

## Nanobiotechnology: A Recipe for Food Revolution

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### Abstract

Nanobiotechnology is primarily driving the reshaping of food geography, distribution, and consumption. These factors investigate the far-reaching effects of nanobiotechnology on the quality and composition of food, providing insight into its role. Additionally, it is transforming food supply chains from farm to plate, streamlining products, distribution processes, and reducing waste. Furthermore, nanobiotechnology has the potential to extend shelf life and reduce food waste. Nanoclay and nanobiosensors play an important role in food quality preservation by detecting food toxins and pollutants in real-time. The struggle against foodborne illnesses takes center stage, demonstrating how nanoparticles can be used as powerful pathogen bombs. The ethical constraints and safety implications of adopting nanobiotechnology into our food system are promoted, as well as a focus on food nanotechnology norms. Finally, this review concluded by projecting unborn developments, stressing nanobiotechnology's undiscovered potential in influencing the food attention. In substance, it offers a taste of the continuing nanobiotechnological food revolution, applying revolutionary power, promising results to major difficulties in food production and consumption.

**Keywords:** Nanobiotechnology, Revolutionizing food, Nanoclay, Food nanotechnology, Nanobiosensors, Nanoemulsions, Nanocapsulation

### Introduction

Food is the most essential source of nourishment for all living organisms in order to live a healthy existence. Compounds known as nutrients are essential for the development, maintenance, and repair of the body tissues as well as to control the critical functions [1]. Nutrients give our bodies with the energy they require to function. Nutrient delivery systems using bioactive nanoencapsulation, biosensors to identify and measure pathogens, organic compounds, other chemicals, and food composition modification, as well as edible film to preserve fruits and vegetables, have already shown promising results and opportunities [2]. The study of materials and devices on nanometer scale is known as nanotechnology, while the application of nanotechnology in studying the biological system is termed as nanobiotechnology. Moreover, nanobiotechnology is becoming more essential in the

food industry. Nanotechnology is the manifestation and programming of nano-sized matter, the distinctive features of which are exhibited and explored in comparison to their bulk counterparts [3]. There are several opportunities for nanobiotechnology to create novel products that can be used in the food chain [4,5]. Three cutting-edge in food innovations based on nanobiotechnology include enzyme immobilisation, development of nanoemulsions [6], nanodispersions, and environmental friendly production of inorganic nanoparticles [7].

Moreover, nutraceuticals ranges at nano size and bioactive substances that are combined into nano-sized delivery methods are commonly referred to as nano-additives. Such nanoparticles remain intended to be introduced to several food and infusion systems or their packaging polymer matrix to enhance their properties

and provide them their diverse activities [7]. The primary motivation for using nanomaterials into food formulations is highly soluble, which increases bioavailability while also protecting bioactive chemicals during the processing or storage of food [8]. The effectiveness, accessibility, nutritional content, and molecular composition of novel ingredients and products may differ at the nanoscale level [9].

There are hundreds of nano-based products on the market today, covering a wide range of industries and uses. Some of these products, such as gold (Au) and silver nanoparticles (Ag-NPs), are made from metals, while others are made from metal oxides, such as zinc oxide (ZnO), copper oxide (CuO), cerium oxide (CeO<sub>2</sub>), and iron oxide (Fe<sub>2</sub>O<sub>3</sub>) nanoparticles [10-13]. Processing of foods is further enhanced by nanocapsulation, which permits for the release of bioactive chemicals, boosts food bioavailability, and extends food shelf life [14]. Nanomaterials such as nanorods, nanofilms, nanotubes, nanofibers, nanolayers, and nanosheet have been produced to increase food safety and agricultural output [15]. To address the food crisis brought by growing populations and environmental concerns, food waste must be decreased in addition to increase the food production. The primary causes of food waste are microbial contamination and food spoiling, which can reduce food quality, jeopardise food security, shorten food product's shelf life, and raise the risk of food-borne illnesses [16].

Further, nano-based distribution technologies enhance the nutraceutical properties of dietary components. In addition, Nanomaterials and their roles in the food business, encourage plant growth and development [17]. For example, titanium dioxide (TiO<sub>2</sub>) has been proven to improve plant growth, while gold nanoparticles boosted seed output in *Arabidopsis*, and cellulose nanocrystals improve seed germination due to their high water uptake capability [18]. When it comes to food product preservation and quality maintenance, edible coatings and nanomaterials incorporating nanoparticles perform better than traditional packaging materials [19]. Nanoparticles can improve the physical and mechanical qualities of packaging polymers by increasing their rigidity, longevity, versatility, barrier characteristics, and reusability [20]. Montmorillonite nanoparticles were dispersed onto starch/clay nanocomposite films using polymer melt processing

methods. Adding 5 % sodium montmorillonite to thermoplastics has been demonstrated to improve tensile strength and elongation at break. Additionally, the temperature of breakdown was elevated while the relative diffusion coefficient of water vapor has dropped [21]. Mechanical characterization data indicates higher modulus and tensile strength. Migration tests were used to ensure the material samples adhered to current laws and European rules on biodegradable materials [22]. Cu-doped ZnO composites with functionalized silver nanoparticles were placed in a poly lactic acid matrix for food packaging applications. Some properties include thermal stability, UV stability, tensile strength, transmittance, and resistance to gas and water vapor. The barrier of poly lactic acid might be greatly enhanced. Additionally, the modified polymer demonstrated significant antibacterial action [23].

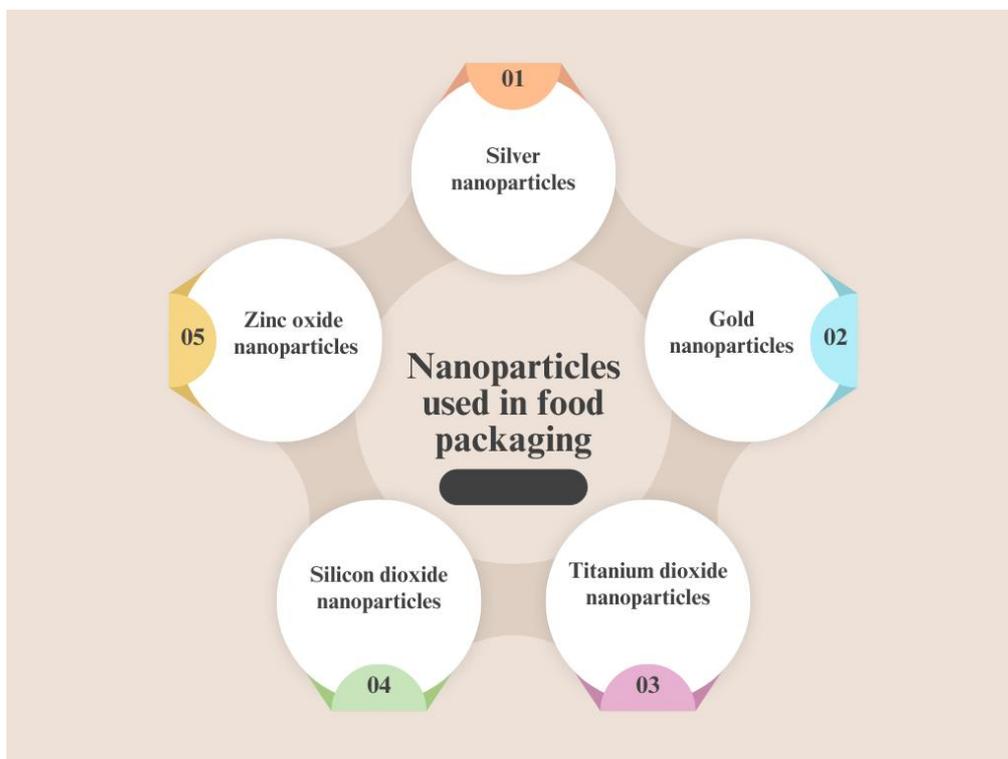
Nanotechnology also enabled the recent development of edible coverings at the nanoscale. A variety of foods, such as fruits, vegetables, meats, cheeses, and baked goods, are coated or filmed with edible substances. Also, it has been successfully applied directly or on packaged food products to improve food quality and safety (detection of toxic metabolites or foodborne pathogens), food fortification (minerals, vitamins, antioxidants, and essential oils), sensory improvement (colour or flavour enhancement), shelf life extension, and antimicrobial food packaging. The food sector has changed as a result of nanotechnology, which has gained prominence in recent decades. A new economic revolution has been brought about by nanobiotechnology, and both developed and developing nations wish to increase their investments in it [24]. This review explains about how nanoparticles helps in food technology like packaging, the composition of food and have also explained nanobiotechnology used in food packaging industries. Since, the field of nanobiotechnology is under development, this article explains about the future trends in nanobiotechnology which can be useful to future researchers to know its importance and they can involve in developing the techniques in food nanobiotechnology.

### **Nanoparticles in plate**

Nanoparticles increasingly being used in the food industry for various purposes, such as food packaging, food additives, and functional food development. While

nanoparticles can offer benefits like increased food packaging life and improved delivery of bioactive ingredients in functional foods, there are concerns about the potential risks associated with consumer exposure to nanoparticles through food consumption [3]. The safety of nanomaterials in food production and packaging is a

topic of ongoing research and discussion. Over the last 2 decades, there has been a meteoric rise in interest in nanoparticles. Additionally, it can be used in food to provide stable flavours, natural food colouring dispersions, and high loadings of vitamins and health-benefit active ingredients [25].



**Figure 1** Some of the nanoparticles used in food packaging.

A review of the previous literatures reveals that nanoparticles like Au, Ag, TiO<sub>2</sub>, silicon dioxide (SiO<sub>2</sub>), and ZnO are being used in food packaging to inhibit microbial growth and extend the shelf life of food products [26]. **Figure 1** shows the different types of nanoparticles used in food packaging. Nanoparticles are also used as food additives to enhance food color, texture, and taste. However, there are concerns about the potential toxic effects of nanomaterials, their ability to penetrate biological barriers, and their impact on human health. It is emphasized that nanomaterials must be used with caution due to their potential to cause toxic effects, travel deeper into the nucleus of cells, and damage DNA [26,27]. The Department of Biotechnology (DBT), the Ministry of Environment, Forests, and Climate Change (MoEFCC), the Food Safety and Standards Authority of India (FSSAI), and the Indian Council of Agricultural Research (ICAR) are among the organisations and laws

that regulate nanotechnology-based agricultural products in India [28].

Additionally, nanomaterials can influence the characteristics of functional meals and control the pace at which bioactive substances are released, which may decrease the negative effects of consuming too many functional foods. Food items nutritional value, safety, and quality could all be enhanced by the application of nanotechnology in functional food creation. However, thorough research is needed to determine the number of auxiliary materials, the safety of carrier materials, the viability of the production procedure, and the stability of storage for nano-functional foods [29].

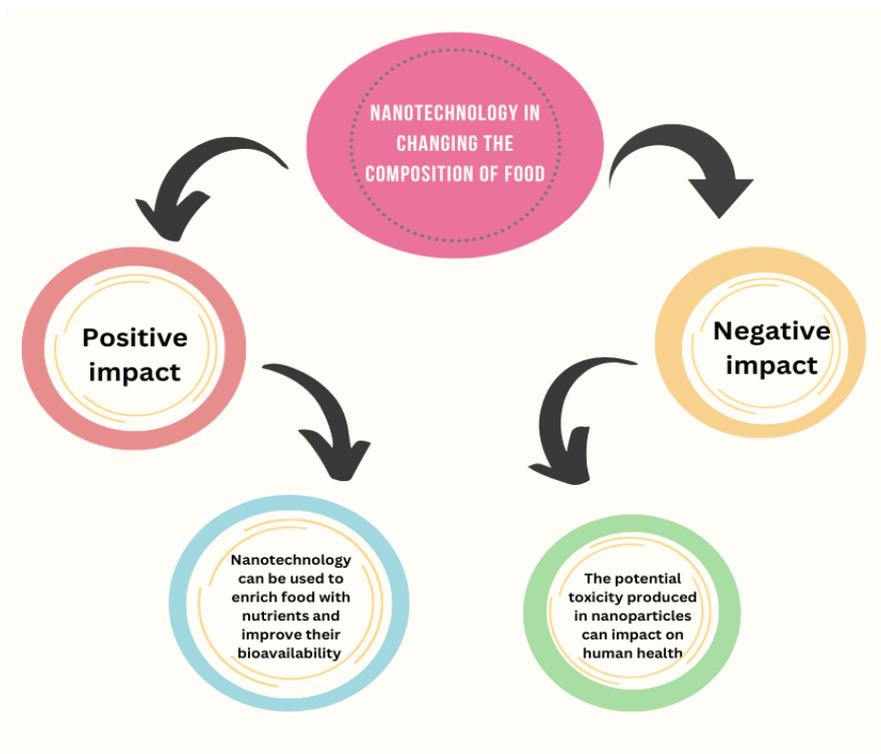
While nanobiotechnology offers various opportunities for improving food production and quality, it is essential to thoroughly understand the properties and potential toxicity of nanomaterials to ensure food safety. Ongoing research is focused on

addressing the potential risks associated with the use of nanoparticles in food products and developing regulatory frameworks to manage these risks effectively [30,31].

### Nanotechnology in changing the composition of food

The problem of consumer exposure to nanoparticles through food consumption is brought up by applications of nanotechnology in the food industry.

**Figure 2** shows how nanotechnology is changing the composition of the food. There's a chance of internal systemic exposure if particles get absorbed in the gut. Large reactive surface nanoparticles like Ag, TiO<sub>2</sub>, and ZnO [32] are widely used for their antimicrobial properties have the ability to penetrate biological barriers once they are within the body and reach areas that are normally shielded from the entry of larger particulate matter [3].



**Figure 2** Changes in composition of food using nanotechnology.

Nanoparticles can affect the nutritional value of food in both positive and negative ways. On the positive side, nanotechnology can be used to enrich food with nutrients and improve their bioavailability [30]. For example, polymer nanoparticles can be used to increase the adhesion of active substances to tissues, improve the delivery efficiency of the gastrointestinal tract to active substances, reduce the impact of intestinal clearance mechanisms, and prolong the residence time of active substances in the body. This can lead to improved nutritional function and health benefits [30,26].

On the negative side, there are concerns about the potential toxicity of nanoparticles and their impact on human health. Large reactive surface nanoparticles have

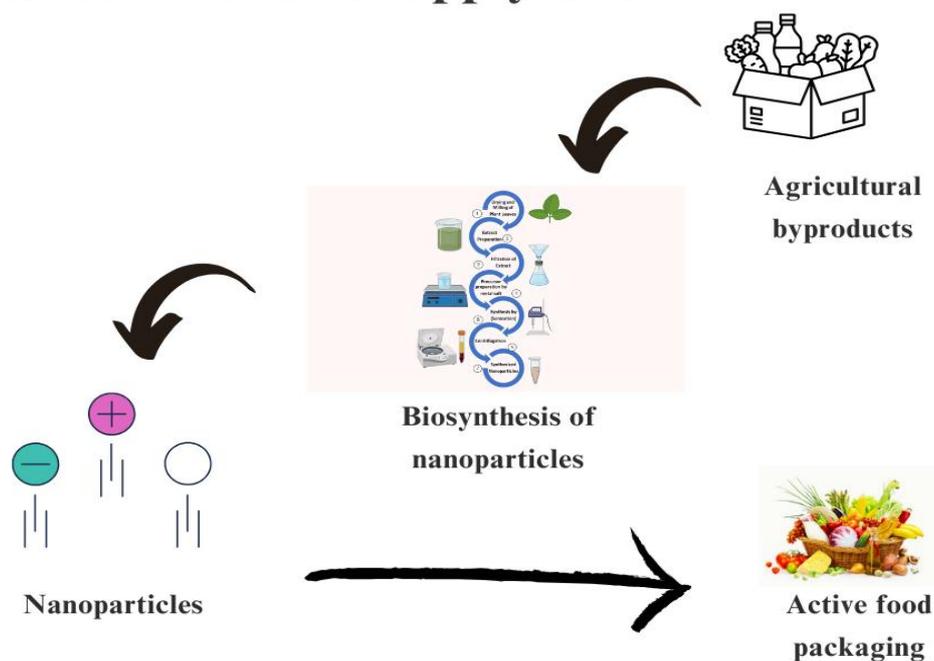
the ability to penetrate biological barriers once they are within the body and reach areas that are normally shielded from the entry of larger particulate matter [26]. The safety of nanomaterials in food production and packaging is a topic of ongoing research and discussion. The physicochemical and structural characteristics of the nanoparticles present in food and beverage products vary widely, influencing their fate in the gastrointestinal tract (GIT) and likelihood of causing toxicity. The composition of nanoparticles greatly influences how they behave in the GIT. When distributed in food, nanoparticles' physicochemical and structural characteristics can alter significantly, which could have a significant impact on their toxicity and future GIT

destiny [29,33]. While nanotechnology offers various opportunities for improving food production and quality, it is essential to thoroughly understand the properties and potential toxicity of nanomaterials to ensure food safety. Ongoing research is focused on addressing the potential risks associated with the use of nanoparticles in food products and developing regulatory frameworks to manage these risks effectively [30].

### Impact on food supply chains

The Food and Drug Administration (FDA) identifies numerous goods that are currently subject to regulation based on the presence of nanoparticles [34]. Organic nanoparticles are utilized as a means of delivering nutrients to nutraceuticals. These can be in the shape of micelles, nanospheres, or other forms made from approved food-grade components that can be purchased in bulk at a reasonable price [25]. **Figure 3** describes the steps involved in food supply chain of nanotechnology. The nanoparticles produced from either microorganisms can also be used in food substance after analysis its toxicity.

## Nanotech's food supply chain



**Figure 3** Steps of nanotechnology in food supply chain.

### Streamlining production, distribution, and waste reduction

The field of nanotechnology has improved the nutritional qualities of agricultural goods and attracted the interest of the food sector and end consumers. It was discovered that adding zinc nanoparticles improved the protein, fat, and fiber content of the Indian vegetarian diet [32]. Agriculture waste by-product recycling, reuse, and recovery need a new integrated approach because waste management in agri-food related sectors has grown challenging [33]. High throughput, site-specific

management of commercial agriculture on a large scale is referred to as precision farming or precision agriculture [34]. Precision farming can help us cut waste and labor expenses while optimizing agriculture management to provide higher yields at lower input costs [32].

Nanobiotechnology has been applied along the food supply chain, including agricultural production, industrial processing, and food packaging, to improve the nutritional qualities of agricultural goods and reduce waste [35]. Precision farming, or precision agriculture,

can help cut waste and labor expenses while optimizing agriculture management to provide higher yields at lower input costs [35].

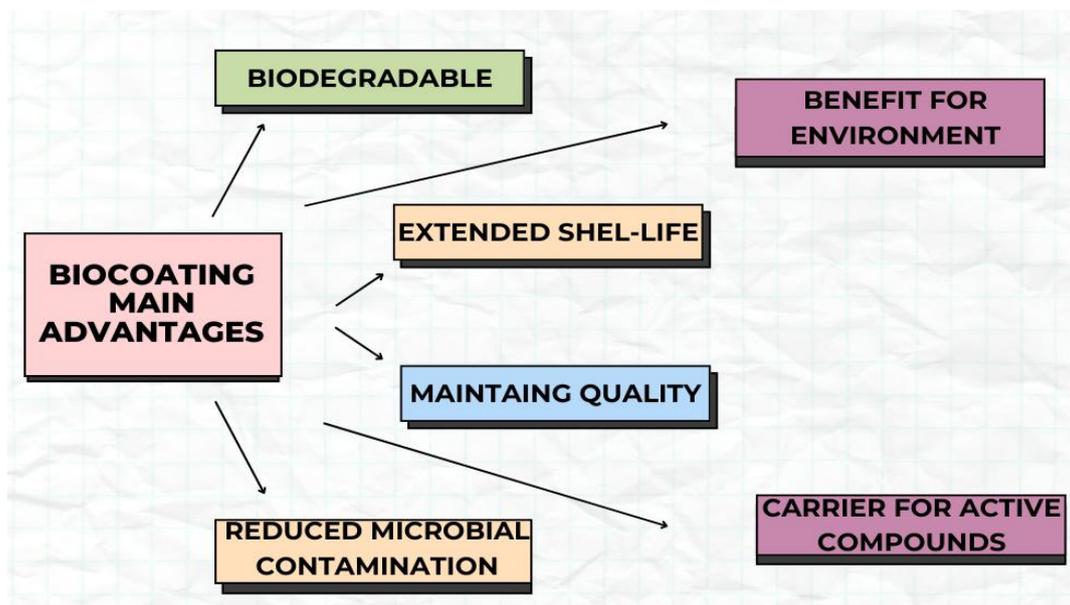
Through the development of nanoscale enzymatic reactors and smart/intelligent systems for nano-encapsulated, controlled nutrient release, nanotechnology may enable the production of new foodstuffs through food fortification. When combined with polymers like ethylene terephthalate, polyolefin, polyamide, and ethyl vinyl alcohol, nanomaterials for food packaging offer a number of advantages, including better mechanical barriers, the capacity to detect microbial contamination, and maybe increased nutrient bioavailability. Applying nano barcodes to food products helps to secure them and can be used to monitor their distribution [39].

On the other hand, reducing the harmful impacts on customers, industry workers, and eventually the environment is the main problem facing nanobiotechnology utilised in the food industry. Their applicability is limited by the lack of knowledge regarding health and environmental hazards, and most

countries have not yet regulated nano-enabled agri-food items. Nanotechnology has not been an exception to the public preference for “natural” food products, which has impeded the use of technologies in food. To control the production, processing, and safety of nanomaterials in food, a standardised international regulatory framework is required [39].

#### Extending shelf life and reducing food waste

To explore the role of nanotechnology in extending the shelf life and reducing food waste, particularly focusing on fruits and vegetables, it is essential to delve into specific applications and advancements within the field [40,41]. Bio-coatings can be fortified with important minerals, vitamins, or bioactive substances that boost the nutritional value of fresh fruits and vegetables. Advantages of bio-coating has been depicted in **Figure 4**. These nutrients can be sourced from natural resources or encapsulated inside the bio-coating material, guaranteeing their regulated release and preservation throughout time [42-44].



**Figure 4** Advantages of biocoating in food packaging.

Nanocomposite coatings have shown promise in improving food quality and preservation by acting as antimicrobial agents against pathogens. For instance, silver nanoparticle coatings have demonstrated efficacy in preventing spoilage and prolonging the shelf life of various items [45]. Additionally, nanocomposites can

enhance plant tolerance to heat and mechanical stress, thereby increasing crop resilience during transportation and storage [46]. The packed foods included fresh fruit (apricot), processed fruit goods (tomato paste, orange juice), and cooked ham, all data on packing materials were adjusted to 1 kg of food product packaged [47].

There are 2 major elements that can affect the shelf life and quality of fruits and vegetables: Pre-harvesting and post-harvesting. Maintaining these characteristics over an extended period of time is a significant problem. As a result, nanotechnology emerged as a viable industry for developing ways for preserving and adding value to agricultural products in terms of quality and safety [32].

### **Preservation of the future**

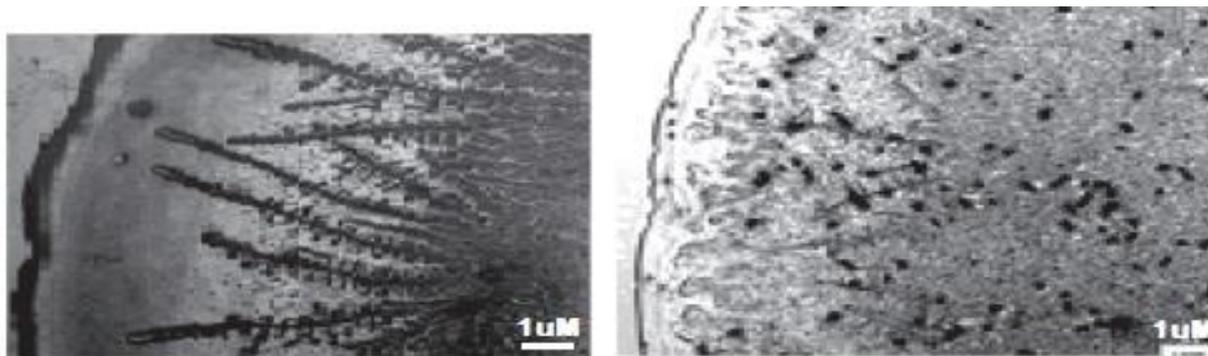
Nanocomposites are utilized in the food industry as an antibacterial coating agent to improve food quality [48]. They may also boost plant resistance to heat and mechanical stress while decreasing oxygen transport rates. Nanocapsules comprising particular nutrients such as vitamins, colorants, and flavor enhancers are inserted into food, and they go dormant and release nutrients when the body requires them. Pathogen identification and diagnosis can be aided by nanoscale biosensors. Nanobiotechnology has the ability to provide bioactive compounds in foods to hosts pathogens while enhancing nanoscale knowledge of food components [49].

Incorporating nanocapsules containing specialized nutrients, such as vitamins, colorants, and flavor enhancers, into food products allows for controlled release upon consumption [50]. This technology ensures optimal nutrition delivery without compromising product integrity and taste. Biosensing capabilities at the nanoscale level enable rapid and accurate pathogen identification and diagnosis. By employing nanobiosensors, the food industry can monitor and control the spread of disease-causing organisms throughout the supply chain [51,52]. Moreover, nanotechnology offers novel insights into understanding food components at the molecular level, which could lead to innovative methods for maintaining food quality and safety [53]. For example, researchers have developed nanostructured lipid carriers (NLCs) to encapsulate bioactive compounds, thus providing health

benefits while retarding oxidative degradation processes [52,54].

Nanocomposites are commonly used in the food industry as a means of preserving food quality and extending shelf life. They usually consist of polymers and nanoparticles, and the presence of the latter enhances the polymer's characteristics. The main purpose of nanocomposites is to create materials with strong barrier qualities by acting as a gas barrier to stop carbon dioxide from escaping from carbonated beverage bottles and cans [18]. The most commonly used nanocomposites in the food industry for preservation include nanoclay, Ag nanoparticles, Cu nanoparticles, and clay polymer nanocomposites. Nanoclay is used for the development of gas barriers, while Ag and Cu nanoparticles have strong antimicrobial properties and protect food from microbes such as viruses, fungi, and bacteria, extending their shelf life significantly [18,55].

Chitosan-incorporated different nanocomposite Hydroxy-propyl methyl-cellulose (HPMC) films have also been used for food preservation [56]. Additionally, biodegradable hybrid nanocomposites of chitosan/gelatin and Ag nanoparticles have been developed for active food packaging applications [18, 56]. Nanocomposites are widely used in the food industry for preservation and extending shelf life. Nanoclay, Ag-NPs, Copper nanoparticles (Cu-NPs), and clay polymer nanocomposites are among the most commonly used nanocomposites for this purpose [46]. Particles enhance film qualities, including mechanical and barrier properties. These films can also be used as active antimicrobial release systems (AARS), having wide antibacterial activity. They effectively suppress the growth of both Gram-negative (*Escherichia coli*) and Gram-positive (*Staphylococcus aureus*) bacteria. Both bacteria demonstrated a 99 % antibacterial activity. A hydrothermal approach was used to evenly distribute nanoparticles throughout the film, which was then manufactured using a solvent-casting method [57].



**Figure 5** AuNPs lose their fractal pattern when they react with *E. coli*, which is disrupted by the addition of *E. coli* to the Au NPs [58].

### Active packaging for fresher food

Foods are highly perishable, making them unpalatable to customers. Food packaging is an important factor in the correct handling and preservation of food quality [19]. The 4 essential functions of traditional food packaging are protection or preservation, containment, convenience, and communication. These fundamental functionalities are upgraded in order to provide better, more active, and smart packaging [59]. Packaging for food has always been a sector of ongoing development and an industry under constant pressure to offer more. Food packaging material works as a barrier against external factors, allowing food to reach consumers in a healthy and trustworthy manner [60]. Passive or traditional food packaging is giving way to active or innovative food packaging, which incorporates nanotechnology to create intelligent, interactive, and responsive food packaging with enhanced functionality [61]. Nanomaterials and coated foods containing nanoparticles outperform traditional packaging materials in terms of preserving food and quality management [19]. Types of food packaging based on its green composites and materials usage has been described in **Figure 6**.

In order to satisfy consumer demands for safe, high-quality, and fresh-like products, active packaging is defined as an intelligent or sophisticated system that integrates interactions between the package or packaging components and the food or internal gas atmosphere. The demand for fresh, clean, high-quality, minimally processed, and long-lasting meals has increased due to customers' changing lifestyles, necessitating the development of creative packaging methods. In the food industry today, cutting-edge technologies like intelligent packaging (IP) and active packaging (AP) are being adopted quickly, but frequently they are still in the development stage and have not yet been used. In the food packaging environment, IP systems are used to increase safety and show several warnings about possible threats. Active packaging includes things like oxygen scavengers like reactive oxygen species, carbon dioxide emitters and absorbers, moisture absorbers, ethylene absorbers, ethanol emitters, flavour releasing and absorbing systems, time-temperature indicators, and films that contain antimicrobial activity [62].

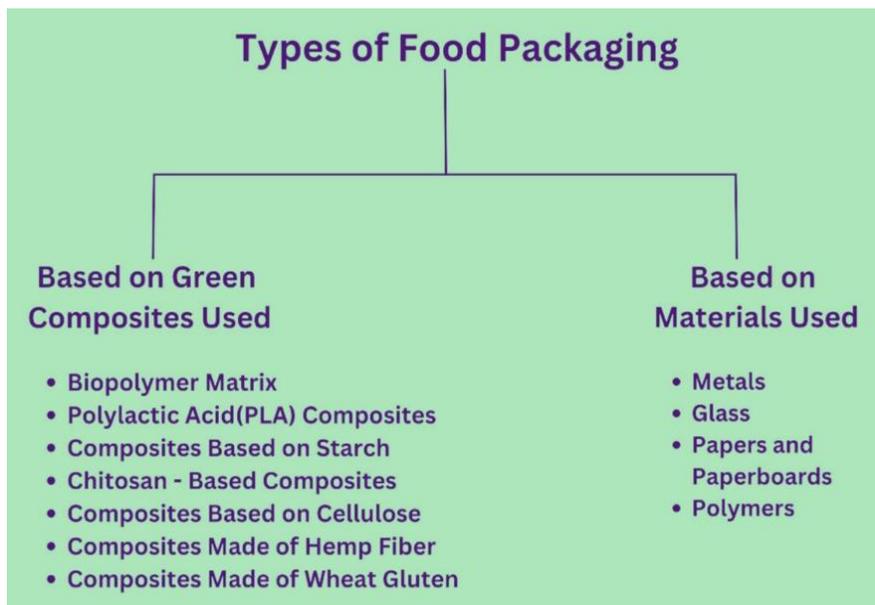


Figure 6 Types of food packaging based on its green composites and materials usage.

Carrageenan is renowned for its exceptional carrier, compatibility, and film-forming properties. It is widely accessible and reasonably priced, which makes it a perfect substitute for a polymer matrix base material in films used for active and intelligent food packaging. Packaging films made of carrageenan are neither mechanically sound, protective, or useful. Utilization of carrageenan in packaging application has shown in Figure 7. Blending carrageenan-based films with

functional chemicals and nanofillers improves their physical and functional qualities. The carrageenan-based film contains many bioactive components, including nanoparticles, natural extracts, colorants, and essential oils. It is also a great source for creating customized packaging films with favourable benefits in active packaging systems [63]. Carrageenan impregnation with a copper metal-organic framework improves packaging film characteristics [57].

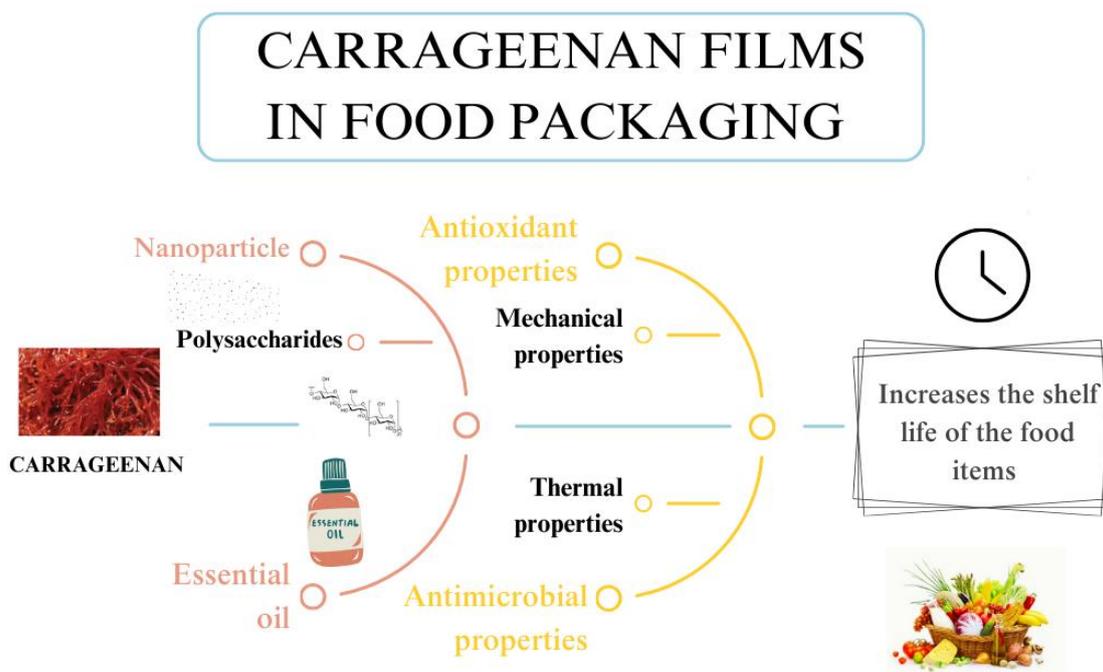


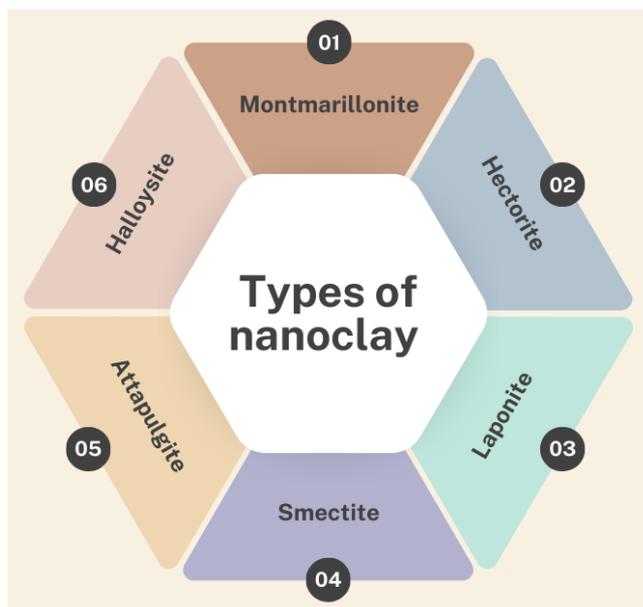
Figure 7 The utilization of carrageenan films in food packaging.

### Nanoclay

The term “nanoclay” describes layered silicate minerals. Temperature, exposure duration, food contact, and the interaction between the nanoclay and the polymer affects each nanoclay’s characteristics. Nanoclay enhances the mechanical and barrier qualities of starch thermoplastic and the biodegradability of synthetic polymers [64]. Nanoclays feature a high aspect ratio with nanoscale thickness, a low specific gravity, a flaky, fragile structure, and a unique platelet shape. Several kinds of nanoclays are added to the polymers to improve their characteristics (**Figure 8**). Both academic and industrial researchers have focused most of their attention on montmorillonite (MMT, MMT-Na<sup>+</sup>) and organophilic MMT (organic modified MMT, OMMT) in the packaging field because of their high surface area, relatively large aspect ratio (50 - 1000), and good

compatibility with the majority of organic thermoplastics [65,66].

Nanoclays were originally utilized in food packaging in the 1990s to improve the mechanical and barrier properties of the packaging [65,67]. They are also naturally occurring aluminum silicates that are predominantly made up of fine-grained particles with a sheet-like structure, phyllosilicates are hydrous silicates with a sheet structure can also been used in food packaging [68]. Clays are organic, affordable, and environmentally benign materials that have a wide range of applications [69]. These clay minerals have received extensive research in practical applications such as geology, agriculture, construction, engineering, process industries, and environmental applications [70]. Clay nanoparticle composites, which have superior barrier qualities, are utilized to make beer, edible oil, fizzy beverage, and film bottles [71].



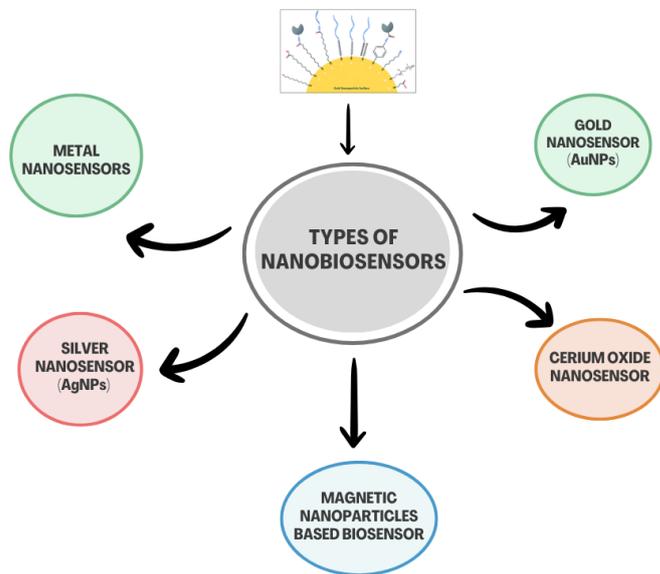
**Figure 8** Types of nanoclays.

### Nanobiosensors

High sensitivity and other innovative features are provided by nanomaterials used in biosensor development. Nanosensors, also known as nanobiosensors, are employed in food microbiology to measure the amount of food ingredients that are available, identify diseases in food material or processing facilities, and alert distributors and consumers to the food’s safety status. When environmental conditions such as temperature or

humidity in storage rooms, microbial contamination, or item deterioration occur, the nanosensor operates as an indicator that responds. Carbon nanotube-based biosensors have also attracted a lot of interest because of its rapid detection, affordability, and ease of use. Additionally, these tools have been useful in identifying harmful substances, microorganisms and other degradation products in food and drink [24]. Biosensors can measure harmful organic molecules, other chemicals, changes in food composition, and can even

keep fruits and vegetables fresh [1]. **Figure 9** describes the various types nanobiosensors used and **Table 1** defines the type of nanobiosensor with its application.



**Figure 9** Types of nanobiosensors.

The food packaging industry uses a variety of nanosensors, including electronic noses, array biosensors, nanocantilevers, nanoparticle in solution, and nano-test strips. Throughout the whole food supply chain, nanosensors are employed to monitor the outside and interior conditions of food products, pellets, and containers. Nanosensors in plastic packaging can detect gasses in food when it begins to spoil, and the packaging

itself can change color to warn consumers [71]. Silicate nanoparticle-packed films can keep food fresh by reducing the flow of oxygen into the packaging and preventing moisture leakage [71]. Since nanosensors can detect some chemical compounds, infections, and poisons in food, they can be utilized in food packaging to replace inaccurate expiration dates and maintain the freshness of food [72].

**Table 1** Types of nanosensors and its nanoparticle types and application.

Type of nanosensor used	Type of nanoparticle used	Applications	Type of contaminant	Effect caused by pollutant	Reference
Metal nanosensors	Graphene	Utilized to alter electrodes designed to identify different kinds of organic molecules, inorganic polyatomic particles, or metal ions in food.	Metal ions and polyatomic particles	Diminished immune function and a shortage of vital nutrients.	[73]
Silver nanosensor (AgNPs)	Silver	Signal transducers	Antibiotics	Cause emergence of multidrug resistant bacteria	[74]
Gold nanosensor (AuNPs)	Gold	The main application of gold metal nanoparticles is mycotoxins determination. Mycotoxins are substances made by mould and other tiny organisms that include	Mycotoxin	Secondary mould products belonging to the <i>Fusarium</i> , <i>Penicillium</i> , and <i>Aspergillus</i> genera	[75]

Type of nanosensor used	Type of nanoparticle used	Applications	Type of contaminant	Effect caused by pollutant	Reference
		fumonisin, trichothecenes, and aflatoxins.			
Gold nanosensor (AuNPs)	Gold	In the absence of dimethoate, the fluorescence of RB (Rose Bengal). Conversely, because the dimethoate molecules competed with RB to adsorb on the surface of AuNP, the fluorescence of RB was regained.	Pesticides	Heavy metal accumulation in soil, water, air and ultimately food.	[74]
Cerium oxide nanosensor	Cerium oxide (Nanoceria)	Because cerium Ce(III)/Ce(IV) possesses a dual reversible oxidation state on the NP surface, nanoceria can change their redox states and surface characteristics.	Food antioxidants	Excess of antioxidants in food may cause diarrhea, dizziness and joint pain	[76]
Magnetic nanoparticles based biosensor	Metal oxide	Greater surface area and the more opportunities to adjust loading, enhance assay kinetics, and boost immobilisation effectiveness.	<i>E. coli</i>	Abdominal and pelvic infection, urinary tract infection, pneumonia, and meningitis	[76]

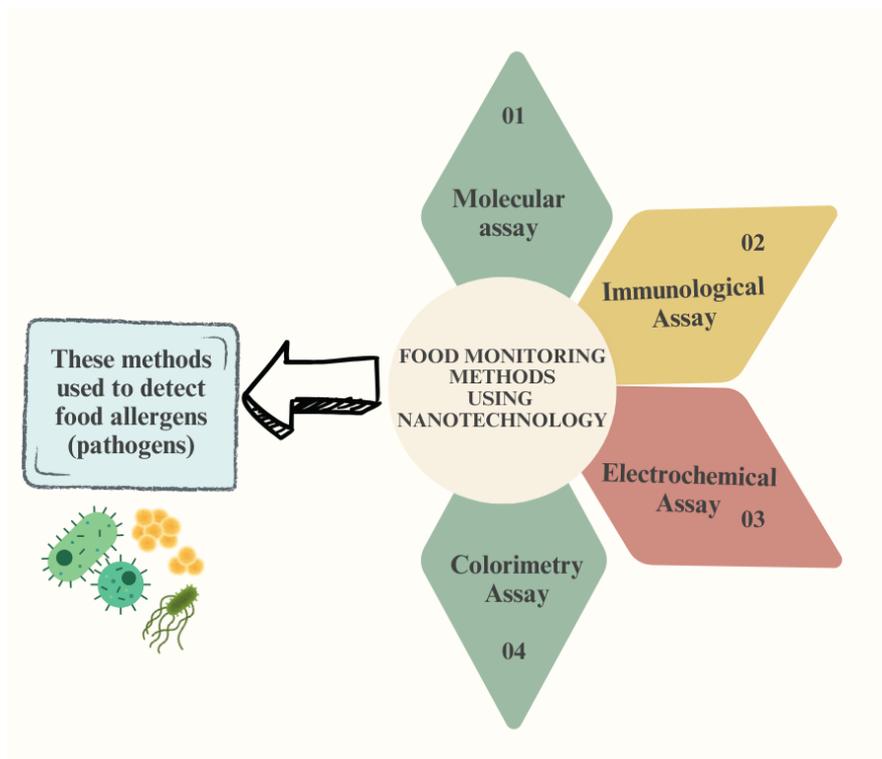
#### Detecting contaminants and ensuring quality

The global dispersion of food supplies and the demand for minimally processed food products have raised severe concerns about food safety. The use of pesticides, fertilisers, and antibiotics close to agricultural food products, the accidental addition of additives at dangerous levels to industrially processed foods, or deliberate adulteration with subpar or unsafe ingredients for financial gain are some potential causes of chemical and biological food spoilage. Cross-contamination with allergens or other substances that can be harmful to sensitive people (e.g., wheat gluten) is another [77]. Several analytical techniques have been established and are being used to assess the safety and quality of food. The most popular and favored procedures are HPLC, GC, ELISA, and PCR [78]. To identify foodborne pathogens (microorganisms), food allergies, biotoxins, heavy metal ions, and other chemical components that might be present in food, numerous microfluidic devices have also been developed. An immunomagnetic separation (IMS) method was developed in a microfluidic nano-biosensor for the detection of pathogenic salmonella using

magnetic beads and quantum dots (QDs) as a fluorescent marker [33].

#### Nanotechnology vs food borne threats

The umbilical cord connecting nanotechnology and food engineering today is undeniably strong. The wide scientific landscape is shifting as a result of recent advancements in nanotechnology [79]. Food quality deteriorates as a result of several chemical interactions between the environment and food ingredients, there are many different types of nanomaterials that can be used to stop these undesirable processes [80]. Due to their assistance of nano materials dispersed in food matrices and their huge surface-to volume ratios compared to conventional macroscale support materials, the use of nanomaterials enables improved enzyme support systems that include improving activity, shelf life, and cost-effectiveness [81]. The identification of an etiologic agent can be made possible by a community or individual outbreak of diarrhea and other diseases that can aid to link food to various disease [82]. **Figure 10** shows the different food monitoring methods used in nanotechnology.



**Figure 10** Food monitoring methods used in nanotechnology.

#### **A look how nanoparticles combat food borne pathogens**

Food safety and public health are seriously threatened by food-borne pathogens such as bacteria, viruses, parasites, and fungi on a global scale [83]. Norovirus, non-typhoidal *Salmonella*, *Clostridium perfringens*, *Campylobacter spp.*, and *Staphylococcus aureus* are the top 5 food-borne pathogens cause majority of domestically acquired diseases [84]. These pathogens are well known for having the ability to cause food-borne illnesses with considerable negative health consequences on humans and detrimental economic implications on the food sector through biofilms [44]. Once any of this foreign pathogens have passed through the body's physical defenses, the immune system can identify them by microbial traits known as pathogen associated molecular patterns (PAMPs) associated with Pattern recognition receptors (PRRs) found on host cells to detect PAMPs [85].

There are many nanoparticles that have different toxicological characteristics depending on how they were made and the substances in the environment. There are few natural particles which are more effective against food borne pathogens, for instance water extracts of rosemary had the least amount of an effect in

comparison to other extracts, while ethanolic extracts of clove and water extracts of thyme significantly affected both *Staphylococcus aureus* (Gram positive) and *E. coli* (Gram negative) strains [86]. In addition Ag-NPs, which have been extensively used in biotechnology and medicine as nanosensors due to their antibacterial capabilities. In this regard, various studies have demonstrated the efficacy of Ag-NPs in preventing the growth of harmful bacteria such *E. coli*, *Proteus vulgaris*, *Streptococcus mutans* and *S. aureus* [87]. Small, spherical nanoparticles have better bacterial killing activity than larger ones when it comes to metal-based nanoparticles' antibacterial properties. The nanoparticles actively come into touch with cell membranes because of their high surface-to volume ratio, which disrupted the bacterial respiratory system and causes death [55].

#### **How nanotechnology keeps an eye on what we eat**

Food component solubility, bioavailability, and stability may be improved by nanoencapsulation while harmful interactions with other food components and foodborne pathogens are avoided [80]. Additionally, the edible nano-coatings on a range of food components

may function as a barrier to moisture and gas exchange in order to transmit flavours, colours, antioxidants, enzymes, and anti-browning agents. Additionally, they might increase the produced meals' shelf life [89]. Some of the nanoencapsulation techniques used in food packaging is showed in **Figure 11**. One of the most common uses of nanotechnology is the encapsulation of

food additives and chemicals. Customers can tailor nano-encapsulated foods to meet their dietary needs and preferences [90]. Because many meals distinctive qualities depend on nanometer-sized components and nanomaterials are a natural aspect of food processing and conventional foods [79].



**Figure 11** Nanoencapsulation techniques used in food packaging.

Lycopene microspheres were effectively employed in a trial to improve the nutritional value of fresh-cut apples and stop enzymatic browning. Excellent lycopene extraction yield is achieved by heating lycopene and  $\text{TiO}_2$  nanoparticles from tomato skin; cis-lycopene isomers predominate. Without affecting the physicochemical or microbiological quality, lycopene microsphere treatment of fresh-cut apples stopped enzymatic browning for 9 days at 5 °C [91].

Chitosan is ecologically safe, non-toxic, and contains strong antibacterial qualities, making it viable nanoparticles for use in packaging [92]. Additionally, it improves the gas and moisture barrier properties of biodegradable polymers, like polylactic acid films. The

mechanical, barrier, and physical properties of bio composite films can all be considerably enhanced by chitosan nanoparticles. Because of their hydrophobic nature, hydrogen production, and covalent bond with the biopolymer, which slows the rate of moisture transport, they also improve antibacterial properties and moisture impermeability [93].

#### **Ethics and safety in nanobiotechnology**

According to a report, as food nanobiotechnology research advances, public worry over the security of such items meant for human consumption and usage is also rising [94]. Like any developing technology, there are still many areas of ignorance in food nanobiotechnology. Current uncertainty, especially over

the use of nanobiotechnology, long-term negative impacts, and the ability to truly ensure safety, has greatly exacerbated consumer worry [25]. The cutting-edge use of nanotechnology and nano-packaging materials in food processing and food shelf-life extension. Likewise, the control of nanotechnologies to guarantee food safety is under developing process [2,95]. The challenges of sustainable development, global food security, and climate change can be addressed with the use of genome editing technologies. The uncertainty surrounding the regulation of genome-edited crops, however, hindered the use of these new technologies, despite their potential [94].

Although the application of nanoparticles in food nanotechnology has advanced significantly, nothing is understood about the toxicity of these materials. When employing nanoparticles, the 2 main safety issues are allergens and heavy metal leakage. Due to a lack of information and laws, nanoparticles are currently being used in food products at a rate that is faster than planned [96]. Nanobiotechnology also ensures food safety and a longer shelf life for food goods, by preventing nutrient loss during packaging. Due to their strong antibacterial capabilities, researchers are currently concentrating more on food packaging materials with incorporated nanoparticles [97-99]. Real-time and on-site sensing of dynamic factors is crucial since it improves operations. Therefore, it is crucial to create a quick tracing technique to identify the contaminated product because it improves food safety and ensures the wellbeing of consumers [100].

#### **Standards in food nanotechnology**

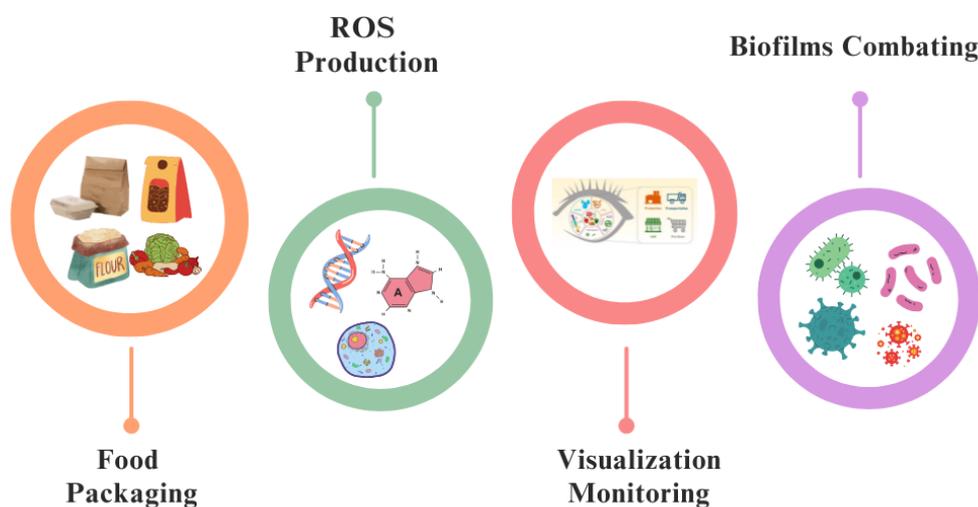
Engineered nanoparticles are currently utilized as additives in food items, and future uses of the technology in the agricultural and food industries are being developed. Trust in the government's oversight of this industry's rules also influenced perceptions of

danger, which were strongly predicted by nanotechnology [101]. Due to consumer attitudes toward and acceptance of emerging technologies and their applications, there has been much discussion about the potential societal responses to (different) applications of nanotechnology. However, there are high-quality evidences regarding consumer acceptance on nanotechnology applied within the agri-food sector. While standards-based laws are crucial for the application of nanotechnology, they are also essential for the creation and sale of goods [102].

#### **Future trends**

Since nanotechnology has advanced so rapidly over the past 10 years, it is impossible to think of a field that does not use nanoparticle materials. Small particles that act as a single unit in terms of their characteristics and movement are generally referred to as nanoparticles [103]. Additionally, nanotechnology attempts to solve food-related disorders such as diabetes and obesity, provide specialized nutritional diets for various target demographics, aging populations, and lifestyles, and maintain the sustainability of food production [104]. There has been a sharp rise in contaminated food products made from meat. The packaging of meat and muscle goods uses advanced nanotechnology to reduce spoiling, avoid contamination, and boost enzyme activity [105]. In the food packaging industry, nanozymes have become new weapons for fighting bacterial infections [106] (**Figure 12**) and offering an alternate method of food preservation [107]. As materials that mimic the catalytic activity of natural enzymes at the nanoscale, nanozymes are a class of catalytic nanomaterials that include metal-based, carbon-based, and single-atom nanozymes. Their inherent antibacterial stem from their surface chemical characteristics are need to be developed for the future usage [35].

## Nanozymes in food preservation



**Figure 12** Application of nanozymes in food preservation.

When it comes to addressing the pressing issues with food security, nanomaterials hold up especially intriguing possibilities. Due to the rising global population, climate change, and restrictions on present agrochemicals, nanomaterials intended to boost crop output are becoming more and more important [108]. Plant-based nanosafety research has now concentrated on intentionally or directly subjecting food crops to particular nanomaterials such as nanopesticides, nanofertilizers, and nanoherbicides [109]. Although the use of antimicrobial nanoparticles in the food industry is promising and there is a problem that needs to be solved in the near future to guarantee total food safety is the release of nanoparticles in food and related toxicity [103].

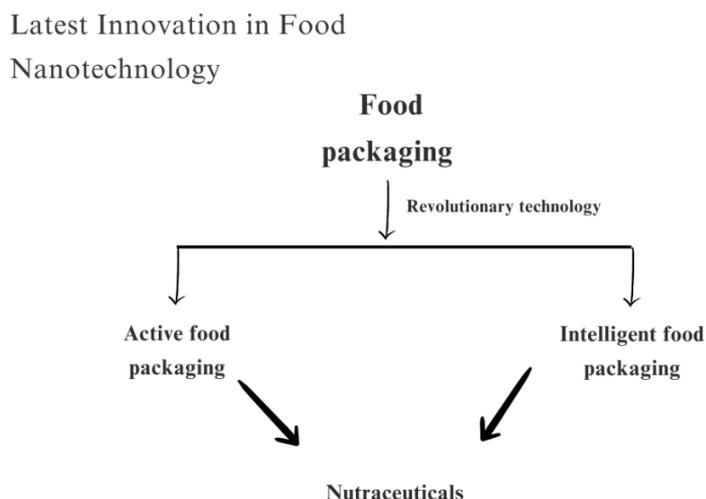
The development of antigen-specific biomarkers, smart packaging (intelligent and active packaging), and the blending of nanoparticles to create nanocomposite polymeric films are just a few instances of innovative ideas that are gradually coming to pass for potential future development and industrial usage [32]. Additionally, more study is being conducted based on cautious considerations, particularly with regard to the migration patterns of nanomaterials in food matrix, the cytotoxicity of nanoparticles to humans, and their possible effects on the environment and consumer health and safety [110].

### Latest innovation

The advent of revolutionary nanotechnologies, where the actives can be in micro- and nano-dimensions and diverse shapes, greatly increased the incorporation of active substances into consumables [111]. The qualities of food packaging materials can be dramatically improved thanks to nanotechnology, but further research and development are needed to determine the possible advantages and disadvantages [112]. According to studies, the basic requirements for food security are crop yields, soil fertility, crop disease control, and water supply, all of which can be mitigated with the aid of this cutting-edge technology [113].

New types of packaging known as active and intelligent packaging have emerged as a result of the development of new technologies. These 2 packaging options have various advantages for food quality, safety, and traceability, improving the consumer experience and enhancing the effectiveness of the supply chain. A revolutionary technology called active and intelligent packaging shields food from contamination and guarantees food quality and safety [114-116]. There are also additional innovative techniques based on nanotechnology being used in the food sector, such as engineering natural proteins as nano-architectures to deliver nutraceuticals [117,118]. Latest innovation in food packaging which leads to the formation of

engineering natural proteins as nano-architectures to deliver nutraceuticals has been shown in **Figure 13**.



**Figure 13** Latest innovation in food packaging which leads to the formation of engineering natural proteins as nano-architectures to deliver nutraceuticals.

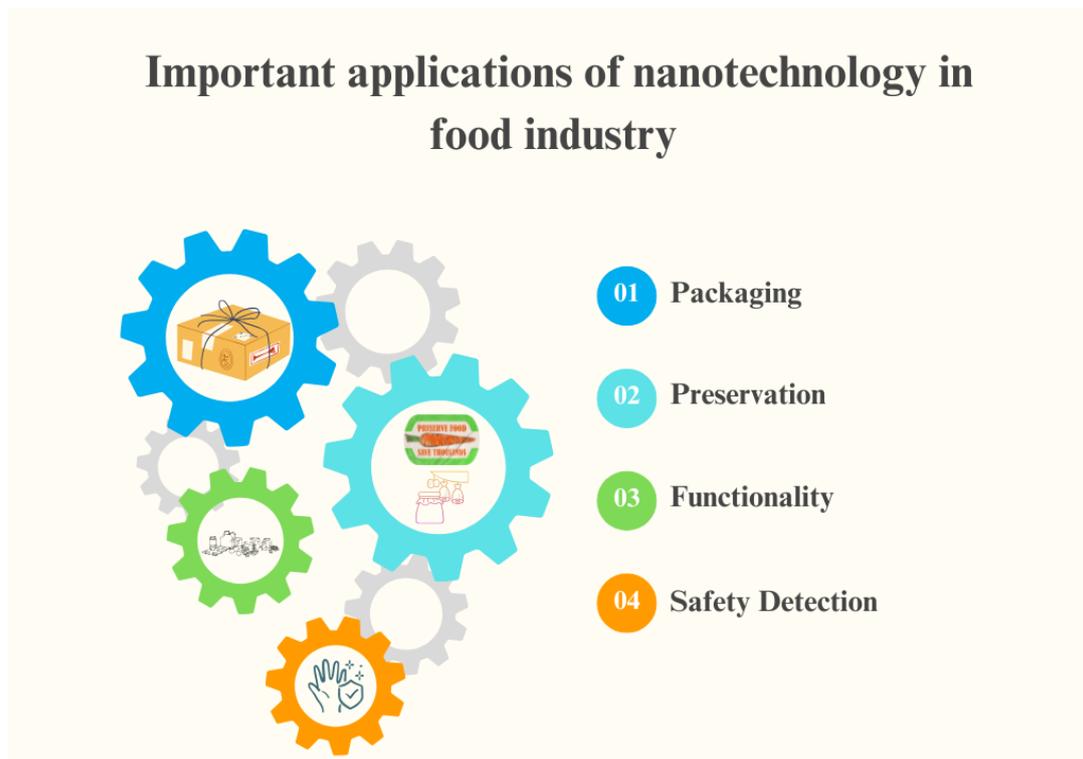
### Challenges and limitations

In the food industry, nanotechnology plays a key role in food processing, packaging, and preservation. Pathogen identification is also a crucial factor in ensuring the overall quality of the food. Utilizing packaging materials that have the capacity to produce nanoscale antibacterial chemicals and antioxidants that can extend the shelf life of food [119]. The development of better food processing, preservation, and storage techniques to produce healthier and more nutrient-dense food for human welfare is the sector's main challenge. Therefore, nanobiotechnology is a different possibility to solve a global issue and assist in giving future generations authenticated, nutrient-dense, safe, secure, shelf-stable, high-quality, fortified, and medicinal food products [120]. By 2050, it is predicted that increased food production will result in a 263 MT increase in the need for macronutrients, making it difficult for the global food production industry to meet this demand [121].

Contrary to other industrial sectors, the food system only has a few minor uses for nanotechnology. The number of agrochemical patent applications is growing substantially, however there are presently no

effective new nano-based food safety solutions that have significantly entered the market in the food business. Therefore, the use of those biomaterials in active food packaging should be ensured by potential commercial inventions in the future [122]. In the agro-food sectors, waste management is a serious concern that necessitates an integrated strategy for recycling, reuse, and recovery.

Globally, agricultural waste accounts for 0.3 G tones of biomass annually, beyond their conventional applications as fuel, fodder, or biofertilizers. For their wider application, these alternate uses of agro-waste require more research and development [123]. Research on water filtration, food clarification, waste from plant extracts, and other undesirable components still needs to advance. The primary problem still lies in the degradation and modification of carbon-based carrier substrates during the integration of metals in food products and the environment [124]. Various agricultural obstacles, such as those relating to productivity and food security, can be methodically overcome through nanotechnology [125]. Most important applications of nanotechnology in food industry has been depicted in **Figure 14**.



**Figure 14** Important applications of nanotechnology in food industry.

### Hurdles for a sustainable food future

The difficulties that come with adding grains in sustainable product categories like plant-based diets must be addressed, and the proper solutions must be found. Additionally, more study is required to develop formulations that will increase consumer appeal without sacrificing nutritional value [126]. Nutritional components like carotenoids and omega-3 fatty acids, as well as phytochemicals like curcuminoids, polyphenols, and phytosterols, are some of the most often investigated bioactive molecules. Many of these compounds provide a number of issues when added to food and beverage products [127]. Stakeholders and users find it difficult to choose and put into practice the right technology to boost agricultural output [128]. These consumers won't cut back on their meat consumption, even if they care about the environment. Relatedly, a significant barrier to the purchasing of insect-based food products is a lack of knowledge about the ecosystem [129]. However, the availability of more plant-based meals that are reasonably priced, practical, sustainable, nourishing, and delectable would help plant-based alternatives. Customers would then find it easier to change their eating habits and adopt a sustainable and healthful diet [129].

### Conclusions

The disquisition of nanobiotechnology's impact on the food geography reveals a transformative trip from enhancing quality to reshaping food chains. Nanotechnology's part in extending shelf life, reducing waste, and combating pollutants signals a significant vault forward in food preservation. While ethical considerations are consummate, the composition underscores the need for standardized approaches in integrating nanobiotechnology responsibly. Looking ahead, the future of food hinges on untapped capabilities, with nanotechnology poised to revise product and consumption. As we defy challenges, the pledge lies in innovative results. Unborn trends anticipate the confluence of nanotech and food safety, sustainable practices, and effective product. The prospect of nanobiotechnology as a driving force in icing a safer, more flexible, and immorally sound global food force emerges as a lamp, encouraging cooperative sweats to navigate challenges and propel us towards a future where invention defines the coming chapter in food elaboration.

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