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Review Article

Intelligent Packaging Systems: Sensors and Nanosensors to Monitor Food Quality and Safety

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The application of nanotechnology in different areas of food packaging is an emerging field that will grow rapidly in the coming years. Advances in food safety have yielded promising results leading to the development of intelligent packaging (IP). By these containers, it is possible to monitor and provide information of the condition of food, packaging, or the environment. This article describes the role of the different concepts of intelligent packaging. It is possible that this new technology could reach enhancing food safety, improving pathogen detection time, and controlling the quality of food and packaging throughout the supply chain.

1. Introduction

Globalization and dynamism in the exchange of products, along with reduced time for selection/cooking with fresh ingredients, and the growing interest in health safety and environment are the main challenges and enhance the development of new improved packaging concepts [1]. According to [2], among packaging optimization strategies to reduce food waste, there are size diversification to help consumers buy the right amount and new packaging designs to prevent the loss of scent and the appropriate moisture content [3].

The safety of food products is one of the main objectives of food law. Quality control in food manufacturing is closely related to technology, physical and sensory attributes of the product, the microbiological safety, the chemical composition, and nutritional value [4].

The functions of the packages include protection, containment, communication with the user, ergonomics and marketing (Figure 1). Containment means ensuring the right quantities of products to avoid spills. The communication function is regulated by law and the proper display will influence the consumer acceptance of the product. The information must contain features such as weight, origin, ingredients, nutritional value, precautions for use, mode of transport, and recycling or disposal. Trademarks used packaging and labels for promotion, marketing, and product sales [5]. Ergonomics in the consumption of a food product is related to minimizing physical effort and discomfort to transport, store, use, and dispose of the container [6]. It has been shown that the physical characteristics and improved containment aspect of food packaging are expectations that affect sales of products and consumer attitudes [7].

According to [8], the global market for active and intelligent packaging will double between 2011 and 2021, growing at an annual rate of 8% until 2016, reaching US $17,230 million, and later at an annual rate of 7, 7%, reaching US $24,650

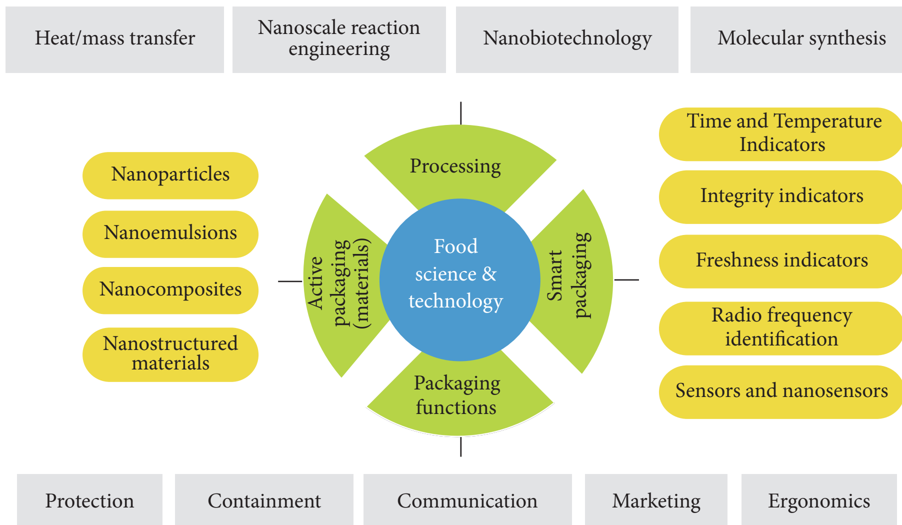

Figure 1: Application matrix of nanotechnology in food science and technology.

million in 2021. The global demand for electronic smart packaging will grow to over $1.45 billion in the next decade [9]. Several relevant markets are forecasted for this type of packaging over the next decade; the most important is United States, with an annual growth of 7.4%, reaching US $3,600 million, followed by Japan, the second largest market, reaching a size of US $2,360 million; Australia, US $1,690 million; UK, US $1,270 million; and finally Germany, US $1,400 million.

2. Smart Packaging Concepts

IP is any type of container that provides a specific functionality beyond function physical barrier between the food product and the surrounding environment [10]. Knowing information about the product quality, the packaging or the environment establishes a bond of responsibility throughout the food supply chain (storage, transport, distribution, and sale). IPs are packaging technologies that through internal and external indicators monitor interaction between the food, the packaging, and the environment [11]. This type of packaging analyzes the system, processes information, and presents it, without generally exerting any action on the food. There are two ways in the intelligent packaging systems, supporting data systems (bars labels or radiofrequency identification plates) used to store or transmit data and indicators of incidents or biosensors in packaging that allow control of the environment and product packaging [12].

Consumers increasingly need to know what ingredients or components are in the product and how the product should be stored, used, and discarded after use. Smart tags and stickers, for example, will be able to communicate directly with the customer via thin film devices that provide visual information. Many companies have deployed IP solutions on the market (Table 1).

Table 1: Commercial applications available on the market IP.

Applications	Trade name	Company
Time and Temperature Indicators	Cook-Chex	Pymah Corp.
	Timestrip®	Timestrip Plc
	Colour-Therm	Colour-Therm
	MonitorMark™	3M™, Minnesota
	Onvu™	Ciba Specialty Chemical and FreshPoint
	Fresh-Check®	Temptime Corp.
	Thermax	Thermographic Measurements Ltd.
	CheckPoint®	Vitsab
Integrity indicators	Novas®	Insignia Technologies Ltd.
	Timestrip	Timestrip Ltd.
	Best-by™	FreshPoint Lab
	O_2 Sense™	FreshPoint Lab
	Ageless Eye®	Mitsubishi Gas Chemical Inc.
Freshness indicators	Fresh Tag	COX Technologies
	SensorQ®	DSM NV and Food Quality Sensor
	RipeSense	RipSense™ and ort Research
Radio frequency identification	Easy2log®	CAEN RFID Srl
	Intelligent Box	Mondi Pic
	CS8304	Convergence Systems Ltd.
	Temptrip	Temptrip LLC

3. Applications

3.1. Time and Temperature Indicators. Because of their simplicity, low cost, affordability, and efficiency, Time and Temperature Indicators (TTI) have been widely used to monitor

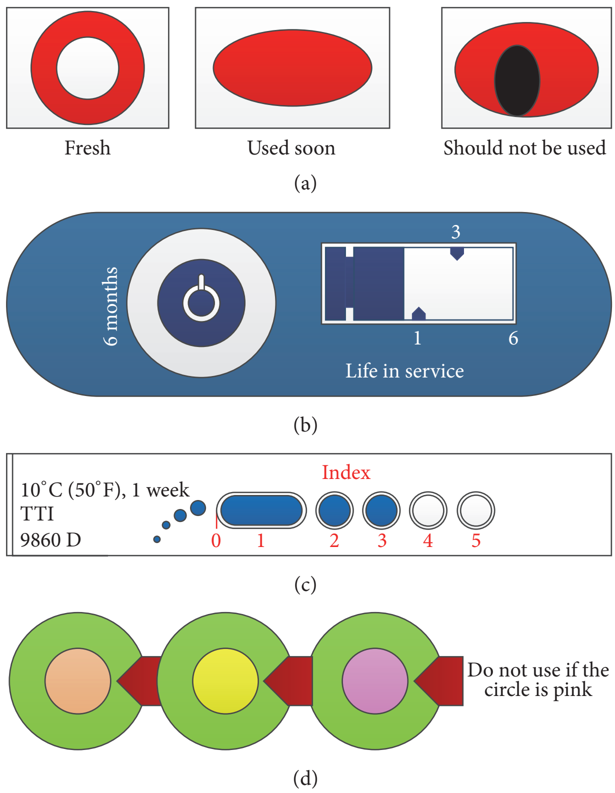

Figure 2: Schematic representation of the TTI. (a) Fresh-Check; (b) Timestrip; (c) MonitorMark; (d) CheckPoint.

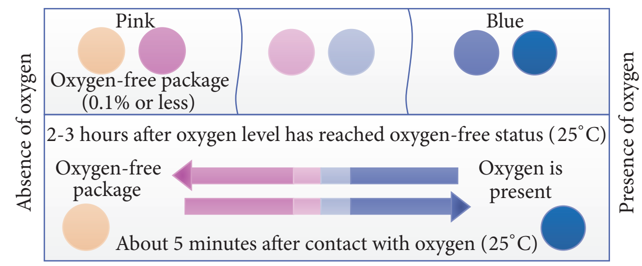

Figure 3: Schematic representation of the leak indicators.

and translate consumer quality of foodstuffs [13]. A prerequisite for the effective implementation of a control system based TTI is the kinetic study and modeling of loss ratios food quality and response [14]. Different types of TTI trade have been developed on the enzymatic base and polymeric and biological reactions [15]. To ensure the safety and quality of food products that need a certain temperature, it is important to monitor changes in the parameters of temperature and time from production to the final consumer [16, 17]. TTI can be placed in transport containers or individual containers as a small sticker; an irreversible chemical change will be reflected if the food is exposed to a different recommended temperature [18] (Figure 2). TTI are particularly important for the quality and safety of chilled or frozen food, where cold storage is a critical control point during the transport and distribution [19].

3.2. Integrity Indicators. The gas composition in the package may change due to the interaction of food with the environment. Gas indicators are a useful means of controlling the toxic composition of the gases produced from decomposing food in a food container that can endanger the health of consumers [20]; as a control measure, a change occurs in the indicator color by chemical or enzymatic reaction (Figure 3). The tag is activated at the time of consumption, the seal is broken when a timer goes off, and a color change is experienced over time [21]. Indicators must be in direct contact with the gaseous environment immediately surrounding the food in a container. The presence of oxygen may indicate that the package was sealed incorrectly, is leaking, or has been tampered with. Reference [22] describes the synthesis and manufacture of a nontoxic surface coating activated by exposure to molecular oxygen of a substrate through the irreversible formation of colored spots. Plastic optical fluorescent films are highly sensitive for the detection of gases and dissolved CO_2 [23]. The detection of CO_2 in modified atmosphere (MAP) and conventional packaging have gained considerable attention in the industry IP [24].

3.3. Freshness Indicators. A freshness indicator directly indicates the quality of the product; it is usually in the form of labels on the container. Typically, these indicators focus on the detection of the first kind of change (pH, gas composition, etc.). These changes are detected by the indicators and transformed into a response, usually a color response which can be easily measured and correlated with the freshness of food.

This response can be conditioned by the modifications of substances that are related to the metabolism of microorganisms, such as the occurrence of volatile nitrogen compounds, amines, organic acids, carbon dioxide, ethanol, glucose, or sulfur compounds during storage indicating microbial growth [25].

This type of indicators is based on indirect detection of metabolites through color indicators (e.g., pH) or based on direct detection of metabolites by biosensors. COX Technologies solutions company launched the Fresh Tag® indicator (colorimetric indicator that informs users about the formation of volatile amines in fishery products) but this product was removed from the market in 2004 [26]. Label sensor is manufactured based on methyl red; red/methyl cellulose membrane works on the increase in pH, due to volatile amines decomposition. It was successfully used as a sensor label for real-time monitoring of fresh meat of broiler chicken [27]. RipeSense™ is the first intelligent sensor label that changes color to indicate the ripeness of the fruit [28]. It works through the reaction of the aromas released by the fruit as it ripens; initially it is red and then graduates to orange and finally yellow, depending on the selection of the desired level of maturity when it comes to eating the fruit (Figure 4).

The indicator SensorQ™ developed by DSM NV (pH sensor based on anthocyanins capable of reporting formation of biogenic amines in microbiological origin meat) is an indicator of freshness for spoilage of fish. This consists of

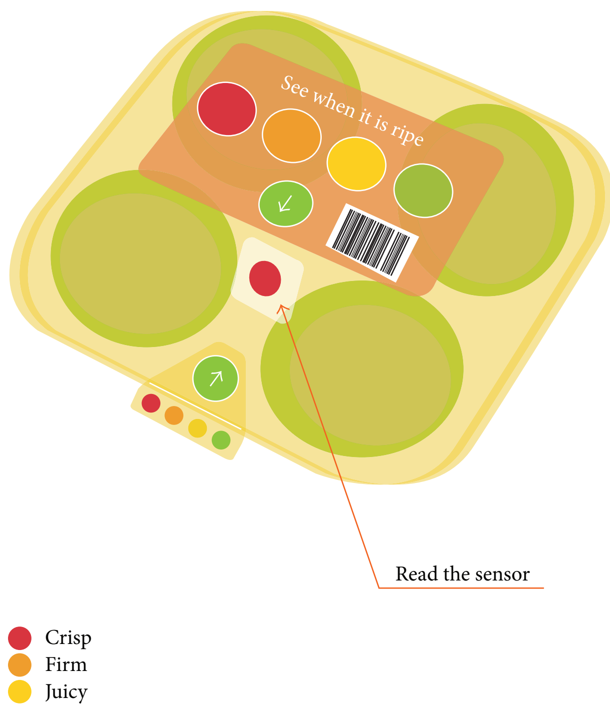

Figure 4: Schematic representation of the RipeSense indicator.

a polymer matrix which contains a solution with green dye bromocresol sensitive to the pH, by monitoring colour changes in the compounds volatile, on the basis of the quantity of amines [29]. This last freshness indicator did not achieve a successful commercialization. Additionally, the authors in [30] developed a new colorimetric sensor for monitoring the deterioration of fish meat.

3.4. Radio Frequency Identification (RFID). RFID tags are an advanced form of support data information that can identify and locate a product with a special tag that emits radio waves. These are classified into four types: active, passive, semiactive, and semipassive, depending on the power supply for communication and other functions. These devices may be coupled to an article, box, container, or pallet and therefore can be identified and tracked [31]. RFID tags can be read from several meters away and beyond the line of sight [32]; active RFID have a reading range of 91 m or more and also have a battery that enables them to communicate autonomously. Passive tags have no internal power supply; therefore, they are not able to communicate until the emission of an RFID reader is activated. The radio frequency field produced by the reader provides enough power to the integrated circuit of the label, to be able to reflect energy to the reader. Its transmission range can reach as much as 6 m. RFID systems are classified depending on the frequency range used: low frequency (LF), between 125 and 134.2 KHz; high frequency (HF), 13.56 MHz; ultrahigh frequency (UHF), 868–956 MHz; and active frequency or microwave frequency, 2.45 GHz. RFID technologies are grouped within systems called automatic identification (Auto ID).

RFID is still an expensive alternative on top of several obstacles to overcome implementation in certain sectors, 100% data reliability, and specific limitations (short-range, narrow bandwidth, and low power) [33]. The long-term vision is able to print RFID labels directly onto paper or plastic instead of silicon, while investments in the components (sensors, tags, antennas, readers, connectors, cables, networks, controllers, software, and consulting and implementation processes) are expensive. Currently, inkjet printed circuits have a very low resolution and cover large surface areas compared to traditional circuits [34].

RFID systems consist of two major components: transponder or tag and interrogator or reader, which create wireless data transmission. Each RFID tag applied to food packaging transmits the identification information to a reader, which allows communication with the RFID tag. The tag then transmits information back to the reader [35]. This information in most cases is passed to a computer (Figure 5). Readers are available as handheld computers or fixed devices that can be placed in strategic locations. According to [36], RFID tags can be read-write (you can add information to the label or write on existing data) or read-only (information stored during manufacturing process).

Many advances have been made in this field such as the development of a pH sensor embedded in a radio frequency transmitter without batteries, for in situ monitoring of deterioration processes of fish products [37]; RFID tag to control the freshness of meat [38]; RFID tag with an optical oxygen indicator for use in MAP [39]; RFID tag with a temperature sensor, a gas sensor, a reader, and a server, making up a tracking system for the freshness of pork [40]; RFID tag with sensors capable of measuring temperature, humidity, and the presence of volatile amine compounds, to estimate cod fish freshness [41]; RFID tag along with CO_2 and oxygen sensor for monitoring the freshness of vegetables [42]; system real-time evaluation of the freshness of packaged milk, marketing, and distribution using RFID tags [43].

4. Contribution of Nanotechnology in the Monitoring of Food Security

Nanotechnology involves the study, design, creation, synthesis, manipulation, and application of materials, devices, and functional systems through the control and exploitation of phenomena and properties of matter on a very small scale, usually between 1 and 100 nanometers' length. The new packaging technologies will depend on the development of nanomaterials and nanoparticles; these may include nanoparticles, nanotubes, fullerenes, nanofibers, nanocylinder, and nanosheets [44]. The unique optical and electronic properties of this nanomaterial enable the development of a new generation of electronic devices, for example, nanotransistors to build future nanoprocessors and nanomemory [45], nanobattery [46], and nanosensors [47, 48].

Nanotechnology is an interdisciplinary powerful tool for the development of intelligent packaging systems. It has been predicted that nanotechnology will have an impact on at least

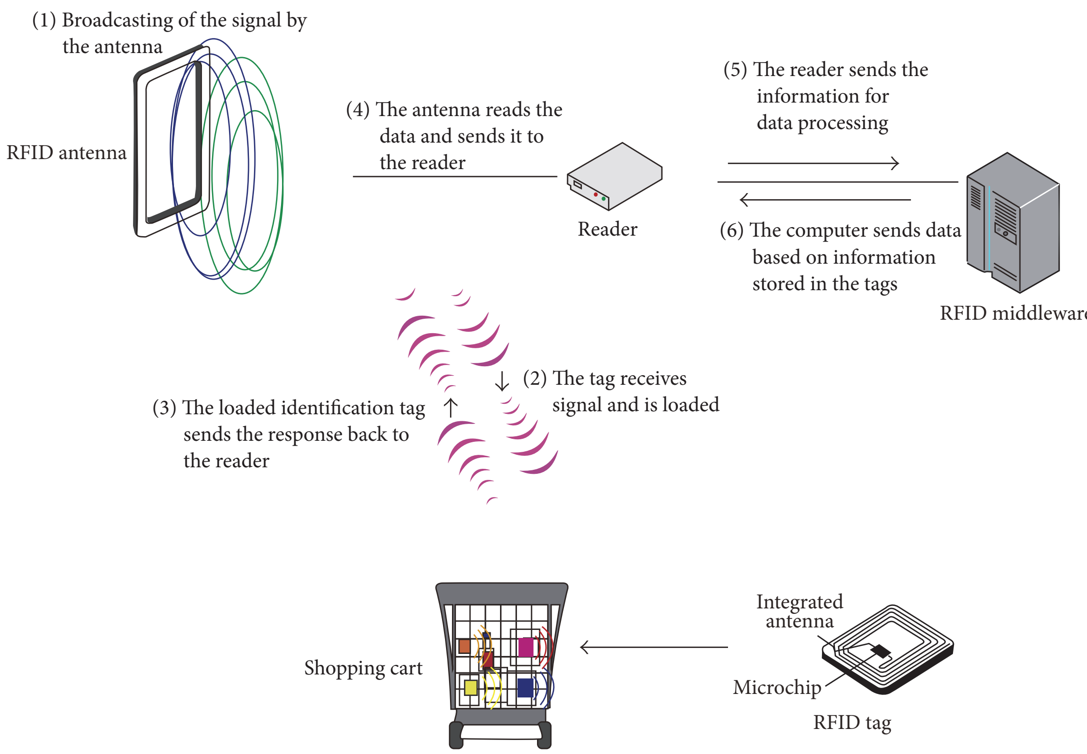

Figure 5: Schematic representation of the RFID system.

$3 trillion in the world economy by 2020, creating a demand for 6 million employers in various industries [49].

For the development of IP, the integration and the technological advancement of the sensors, nanosensors, and indicators are essential. These three terms are used interchangeably, but they are not. A sensor/nanosensor measures only certain aspects, while an indicator integrates measurement and display. The sensors and nanosensor must be connected to a device for signal transduction of the receptor, while an indicator directly provides qualitative or semiquantitative information of the quality for a visible change [50].

Nanotechnology enables the application of nanosensors in the food packaging to control their quality, during the various stages of the logistic process, and to ensure product quality to the final consumer [51]. Nanotechnology through IP can help in providing authentication, tracking, and locating product features to avoid falsification, adulteration, and prevention in the diversity of products intended for a specific market [52]. There are still many concerns for consumers of food nanotechnology; one of the most important is the uncertainty of the behavior of nanoparticles in the body and the toxic effects they could have. For this, it is necessary to establish a set of protocols and regulations on the food security of IP implications. The use of nanotechnology depends on the market and the geographical position; China's consumers are more willing to accept new technologies, while consumers in Switzerland tend to be less responsive [53].

4.1. Sensors and Nanosensors. Thanks to technological advances and the research design, the fabrication of nanoscale components is a reality. Such components are used to set up basic structural and functional devices called nanomachines (NM), whose size is expressed in nanometers and unit of length equals a billionth part of a meter ($1\,\text{nm} = 10^{-9}\,\text{m}$). Generally, sensors/nanosensors are placed in food packaging to control internal and external conditions of food [54]. From a microbiological point of view, the main objective is to reduce nanosensors pathogen detection time from days to hours or even minutes. Several authors have worked in the development of nanosensors. These NM are used in the detection of molecules, gases, and microorganisms and detection by surface enhanced Raman spectroscopy (SERS) [49]; nanosensors in raw bacon packaging for detecting oxygen [55]; electronic tongue for inclusion in food packaging consisting of an array of nanosensors extremely sensitive to gases released by spoiled food, giving a clear and visible sign if the food is fresh or not [52]; use of fluorescent nanoparticles to detect pathogens and toxins in food and crops [56], for example, detection of pathogenic bacteria in food (*Salmonella typhimurium, Shigella flexneri, and Escherichia coli O157: H7*), based on functionalized quantum dots coupled with immunomagnetic separation in milk and apple juice [57]; nanosensors to detect temperature changes [58, 59], where food companies like Kraft Foods are incorporating nanosensors that detect the profile of a food consumer (likes and dislikes), allergies, and nutritional deficiencies [60]; nanosensors for the detection of organophosphate pesticide residues in food [61]; nanosensors to detect humidity or temperature changes due to moisture [62]; sensor for detecting *Escherichia coli* in a food sample, by measuring and detecting scattering of light by cellular mitochondria [63]; biosensor for instantly detecting *Salmonella* in foods [64] and sensor to detect CO_2 as a direct indicator of the quality of the food [65]; biosensor for the detection of the pathogen food, *Bacillus cereus* [66]. Research and development in nanosensors have led to important scientific advances that enable a new generation of these NM. Nanosensors researches applied to IP are in their early stages of development.

4.1.1. Communication between Nanosensors and Their Application in Intelligent Packaging. The IP incorporating nanosensors will have great benefits for the food industry. These NM in the form of tiny chips invisible to the human eye are embedded in food or in containers, for use as electronic bar code, which allows for the monitoring of food in all its phases (production, processing, distribution, and consumption) [67]. There is no record of any investigation that extends this monitoring process until the last stage.

Communication between NM is a promising technology that ensures the development of new devices capable of performing basic and simple tasks at nanolevel (computing, data storage, detection, and triggering) [68].

The nanosensors have a limited field of measurement; therefore, the development of the wireless nanosensor networks (WNSNs) is essential for the IP industry. Such networks are a set of nodes of nanosensors dynamically self-organizing necessarily in a wireless network with possible use in any preexisting infrastructure [69]. WNSN is in its early stages of research and development for application in IP. However, matrices sensitive to gases released by spoiled food are developing nanosensors.

One major drawback is the limited energy that can be stored in a nanosensor speck in contrast to the energy required by the device to communicate. Recently, novel collecting energy mechanisms have been proposed to replenish energy stored in nanodevices. With these mechanisms, WNSNs can overcome the bottleneck and even have infinite life (perpetual WNSNs) [70]. For now, the limitations of size and power of nanodevices limit the applicability of wireless communication.

One of the most recent alternatives is based on the use of graphene, a nanomaterial of one-atom thickness, which was first obtained experimentally in 2004 [71]. Graphene enables wireless communication between nanosystems, because of its ability to support surface plasmon polariton (SPP) in the terahertz frequency range [72]. The main difference between classical plasmonic antennas and graphene-based plasmonic antennas is that SPP waves in graphene are observed at frequencies in the Terahertz Band, for example, two orders of magnitude below SPP waves observed in gold and other noble materials [73]. The SPP waves require less energy making the communication between NM feasible [74, 75].

5. Conclusions

The current advance of nanotechnology has a high potential benefit to society especially for the food industry. The development of intelligent packing systems is an emerging field that will focus on food security and will grow exponentially in the coming years. The future of food security depends largely on the technological advancement of nanosensors, integration of a nanosensor in a food container, and generating breakthroughs in IP solutions. This new packaging system can assist in the detection, monitoring, tracking, recording, and communication throughout the supply chain. The interconnection of nanosensors can extend the capabilities of a single nanosensor by allowing it to cooperate and share information; thus, the WNSNs will have a major impact on almost all areas of our society and change our daily lives. Currently, these networks are at an early stage of research and development; an example of this is the limitations that exist in the nanocommunication and the nanobatteries. The commercialization of this technology is linked to the advancement of printed electronics for mass production; it is expected that smart labels and smart packaging will reach low cost relative to the food product.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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