# Chapter 10
# Applications and Implications of Nanoparticles in Food Industries

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## 1 Introduction

During the past few years, nanotechnology (NT) has increasingly been taken into consideration as an innovative technology that has revolutionized many industrial sectors including food (Mansurov 2020). The nanoparticles (NPs) possess one or more dimensions on the scale of 1–100 nm and unique physicochemical and biological characteristics. The specific characteristics such as surface to volume ratio, color, optical and magnetic property, solubility, diffusivity, toxicity, and many others make NMs unique for applications (Elemike et al. 2019). Nanotechnology has brought a revolution in every sector that developed and many developing countries are investing a huge amount of funds in NT research (Tahmooresnejad and Beaudry 2019). Consequently, NT offers a large variety of opportunities for the development

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of agricultural (Pramanik et al. 2020) and food products (Otles and Yalcin 2010; Bieberstein et al. 2013) that help in enhancing the food quality, storage, and fortifications (Ameta et al. 2020).

Nanostructured material and nanosensing are two major areas in the food sector where NMs have gained popularity (Azar et al. 2020; Yang and Duncan 2021). It includes a range of applications that is from food processing to packaging (Katouzian et al. 2017). These nanostructures are used to act as additives, anti-caking agents, and smart delivery agents/carriers for the delivery of nutrients, to improve the durability and mechanical strength of the packaging material. However, nanosensing is used to apply for attaining improved food quality and safety assessment (Casalinuovo et al. 2006; Wong and Khor 2021).

The rising applications of NMs are giving a major concern to consumers about food safety and that persuade the researchers to work on improving the food quality without altering the nutritional quality (Berekaa 2015). In the last few years, the application of NPs in the food industry has significantly increased as many of them are resistant to high temperature and pressure, have essential elements, and are also nontoxic under a certain dose (Talebian et al. 2021). Nanotechnology can guide the food industry in manufacturing, processing (Bochicchio et al. 2020), quality control (Jildeh and Matouq 2020), and also its packaging (Bieberstein et al. 2013; Naskar et al. 2018) that can truly lead to a major change in the food industry for sustainable food technology (Ameta et al. 2020; Bhusare and Kadam 2021) (Fig. 10.1).

Nanoencapsulation of nutraceutical compounds (Subramani and Ganapathyswamy 2020), enhancing the flavors and aromas (Saifullah et al. 2019), nanobiosensing for identification and recognition of pathogenic bacteria or allergen (Joyner and Kumar 2015), and quality monitoring (Raju et al. 2020; Wang et al. 2021) are potential

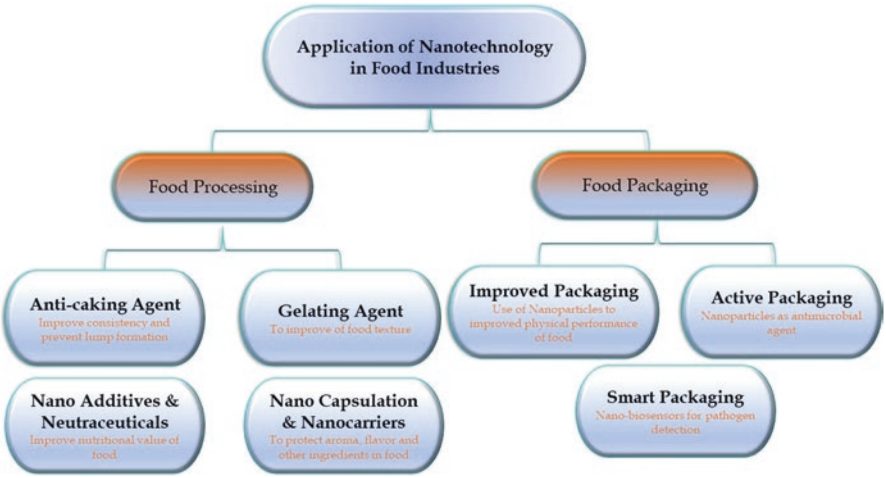


**Fig. 10.1** Nanotechnology and its application at various steps in the food industry

applications and advances in the food sector. Apart from these applications, improvement in the food packaging quality is also being researched for a better alternative of packaging or smart packaging that can improve the shelf life of the food and protect it from the pathogen (Mohammadpour and Naghib 2021). Nanocomposite food packaging materials are also very promising in terms of protection from foodborne pathogens (Bumbudsanpharoke and Ko 2019).

In the last decade itself, the application of NMs in every sector has greatly increased (Talebian et al. 2021). The high demands and application of NMs are posing a greater environmental concern (Maiga et al. 2020; Temizel-Sekeryan and Hicks 2020). Nanomaterials have been reported in the abiotic and biotic components of the environment including food chains (Martínez et al. 2021). The presence of NMs in the water that is used for irrigation and presence in the soil can easily affect the agriculturally important soil microflora and alter the growth characteristics of crops (Du et al. 2017; Odzak et al. 2017; Rajput et al. 2020a). The entry of NMs into the food chain via any routes can be a major threat to several aquatic (Rajput et al. 2019a; Blinova et al. 2020) and terrestrial species (Rajput et al. 2017; Bobori et al. 2020) as well as to human health. Owing to their unique physicochemical properties, NMs are very prone to affect and alter the biomolecules (AshaRani et al. 2009; Maurer-Jones et al. 2010; Ding et al. 2017). Several metal-based NPs have been reported to have toxicological implications for human health (Rajput et al. 2020b; Irshad et al. 2021; Ranjan et al., 2022).

This chapter critically discusses the application of NMs in the food sector, starting from manufacturing to packaging, NMs used in food processing, smart food packaging, and nanosensing for food quality and safety. The chapter also discusses the growing environmental health concern due to the inevitable release of NMs by several applications.

## 2 Nanomaterial in the Food Industries

Ample new opportunities have sprung up in the food industry with NT as the novel properties of NMs are greatly useful in several industries including food (Cho et al. 2008). Nanostructures with a variety of functionalities are used as basic components for introducing unique food processing methods by utilizing the nanostructures that include nanoemulsions, NPs, nanoliposomes, and nanofibers (Weiss et al. 2006; McClements et al. 2007). In the food sector, both inorganic- and organic-based NMs find their usage. Nanoparticles with the possibility of being found in nanofood products, engineered nanomaterials (ENMs) are categorized as inorganic, surface-functionalized materials, and organic ENMs (Lombardo et al. 2020; Gulin-Sarfraz et al. 2021; Makvandi et al. 2021).

### 2.1 Inorganic Nanomaterials

In ENMs mostly d-block metals like silver (Ag) and iron (Fe), alkali earth metals like magnesium (Mg) and calcium (Ca), and nonmetals like silicates ($SiO^{4-)}$ and selenium (Se) are used for their application in food, food packaging or storage, and food additives (Ganesh and Ramakrishna 2020; Jafarzadeh et al. 2020; Medina-Reyes et al. 2020). Titanium dioxide ($TiO_2$) is another crucial ENM that can be effectively used in the food sector (Gunputh et al. 2018; Zhang et al. 2019). For metal/metal oxide ENMs, food packaging is a sector that finds a major proportion of its application. Nano-silver, having outclassed all kinds of ENMs, is currently used in different divisions as an antimicrobial, anti-odorant, and a health supplement (proclaimed). It is now also gaining popularity in several consumer products like edible products, food contact surfaces, drinking water, and packaging materials in terms of its effective uses (Hoseinnejad et al. 2018). Amorphous nano-silica finds its use in food contact surfaces and food packaging applications (Biswas et al. 2019; Lu et al. 2021). After numerous proclaimed health benefits of selenium in the human body, the marketing of nano-selenium as an additive to a green tea product has subsequently increased (Ye et al. 2020). Intended to be used in chewing gums and reportedly known for aiding remineralization of tooth enamel, nano-calcium salts also have a greater scope (Gao et al. 2020). Studies on Ca NPs and Mg NPs salts for development as health supplements are also on the rise (Naghsh and Kazemi 2014; Erfanian et al. 2017; Longbaf Dezfouli et al. 2019).

Iron NPs have also gained popularity as a health supplement (Pereira et al. 2018). In the process of development is a soluble nanomaterial, known as nanosalt, whose smaller quantities will be able to cover a larger surface area of food substances and help consumers to keep a check on their salt intake (Vinitha et al. 2021). Two nanotechnology-based food products, namely, cola-tasting nano-milk and with less fat content, nano-mayonnaise, have been developed by Wageningen University, Holland, which is the best demonstration of future nano-foods (Bayram and Gökırmaklı 2020). To drastically prolong the shelf life of edible products and to ease further transportation, NT would also help to manufacture “smart” packaging (Mohammadpour and Naghib 2021). Containing nano-sensor and antimicrobial activators, smart packaging is developed in a way that will be able to identify spoilage of food products and would also expel nano-antimicrobials to enhance the shelf life of food substances (Biswas et al. 2019; Jafarzadeh et al. 2020). This would enable groceries to store food for longer durations before it can be sold. Invisible to the human eye, nano-sensors in the form of tiny chips that are embedded into food products would also function as electronic barcodes (Dobrucka 2020; Mohammadpour and Naghib 2021).

### *2.2 Surface-Functionalized Nanomaterials*

Their role is to enhance various kinds of functional utilities to the matrix, like antimicrobial activity or absorbing oxygen and performing a preservative function. The use of functionalized ENMs in food packaging materials is by binding with the polymer matrix, offering robustness and mechanical strength or preventing the movement of gases, volatile constituents (like flavors and odors) or moisture, by acting as a barrier. Compared to inert NPs, these functionalized ENMs may not be available to migrate out of packaging materials, or movement to other organs exterior to the gastrointestinal tract as there is more chances of reaction with other food components and may bind to the matrix of food. Montmorillonite or bentonite is the principal nanoclay mineral. It is mostly natural clay acquired from volcanic ash/rocks (Guo et al. 2018). With a natural nano-scaled, layered structure, nanoclays are organically modified to enable binding with polymer matrices. In food packaging, using functionalized nanoclays will help develop materials with greater gas-barrier properties (Echegoyen et al. 2016; Ahari et al. 2021).

### *2.3 Organic Nanomaterials*

Most organic NPs are naturally occurring or have been formulated for their usage in food products or feed for animals. As compared to conventional bulk equivalents, they ensure enhanced uptake and absorption, and the bioavailability of vitamins and antioxidants is also reported to be increased (Khalid et al. 2020). Several materials in this group are available, such as food additives (e.g., benzoic acid, ascorbic acid, citric acid) and nutraceutical supplements such as vitamins A and E, lutein, omega-3 fatty acids, beta-carotene, isoflavones, and coenzyme Q10 (Li et al. 2012; Soveyd et al. 2017; Ahamed et al. 2019). A popular example of organic nanomaterial can be tomato carotenoid lycopene which is a synthetic nanosized form of lycopene, equivalent to the natural lycopene (Ahmed et al. 2021). Other examples of organic NPs are proteins, fat and sugar molecules, and nutraceuticals comprising food additives that are derivatives of plants. Nanotechnology has also opened new avenues for introducing different functional utilities, such as antimicrobial activity in decomposable/biodegradable materials (Gutiérrez 2018; Jafarzadeh et al. 2020).

## 3 Food Processing and Nanotechnology

The food sector includes four basic areas that are crucial for its function, and it includes production or farming, processing, fortification (if necessary), and packaging. Nanomaterials that have been proclaimed to enhance taste, consistency, and texture, food ingredients are being manufactured largely and used for food processing (Ameta et al. 2020). It has been extensively helpful in prolonging the storage life span of different food materials and successfully reducing wastage of food that occurred because of microbial/pathogenic infestation (Pradhan et al. 2015). Without modifying the basic structure of the food products, nanocarriers have been used as transport systems to deliver food additives into them. Transporting any bioactive substance to active sites inside the body may be directly influenced by the particle size. It has been observed in some cell lines that only submicron NPs could be effectively absorbed not the larger particles (Ezhilarasi et al. 2013).

An ideal delivery system in food processing should possess properties: (i) delivery of the active compound precisely at the site of action (ii) ensures the availability at a target time and a specific rate and (iii) must be efficacious enough to maintain appropriate levels of active compounds for extended periods concerning storage. Encapsulation, emulsions, biopolymer matrices, simple solutions, and association colloids developed using NT provide effective transport systems at target sites with all the aforementioned properties (Liu et al. 2021; Rashidi 2021). In food packaging, nanopolymers are serving as replacements for conventional materials. Using a nano-sensor, one can substantiate the presence of contaminants, microorganisms, and mycotoxins in food (Bratovčić et al. 2015).

Encapsulation and release efficiency of NPs have been reported to be far better than the conventional encapsulation systems. Nanoencapsulation helps mask odors or tastes, controls interactions of active compounds with the matrices of food, and controls their release and offers protection against moisture, heat, and biological or chemical degradation during processing, storage, and usage. It also provides conformity with other compounds in the system (Hosseini and Jafari 2020; Mahato et al. 2021). Furthermore, these delivery systems can penetrate deeper into the tissues because of their submicron size and hence allow efficacious translocation of active substances to various target sites in the body (Rashidi 2021).

Supplementary to this, the significance of NT in the food processing industry can be assessed by contemplating the job it plays in improving the quality of food products in terms of their (i) texture, (ii) appearance, (iii) taste, (iv) nutritional value, and (v) shelf life. It is worth mentioning that NT not only enhances the abovementioned aspects but also has contributed significantly to the improvement of food products by introducing novel attributes and utilities to them (Table 10.1).

A schematic figure also elaborates the individual segment in the food sector and the category of application the NT has gained popularity (Fig. 10.2).

## 4 Nanotechnology in Food Packaging

Typical packaging material should have gas- and moisture-absorbing capacity, which possesses both strength and biodegradability (da Silva Filipini et al. 2020; Amin et al. 2021). Several advantages of nano-based “intelligent” and “active” food packaging over the traditional packaging methods can be listed which range from improved mechanical strength of packaging material, barrier properties, and

**Table 10.1** Nanomaterials, types, and their application in the food sector

| Nanomaterials | Types | Applications | References |
|---|---|---|---|
| Metal oxide NPs | Ag, ZnO, Mg, $SiO_2$ | Packaging material, protecting from the contaminants and antibacterial properties by oxidizing them | Jafarzadeh et al. (2020) |
| Polymeric nanocapsules | Bioactive compounds | Enhance the efficacy and solubility of ingredients/ bioactive compounds and controlled release | Sabliov and Astete (2015) |
| Nano-cochleates | Coiled NPs | Food fortification: Improves the nutritional value of food, adding antioxidants, provides better food protection and shelf life | Ahiwale et al. (2021) |
| Nanocomposite | Fe-Cr/$Al_2O_3$<br>Ni/$Al_2O_3$ | Increases the shelf life of the food, protects the food, and is also used in the food packaging | Naskar et al. (2018), Mathew et al. (2019) |
| Nanoemulsion | Tweens or spans; gum arabic or modified starch, soy, caseinate, lutein | Encapsulation of ingredients, or antimicrobial compounds, storage, shelf life, and colorant | Liu et al. (2021) |
| Nano-micelles | Hydroxyethyl starch, Aquanova (NovaSOL® technology) | Liquid carrier, enhanced solubility | Chen et al. (2020) |
| Nano-sensors | Nanobiosensors or aptasensors that detect DNA, RNA, antibodies, or any other biomolecules | Detection of toxins, pathogens, allergens, carcinogens, etc. | Shawon et al. (2020) |
| Nano-sieves | Silicon nitride ($Si_3N_4$), ceramic, carbon nano-sieves, Au-PP SANSs, etc. | Ultrafiltration and removal of pathogens | Chang et al. (2020) |
| Nanospheres | Starch nanosphere, selenium nanosphere, carbon nanosphere, etc. | Food encapsulation, synthetic adhesives | Wang et al. (2020) |

antimicrobial films to nanosensing for detecting pathogens and informing consumers about food safety status (Kaushal and Wani 2017; Shawon et al. 2020).

Similar to active materials for material coating and packaging of food, the use of nanocomposites can also improve food packaging (Pinto et al. 2013). Significant studies have been conducted in the interest of organic compounds like essential oils, organic acids, and bacteriocins and their use in the matrix of polymers as antimicrobial packaging (Faleiro and Miguel 2020; Gumienna and Górna 2021; Papadochristopoulos et al. 2021). Nevertheless, as these compounds are extremely sensitive to physical conditions like those of temperature and pressure, they are not suitable for many food processing (Ben Braïek and Smaoui 2021). A very high antibacterial activity can be obtained at comparatively low concentrations with more stability in extreme conditions with the use of inorganic NPs. Thus, the use of

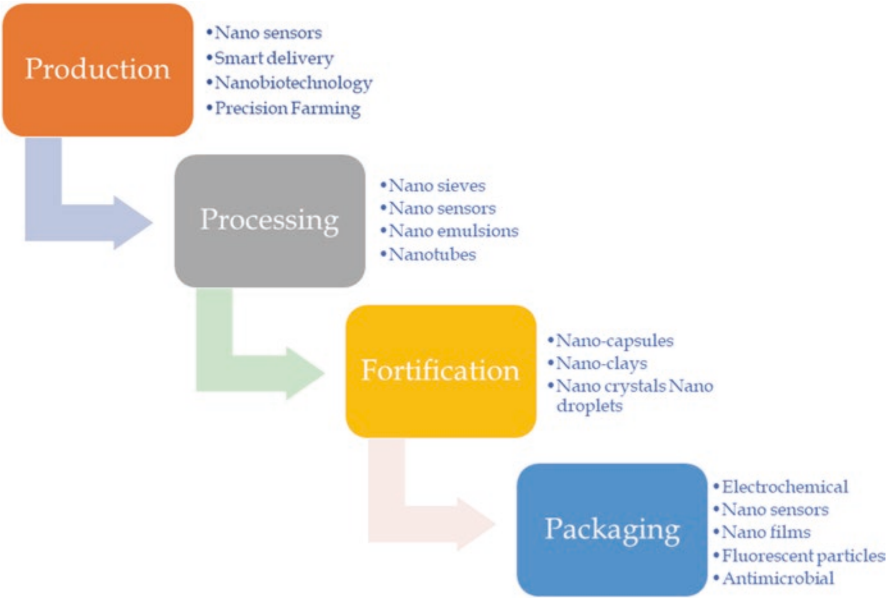


**Fig. 10.2** Category of applications in the individual sector of food production where NPs are playing key roles

these NPs in antimicrobial food packaging has shown increasing interest recently (Jafarzadeh et al. 2020). A type of active packaging with biological properties, antimicrobial packaging, comes in contact with the food product or the space inside to retard microbial growth which might be present on the surface of food particles (Yildirim et al. 2018). Antibacterial properties have been reported in several NPs such as Ag, copper, chitosan, and metal oxide NPs like titanium oxide or zinc oxide (Longano et al. 2012; Gunputh et al. 2018; Biswas et al. 2019).

## *4.1 Active Food Packaging*

Active packaging is comprised of the outcomes of materials science and engineering that have brought packaging technology with certain attributes that help to protect and preserve the food quality (Yildirim et al. 2018). The active food packaging mainly has three unique properties, (a) a releasing system that delivers antimicrobial substances, antioxidants, and flavors (Subramani and Ganapathyswamy 2020); (b) scavengers or absorbers to control $O_2$, $CO_2$, or odor (Lee et al. 2018); and (c) a control system to limit the moisture, temperature, or microwaves (Singh et al. 2018; Gaikwad et al. 2019). Nanoparticles have played a crucial role in the development of varieties of the active packaging system, and it has significantly enhanced food quality. It has helped by bringing precision farming (Chiranjeeb and Senapati 2020), delaying oxidation of food like meats (Lee et al. 2018), controlling moisture (Gaikwad et al. 2019), and limiting microbial growth (Gumienna and Górna 2021). The packaging system has also been developed for selective modification of gaseous content within the package (Kumar et al. 2021).

Nanoparticles are not just employed in antimicrobial food packaging; but nanocomposite and nanolaminates have also been used in food packaging to create a barrier against high temperature and mechanical shock, hence prolonging food shelf life (Aragüez et al. 2020; Aga et al. 2021). Hence, incorporating NPs into packaging materials provides high-quality food with a longer shelf life. In this context, biopolymer composites or PVC-based CMC-hydrogels have also been developed to provide more thermostable and mechanical packing materials (Kochumalayil et al. 2010; Roy et al. 2012). To generate better polymer composites, many inorganic or organic fillers are used, and metal NPs and carbon nanotubes have also been used as nano-filler (Rezić et al. 2017). The use of NPs in polymers has enabled the development of more cost-effective packaging materials (Sorrentino et al. 2007). Besides, the inclusion of inert nanoscale fillers into the polymer matrix, such as clay and silicate nanoplatelets, silica ($SiO_2$) NPs, chitin, or chitosan, makes it lighter, stronger, and more fire-resistant and and has increased thermal properties (Duncan 2011; Othman 2014). Thus, because of their structural integrity and barrier qualities, antimicrobial nanocomposite films formed by impregnating fillers with at least one dimension in the nanometric range of NPs into polymers provide for a two-way benefit (Rhim and Ng 2007; Shankar and Rhim 2017).

## Antimicrobial Food Packaging

Antimicrobial packaging inhibits the growth of those microorganisms by outspreading the lag phase of the growth (Jafarzadeh et al. 2020). Inorganic antimicrobial agents are the most suitable substances as they have better stability and lesser safety concerns. However, organic antimicrobial substances may pose consumers' health risks and alter the flavors (Hoseinnejad et al. 2018). The choice of antimicrobial packaging agent is again dependent on factors like the type of food products, temperature, moisture content, and chemical nature and composition of food products. Organoleptic properties, toxicity, and resistance to microbes are key points to consider before the selection of antimicrobial agents (Ahari et al. 2021; Anvar et al. 2021).

Other aspects about packaging materials can be considered as control release of antimicrobial agents, physical and mechanical properties of packaging materials, and its permeation (SeyedReihani and Ahari 2020; Subramani and Ganapathyswamy 2020). Controlled releases of ingredients have been popularly used in the delivery of drugs by the pharmaceutical industry, however its evolving concept in food packaging. For efficient antimicrobial packaging, the microbial growth rate and the release of antimicrobial agents should be the same; both too slow and too fast release rates of the ingredients would lose the characteristic of antimicrobial packaging (Almasi et al. 2020). Nanosized inorganic antimicrobial agents are used in food packaging due to their enhanced reactivity and potential. Nanoparticles like $Al_2O_3$, Au NPs, CuO NPs, $Fe_3O_4/Fe_2O_3$, $TiO_2$, $SiO_2$, and ZnO are popularly used (Jafarzadeh et al. 2020). The nanosized particles have advantages over the bulk compounds and other antimicrobial agents in that they have high efficiency, require comparatively lesser time to kill the microbes, and can also overcome the microbial resistance that commonly develops in the conventional/organic antimicrobials (Rezić et al. 2017).

## 5 Nano-sensor for Pathogen Detection

The food sector always needed stringent quality control and monitoring potential applications that nano-sensor has fulfilled. It provided better sensitivity and detection abilities. In the food sector, nano-sensor or nanobiosensors help detect the pathogenic microbes and allergens during the food processing (Weng et al. 2021) (Aquino and Conte-Junior 2020), carcinogen detection and quantification (Wong and Khor 2021) assessment of constituents/ingredients (Joyner and Kumar 2015), etc. The nano-sensor principally works on changes in the condition of the environment, such as a change in the temperature in the storage (Manoj et al. 2021), change in relative humidity (Mohammadpour and Naghib 2021), contamination with microbes, or degradation of food products (Shawon et al. 2020). The nanostructures like NPs, nanofibers, nanorods, and nano-films have been evaluated for their use in food industries (Hsieh 2018; Prakash et al. 2019; Baysal and Doğan 2020).

Detection of pathogenic microbes has been feasible by immune-sensing, which involves a thin-optical film coated with suitable antigen/antibody/protein molecules against the microbes. The binding of microbes/their epitope/protein with the molecules coated on the films emits the signal that is being detected (Pires et al. 2021). A rapid detection method using dimethylsiloxane microfluidic-based immunosensor combined with specific antibodies restrained on alumina nanoporous membrane was developed for the detection of *Staphylococcus aureus* and *Escherichia coli* O157:H7 (Tan et al. 2011). In recent years, NMR-based detection system has been developed for the rapid detection of pathogens using NPs of superparamagnetic ultrasmall iron oxide integrated with membrane filtration and low field nuclear magnetic resonance (Jin et al. 2020). Time-domain nuclear magnetic resonance (TD-NMR) has also been helpful in the rapid detection of *Salmonella* in the milk samples. The superparamagnetic nanoparticle (SMN) is used in the development of this biosensor that works on the free binding of biotinylated antibodies to the *Salmonella*, and this approach can detect the $10^4$ CFU $mL^{-1}$ within 2 h (Zou et al. 2019).

The presence of pesticides and toxins has also been assessed using a nano-sensor to improve food quality (Palchetti and Mascini 2008). The nano-sensor based on carbon nanotubes has gained so much popularity because of its ease of use, low cost, and rapid detection. It has been successfully used for the detection of microbes (Choi et al. 2017; Hasan et al. 2018; Sobhan et al. 2019), pesticides (Wang et al.

2020), carcinogens (Wu et al. 2021), etc. in food products. Nano-immunosensors are also utilized for the detection of nano-diagnostic purposes, where they help in the identification of pathogenic fungal in the crops. Antibodies against the specific toxins are used to detect the presence of toxins and changes in the conductivity are assessed (Wang et al. 2009). Nanomaterial-based myco-sensor helps to detect the presence of mycotoxins (FB1/FB2, ZEN, DON, and T-2/HT-2) in real time and for multiple crops like barley, corn, oats, and wheat. It can well detect the mycotoxins below the EU limits (Lattanzio et al. 2012).

Modified quartz crystal surfaces with a set of functional groups or molecules such as amines, enzymes, lipids, etc. are used for the identification of key components of aroma and flavors. An array of such nano-sensor is also used as electronic noses or tongues for monitoring aroma, flavors, and other food conditions (Tan and Xu 2020; Wong and Khor 2021).

## 6 Health Safety and Environmental Issues

Nanomaterials, owing to their properties, have acquired a wide range of applications in every industrial sector including food. To fulfill the ever-increasing demand, NM manufacturing has increased many folds in the past few years. Large-scale manufacturing and applications of NM are posing a greater environmental and health risk. Sources, fate, and effects of NPs in the environment have now been broadly understood by researchers, and their findings have made significant progress in recent years. Nanoparticles enter the environment during the manufacturing of nanoaided products and also from raw materials. They are also released during application and after disposal of nanoproducts or waste (Gottschalk et al. 2013; Tolaymat et al. 2017). The release of NMs follows two fundamental ways, directly and indirectly. Directly, NPs are emitted to the environment during manufacturing and handling; however, in an indirect way, they are being released through NP-based products like agrochemicals (Campos et al. 2015; Fatima et al. 2020), fertilizers (Kopittke et al. 2019), pharmaceutical and cosmetic products (Nyström and Fadeel 2012; Subramaniam et al. 2019), and electronic appliances (Tang et al. 2019) and also from the leachates from landfills and effluent (Kaegi et al. 2010; Al-Kattan et al. 2015).

The release pattern and the extent depend on the type of NPs and their application. Modeling studies have been helpful to understand some extent for estimation of their concentration in the environment and their emissions and also predict their fate (Boxall et al. 2007; Mueller and Nowack 2008). Metal-based NPs enter the food chain with significant toxic consequences. They directly or indirectly find their ways to air, soil, sediment, and water or in the food chain. NPs like Ag NPs have been analyzed in the soil, surface water, and sediment (Li et al. 2018; Wimmer et al. 2019a, b).

After entering the environment, these NMs face a series of modifications that impact their outcome in tropical transfer, for example, dissolution, binding to environmental ligands, and aggregation/agglomeration. These alterations play a critical role in assessing the toxicity, higher bioaccumulation, and precipitation (Tangaa et al. 2016).

In recent studies, ecotoxicological profiles of Ag NPs have been evaluated using *Daphnia magna* and *Raphidocelis subcapitata*, which are representatives of two different levels of the aquatic trophic chain, and seeds of *Lepidium sativum*, *Cucumis sativus*, and *Lactuca sativa*. The study infers that *Daphnia magna* is easily affected by the presence of NPs (Falanga et al. 2020).

The presence of NPs is also expected to increase in soil mainly through agricultural applications (Rajput et al. 2018). Nanoparticles, when get accumulated in the soil, affect the flora and fauna, and they are transported via interfaces of soil particles (Rajput et al. 2017, 2019b). They form aggregation and are immobilized or also adsorbed on the particles of the sediments/soil where they are easily taken up by soil microbes. Metal NPs like Ag NPs enter into the water bodies and tend to be engrossed by the muds and sewage wastes and also reach farms through irrigations. This way the NPs have a greater chance to reach the crops and plants and affect them negatively (Blaser et al. 2008).

$TiO_2$ NPs are reported to be transported across the trophic chain and accumulate in the freshwater as well as sandy loam sediment where they are easily absorbed by the lower plants like duckweeds, water dropworts, and quillworts. They are also taken up by the organisms like earthworms (*Eisenia fetida*), juvenile bullfrogs (*Rana catesbeiana*), river snails, and Chinese muddy loaches (Unrine et al. 2012). Bioaccumulation of NPs through the soil in the various organs such as the kidney, liver, muscle, spleen, and intestine of the juvenile bullfrogs infers that it is also a threat to higher trophic level animals (Bertrand and Leroux 2012). $TiO_2$ is broadly used as a water disinfectant to control the coliform, they get a route from the sewage/wastewater treatment plants where the NPs cannot be removed effectively, and it results in its flow with the water and surface waters and also to the organisms (Westerhoff et al. 2011).

The presence of NPs in the food chain is also threatening the consumption of fish and seafood and making consumers chances of exposure (Ward and Kach 2009). However, very few studies are available on the presence of NPs in meat and animal tissues. In a study, Ag NPs have been reported to accumulate in the livers of 80-week-old male broiler chickens when fed with Ag NPs-contained feed/drinking water at various concentrations (4, 8, and 12 mg/dm$^3$) for 42 days (Loghman et al. 2012). A recent review on the migration of NPs from the food packaging to the food materials has discussed the scenario in detail. Most of the studies included in the review have confirmed the migration levels to be lesser than the permitted levels. However, the migration of Ag NPs is identified to be higher in the acidic environment. It has been observed that studies on the migration of Ag NPs are not congruent with each other; however, all studies in this regard agree upon the fact that Ag NPs have high migration levels in acidic environments. The studies also highlighted the migration of various NPs depending upon the factors like the concentration of additives used, area of food products in the contact of packaging material, the solubility of packaging material, the density of remaining segments, duration of contacts of food material, and heat. Unfortunately, the information is very insufficient about the NPs' toxicity of food materials, and it would be too early to draw any conclusion (Paidari et al. 2021).

Besides its potential application, the environmental and health threat cannot be neglected in the absence of information or research data. Researchers however have taken up the issues and emphasized the consumer's health (Bradley et al. 2011). Although certain NPs are referred to as GRAS (generally regarded as safe) substances (Naseer et al. 2020), additional studies are of utmost necessity to gather more knowledge about its toxicological implications. For instance, the silica ($SiO_2$) NPs are commonly used as anti-caking agents found to be cytotoxic in human lung cells (Athinarayanan et al. 2014), Chromium NPs have been reported to affect human lymphocytes by elevating reactive oxygen species (ROS), reducing matrix metalloproteinases (MMP), and altering the membrane system of lysosomes. Cr NPs have also been reported to cause lipid peroxidation (Seydi et al. 2020). A study on ZnO NPs reports that ZnO NPs do not cause significant toxicity to intact human skin; however, after the dissociation of NPs, the zinc ions are released and can cause toxicity to the viable epidermis if the stratum corneum has been penetrated (Holmes et al. 2020). Similarly, at higher doses, Cu/CuO NPs are also reported to affect the human intestinal cell lines Cao-2 by having moderate solubility, ROS-dependent DNA damage, and apoptosis (Li et al. 2020).

Again, the toxicity of NPs in humans is also dependent on dissolution, surface morphology, concentration, surface energy, aggregation, adsorption, etc. (Cushen et al. 2014). It is also expected from the regulatory authorities and policymakers to come up with frameworks that can enable standards and guidelines/regulations to check the possible emissions and identify concurrent sources of emission that may affect the biotic and abiotic components.

## 7 Conclusion

In the past few years, industrial or technological innovations have been revolving around the application of NPs. In the food sector, they are extensively used for enhancing the quality of foods in terms of flavors, aroma, shelf life, balanced ingredients/constituents, quality monitoring control, and also packaging. The manifold growth in the application of NPs certainly poses a greater risk to the environment, to food chains, and also to human health; however, the effective application of NPs in the food sector is still a handful and limited.

The application of NT in the food sector enables innovative challenges for the industries and policymakers. The industries have to ensure the consumer's health and confidence for having greater acceptance of NM-based food/food products. International and local regulatory agencies should also play key roles in the safety evaluation of the food and packaging concerning the environment and human health. Mandatory testing of NM-based foods with suitable guidelines supported with stringent scientific evidence can certainly help to limit the chances of exposure of consumers. In the absence of evident research data and regulatory guidelines, consumers may have a state of dilemma for the safety of food. In that case, labeling the NM-based foods with suitable and easy symbols must be helpful for the consumers. Further scientific exploration with novel approaches toward the study of NPs on various human cell lines should also be promoted for further assessments. Last but not the least, development of new analytical methods for the detection of NPs would also be a key contributor not only in strengthening the food sector but also for environmental and health monitoring.

## 8 Future Perspective

With the potential to transform almost every aspect of modern life, NT is regarded as the fastest emerging technology of our times. In anticipation of the future perspective of NT in the food industry, it is quite obvious that more sound research in this domain would definitely result in creating tools and mechanisms for expansion and improvement in the industry in terms of enhanced shelf life, smart and antimicrobial packaging, efficient nutraceutical supplements, fortified food products, pathogen detectors, etc. with the greater population being benefitted from such advancements. It may also help in tackling persistent issues related to food and nutrition and has the potential to offer long-term economic gains. Cost-effective, healthy, and environmentally sustainable food production is the need of the hour, and NT is the answer for all such global problems.

Nevertheless, the need to address the safety concerns remains the topmost priority of the moment. With extensive acute and chronic toxicity studies, careful safety assessment would enable faster commercial availability of such products. With the introduction of new nano-based products and technologies in the market also lies a requirement of attaining social and environmental collaboration to ensure that the respective interests are not undermined. So far, only a handful of nations have standard regulatory guidelines for the use of NT in the food industry, which is why insufficient scientific research and data are available for concluding on efficacies and safety of nano-food and packaging. If managed well, there is no end to the opportunities offered by NT in the food industry. Properly guided scientific exploration is the key in gaining indefinite insights into the future of this industry.

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