

A Review on **Nano-FoodPackaging**: An Untapped Revolution in Food Packaging

Abstract

Spoilage of food is a worldwide concern because of poor faulty packaging material. **Today the** evolution of nanotechnology in the food industry **providesseveral** benefits in **food preservation**, food processing, and food packaging. Nano packaging has found many applications in the food industry. Nano packaging of food provides many benefits such as oxygen (O₂) scavengers, moisture scavengers, antimicrobial, gas barrier properties, strength, flexibility, keeping an eye on freshness, etc. **These nanomaterials help to increase the shelf life of food, and maintaining the quality without causing any alteration is a primary concern.** Nano packaging made it possible to transport food globally by increasing the shelf life of food products. Nano food packaging, however, is still in the fetalstage; therefore, this review crisps the present status and recent advancement of this technology. Furthermore, address the toxicity of nanoparticles (NPs) in food packaging and safety concerns. The pros and cons of this novel technology will describe **its usefulness** and appropriateness in the food packaging industry.

Keywords **Nano-Foodpackaging**. Active packaging. Improved packaging. Intelligent packaging. Food industry.

Toxicity

Declarations

Conflict of interest The authors declare no competing interests.

1. Introduction

Food packaging is defined as the process of enclosing the food for containment, storage, transportation, distribution, retailing, and fulfilling the consumer's needs with minimal cost. Packaging plays a significant role in the preservation and marketability of any product and ensuring its safe delivery to the consumer whilst providing essential information regarding the product (Shin and Selke 2014). Packaging provides a shield to food products protecting them against damage from any physical, chemical, and biological changes like spilling, leaking, or contamination by microorganisms, or toxins (Fig. 1). In earlier times, food was consumed instantly as it was found. Natural products like leaves, shells, animal hides and organs were used when containment of food was needed. As humans started traveling to new places, their need for storing food increased. As discoveries and inventions were made, packaging also changed with that. Present packaging has changed a lot and we are using complex materials and processes in making modern packaging what we use nowadays (Prasad and Kochhar 2014). In today's advanced commercial food industry, there are very few products that are being sold unpacked, and hence food packaging plays a major role in the handling and transporting of food products to the end of the supply chain. Packaging plays a prime role in preserving food products and beverages and minimizing the deterioration of health and quality of the packed food products caused by exposure to the external environment (Wyrwa and Barska 2017). According to the World Packaging Organization (WPO), 25% of food products are wasted just because of faulty and improper food packaging (Briand 2009). Furthermore, around one-third of the food products all over the world are wasted and lost because of poor and inadequate food packaging (Wikström et al. 2019). Food packaging is critical for every single food industry as it is a link between producers and consumers. In today's society, people are more than ever aware of fresh, healthy, nutritious, minimally processed, and hygienic food with standard labels. Packaging is a major issue for the food industry worldwide to fulfill the rising demands for healthy, safe, and fresh food as well as meet safety standards. Hence continuous developments and innovations in the packaging sector are vital for the food industry (Sharma et al. 2017).

This review highlights the active, improved, and intelligent nano packaging materials that extend the shelf life of food products. Furthermore, studying the toxicity of nanomaterials in the human body and ecosystems is a primary concern that has been discussed in this review. Moreover, this review as to bridge the gap required for the coming research opportunities in the future.

-Food packaging

Food packaging is a global concern as its internal heterogeneity affects the food product. Food quality, shelf life, and microbial contamination are the major problems faced by the food industry worldwide due to the increased interaction between food and packaging material (Chen et al. 2019). There is an increased demand for fresh food, with a prolonged shelf life and premium quality. To maintain such applications, an emerging force for the evolution of new packaging material is required. Therefore, manufacturers are looking for packaging materials that can be transparent and tamper-resistant, compatible with the food product, provide ultraviolet (UV) protection, limit ingress of gases, extend the shelf life, be free from microorganisms, and be disposed of or recycled easily minimizing environmental damage while remaining cost-effective simultaneously (Dainelli et al. 2008; Kubiak and Borowy 2013). Nanotechnology is emerging as a boon for the food packaging industry for such applications (Echegoyen 2015).

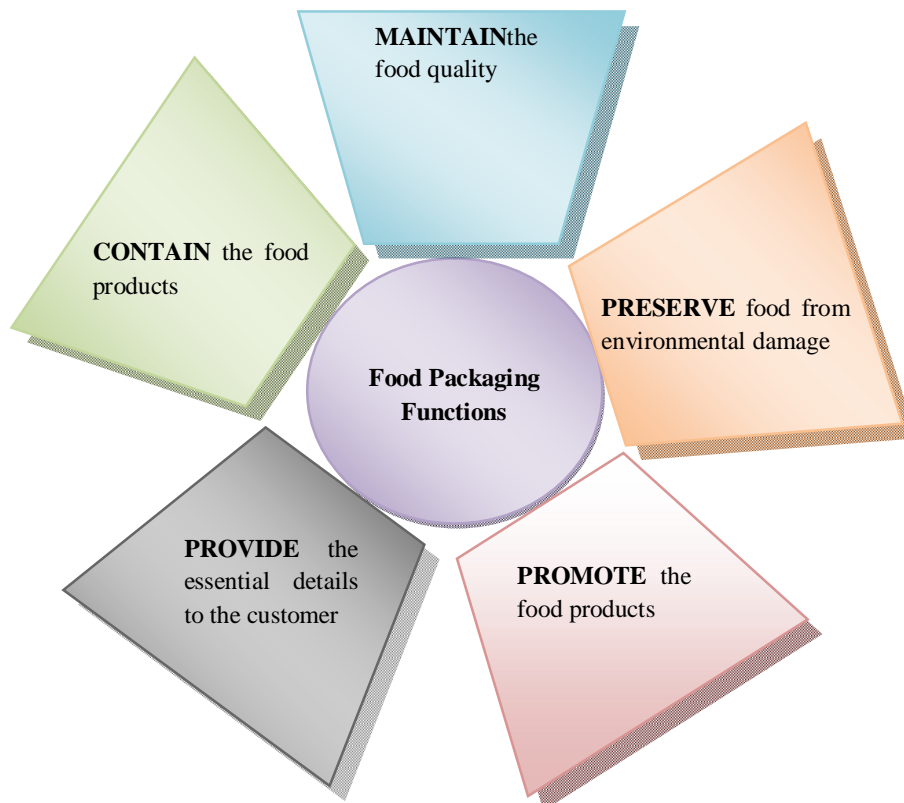


Fig. 1 Food packaging functions

-Nanotechnology in food packaging

Nanotechnology is a technique introduced by Richard Feynman in 1959 and later in 1974 term "nanotechnology" was coined by Norio Taniguchi. The term "nano" simply means tiny, micro, and very small in

size. The particle size is as small as the diameter of the human hair. Nanotechnology is a de novo technique involved in the manipulation, fabrication, and characterization of molecules ranging from 1-100 nm in length (Enescu et al. 2019). In both developed and developing countries, the arrival of nanotechnology has a prominent picture in multidisciplinary areas of research such as biological, chemical, physical, and engineering (Sing et al. 2017). In 2020, nanotechnology robust worldwide economy by \$3 trillion (Duncan 2011). Recently, **the increased** demand for nanomaterials in 2015, especially in the food industry generated revenue of \$2.5 million and in 2022 it is expected to reach \$9 million (Primožic et al. 2021). The advent of nanotechnology in food packaging revamps the whole food industry to create and design innovative packaging materials for the welfare **of consumers** (Hoseinnejad et al. 2018). In contrast with macroscale material, nanomaterials have larger surface activity, area, and volume as well as better physical, optical, electronic, and chemical properties. Just because of their nano size, nanotechnology in food packaging expanded in the last 10 years due to the boundless advantages in extending the shelf life of food products, blocking environmental stressors, heat, light, dust, volatile, and maintaining the quality and safety of food (Hamad et al. 2018).

-Heterogeneity in nano packaging materials

Numerous types of nanotechnology-based food packaging materials that are used in the food industry comprise active packaging, improved packaging, and intelligent packaging.

2. Active packaging

Active packaging means packaging material directly acts on the food products and their environment to extend the **shelf life** and certify the safety and quality of the packed food. According to European regulation (no 450/2009), active packaging means "*deliberately **incorporating** components that would release or absorb substances into or from the packaged food or the environment surrounding the food*" (European Commission 2009). Therefore, active packaging is an excellent food packaging that can maintain the parallel relationship between the food and its surrounding, and keep the food quality simultaneously (Domínguez et al. 2018). The basic fundamental principle of active packaging technology concept that could release (emitters) and absorb (scavengers) substances inside the wrapped food and its food environment (Gaikwad et al. 2019a). However, the emitters release antioxidants, antimicrobial substances, carbon dioxide (CO₂), ethylene (C₂H₄) or ethanol (C₂H₅OH), and flavors (Momin and Joshi 2015). These active compounds are helpful to maintain favorable conditions inside the packaged food. **It also** ensures the quality of storage and stable **conditions** for increases in the shelf life of food (Majid et al. 2018). On the other hand, scavengers act to remove the unwanted substances

from the surroundings of the packed food such as CO₂, moisture, oxygen(O₂), C₂H₄, and odor (Arora and Padua 2010). Additionally, there is no direct association between the food and the scavengers, but it helps to enhance the condition of food inside the packet as well as boost its shelf life (Singh et al. 2016). Various types of active packaging are used commercially in the food industry (Fig. 2) (Kapetanakou and Skandamis 2016; Lee et al. 2015; Pascuta and Vodnar 2022; Pereira de Abreu et al. 2012; Realini and Marcos 2014). In comparison with the traditional packaging system, active packaging extends the shelf life of the food and preserves the quality, and standard during the reaction between the environment and the food product (Vilela et al. 2018). Therefore, active packaging appraises to be exemplary packaging in the food industry (Singh et al. 2019).

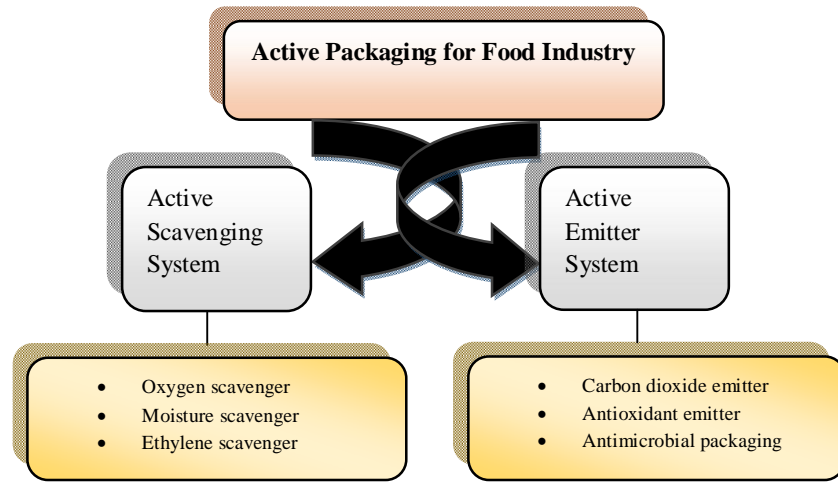


Fig. 2 Various types of active packaging used for the food industry

-Oxygen scavengers

O₂ access to the food package is most often an aspect that reduces the shelf life of food products (Arvanitoyannis and Oikonomou 2012; Dey and Neogi 2019). Oxidation of food results in nutrient losses, rancidity, browning, color lessening, off-odors, off-flavor, and growth of aerobic microorganisms which affects the quality (Hutter et al. 2016; Kuswandi 2017a; Mane 2016; Van Bree et al. 2012). O₂ scavenging agents used in food packaging are iron (Fe) powder, ferrous oxide (FeO), ascorbic acid (C₆H₈O₆), tocopherol (C₂₉H₅₀O₂), sulfite (SO₃²⁻), titanium oxide (TiO₂), glucose (C₆H₁₂O₆) oxidase, and C₂H₅OH oxidase (Gaikwad et al. 2018c; Gauthier 2015; Kasai 2015). O₂ scavenging mechanism based on substances absorbs O₂ based on iron compounds particularly placed on sachets. Due to the high sorption capacity of iron compounds, it is the most effective method to extend the shelf-life of food in the market. These iron compounds absorb O₂ available in the market labels present inside the packet, bottle caps, or integral parts of the packet (Pandey et al. 2022). In Japan, Germany, USA, Switzerland, and Finland O₂ scavenger trade is presumed to gain 2.41 billion USD by 2022 and

from 2017 to 2022 the compound annual growth rate (CAGR) is 5.1% (Anonymous 2017a; Anonymous 2017b). In addition, for example, a study conducted that **C₆H₈O₆-based** O₂ scavenger sachets were developed by using activated carbon (C) and sodium L-ascorbate (C₆H₇NaO₆) to increase the shelf life as well as reduce the microbial growth in meatloaf (Lee et al. 2018).

-Moisture scavengers

Moisture and humidity are major factors that are responsible for food spoilage (Mohan and Ravishankar 2019). **Active moisture** scavengers are moisture absorbers and desiccants and they are hygroscopic in nature or **attract water** molecules from the surrounding (Day 2008; Suppakul 2015). The moisture absorber can be used in the form of sachet, pads, blankets, and sheets (Fig. 3) applied under fresh food products such as fish, fruits, vegetables, poultry, and meat in the various packaging system. Such absorbing pads are composed of linear low-density polyethylene, low-density polyethylene, and polyethylene-laminated (Gaikwad et al. 2018a). On the other hand, desiccants are used in the form of sachets, bags, and pads put into the headspace of the food package. Some examples of desiccants are clays, silica (SiO₂) gel, zeolite (Na₂Al₂Si₂O₈.xH₂O), cellulose (C₆H₁₀O₅)_n fibers, sodium chloride (NaCl), magnesium sulfate (MgSO₄), calcium oxide (CaO), and sorbitol (C₆H₁₄O₆) (Gupta et al. 2020).

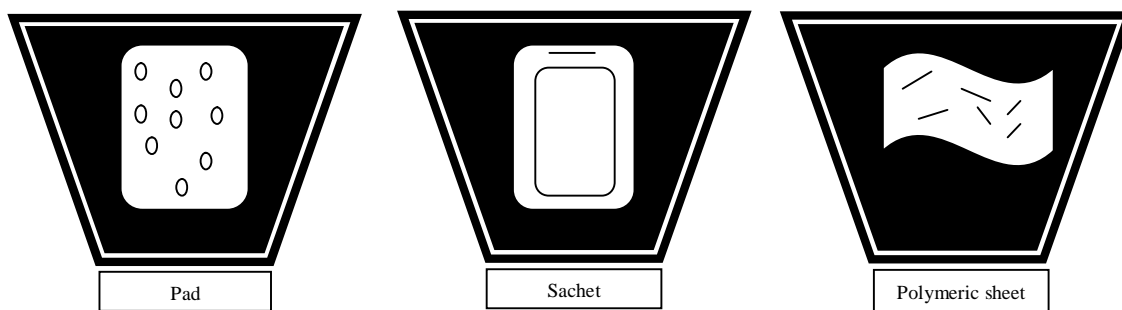


Fig. 3 Types of moisture absorbers **for the active** packaging system

-Ethylene scavengers

C₂H₄ is a plant hormone that plays a key role in shortening the postharvest life of fresh food during storage. C₂H₄ accelerates the ripening resulting in softening, and chlorophyll (C₅₅H₇₂MgN₄O₅) degradation leads to the deterioration of fruits and vegetables (Gaikwad et al. 2018b; Zhu et al. 2019). C₂H₄ scavenging agents used in food packaging are Na₂Al₂Si₂O₈, **potassium permanganate** (KMnO₄), silver nitrate (AgNO₃), palladium (Pd), **propylene** glycol (C₃H₈O₂), polyethylene (C₂H₄)_n, activated charcoal (C), SiO₂ gel and aluminum oxide (Al₂O₃) (Wei et al. 2021). Commercially, C₂H₄ scavengers are sold in the form of the C₂H₄ Control Power Pellet sachet, Bio-fresh packaging system, Retarder®, Ethisorb, Profresh, EvertFresh Green Bags®, and

PEAKfresh® (Gaikwad et al. 2019b). For example, chitosan (C₅₆H₁₀₃N₉O₃₉)-TiO₂ nanocomposite film is used to extend the shelflife of tomatoes for 14 days (Kaewklin et al. 2018).

-Carbon dioxide emitters

CO₂ amount (60 to 80%) in the food packet inhibits microbial growth and therefore extends the shelf life of the food product (Holck et al. 2014). Food properties such as the potential of hydrogen (pH), surface area, water, protein, and fat affect the solubility of CO₂ (Chaix et al. 2015). Generally used CO₂ emitters are sodium bicarbonate (NaHCO₃), sodium ascorbate (C₆H₇NaO₆), ferrous carbonate (FeCO₃), and C₆H₈O₆ (Robertson 2012a). The CO₂ emitters mechanism is based on O₂ absorbed with the help of an O₂ scavenger and replaced with CO₂. In this mechanism bifunctional sachets are used which contain O₂ scavengers and CO₂ emitters simultaneously which absorb O₂ and produce the same amount of CO₂ (Alves et al. 2023). Commercially, CO₂ emitters have been sold in the form of FreshPax (India), Ageless (Japan), Freshlizer (Japan), Verifrais™ package, SARL Codimer (Paris, and France) (Bhardwaj et al. 2019). For example, CO₂ emitters are used for the packaging of fresh food products such as meat, poultry, fish, cheese, and vegetables (Haghighi Manesh and Azizi 2017).

-Antioxidant emitters

Antioxidants in packaging material help to provide oxidative stability as well as to prevent microbial growth, discoloration, change in texture, nutritional losses, and off-flavor of the food products (Gómez-Estaca et al. 2015). Antioxidant emitters used in food packaging are butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), C₂₉H₅₀O₂, polyphenols, essential oils (EOs), and plant extracts (Barbosa-Pereira et al. 2014). Furthermore, antioxidant packaging is used in the form of sachets, labels, coatings, and multilayers (Bolumar et al. 2011). For example, a study conducted on natural antioxidants such as orange, lemon, and beetroot peels EOs has the potential to prevent rancidity during cold storage in sardines (Djenane 2015).

-Antimicrobial packaging

An antimicrobial packaging system has been designed to inhibit the growth of pathogenic microorganisms to extend the shelf life of food products (Kim et al. 2022). Antimicrobial substances used in food packaging are bacteriocins, enzymes, natural extracts, NPs, fungicides, organic acids, and polymers (Kamarudin et al. 2022). Antimicrobial packaging can be used in the form of sachets or mats, incorporated, coated, immobilized, and modified on the surface of packaging material (Coma 2008). Commercially available antimicrobial packaging is AgIon®, Zeomic®, Microban®, and Irgaguard® (Ashfaq et al. 2022). For

example, carvacrol (C₁₀H₁₄O) and thymol (C₁₀H₁₄O) EOs was used to prevent the growth of *Botrytis cinerea* in strawberry without organoleptic changes (Campos-Requena et al. 2015).

3. Improved packaging

The basic fundamental principle of improved food packaging by the fusion of traditional polymer materials into functional nanomaterials thus improving the packaging property (Pandey et al. 2013). It can provide great physical and mechanical properties such as high barrier quality, tough resistance to humidity, temperature, flexibility, and mechanical strength (Nath et al. 2022). The combination of nanomaterials in food packaging has more advantages as compared to the traditional polymer packaging material (Chausali et al. 2022). The various types of the nanotechnology-based packaging system for improving quality and extend the shelf life of food products (Fig. 4) (Babu 2021).

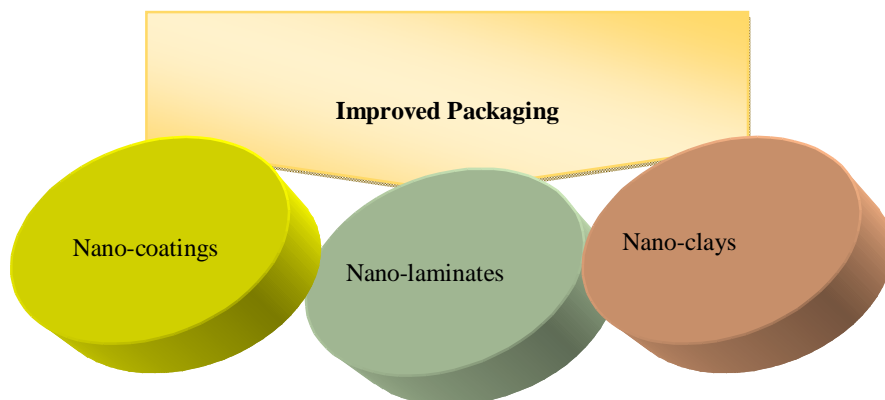


Fig. 4 Nanotechnology-based improved packaging system

-Nano-coatings

Nano-coatings or a film is a thin layer that can be used to wrap the food products and create a barrier to mass transfer. The coatings can act as a barrier to moisture, O₂, gas, etc (Bourtoom 2008; Rovera et al. 2020; Valdes et al. 2017). Nano-coatings in food can be divided into edible and non-edible coatings. Edible coatings can be directly applied to food products, on the other hand, non-edible coatings act as a protective layer without being part of the food product (Maringgal et al. 2020; Paidari et al. 2021; Petkoska et al. 2021). Also, coatings in food can be applied in two ways either direct application of liquid solution or by using molten compounds (Baldwin et al. 1996). NPs integrated edible coatings can be used in a variety of food products such as fruits, vegetables, bakery products, meat, fish, cheese, candies, and chocolates (Azeredo et al. 2009; Costa et al. 2018; Dhital et al. 2017; Nile et al. 2020). Various types of packaging materials are used in edible coatings in the food industry (Fig. 5) (Kumar et al. 2022; Perera et al. 2021; Tavassoli-Kafrani et al. 2022).

-Nano-laminates

Nano-laminates mean the deposition of one or more layers with materials whose dimension (D) is less than 100 nm per layer. Layer-by-layer assembly technique is the most dynamic method in which charged surfaces are attached with chemical bonding such as covalent bonding, electrostatic bonding, hydrogen bonding, charge-transfer interactions, and hydrophobic interactions. However, electrostatic bonding is the only method used in the food industry (Acevedo-Fani et al. 2017a; Acevedo-Fani et al. 2017b; Borges and Mano 2014; Flores-López et al. 2016). Different types of adsorbing materials are used to create nano-laminated films such as polyelectrolytes (proteins, polysaccharides), lipids (surfactants, phospholipids), and colloidal particles (droplets, micelles, vesicles) (Kuswandi and Moradi 2019; Weiss et al. 2006). Additionally, there are two ways of using nano-laminates in the food industry that is spraying and dipping methods (Ramachandiraiah et al. 2015). Also, it is possible to incorporate different active functional agents in nano-laminate films such as (antioxidants, antimicrobials, anti-browning agents, flavors, odor, enzymes, etc.) by extending the shelf life and quality of the food (Galus et al. 2020; Salgado et al. 2015).

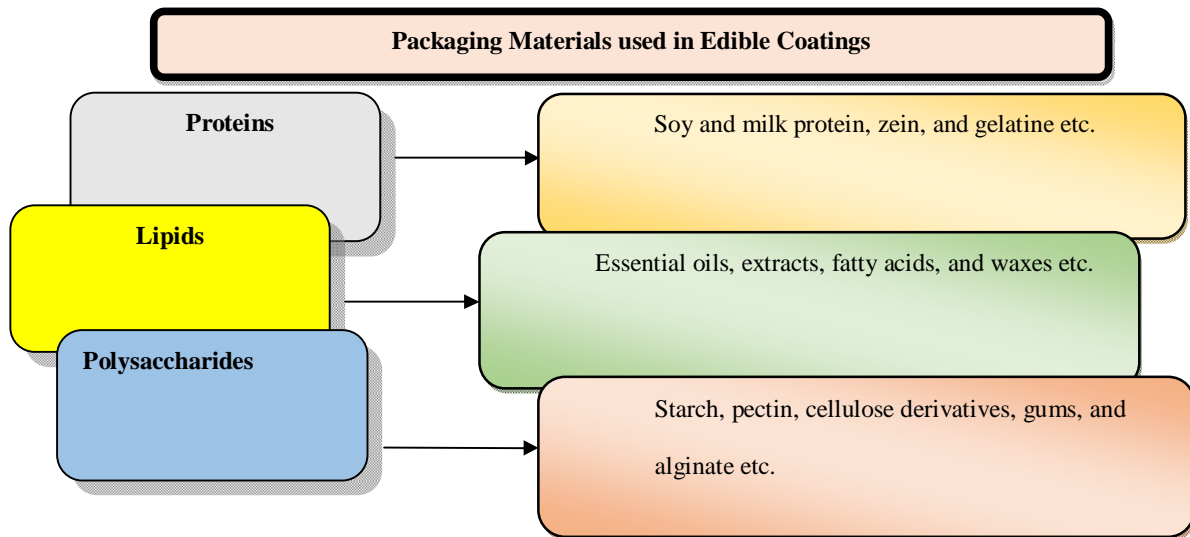


Fig. 5 Packaging materials used in edible coatings

-Nano-clays

Among the food packaging system, nano-clay was the first substance to appear on the market (Silvestre et al. 2011). At present, it is the most widely used nanomaterial in the food packaging industry. Because it represents the excellent mechanical and barrier properties by embedding and incorporating the nano-clays into the polymer matrix (Bumbudsanpharoke and Ko 2019; Majeed et al. 2013). Nano-clays consist of a 2D structure, several microns long, and usually 1 nm thickness. Also, the synergism between the polymer matrix

and the clays comes up with extends the shelf life, resists heat and shattering, and is lightweight (De Azeredo et al. 2011; Jorda-Beneyto et al. 2014; Kim and Cha 2014). Due to the presence of the nano-clays in a polymer matrix, the pathway of the diffused molecules is obstructed, increasing tortuosity, which results in the non-linear passage for O₂ and water vapors (Fig. 6) (Bumbudsanpharoke et al. 2015). For example, in a study conducted by formulation of the film with agar and nano-clay (Cloisite Na⁺), the result showed that water vapor permeability, tensile strength, and the hydrophobic property of film due to the presence of clay (Rhim 2011). One more study reported that the application of both nano-clay and silver (Ag) NPs showed antibacterial properties and extends the shelf life of shrimp (*Penaeussemisulcatus*) (Paidari and Ahari 2021).

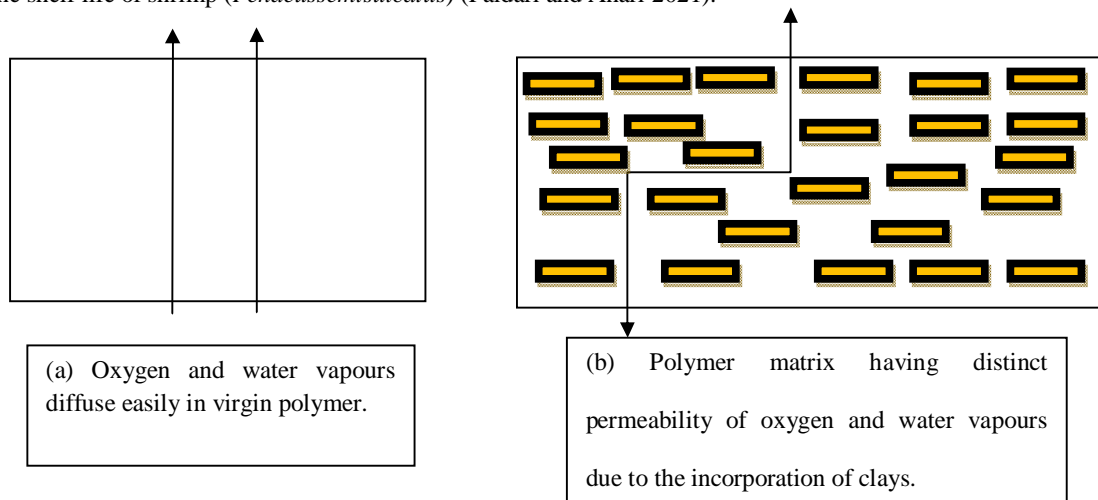


Fig. 6 Tortuous pathway of water vapor permeability created by the incorporation of clay in polymer matrix

4. Intelligent packaging

According to European Food Safety Authority (EFSA), intelligent packaging defines as "materials and articles that monitor the condition of packaged food or the environment surrounding the food" (European Food Safety Authority 2009). By using NPs, intelligent packaging sensing and communication chemical, biochemical, or microbial spoilage of the food products or their environment without direct interaction with the food products (Biji et al. 2015; Madhusudan et al. 2018). The main objective of intelligent packaging is to assess and monitor the food to inform the consumer and assure its safety and quality (Müller and Schmid 2019). Therefore, various types of intelligent packaging are used in the food industry (Fig. 7) (Ghaani et al. 2016).

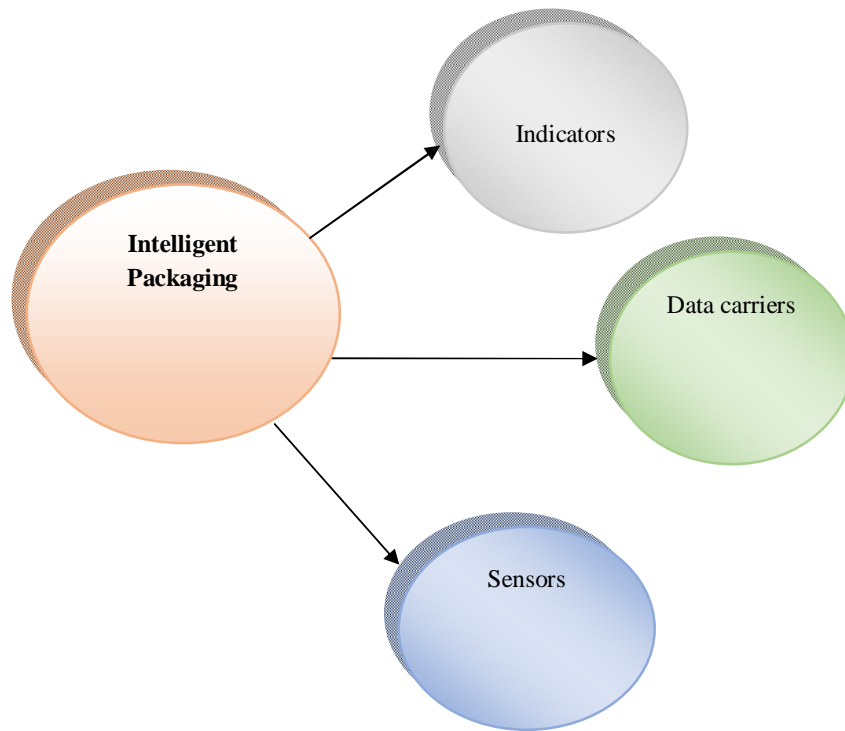


Fig. 7 Types of intelligent packaging used in the food industry

Indicators

Indicators indicate the presence, absence, or concentration of the chemical substance in the food products and the degree of a chemical reaction between the two or more substances using color change (Hogan and Kerry 2008; Kuswandi 2017b; Mohebi and Marquez 2015).

-Time-temperature indicators

Time-temperature indicators (TTIs) are focusing on checking the food quality through visible color development specifically correlates with food quality at a particular temperature (Mihindukulasuriya and Lim 2014; Pavelkova 2013). An important indicator is useful in controlling and monitoring the handling, distribution, and storage of food products (Ranjan et al. 2014). TTIs are user-friendly, cost-effective, commonly used in the form of tags or labels, and fixed to food packaging (Kuswandi and Jumina 2020). For example, commercially based TTIs are 3M Monitor mark (3M Company). It has a fixed melting point of fatty acid esters melts, which indicates a color change to a blue dye (Gregor-Svetec 2018; Kuswandi et al. 2011).

-Freshness indicators

Freshness indicators (FIs) aim to provide actual information about the foodstuff during its storage, sale, transportation, and consumption when food became unacceptable for eating (Lee and Rahman 2014). Thus, they serve or display information regarding microbial contamination, microbial growth, and chemical reaction including- biogenic amines, CO₂, organic acids, C₆H₁₂O₆, C₂H₅OH, sulfuric compounds, and volatile nitrogen compounds, (Siracusa and Lotti 2019; Sohail et al. 2018). FIs are used on the surface of food packaging in the

form of labels to identify the quality of the food products (Fuertes et al. 2016). Additionally, newly developed FIs are used in the form of a smart cap to determine the freshness of the milk without opening the seal of the cap (Lu et al. 2013).

Data carriers

Data carriers are also known as automatic identification tool that facilitates the flow of information within the whole supply chain and also maintains the traceability, protection from theft, and automatization of food products (Chowdhury and Morey 2019; McFarlane and Sheffi 2003). The most common data carriers used in the food industry are barcode and radiofrequency identification (RFID)(Robertson 2012b).

-Barcode

A barcode is the most economical, cheap, and widely used optical, machine-readable, graphical representation of the data used to facilitate the recording of stocks, control the inventory, and checkouts of food products (Magasura 2018; Manthou and Vlachopoulou 2001). In the 1970s, Universal Product Code(UPC) was introduced. The UPC was linear, 1D represents only 12 digits of the data and depicts only the manufacturer number and item number (Mirza Alizadeh et al. 2020). Later in 2011, a matrix code-based 2D barcode named Quick Response (QR) was introduced and used in the food industry (Hakola et al. 2021; Liu et al. 2008). QR stores a large amount of information which is very useful to retailers and consumers. For example, batch number, nutritional information, packaging date, packaging weight, and preparation instructions (Cata et al. 2013; Cipriani 2017; Drobnik 2015; Gao et al. 2007).

-Radiofrequency identification

RFID tags or a label is an advanced form of wireless data transmission attached to the food packet to collect real-time information (Bibi et al. 2017). They have a 1-megabyte data storage capacity and trace the packet with the help of a radiofrequency electromagnetic field (Abad et al. 2009; Aguzzi et al. 2011). As compared to barcodes, RFID is a little pricey and requires a strong electronic network (Brockgreitens and Abbas 2016). Moreover, RFID provides information on the whole supply chain such as inventory management, traceability, and quality or safety of the food products (Kumar et al. 2009). RFID consists of three components (i) the RFID tag which is used to store information, (ii) the interrogator that receives information from the RFID tag, and (iii) software that manages and controls the operation (Ahmed et al. 2018; Dabbene et al. 2014).

Sensors

A sensor is a device or tool used to measure physical energy and converts it into a signal read by the observer (Vanderroost et al. 2014). The excellent feature of the sensor is fast response time, high sensitivity and

selectivity, long-term stability, full reversibility, good reliability, and wide dynamic range (Hanrahan et al. 2004). Thus, the most widely used sensor used in food packaging is biosensors and gas sensors (Adley 2014).

-Biosensors

A biosensor is an analytical device that can detect, record, and transmit information regarding biochemical reactions such as antigens, antibodies, enzymes, nucleic acids, hormones, and phages (Chaudhary et al. 2022; Thakur and Ragavan 2013; Yam et al. 2006). Furthermore, a biosensor can be used in food packaging for the detection of pathogens and microbes, especially in the meat and fish industry (Alocilja and Radke 2003; Sobhan et al. 2021). For example, nano biosensors can be used to detect the food toxicants such as pesticides, additives, bisphenol A, and aflatoxins even in minute quantities (Raja et al. 2021).

-Gas sensors

A gas sensor is used to assess the concentration of certain gases inside the food packet such as CO₂, and hydrogen sulfide (H₂S)(Matindoust et al. 2016). Therefore, these gases indirectly monitor the spoilage status of food. A list of the gas sensor which can be used in the food industry is amperometric O₂ sensors, organic conducting polymers, potentiometric CO₂ sensors, metal oxide semiconductor field-effect transistors, and piezo-electric crystal sensors (Firouz et al. 2021; Kalpana et al. 2019).

5. Application of nanotechnology in food packaging

Nanotechnology finds its application in several sectors of foods such as bioavailability, encapsulation, packaging, processing, fortification, food safety, pathogen detection, etc(Thangadurai et al. 2020).The application of nanotechnology in food packaging (Table 1) **has been** studied by various authors.

Table 1 Applications of nanotechnology in food packaging (2015-2022)

Food applications	Effects	Nanomaterials	Packaging type	References
Bakery products	Slow down the growth of molds for 2 to 10 days.	Pd	O ₂ scavengers	(Ruegg et al. 2022)
Whole-wheat breadsticks	Shelf life extension.	Rosemary extract	Antioxidant emitters	(Alamprese et al. 2017)
Milk chocolate cereals and dark chocolate peanuts	Improvement of oxidative stability.	Green tea extract	Antioxidant emitters	(Carrizo et al. 2016)
Cake	Maintains chemical and sensory	Zinc	Antimicrobial	(Sahraee et

	quality, and also prevents fungal growth.	oxide(ZnO)	packaging	al. 2020)
Fresh pizza	Allylisoithiocyanate (AITC) inhibits the growth of <i>Aspergillusparasiticus</i> and aflatoxins after storage for 30 days.	AITC	Antimicrobial packaging	(Quiles et al. 2015)
Sliced pan loaf	Garlic extract prevents the growth of mold for 30 days.	Garlic extract	Antimicrobial packaging	(Heras-Mozos et al. 2019)
Dark, white, and milkchocolate	Used to assess the quality of chocolate.	Metallo porphyrin and gold (Au) NPs peptide gas sensor	Gas sensors	(Compagnon et al. 2015)
Strawberries and tomatoes	Regulates relative humidity below 97% at different temperatures for 7 days.	NaCl	Moisture scavengers	(Rux et al. 2016)
Guava	The shelf life of guava is extended to 32 days.	Phenols(C ₆ H ₆ O) and C ₆ H ₈ O ₆	Moisture scavengers and C ₂ H ₄ scavengers	(Murmu and Mishra 2018)
Fruits and vegetables	Reduction ripening.	SiO ₂ , KMnO ₄ , nitrous oxide (N ₂ O), and 1-methyl cyclopropane	C ₂ H ₄ scavengers	(Sadeghi et al. 2021)
Peach and Nectarine	Shelf life increased with excellent sensory quality.	Na ₂ Al ₂ Si ₂ O ₈ coated with	C ₂ H ₄ scavengers	(Emadpour et al. 2015)

		KMnO ₄		
Tomato	Ripening process delayed.	TiO ₂	C ₂ H ₄ scavengers	(Kaewklin et al. 2018)
Sapodilla	Loss of vitamin C and firmness delayed. Also retarded internal and external appearance, pulp, and color changes.	KMnO ₄	C ₂ H ₄ scavengers	(Álvarez-Hernández et al. 2019a)
Blueberry	Highly delayed both weight and firmness losses, also removed C ₂ H ₄ and fungi.	KMnO ₄	C ₂ H ₄ scavengers	(Álvarez-Hernández et al. 2019b)
Apples	Reduced effective respiration rate and extends the shelf life by 7 to 11 days.	C ₅₆ H ₁₀₃ N ₉ O ₃₉ -caseinate coating	Antioxidant emitters	(Volpe et al. 2019)
Tomato puree	Decrease the bacterial growth: <i>Escherichia coli</i> and <i>Saccharomyces cerevisiae</i> .	Cinnamon essential oil	Antimicrobial packaging	(Gherardi et al. 2016)
Strawberries	Extending the shelf life and maintaining quality.	Limonene(C ₁₀ H ₁₆)	Nano-coatings	(Dhital et al. 2018)
Fresh pineapple	Improving the shelf life of cut pineapples with anti-cancer property.	Curcumin (C ₂₁ H ₂₀ O ₆)	Edible nano-coatings	(Ghosh et al. 2021)
Cabbage	Inhibit the growth of <i>Escherichia coli</i> , and <i>Pichiapastoris</i> .	C ₁₀ H ₁₄ O	Edible nano-coatings	(Sow et al. 2017)
Fresh cut apple	Reduced the growth of <i>Escherichia coli</i> and bacterial growth.	Lemongrass essential oil	Edible nano-coatings	(Salvia-Trujillo et al. 2015)

Tomato	Extending shelf life, decreased weight loss, microbial growth, also reduced exchange of gases and C₂H₄production.	<i>Flourensiacerna</i> extract	Nano-laminates	(Salas-Méndez et al. 2019)
Orange	Reduced the rate of respiration and weight loss, also enhance nutritional quality and sensory acceptability.	Carnauba wax nano-clays	Nano-clays	(Motamedi et al. 2018)
Non-pasteurized angelica juice	Used temperature above 13.5°C.	Isopropyl palmitate (IPP) diffusion	TTIs	(Kim et al. 2016)
Fresh cut fruits	The indicator works best at 18–19°C. This response is directly converted into an RFID signal and works fast as compared to critical temperature.	Dimethyl sulfoxide (C ₂ H ₆ OS)with RFID	TTIs	(Lorite et al. 2017)
Grape	Chlorophenol red-based simple indicator impairs the filter.	pH	Freshness indicators	(Kuswandi and Murdyaningih 2017)
Refrigerated fruits	Used to estimate energy consumption in cold storage and water loss from fruits.	RFID and wireless sensor networks.	RFID	(Badia-Melis et al. 2015)
Cabbage, and lettuce	Detection of pesticides.	C nanotubes	Biosensor	(Griesche and Baeumner 2020)
Cod loins	Initial firmness improved, also sensory and microbial shelf life	CO ₂ , Nitrogen (N ₂)	CO ₂ emitters	(Hansen et al. 2016)

	extends.			
Fresh beef	Inhibits lipid oxidation and longer the display life.	Eugenol(C ₁₀ H ₁₂ O ₂)	Antioxidant emitters	(Navikaite-Snipaitiene et al. 2018)
Beef	Lowersthiobarbituric acid(TBARS), and improves oxidative stability.	Resveratrol(C ₁₄ H ₁₂ O ₃)	Antioxidant emitters	(Busolo and Lagaron 2015)
Chicken, and fish	Reduced water vapor permeability and water solubility, also shelf life extends up to 12 days.	<i>Amaranthus</i> leaf extract (betalains)(C ₂₄ H ₂₆ N ₂ O ₁₃)	Antioxidant emitters	(Kanatt 2020)
Shrimp	Reduced the growth of <i>Vibrio parahaemolyticus</i> , <i>Escherichia coli</i> , and <i>Staphylococcus aureus</i> , alongside increased shelf life.	Nano-clays and nano-Ag	Nano-clays	(Paidari and Ahari 2021)
Beef	Excellent thermal insulation maintains temperature and is stored for 8 days.	Soybean oil and tetradecane (C ₁₄ H ₃₀)	TTIs	(Singh et al. 2018)
Cheese	Prevents the growth of <i>Listeria monocytogenes</i> for 14 days.	Nisin(C ₁₄₃ H ₂₃₀ N ₄₂ O ₃₇ S ₇)	Antimicrobial packaging	(Divsalar et al. 2018)
Cheddar cheese	Significant reduction of moisture, and microbial growth and also increased shelf life.	Alginate(C ₆ H ₈ O ₆) _n and C ₁₄₃ H ₂₃₀ N ₄₂ O ₃₇ S ₇	Nano-laminates	(Khairi and Al-Mosowy 2018a)

Monterey Cheese	Decrease the moisture and acidity, further improving sensory attributes.	(C ₆ H ₈ O ₆) _n and turmeric	Nano-laminates	(Khairi and Al-Mosoway 2018b)
Gouda cheese	Reduced the growth of <i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Salmonella enterica</i> , and <i>Saccharomyces cerevisiae</i> . Hence, shelf life increased.	Nano-clays and C ₅₆ H ₁₀₃ N ₉ O ₃₉	Nano-clays	(Mohamma dzadeh-Vazifeh et al. 2020)
Kimchi	Detected CO ₂ from kimchi.	CO ₂	Freshness indicators	(Meng et al. 2015)
Milk	Reduced food-born microorganism growth such as <i>Vibrio parahaemolyticus</i> , <i>Salmonella</i> , <i>Staphylococcus aureus</i> , <i>Listeria monocytogenes</i> , <i>Shigella</i> , etc. Furthermore ultrasensitive, rapid, and multiplexed applications in food safety.	Au NPs amplified microcantilever array biosensor	Biosensor	(Zheng et al. 2019)

6. **Role of nano packaging in dairy products**

In the dairy industry, nanotechnology played a significant role in packaging, particulate delivery system, food safety, and shelflife. Nano packaging in dairy products involves the prevention of moisture and gas exchange, edible nano food wrappers, containing nanosensors, and anti-microbial activators that detect the spoilage of food

and release anti-microbial agents to extend the shelflife of the dairy food products (Radha et al. 2014, Pusparaj et al. 2022).

7. Toxic effects of nanomaterials: a primary concern

Even though quality and safety are major primary concerns when using nanotechnology-based applications in the food industry. Public health and safety regarding its toxicity are equally important. As we know humans interact with NPs through foodstuff coated with nanomaterials. Therefore, researchers have focused their work on the transfer of ultrafine NPs from packaging to the human body has been increasing daily. Also, it will show negative impacts on human health and cause several diseases (Golja et al. 2017; He and Hwang 2016).

NPs enter the human body through ingestion, inhalation, and injection (Maisanaba et al. 2015). Once they enter the human body, NPs interact with biological molecules such as (proteins, lipids, and sugars)(Farhoodi 2016). In the human gastrointestinal tract, food takes 3-4 h for complete digestion in the stomach(Hu et al. 2022). During that period, NPs produce toxic compounds in the body fluid and reach the different organs of the body such as the liver (Choi et al. 2016), brain (Yin et al. 2017), and kidney (Kononenko et al. 2017) and thus cause many harmful health effects and diseases. The key point for monitoring the behavior of the NPs in terms of specification, quantification, and biodistribution is crucial for hazard assessment(Hardy et al. 2018).Furthermore, the smaller the particle size, the toxicity level further increases (Schrand et al. 2010).Although not the only human body, ecosystems are also affected by NPs that are used in the food industry. These NPs accumulate in the soil or water and result in affecting the biota of that particular region and are also toxic to the species (Pradhan et al. 2015).

8. Present status and future recommendations

At this time, the use of nanotechnology in food packaging increased every day. Nano packaging results involves the use of NPs in different packaging composition to make it versatile for the use of the consumers. Furthermore, there is still a gap between the toxic effects of NPs in food packaging. There is a need for additional investigations and research on NPs' physicochemical characteristics, composition, shape, size, stability, and dose. Also, standardized test methods need to be developed that detect the toxicity of the NPs in food packaging. The investigation also studies the behavior, interaction, and stability of the NPs in the gastrointestinal tract and associated organs.

9. Conclusion

The favorable results that are obtained from previous research validate the use of nanotechnology in food packaging offers tremendous benefits to both consumers and the industry. NPs used in food packaging show many advantages as compared to conventional packaging. Active and improved packaging helps to improve mechanical properties, better barriers, and thermal properties, and prevent the growth of **microorganisms**, this will overall **help** to increase the shelf life and safety of food. The use of nanosensors, as intelligent packaging, helps to visualize the state of food inside the packet.

Regardless, the application of nano packaging can give numerous benefits and improves conventional packaging materials; the toxicity of the nanomaterials cannot be ignored. There is a need for more investigations and research to better understand the toxicological aspects of various types of NPs in food packaging. Also, nano packaging provides several benefits in the food industry. Still, **there is doubt in the public** to accept this latest technology and it is very common nature while **accepting** new things in the market. **So**, there is a need to create awareness and understanding among the common people for the novel application of nanotechnology in food packaging. In our point of view, nanotechnology is quite young and has an outstanding future, so there is a need for meticulous efforts to make it booming and flourishing in every single corner of the world. After successful popularization, demand will increase automatically which may help to reduce the market price of nano food packaging.

10. References

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