption of NH$_3$ molecules. In (Karuppuswami et al., 2020) an Inductor-Capacitor (LC) is proposed, based on the use of resonant tanks as an RFID sensor, as illustrated in Fig. 7 (c). The interdigitated capacitor was coated with PANi, which is used to detect NH$_3$ gas. NH$_3$ gas is absorbed by PANi and trapped on the surface of the sensor, thus changing the effective capacitance and leading to the resonant frequency being shifted. However, these sensors can only detect NH$_3$ gas, which is not sufficient to estimate the freshness of food. Thus, a multi-parameter sensor is essential.

When a meat product is spoiled, it will generate an amount of total volatile basic nitrogen (TVB-N). The main components of TVB-N are NH$_3$ and the related TMA and dimethylamine (DMA). Chung et al. (2017) developed a battery-free RFID system to monitor fish freshness by modifying typical passive RFID tags. The tag can detect H$_2$S or NH$_3$ gas concentration in packaging, by using a hydrogen sulfide sensor and an ammonia sensor on the tag. Although this RFID sensor is battery-free, it's still hard to apply in food packaging due to the tag size. Furthermore, embed two commercial sensors in RFID tags would be too expensive.

There is another small size and low-cost paper-based electrical gas sensor (PEGS) proposed in Barandun et al. (2019). PEGS can sense water-soluble gases such as NH$_3$, trimethylamine (TMA), CO_2, etc. The
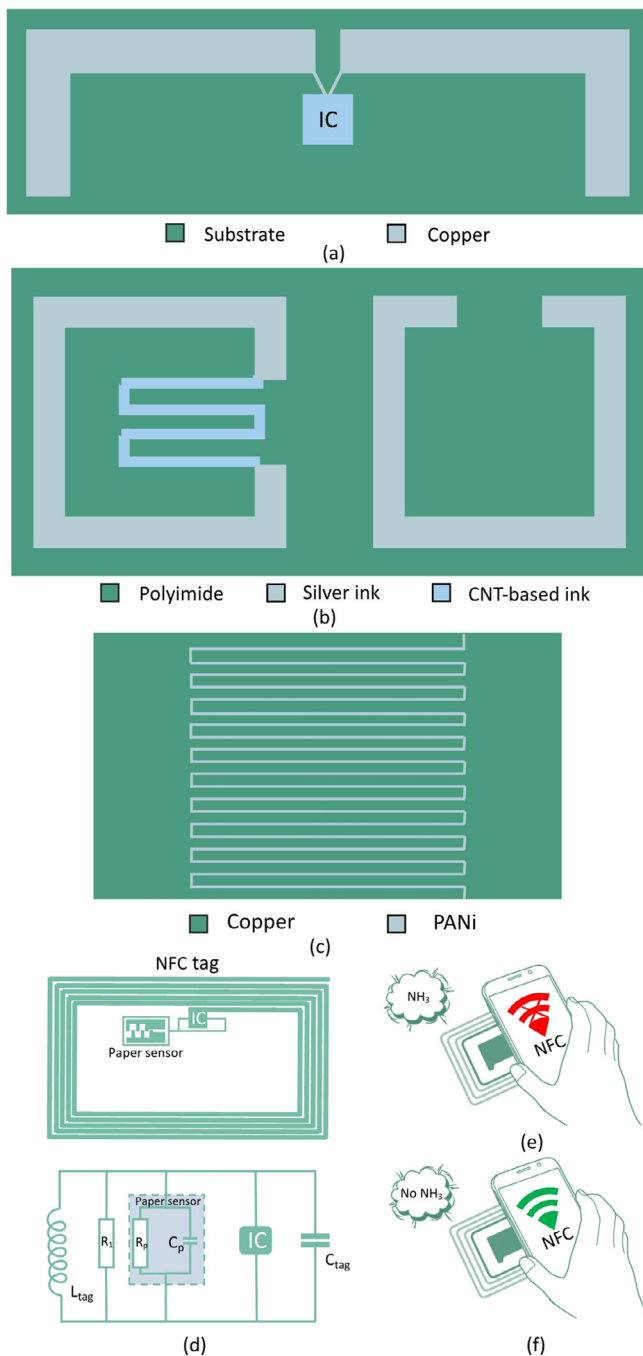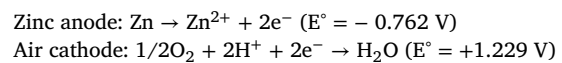
Fig. 7. (a) The layout of pressure monitoring UHF tag (Li et al., 2009). (b) The layout of two SRRs in different polarization directions(Vena et al., 2013). (c) Schematic of the Inductor-Capacitor (LC) resonant tanks (Karuppuswami et al., 2020). (d) The schematic of the NFC tag is modified by PEGS. Once a certain concentration of ammonia is present, communication between the reader and the tag will be disrupted. The resistor R1 is used to adjust the tag gas sensing concentration threshold at which the tag stops working. (e) The tag responded when there was no ammonia in the box. (f) Smartphones cannot detect NFC tags when ammonia is present (Barandun et al., 2019).

carbon ink is used to print two graphite electrodes on cellulose paper to form PEGS. The intrinsic hygroscopic characteristics of cellulose paper are used to absorb water-soluble gases, which alter the electrical impedance between graphite electrodes. The PEGS exhibited a high intrinsic selectivity toward ammonia, compared to the other gases tested (TMA, H_2S, CO_2, CO). When the relative humidity is 70%, the lower

limit for the detection of NH_3 is about 0.2 ppm. This PEGS can be integrated into a commercial NFC tag. Therefore, we can enable a smartphone to probe a NFC tag, as shown in Fig. 7 (d). Despite the PEGS showing high sensitivity to water-soluble gases, it can only provide qualitative information and its results are highly dependent upon the relative humidity level.

The oxygen levels in the food package are vital for food quality and safety. It can spoil food in several ways, including oxidation, enzymatic reactions and microbial proliferation (Kim et al., 2003; Mills and Andrew, 2005). Nowadays, the biggest obstacles to applying oxygen sensors to food packaging are power and large size. In Won and Won (2021) present a self-powered, mini-size oxygen gas sensor. Its power source came from metal-air batteries, it can utilize oxygen from the air to oxidize metals and generate power. The whole oxygen sensor consists of three layers. It contains a silver-deposited oriented polypropylene film as cathode, a zinc sheet as anode and an adhesive gel electrolyte. The electrochemical reactions of these metal-air batteries can be described by the following equations (Mainar et al., 2018):

Zinc anode: $Zn \rightarrow Zn^{2+} + 2e^-$ (E° = − 0.762 V)
Air cathode: $1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$ (E° = +1.229 V)

E° represents the standard reduction potential. The open circuit voltage between cathode and anode is typically proportional to the logarithm of the oxygen concentration. The closed circuit current/voltage is also proportional to oxygen concentration. We can quantitatively determine oxygen concentration in food packaging by measuring open circuit voltage or closed circuit current/voltage. This oxygen sensor is basically made of non-toxic materials, and its features of small size and self-powered make it suitable for food packaging. And furthermore, the authors plan to integrate the self-powered oxygen sensor into RFID tags in future progress.

The process of assessing food quality and safety is complex, and the presence and activity of microorganisms are related to multi-gases produced during food spoil, such as the way that vegetable freshness can be estimated by monitoring the levels of oxygen and carbon dioxide. Thus, the RFID sensors that can detect multi-gases will more accurately estimate the condition of food and extend the expiry dates, another important research direction for gas monitoring. The chip MLX90129 produced by Melexis Company, which has a wide range of interface possibilities and it has an internal temperature sensor. Hence, the chip MLX90129 is often applied in chip-based RFID sensors to detect multi-parameters (Chung et al., 2017; Ki et al., 2012; Yuan et al., 2018).

3.4. pH monitoring

The activities of microbials in food are the main factor in the process of food spoilage, and amino acids are the main products of the metabolic activities of microbial life (Nychas et al., 2008). Consequently, there is leads to a pH level change in the perishable food, as it spoils. The research in detecting pH levels based on RFID technology is limited.

A pH sensor RFID tag is proposed in Hillier et al. (2017). A commercial moisture sensing RFID tag has been modified in this study. In the original tag, when the substrate is permeated with water from the humid environment, the electrode capacitance will change, and the transponder chip sends the new sensor code value to the reader. Therefore, the tag can alter functions if the substrate is coated with pH-responsive material. The pH sensing polymer film consists of two variants of polydimethylsiloxane (PDMS). More $NH3^+$ groups are formed in pH sensing polymer membranes under the influence of high pH fluids. This dielectric variation will cause the chips array of capacitors to modulate, changing the sensor code values by shifting the frequency. There are other materials with similar functions to PDMS, such as polyaniline (Potyrailo et al., 2011). However, the food safety of these two materials has not been tested. Therefore, more research on pH-sensitive materials suitable for food packaging is needed.
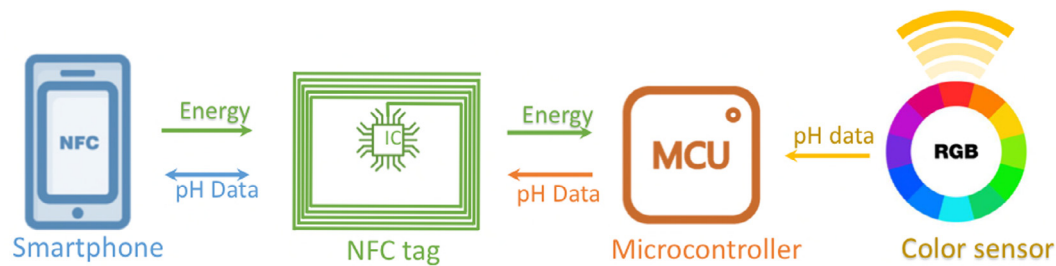
Fig. 8. Architecture of pH sensor based on color determination(Boada et al., 2019).

Another pH-sensitive material is chitosan, which is also food safe and biodegradable. In Athauda et al. (2020) authors did microwave characterization of chitosan hydrogel. They found out the chitosan hydrogel's frequency (ultra-wideband frequencies) response has shift left occurred in both pH 4 buffer solution and in pH 10 buffer solution. The main reason for that is chitosan hydrogels swell or de-swell, the molecular structure may change at the same time, which decreases the electronic transferability of the material, resulting in the alteration of dielectric properties. The advantage of this chip-less RFID sensor is that it has good biocompatibility, but the disadvantage is that its frequency response range to acidic and alkaline mediums is hard to distinguish.

RFID sensors are mostly based on a resonant frequency shifting method to transmit sensing data. This method is quite popular among wireless methods due to its simple structure. However, the resonance frequency is highly related to the inductive coupling between the RFID sensor antenna and the pickup coil of the reader, such that the reading distance will also have an effect. To solve these problems, a pH sensor based on a digital modulation method is proposed in Mondal et al. (2019). The reading range was kept at 45 cm, where the reader was set at 15 dBm of transmission power. The reading range can be further improved by higher power or better gain antenna. But the pH electrode in this study needs to be dipped in the target solutions to get the measurement results, which limits its real-world applicability.

Currently, most smartphones are now equipped with NFC chips. Smartphones can be used as potential RFID readers. In Boada et al. (2019) a battery-less color sensor based on NFC is presented, which can be applied to pH monitoring. The architecture of pH sensors is indicated in Fig. 8. This sensor has a color light-to-digital TCS3472 converter from TAOS, which is used to measure the color of a pH reactive compound. The Author also designed a smartphone App, which can read data directly from an NFC tag to further decrease the cost of pH monitoring. This sensor has the potential to be combined with the pH-sensitive smart packaging indicators based on natural food colorants, and biopolymers. RFID sensors and indicators, the two smart packaging technologies have characteristics that can work in combination.

3.5. Humidity monitoring

Humidity is one of the main elements which influence food preservation. Humidity monitoring is widely applied in the food supply chain. Many food products need to be stored at the right temperature and humidity to stay fresh before they arrive at their destination. Due to the effects of humid environments, the research on humidity sensor tags is mostly about chipless RFID sensors.

In Deng et al. (2018) a chipless RFID sensor tag based on the 'I' slot structure is presented. This RFID sensor is composed of multiple slot resonators. Different lengths of the slots resonators can generate different resonant frequencies, and it can be coded according to the presence or absence of resonators. When the resonators are present, it will be encoded as '1', otherwise the code is '0'. Three different length slot resonators are used to encode the ID information of the tag. Another three slot resonators of the same lengths are covered with humidity-sensitive material to act as humidity sensors, as shown in Fig. 9 (a).
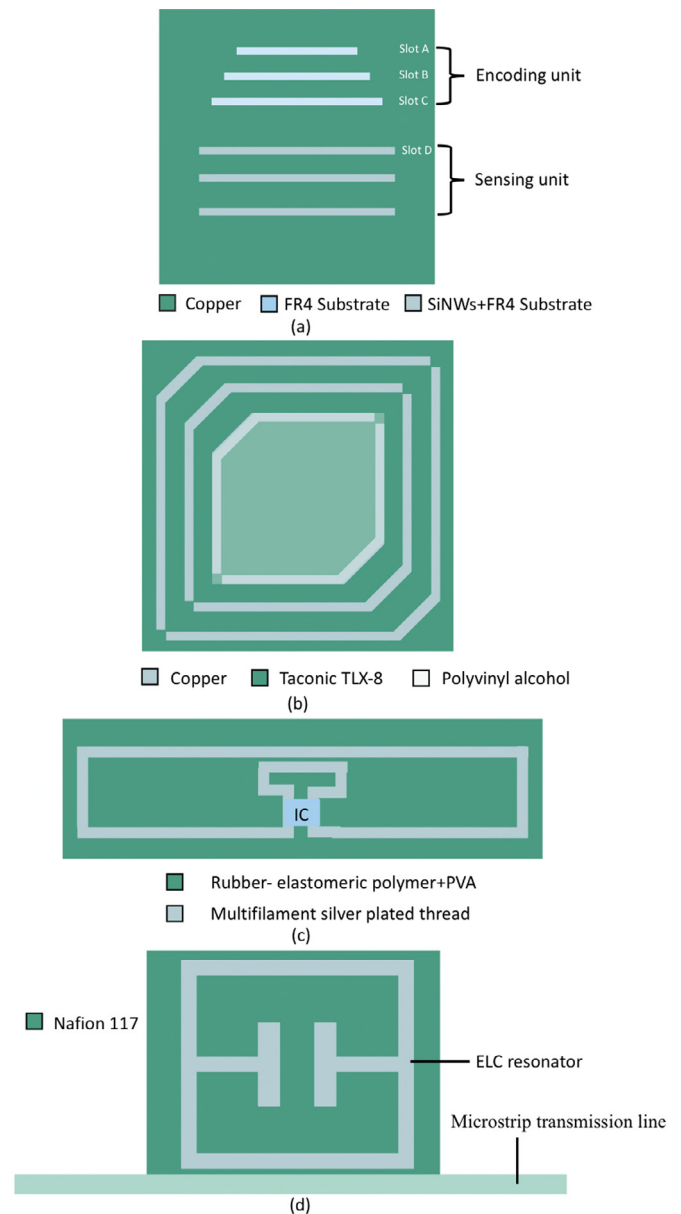

Fig. 9. (a) The structure of chipless RFID humidity sensor(F. Deng et al., 2018). (b) Illustration of cross polarization humidity sensor (Fan et al., 2018). (c) The structure of the humidity sensor based on RSSI value (He et al., 2020). (d) Schematic of chipless RFID humidity sensor using an ELC resonator (Marchi et al., 2020).

Si Nanowires (SiNWs) shows excellent performances for humidity sensing (Vena et al., 2018), so SiNWs are used as humidity sensing material in Deng et al. (2018). Slots A, B, and C in Fig. 9 (a) are combined into the encoding units. The resonant frequency of the encoding unit scarcely changes with humidity. Slot D belongs to the sensing unit, and the resonant frequency is 3.725 GHz at 30% relative humidity (RH). When RH reaches 90%, the resonant frequency is 3.512 GHz. The sensing unit has 3 slots to verify consistency of environmental humidity data. Therefore, this sensor is suitable for long-term humidity monitoring. But this tag is co-polarized, which is not suitable for complex environments.

Cross polarization of the tag means that its RCS will generate resonant peaks in both orthogonal directions (horizontal direction and vertical direction). As the backscattered signal from other environmental objects are co-polar, the cross-polarization tag is more robust against environmental interference. In Fan et al. (2018) the authors present a cross polarization tag for humidity sensing. As shown in Fig. 9 (b) the tag consists of three nested resonators, Polyvinyl alcohol (PVA) film is deposited on the surface of innermost resonator to monitor humidity variation, which the other two resonators on the outside, to encode by adjusting length.

Most of RFID sensors are based on either frequency domain, or time domain, in He et al. (2020) in order to produce a passive sensor based on a received signal strength indicator (RSSI) value. This UHF tag substrate layer is 3D printed, consisting of rubber-elastomeric polymer and PVA, as shown in Fig. 9 (c). Under the condition of high humidity, the PVA of the substrate layer will dissolve. Hence, the substrate becomes soft and leads the tag to curve. As the tag curve deepns, the reading range and RSSI value with be more significantly affected. However, it only experienced significant change in a high humidity (>60% RH) environment, which is not suitably reflective of real-life applications.

To further increase the humidity monitoring range, a humidity sensor response range in the range 0% - 90% of RH was developed in (Marchi et al., 2020). This was a chipless sensor composed of an ELC resonator, a microstrip transmission line and a Nafion 117 sensitive layer, as illustrated in Fig 9 (d). Due to Nafion 117's inner structure, it reacts strongly with water molecules. However, there are not many studies on the microwave characterization of the Nafion 117. Thus, the connection between the dielectric parameters of Nafion 117 and the humidity level needs to be studied further.

Regarding humidity monitoring, some research based on the passive RFID tags can be found in the literature. In Borgese et al. (2017) a silver nanoparticle ink is printed on a substrate, and the test results demonstrate that the phase shift of the resonant peak is related to the variations in RH. In Huang et al. (2018) Graphene Oxide (GO) is deposed on the tag, whose resonance frequency changes with humidity. In Irene et al. (2020) TiO_2 nanoparticles are deposed on the sensor to enhance sensitivity to humidity level.

3.6. Integrity monitoring

With the rapid growth of E-commerce, there is a growth in the number of consumers who purchase food products online. If the package is damaged, it will accelerate the speed of food spoilage. The opened packages require identification and handling, in good time. Therefore, there is a necessity to be aware of the package status along the entire supply chain from production, distribution to storage. To deal with these cases, a kind of sensor that can monitor the open/closed condition of the packages in real-time is essential.

In Wang et al. (2020) a battery-free, low-cost, RFID-based solutions for the integrity of package detection, is presented. The anti-open sensor uses the RFID antenna for sensing, rather than using a specific sensor to sense the package status. The tag sensor is composed of an RFID chip and a flexible foldable dipole antenna. The dipole antenna is divided into two parts, which are located on the inner side of the top and parallel to each other, as shown in Fig. 10 (a). When the package is closed, (with an opening angle of 0°), the two parts of the antenna counteracts

the each other signals, so that the reader can't receive an RFID tag signal. However, when the package is open as illustrated in Fig. 10 (b), the unfolded antenna enables the tag to transmit the signal. While the opening angle is 45° to 270°, the reader can communicate with an RFID tag in the UHF band (860MHz~960MHz). Hence, the state of packages is determined by whether the possibility that the reader can communicate with it, or not.

The RFID-based anti-open sensor discussed above can only identify opening of the top of the package. However, the other damage to the package cannot be detected if no sensors are placed on other sides of the package. In Wang et al. (2018) it is show that author can provide all-around package security by using only one RFID tag. A feed line, also known as a transmission line, is a type of interconnection that can transfer signals between an RFID chip and an antenna. In this study, feed lines also serve as the opening detection sensor. It can be used to cover all edges or surfaces of the package, as shown in Fig. 10 (c). Any attempt to open the package from any side will break the feed line, which results in the variation of the RFID antenna signal. By sensing this change in signal, an RFID reader can detect whether the package have been opened, or not.

For smart packaging to achieve the inspection of the state of food and packaging, the capability of sensing multi-parameters is required. In Zhou et al. (2020) a flexible smart packaging system is purposed, which has an integrated temperature sensor, an ammonia sensor, and an anti-open sensor. Fig. 10 (e) illustrates the circuit structure of the anti-open sensor. When the package has been opened, the readout value of V_{AO1} and V_{AO2} will change. The interconnect line is screen-printed on the substrate by Ag paste, and resistance is composed of poly (3,4-ethylene dioxythiophene): poly (styrenesulfonate) (PEDOT:PSS) printed resistive layer by printed. The layout of the sensor is designed to cover all key areas. If the package has been broken, the sensor will respond.

3.7. Food traceability

When raw food materials are contaminated and not handled in time, it is hard to identify and isolate the contamination source in the food supply chain. Although food safety crises could occur at any stage of the supply chain, the lack of traceability information flow commonly makes it more difficult to confirm where the contamination has happened. Therefore, the traceability technology can help distinguish the liability of each member within the supply chain.

According to Piramuthu et al. (2013), logistics information is divided into different data granularity levels, such as item, batch, and SKU levels. Then, three different levels of data granularity are combined with RFID technology to determine the correct allocation of liability cost among different players in the supply chain. Liability cost only occurs if there is contamination at any node or route of the supply chain. In Gautam et al. (2017) RFID tags are used as a medium for traceability information instead of barcodes to determine the liability cost in the Kiwifruit supply chain. This work has proposed a newly developed approach of the Plant Pollinator Optimization (PPO) Algorithm to achieve two objectives. (1) Minimize the logistics cost of replacing barcodes with RFID tags; (2) Minimize the liability cost of contamination. The food traceability based on RFID technology can help managers to minimize the risks of delivering perished food and reduce the liability costs by tracing it at an earlier stage.

In general, the main purpose of RFID sensors deployed in the food supply chain is to prevent defective products from reaching consumers. Currently, little work has been done to integrate these sensors with food traceability. Blockchain is a distributed ledger technology that uses a chain structure with a timestamp to store data, adding a time dimension and making the data highly verifiable and traceable. The visibility of food product traceable information across different supply chains can become a reality with the integration of RFID sensor technology and blockchain-based data management systems (Pang et al., 2015). In (Mondal et al., 2019) purposed a 900 MHz RFID coupled sensor was em-
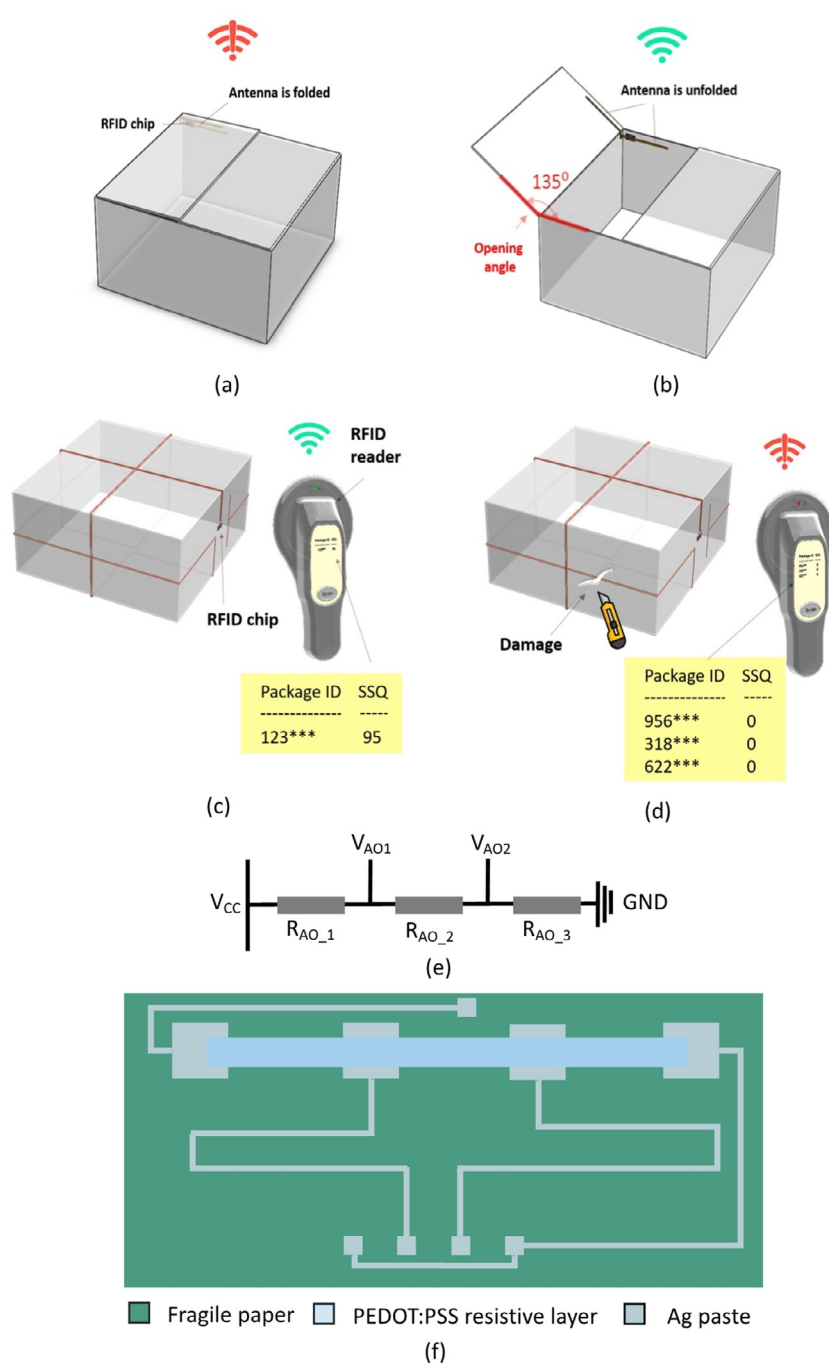
Fig. 10. (a) When the package is closed, the antenna is folded and located on the inner side of top, with the halves parallel to each other. (b) When the package is opened, the antenna unfolds (Wang et al., 2020). (c) The reader receives a backscatter signal from the package, indicating that it has not been opened. (d) The reader did not receive a backscatter signal, indicating that the package was open (Wang et al., 2020). (e) Circuit structure of the anti-open sensor. (f) Schematic of the anti-open sensor (Zhou et al., 2020).

ployed for monitoring chickens, by them wearing a foot-ring, based on the block chain and RFID technology. This can trace the whole process of breeding, transportation and sales, and provide transparent, secure, and trustworthy food safety data to consumers.

4. Challenges

Although a large amount of research has been conducted on the RFID sensor technology, there are still several challenges that block RFID sensors from being widely used in food packaging.

4.1. Food-safe material

The polymers-based sensors could make RFID tags smarter, but it lacks of biocompatibility, which may be an obstacle to application in food packaging. Therefore, organic oil is used as a smart material to achieve the temperature sensing function, while ensuring that it cannot adversely affect the food item being monitored (Neethirajan et al., 2009). In the future, is a good research direction would be the use of biocompatible, conductive organic inks and dyes to print the RFID tag. The food safety of the sensors for food packaging will be a significant challenge that needs to be investigated fully for commercial applications.

4.2. Restricted energy harvesting and reading range

These are the two most significant challenges of RFID tags (Kantateddy et al., 2019). Most of the RFID tags implemented in IoT are passive, meaning that typically, they can only transmit sense data within the reader's reading zone. The passive tags are powered by the

integrated energy harvest module, which can reduce costs but will also mean that long-range transmission will be limited. The propagation of RF signal is affected by objects in the environment that can cause absorption, detuning, reflections and impedance mismatch, commonly leading to a dramatic reduction of the RFID system's read range. Especially if the sensor unit is made of a smart material, the RF signal will be attenuated by the smart materials, which severely affects the read range of the RFID sensor. In Barge et al. (2018) it is reported that the reading range of RFID tags is highly influenced by tag orientation with respect to the antenna, as well as by the chemical composition and temperature of the food product. The main reasons can be summarized as (1) the reflection of the RF signal at the interface when it passes between two substances having different dielectric characteristics, (2) the electromagnetic field energy loss when the RF signal passes through a dissipative medium.

4.3. Multi-tag collision

An RFID sensing system is composed of at least one reader and several RFID sensors. Multi-tag collision refers to the phenomenon that when the reader sends a signal, there are multiple tags in the signal range to respond at the same time, and the reader cannot recognize multiple tags. When the whole system is running, sensor responses collisions will cause a lot of problems. For instance, energy wastage, increases in identification time, and decreases of the reading rate. Two kinds of algorithms are proposed to solve the tag collision problem: a deterministic algorithm based on binary tree and a stochastic algorithm based on ALOHA(Wang et al. 2010). With the algorithm based on ALOHA, when the number of identified tags is large, the probability of tag collision will increase. Although the algorithm based on the binary tree has a longer recognition time, it can achieve a 100% tag reading success rate. In Zhou and Jiang (2021) a Hybrid of ALOHA and Tree (HAMT) Algorithm is proposed. The results of the simulation show that when the number of tags needing to be recognized is 1000, the time slot required by the HMAT algorithm is about 1400. The HAMT algorithm is better than ACT, AHT, and DFSA algorithms. When the number of tags is large, the optimization effect is clearer to see.

4.4. Multi-parameter sensors

The ultimate purpose of RFID sensors for food packaging is to detect the safety and quality of food products. Thus, a multi-parameter sensor that can detect the condition of the food more accurately is required. For example, when the fish spoils, it emits H_2S and NH_3 gas. Therefore, the existence of both H_2S and NH_3 sensors in a single RFID tag leads to more accurate determination of food states. The sensors used in Chung et al. (2017) are all commercial, but their size makes it hard for them be applied in packaging. The author in Javed et al. (2021) has proposed a chipless RFID tag using Kapton®HN substrate as a humidity sensing material, and the chipless RFID tag being coated with smart materials of MWCNTs for CO_2 sensing, to achieve multi-sensing attribute. A chipless, multi-parameter RFID sensor would be advantageous in terms of sensor profile size and cost, but further research is required in this field.

4.5. Security and privacy

RFID technology can bring us more convenience and higher efficiency, but the feature of automatic identification also creates the challenge of security and privacy of information for the company. Despite RFID having been widespread use in the food supply chain, the related security and privacy risk remains unclear and ambiguous. In Tu et al. (2020), the four critical risks of RFID that apply in the context of a supply chain, are summarized (Table 4).

4.6. Recycling issues

The Green Economy and Recycling Economy make the current global economy more sustainable. Recyclable RFID tags are not only beneficial for the natural environment, but also helps to decrease the cost of RFID tags. The generated waste from RFID tags, such as adhesives, chips, pieces of metal and conductive inks, can impact the recycling process of other food packaging(Kumar et al., 2009). Thus, there is a challenge to resolve recycling issues of RFID tags, either by choosing recyclable material or reusable tags.

4.7. Cost

The main challenge of cost is to decrease the per unit cost of RFID tags. A high cost would not be appropriate as it would hinder a large number of item tagging applications, such as required food packaging. But the per unit price is greatly dependent on the number of tags purchased. For example, the purchase number of tags increases from 10 to 100 thousands pcs. The unit price can be lower by about 17–33%, as shown in Table 5. Substrate, metal or conductive ink, and fabrication process are the three main factors relating to cost. A wise selection of substrate, conductive ink or metal and fabrication technology is the main research direction for reducing the cost of RFID sensors. Reducing tag prices, combined with improved fabrication techniques may lead to widespread adoption of RFID technology.

5. Future trends

When RFID sensors are applied in the food supply chain, a massive amount of data will be generated. There's a lot of valuable information in it that requires capture. Let us take a supermarket with RFID technology as an example. In a supermarket, there are about 700,000 RFID tags. Approximately 12.6 GB of RFID data will be produced per second, and the data will reach 544TB per day (Shen et al., 2010). Thus, it is necessary to develop effective methods for managing, analyzing and mining RFID data. Dynamic shelf life has advantages over fixed shelf life in terms of profit, reducing food waste and maintaining food safety, but this depends on real-time access to food quality data, which RFID sensors can achieve. Combining dynamic shelf life and discounting, allows for a further reduction of food waste (Buisman et al., 2017).

A Wireless Sensor Network (WSN) consists of a collection of independent devices distributed everywhere. Sensors are interconnected to form a WSN, accompanied by gateways and a coordinating device, to sense the environmental or physical conditions of a system, and to monitor or control it. The integration of RFID technology and WSN can upgrade the Internet of Things into a new network system that can fully perceive environmental factors and can highly communicate with each other (Landaluce et al., 2020). Nevertheless, most of the WSN nodes are passive tags, and their energy acquisition methods still need to be optimized to achieve a more energy efficient WSN (Anjum et al., 2019).

6. Conclusion

The key technologies to promote the development of the Internet of Things are sensor technology, RFID tags and embedded system technology. The development of the internet of things can enable intelligence of food packaging, enhance food logistics management, reduce food loss and waste, and bring better food quality and safety to consumers. RFID technology seems to have the potential to achieve all of this. RFID tags possess numerous advantages over barcodes, because they are more efficient, accurate, speedy and have a higher storage capacity than barcodes. Although RFID technology has been widely used in modern life, like any other new technology, it still faces many challenges to be overcome. For example, food safety, cost, reading range, multi-tag collision, multi-parameter sensors, recycling issues, security and privacy of RFID

Table 4

Critical risks of RFID in supply chain.

Risk	Type	Solution	Refs.
Physical security risks	Cloning attack	Duplication in manufacturing	(J. Huang, et al., 2017)
		Radio data emulation	(Dimitriou, 2005)
	Disabling attack	Termination with KILL command	(Phillips et al., 2005)
		Memory rewrite	(Gandino, et al., 2010)
	Removal attack	Detach, reattach	(Tu, et al., 2018)
		Ticket-switching	(C & C, 2015)
Network security risks	DoS/Desynchronization attack	Blocker tag	(Juels et al., 2003)
		Block with LOCK command	(Urien & Kiennert, 2012)
	Replay attack	Repeated credential use	(Mitrokotsa, et al., 2010)
		Delayed credential use	(Mitrokotsa, et al., 2010)
	Relay attack	Mafia fraud	(Chong, et al., 2011)
		Terrorist fraud	(Chong, et al., 2011)
Secrecy security risks	Encryption attack	Backward traceability	(Piramuthu, 2011)
		Forward secrecy	(Sundaresan, et al., 2014)
	Transmission integrity attack	Eavesdropping	(Jiang & Yang, 2012)
		Interception and modification	(Phillips, Karygiannis, & Huhn, 2005)
	Privacy attack	Tracking and tracing	(Sundaresan, et al., 2015)
		Ownership transfer	(Kapoor & Piramuthu, 2012)
Download security risks	Code injection attack	Limited exposure	
	Phishing attack	Limited exposure	
	Malware attack	Limited exposure	

Table 5

Unit price of different quantities of RFID tags (Janeczek et al., 2018).

Distributor/ producer	RFID chip	Unit price (USD)	Number of purchased RFID tags
Distributor 1	xWing Monza R6	0.11	100,000
Producer 1	DogBone Monza R6	0.12	10,000
Distributor 2	DogBone Monza R6	0.17	10,000
		0.14	100,000
Producer 2	DogBone Monza R6	0.11	10,000
		0.09	100,000
Producer 3	DogBone Monza R6	0.18	10,000
		0.12	100,000

system should be solved. We realize that the cost has been a major problem for RFID technology to have widespread application in the food industry. According to the present study, a chipless RFID sensor has the potential to deal with these issues by offering simpler low-cost tag system, but there are still several challenges to be overcome. In the future, we shall see even more clearly how RFID technologies combine with sensor technology and the internet to build a more robust and less power-demanding sensors network.

Submission declaration

We confirm that this manuscript has not been published elsewhere and is not under consideration by another journal. All authors have approved the manuscript and agree with submission to **Journal of Future Foods**. The authors have no conflicts of interest to declare.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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