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Review Article

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Nanotechnology in Food: Advances in Processing, Packaging, Safety, and Emerging Challenges

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Abstract

Nanotechnology offers transformative potential in the food industry by enhancing food quality, safety, and shelf life through nanoscale innovations. This review highlights the application of nanomaterials, such as nanosilver for antimicrobial packaging, nanoencapsulation for improved bioavailability, nanoparticles, nanoemulsions, nanocomposites, and nanosensors in food processing, packaging, and preservation. Nanocomposites strengthen packaging and inhibit microbial growth, while nanoencapsulation improves the stability, targeted release, and absorption of nutrients and bioactives like vitamins and polyphenols. Additionally, nanosensors integrated into smart packaging enable real-time detection of spoilage and contaminants, enhancing food traceability and consumer safety. However, the adoption of nanotechnology is challenged by concerns related to nanoparticle migration, toxicity, and environmental impacts, which are influenced by their size, shape, source, and synthesis method. Public perception and regulatory uncertainties further limit commercial integration. Further, this review lies in its comprehensive analysis of recent technological advances, safety and toxicological considerations, and both national (India) and international regulatory frameworks (Food and Drug Administration (FDA), European Food Safety Authority (EFSA), and Codex), alongside public perception. This review thus aims to provide a comprehensive overview of recent advancements in food nanotechnology, focusing on packaging, preservation, nanosensors, and nanoencapsulation. It also highlights market products, regulatory roles, challenges, and public perception.

Keywords

Food preservation, Food safety, Food packaging, Nanoencapsulation, Nanotechnology

Introduction

Nanotechnology manipulates the atomic, molecular, and supramolecular matter, bringing its size to the nanoscale i.e., below 100 nm. This technology develops nanomaterials with unique and useful physical, chemical, and biological properties such as size, shape, surface area, surface: volume, catalytic activity, biocompatibility, and antimicrobial activity [1, 2]. This scale allows the creation of NPs and nanostructures that can perform certain functions more efficiently than their larger counterparts. Over the decades, this technology has emerged as a useful force for various industries, and the food industry is also one of them [3]. In the food industry, nanotechnology offers many benefits such as food safety, improved shelf life, traceability, and quality in the form of NPs, nanoemulsions, nanoencapsulation, nanolaminates, nanocomposites, and nanosensors as shown in figure 1. Nanocomposites and nanolaminates make food packaging stronger

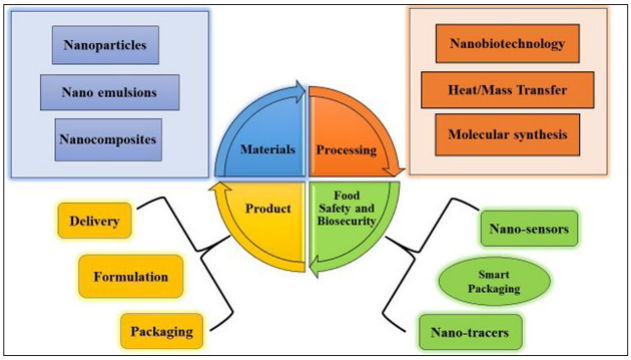

Figure 1: Various possible applications of nanotechnology in the food sector.

and more flexible while lowering food spoiling. For instance, antimicrobial agent incorporated nanocomposites hinder microbial growth and improve food safety. In addition, nanoencapsulation prevents the degradation of nutrients and bioactives, making it an effective and desired technique for food fortification without degrading and compromising nutritional significance [4]. Moreover, nanoemulsions enhance the delivery and stability of the flavor compounds in the food systems. Another significant application is in the development of nanosensors, which can detect contaminants and pathogens at very low concentrations. In smart packaging, these nanosensors enable the real time monitoring of the food products upon storage and transport, ensuring their continuous quality controls, thus boosting consumer trust in the product [5].

Although nanotechnology has brought significant advancements to the food industry, its integration is not without challenges (discussed in detail in Section 5). Due to their small size, NPs can penetrate biological barriers and accumulate in tissues, raising questions about toxicity, long-term exposure, and even biodegradability [6]. These safety concerns necessitate the development of rigorous testing protocols, comprehensive risk assessments, and regulatory frameworks to ensure the safe and responsible use of nanotechnology in food systems.

Overall, nanotechnology holds tremendous potential to revolutionize food production, processing, packaging, and safety by offering innovative solutions that can meet the growing demands for healthier, safer, and more sustainable food systems and products. Accelerated advancements in food nanotechnology are reshaping how food quality, safety, and shelf life are managed and monitored [7]. Simultaneously, consumer concerns about the transparency and safety of nanotechnology application in food are increasing, leading to the demand of cleaner labels and sustainable practices [8]. In this regard, the regulatory authorities such as EFSA and FDA are actively addressing the safety, labelling, and risk assessment of the nanomaterials in the food systems [9]. Thus, this review paper aims to provide a comprehensive overview of recent advancements in nanotechnology within the food industry in the context of food packaging and preservation, nanosensors for monitoring food quality and safety, nanoencapsulation for safe and targeted delivery of active compounds, and application of nanomaterials. Moreover, this article will also focus upon related products available in the market, government role, related challenges, and public perception.

Nanomaterials in Food Packaging and Preservation

Food packaging maintains the food quality and extends the shelf life by protecting it from any harm from its surroundings, in addition to providing product information to the consumer. One of the most significant advancements is the creation of nanocomposites, which incorporate NPs into the packaging to enhance their mechanical and barrier properties as shown in figure 2. These nanocomposites offer more strength, flexibility, and resistance towards external parameters like oxygen, moisture, and ultraviolet light, thereby significantly reducing spoilage [10]. Usually, ordinary polymers or biopolymers are impermeable to gases or water vapor and also show some drawbacks such as poor strength, and thermal, mechanical, and barrier properties, however, these drawbacks can be overcome by reinforcing the biopolymers with the different types of NPs which can act as nanofillers or by introducing nanocomposites [11]. These nanofillers could improve chemical and physical properties such as chemical stability, reactivity, mechanical strength, thermal stability, and barrier properties, along with providing antioxidative, antimicrobial, and biosensing properties. Furthermore, this innovative packaging integrated with antimicrobial nanomaterials for food products (such as fresh fruits, vegetables, meat, poultry, seafood, dairy products, and ready-to-eat meals) can lengthen their shelf life and thus decrease the amount of food waste.

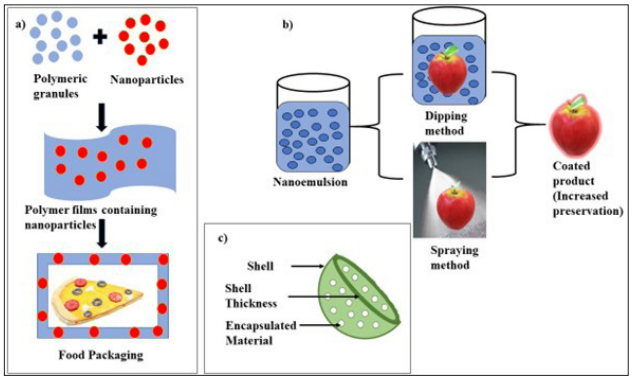

Figure 2: Role of nanotechnology in enhancing the shelf life and quality of food products by **(a)** incorporating NPs in the packaging, **(b)** coating the product with nanoemulsions, and **(c)** enclosing the key ingredients by nanoencapsulation.

Metal-based NPs

Various metal-based NPs commonly employed in food packaging include ZnO, silver (Ag), copper oxide, iron oxide, and nanoclays. Some of the applications of NPs are summarized in table 1. These mainly possess antimicrobial properties resulting in the safer storage of food products. The inhibitory effect of the NPs on microbial growth depends upon the degradation of the cell membrane and the production of free radicals which can induce oxidative stress. AgNPs among all metal NPs have attracted researchers due to their potential antimicrobial activity [26]. Badawy et al. [27] prepared the chitosan AgNPs to preserve minced meat, highlighting their suitability as antimicrobial agents. Similarly, AgNPs-coated cellulose paper enhanced the shelf life of tomato fruit by de-

Table 1: Application of NPs and nanocomposites in food products.

Film	Product	Characteristics	Key importance	Ref.
Chitosan/Zinc oxide (ZnO) nanocomposite	Meatballs	Nanocomposite showed a suppressing effect on the growth of Gram-negative bacteria. Chitosan-ZnO NPs 0.05% prolonged the shelf life beyond 24 h as indicated by the lower aerobic microbes (4.30 log CFU/g) than the consumption threshold (5 log CFU/g). However, the coating solution significantly affected the pH of the meatballs upon storage which lowered their sensory acceptance	Lowered the microbial count, thereby leading to enhancement in the shelf life of the meatballs	[12]
Chitosan/ZnO nanocomposite	Fresh pistachio	The developed nanocomposite significantly led to shelf life extension of the pistachios up to 35 and 40 days at the concentration of 250 and 500 mg/L of chitosan/ZnO coatings, respectively. Significant reduction in weight loss, aflatoxin content, hull browning, peroxide value, free fatty acids, polyphenol oxidase, and glutathione-peroxidase, and enhancement in their firmness, oil, protein, carbohydrates, antioxidant properties, anthocyanins, flavonoids, and sensory properties were observed	Improved shelf life, nutritional profile, and polyphenolic content of fresh pistachio	[13]
Chitosan/ ZnO nanocomposite	Freshly cut papaya	The developed nanocomposite film containing ZnO NPs possessed a slightly smooth and homogeneous surface over the papaya flesh. The coating restricted the microbial growth of both Gram-positive and Gram-negative bacteria below the safe threshold for consumption compared to the control sample	Restricted the microbial growth in freshly cut papaya	[14]
Chitosan coating modified with nanostructured ZnO	Strawberry	The coating maintained the freshness and appearance of the sample fruit even after eight days of storage. In addition, the microbial load was also found to be reduced	Reduced microbial growth and maintained freshness of strawberry	[15]
Chitosan film containing Kaolin clay and AgNPs	Fresh apple slice	The developed film increased the tensile strength to 24 MPa from 16 MPa and also showed better antioxidant and antibacterial properties and improved barrier towards extrinsic food spoilage parameters like light and moisture	Improved antioxidant and antibacterial properties	[16]
Nanosilver-incorporated carboxymethyl cellulose and guar gum coatings	Loquat (*Eriobotrya japonica* Lindl.)	AgNPs based coating showed an increase in ascorbic acid, total phenols, antioxidants, and titrable acidity, whereas weight loss, total sugars, and total soluble solids (TSS) were lowered	Increased polyphrnolic content and antioxidants	[17]
Chitosan-based Ag nanocomposite	-	The nanocomposite showed a maximum zone of inhibition (dia = 12.47 ± 0.26) at a concentration of 75 µl in *Streptococcus*, while at a lower concentration (25 µl), smallest zone of inhibition (dia = 10.27 ± 0.18) was observed for *Klebsiella pneumoniae*. It also showed inhibition against the fungal organism such as *Aspergillus niger, Aspergillus fumigatus* and *Fusarium oxysporum*	Reduced microbial content	[18]
Carrageenan and ZnO NPs-based nanocomposite	Mango	The coating of mangoes with nanocomposite showed antimicrobial properties against *Escherichia coli* and maintained the shelf life	Shelf life maintenance	[19]
Polyvinyl alcohol/agar/maltodextrin/AgNPs nanocomposite	Banana	The nanocomposite lowered the respiration rate, weight loss, TSS, and softening of the fruits and maintained their appearance compared to the control. It also showed excellent inhibition of bacterial growth	Inhibited bacterial growth	[20]
Nanocomposite containing bacterial cellulose and Ag	Orange and tomato	The developed nanocomposite showed excellent antibacterial and antifungal properties and retained the sensory attributes of the samples up to nine weeks even when stored at different temperatures	Antibacterial and antifungal properties	[21]
Agar films containing ZnO nanoparticles	Green grapes	Improvements in thermal stability, film thickness, and elongation, while a reduction in transparency and tensile strength were observed after loading the ZnO NPs into films. In addition, grapes stayed fresh for up to 14 and 21 days when packed in the films containing 2% (w/w) and 4% (w/w) NPs, respectively	Freshness of green apples was maintained	[22]
Essential oil and montmorillonite incorporated starch films	Fresh strawberries	The developed films showed better mechanical, antioxidant, and light barrier properties, which led to the shelf life extension of strawberries	Increased shelf life	[23]
Starch films containing nanoclay (montmorillonite) and starch nanocrystals	Strawberries	The films increased the tensile properties and decreased the water vapor transmission rate. This increased retention of the physicochemical properties, antioxidant properties, phenolic and anthocyanin contents, and reduced microbial content leading to enhanced shelf life of strawberries compound content control samples	Enhanced shelf life and phenolic content	[24]
LDPE nanocomposite containing titanium dioxide (TiO_2) and clay NPs	Pears	The sample packaged in the nanocomposite showed higher ascorbic acid and peroxidase content while lower ethylene production, sugar content, and polyphenol oxidase activity	Improved compositional attributes	[25]

laying microbial decomposition [28]. Iturin A, a lipopeptide, exhibits excellent antifungal activity and lower antibacterial activity, however, AgNPs exhibit antibacterial activities. Thus, Iturin was used to synthesize AgNPs (~30 nm) which possessed a wider antimicrobial spectrum [29]. Along with these benefits, nano-packaging food exhibits less refrigeration requirements and can stay fresh for a long duration. Nanoclay, a different type of nanomaterial used in packaging, is made of finely ground silicate minerals that occur naturally and have a layered, sheet-like shape with thicknesses of less than 100 nm [30]. Nanoclay provides viscosity which lowers the water absorption, improves rupture rate, enhances tensile strength, and offers good heat resistance properties, leading to shelf life extension.

Nanolaminates and biopolymer-based nanocomposite

Moreover, nanolaminates can be used as edible and non-edible coating and films as barriers against moisture and gases, which thus increases the food quality and can also act as carriers of functional compounds such as nutrients, antioxidants, colors, flavors, and antimicrobials. Nanolaminate layers can be formed over food surfaces either via layer-to-layer interfacial films of multiple nanolayers or differing material or by spraying the substance over the food surface. The composition of protein and polysaccharide-based films provide barriers against oxygen and carbon dioxide while lipid-based films provide moisture protection, and furthermore additives can be selectively added to improve functionality of the films [31]. It was discovered that utilization of thinner hybrid edible films (less than 100 μ thick) enhances protection against carbon dioxide, oxygen and moisture, and also improves the shelf life of the food items [32]. The use of alginate coated Ag-montmorillonite NPs on the surface of carrots and sequential packaging with polypropylene bags extended shelf life of carrots to 70 days compared to 4 days in usual uncovered carrots [33]. The addition of cellulose nanofibrils in edible films from mango puree greatly enhances their tensile strength and barrier properties. The incorporation of the nanofibrils increases Young's modulus and tensile strength by creating a well-packed, interpenetrating network within the film matrix. They also enhance the sinuosity of the film, making its path more resistant to gases and moisture, thus improving the barrier function [34]. Nanocellulose offers fine oxygen barrier properties, which extend shelf life for both fresh and processed food products. Hydrogen bonding between biopolymers such as starch and soy protein and nanocellulose is strong, enhancing water barrier and cohesiveness of films and rendering it more resistant and effective [35]. Nanolaminates and nanopackaging serve as a versatile and practical choice for enhancing food safety, shelf life, and nutrient delivery [36].

Migration and safety concerns

Some studies have reported the migration of NPs into foodstuffs, which makes their application more challenging in food packaging. This thus necessitates the application of NPs in optimal size and concentration for their low migration rates and high antimicrobial properties. In this regard, Anvar et al. [37] prepared the AgNPs in the optimum size (~50 nm) and examined their microbial activity and migration rate by varying the concentration from 1000 to 6000 ppm. The study concluded the significant decrease in microbial content in 5000 and 6000 ppm nanosilver packages with a negligible migration rate in the sample (Sturgeon caviar). Another important finding suggested that single metallic NPs cannot lead to the destruction of all pathogenic microorganisms, thus their combination can be more effective. For instance, a study used the three metal NPs as Ag, copper, and tungsten carbide in combination and found them to exhibit significantly higher antimicrobial properties against *Pseudomonas aeruginosa* and *S. aureus* than was used separately [38].

Therefore, the source and composition of nanomaterials critically influence their biological activity, functionality, and effectiveness in food applications due to variations in size, shape, surface charge, crystallinity, and surface chemistry. For example, biosynthesized NPs often have biomolecule coatings (proteins and phenolics) that enhance biocompatibility and stability, while chemically synthesized ones may exhibit higher reactivity but greater cytotoxicity. These physicochemical characteristics directly impact mechanisms such as cellular uptake, antimicrobial action (e.g., membrane disruption and ROS generation), and signal transduction in nanosensors. Overall, all the parameters such as type of NPs, their size and concentration, and their use either alone or in combination must be used in carefully examined for their use in food-related applications.

Nanosensors for Food Quality and Safety Monitoring

Nanosensors, another innovative application in intelligent or smart packaging systems, represent cutting-edge advancement in food quality and safety monitoring, leveraging the novel properties of nanomaterials to detect contaminants, pathogens, and spoilage indicators with unprecedented sensitivity and accuracy [5, 39-41]. Some of the nanosensors, material used, and their key findings along with possible application are listed in table 2. These nanosensors operate by detecting specific target analytes-such as pathogens, toxins, allergens, or chemical residues-through selective interaction with recognition elements like antibodies, aptamers, enzymes, or functionalized NPs (Figure 3). This recognition elements bind specifically to the analyte present in the food sample, triggering a physicochemical change [39]. This interaction is then converted into a measurable signal through a transduction mechanism, such as a change in fluorescence intensity, electrical conductivity, or refractive index. The transduced signal is amplified and processed using integrated electronics or optical systems, ultimately producing a clear, quantifiable output display. This enables rapid, sensitive, and often real-time detection of food contaminants, contributing to improved food safety and quality control.

The nanosensors provide the real time and on time monitoring of the food products [5]. This real-time monitoring capability thus helps maintain the food quality and provides consumers with clear information on the freshness of the products they purchase. Furthermore, nanotechnology has en-

Table 2: Nanosensors and their application in the food sector.

Nanosensors	Material used/synthesis method	Key features/findings	Application	Ref.
ZnO NPs as nanosensor	NPs were synthesized using aqueous leaf extract of the *Phragmanthera austroarabica*	Possessed excellent sensitivity for chromium detection. Exhibited antioxidant activity. Showed strong catalytic degradation of dyes	Can be employed as an antioxidant, environmental sensor for detecting harmful substances, and as nanocatalyst for degrading toxic dyes	[42]
GA-AuNP@ Tollens complex	Gallic acid (GA) and gold NPs	Elective detection of formaldehyde and benzaldehyde using plasmonic response	Can be employed for detecting formaldehyde and benzaldehyde in preserved food products	[43]
Plasmonic nano sensor	AgNPs developed using *Elsholtzia blanda* Benth. Flower extract	Plasmonic nano sensor detected the thiocyanates with high selectivity	Detection of thiocyanate in milk samples which is used to activate natural lactoperoxidase activity	[44]
Nonadiabatic tapered optical fiber sensor	AgNPs	AgNPs interacted with *E. coli* by anchoring to or penetrating its cell wall, causing changes in the refractive index detected by the sensor. Biosensor being rapid, measured bacterial inhibition, depicting results similar to traditional methods	Can be employed as an alternative to traditional colony counting for assessing antimicrobial activity	[45]
Fluorescent nanosensors	AgNPs	The method showed strong sensitivity, antimicrobial activity, and eco-friendliness, validated under ICHQ2 (R2) guidelines	Useful for drug detection in pharmaceutical and biological samples	[46]
Gold nanosensor	Nanorods modified with sulfhydryl compound linked with fluorescent dye	sensor showed strong antibacterial activity through combined fluorescence response and photothermal effects	Can be employed for the detection of *E. coli* in food samples like milk, meat, and eggshells	[47]

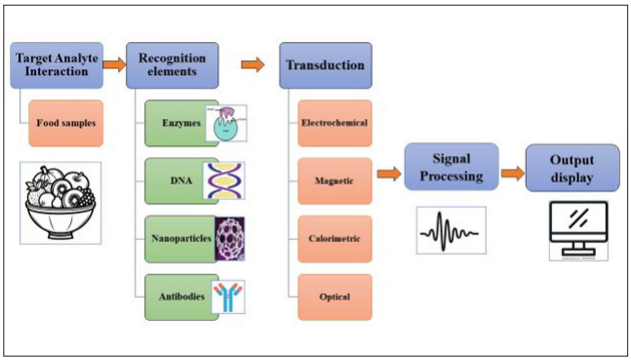

Figure 3: Mechanism of nanosensors.

abled the creation of active packaging that can interact with the food to release preservatives or absorb unwanted substances. For example, packaging materials incorporating nano-encapsulated preservatives can release these substances slowly over time, providing extended protection against spoilage. Essential garlic oil encapsulated in a chitosan film-embedded nanoliposome based on soybean phosphatidylcholine and cholesterol demonstrated antibacterial action and delayed lipid oxidation [40]. Similarly, nanomaterials can be used to create packaging that absorbs ethylene, a ripening agent emitted by fruits and vegetables, thereby slowing down the ripening process and prolonging freshness [41].

Recent developments in nanosensor technology have focused on enhancing their specificity, sensitivity, and integration into food packaging and processing environments. One significant breakthrough is the development of nanosensors based on metal NPs, such as gold and Ag, which exhibit exceptional optical properties used in Surface-enhanced Raman spectroscopy (SERS) [48]. These SERS-based nanosensors can detect trace amounts of chemical contaminants and pathogens by amplifying the Raman signal of the molecules of interest [49]. Additionally, graphene and carbon nanotubes, have been employed to create highly sensitive electrochemical nanosensors which can detect minute changes in electrical signals when they interact with specific foodborne pathogens or toxins, enabling early and accurate detection [50]. Some compounds like vitamins and minerals which can degrade easily upon processing, storage, and transportation can be easily detected by the use of nanosensors. Single/multi-walled carbon nanotubes with ionic liquid nanocomposites can be used for sensing folic acids, amino acids, ascorbic acid, and tryptophan [51]. Similarly, nickel oxide NPs can sense ascorbic acid. Furthermore, maturity level and ripening of the fruits and even the detection of aflatoxin can be detected with nanosensors [52, 53]. However, despite these advantages, the widespread adoption of nanosensors is facing challenges like high production cost, scalability, regulatory approval, and public acceptance.

Nanoencapsulation in Food Processing

Another advancement in the field of food nanotechnology is nanoencapsulation, which involves encasing bioactive compounds, nutrients, and additives within nanoscale materials (Figure 2) to enhance their stability, bioavailability, and controlled release. Nanoencapsulationn of the compounds is more critical compared to the microencapsulation. The various ways of encapsulation such as nanoemulsion (Figure 2), liposomes, and nanocapsules can be achieved by any of three approaches: top-down (high-energy methods like spray drying and ultrasonication), bottom-up (low-energy methods like precipitation and self-assembly), and hybrid techniques. Some of the natural biopolymers like proteins (albumin, collagen,

lactalbumin, gelatin) and saccharides (chitosan, starch, alginate) are used as delivery systems. Various nanoencapsulation methods include ultrasonication, high-pressure homogenization, microfluidization, nano-fluidics, nano-spray drying, electrospinning, and electrospraying.

Nanoencapsulation prevents the degradation of the encapsulated compound from the effect of external stimuli such as temperature, pH, salts, and acids. Ingredients like ω-3 polyunsaturated fatty acids (PUFA), for example, are highly nutritious and vital to our bodies, however, their consumption in purified form reduces their efficacy due to their susceptibility to oxidative degradation. Nanotechnology methods thus can be used to stabilize and shield ω-3 PUFA from unfavorable oxidative reactions [54]. Through material coating, inorganic compounds in their nanostructure form, such as TiO_2 (E171), magnesium oxide (E530), and silicon dioxide (E551) can also be employed as moisture and oxygen barriers [55]. To create nanoencapsulated powders, green tea extract NPs were encased in maltodextrin and freeze-dried [56]. For the various ratios of 30% maltodextrin solution and dry tea extract (1:5; 1:10, 1:15), the encapsulation efficiency increased from 41.27, 45.92, and 57.51%. Furthermore, when compared to free green tea extract, these nanocapsules demonstrated regulated release that was delayed under intestinal simulation environments. Similarly, polyphenols such as catechin, epicatechin, and proanthocyanidin were encapsulated into the tapioca starch NPs. These showed low cytotoxicity and improved scavenging activity [57]. Polyphenols-rich extracts from *Bauhinia forficata* were nanoencapsulated by spray drying in maltodextrin and colloidal silicon dioxide. These nanocapsules showed higher thermal stability and *in vitro* bioaccessibility with high antioxidant activity ranging from 52.27% - 70.55% [58]. Apart from these compounds, the protection of the vitamins is also very crucial to prevent them from degradation from the external environment and increase bioaccessibility. Lipid nanocapsules and nanostructured lipid carriers (NLCs) loaded with vitamin E showed encapsulation efficiencies of 99% and 95%, respectively, in this regard and protected it from degradation from the acidic environment [59]. Vitamins such as B_9 and B_{12} co-encapsulated in poly(lactic-co-glycolic) acid (PLGA) NPs showed encapsulation efficiency of 89% and 71%, respectively [60]. In addition, the developed NPs also possessed stability for at least 8 weeks at room temperature and showed improved bioavailability and bioaccessibility of the vitamins. In another study, Vitamin D_3 was nanoencapsulated in zein polymeric matrices to improve its physicochemical stability and availability. Acca sellowiana was fortified with the developed the nanoencapsulated vitamin D3, which then showed high content of bioactive compounds (phenolic and flavonoids) with antioxidant capacity [61]. To increase its physicochemical stability and availability, vitamin D3 was nanoencapsulated in zein polymeric matrices. When *Acca sellowiana* was supplemented with the newly created nanoencapsulated vitamin D3, it revealed a high concentration of bioactive substances with antioxidant potentials, such as flavonoids and phenolic compounds [61]. Nanoencapsulation provides the opportunities for rigorous delivery of multiple functional bioactives like lycopene, ascorbic acid, citric acid, omega-3 and omega-6 fatty acids, lutein etc., in nano-capsules where nano-carriers resist heat destruction and the occurrence of undesirable flavors and odors [62]. They not only improve bioavailability and bioaccessibility but also increase oxidative stability, retain volatile compounds and elevate sensory characteristics [63]. Nanocapsules regulate the storage of food and controlled supply of desirable compounds, which are translocated through the digestive tract, hence enhancing bioavailability in the body [64] and covers undesirable flavor or taste and encourages improved dispersal of insoluble additives with no use emulsifiers [65]. Nano-liposomes aid in targeted delivery of bioactive compounds including minerals, nutraceuticals, enzymes, antimicrobials, vitamins, and additives [31, 63]. Nanostructured proteins, with their regular primary structure and reactive amino groups, possess strong capacity to create nanocomplexes and deliver bioactive substances, increasing bioaccessibility and bioavailability. Their amphiphilic character and large surface area facilitate efficient interaction with bioactive constituents, allowing enhanced solubility and stability of incorporated nutrients during digestion. This leads to improved absorption and site-specific delivery of compounds in the gastrointestinal tract [62, 66].

Most significant advancements in this field are the application of biopolymer-based nanocarriers, such as chitosan, alginate, and proteins. These can prevent the compounds from degradation from external stimuli. Novasol, a nanocarrier developed by Aquanova for encapsulating vitamins C and E and fatty acids [67]. Aquanova and Zyme are providing omega 3 in 30 - 40 nm nanocapsules, which are 4000 times smaller than the existing products available on the market [68]. Likewise, one of BioDelivery Sciences International's products, Bioral-TM nanocochleate, is an effective way to deliver nutrients [69]. It consists of a soybean-derived phosphatidylserine carrier, approximately 50 nm in size. This technique is employed not only for delivery but also for safeguarding antioxidants and micronutrients from deterioration during production and storage. Further, Aquanova makes claims about enhanced pH and heat stability of encapsulated functional chemicals and standardized additive doses [70]. Some of the applications of nanoencapsulated compounds and materials are listed in table 3.

Another noteworthy finding is using liposomes; spherical vesicles made of phospholipid bilayers. They offer a variety of alternatives for delivering a broad range of nutrients and bioactive substances because they may encapsulate both hydrophilic and hydrophobic molecules. The regulated release of active components at specific places in the gastrointestinal tract using nanoencapsulation extends the retention period [79]. However, nanotechnology makes it simple to solubilize lipophilic substances like carotenoids, phytosterols, and antioxidants in water. In this regard, NLCs can more effectively encapsulate and protect sensitive compounds than conventional lipid carriers [80]. The encapsulation of probiotics using nanotechnology has also emerged as a crucial area of research [81]. This can protect probiotic bacteria from harsh environmental conditions of the stomach, ensuring their viability and effective colonization in the gut.

Table 3: Application of nanoencapsulation in the food sector.

Nanoencapsulated compound	Type of nanoencapsulation	Key features/ findings	Possible applications	Ref.
Tocopherol	Nanoemulsion	Retarded oxidative degradation of fatty acids and maintained the color in fish sausages	Food preservation	[71]
Quinoa peptide-loaded nanoliposomes	Nanoliposomes	Improved the antimicrobial and antioxidant activity of the burgers	Food preservation	[72]
Grape and apple pomace phenolic extract	Chitosan and soy protein isolate nanocapsules	Provided a protective environment for the loaded polyphenols. Polyphenols were kinetically released from the nanocapsules	Food preservation	[73]
Phenolic compounds of jaboticaba peel	Nanoemulsion	15% of jaboticaba extract showed excellent encapsulation efficiency (85.6%) and possessed stability for 60 days at 8 °C	Food enrichment	[74]
Native potato phenolic extracts	Spray-drying nanoencapsulation	Enhanced encapsulation yield and efficiency, antioxidant capacity, total phenolic compounds, and flavonoids. Minimized hygroscopicity, water activity, and moisture	Food preservative	[75]
Co-loaded GA and quercetin (Qu)	nanoliposomes	GA-loaded nanoliposomes showed higher encapsulation efficiency and improved cytotoxicity, especially against lung cancer cells. Loading GA and Qu into nanoliposomes significantly boosted antibacterial activity against Gram-positive bacteria	Can be employed for potential pharmacological activity and enhanced cancer therapy	[76]
Phenolic acids and flavonoids of blueberry leaves	Nanoemulsions	High dose nanoemulsion boosted brain dopamine and liver antioxidant enzyme activity in mice. Demonstrated potential as a neuroprotective and antioxidant-rich health food	Antiaging effect	[77]
Co-encapsulation of vitamin D3 and *Cordia myxa* fruit peel extract	Nanoemulsion	Encapsulated nanoemulsions of Cordia myxa peel extract and vitamin D3 showed enhanced antioxidant (49.25–55.7 mg/100g) and antimicrobial activity, especially against *E. coli.* Gas chromatography-mass spectrometry analysis identified key bioactive like pyrocatechol and cholestanoids, with highest cytotoxicity. Encapsulation improved stability, controlled release, and bioavailability	Can be employed for functional foods and therapeutic applications	[78]

A variety of substances, including beta-carotene, phytosterols, and lycopene, are combined with nano-carriers to produce nutritious food items, mostly to stop cholesterol from building up in our bodies [82]. To conceal the taste and odor of tuna fish oil and to transfer it directly to the stomach, nanocapsules have been produced [83]. Thus, the nanoencapsulation technology has found significant attention and usage in the various food industries specifically in the fields of preservation, safety, supplementation, drug/nutraceutical delivery, bioaccessibility, and bioavailability. However, further implications and global support via regulations are required to understand and improve the safety and toxicity of the nanomaterials.

Challenges

Despite these advancements, the use of nanomaterials in food packaging and preservation raises several challenges and concerns. Safety and regulatory issues are paramount, as the potential health effects of NPs migrating into food are not yet fully understood. NPs, due to their extremely small size (typically 1 - 100 nm), exhibit unique physicochemical properties that differ from their bulk counterparts. While these properties offer exciting possibilities across various industries, they also raise significant safety concerns regarding potential health and environmental impacts (Figure 4). Exposure to NPs can occur through inhalation, ingestion, and dermal contact, and their small size facilitates penetration of cellular membranes and translocation to various organs, including the lungs, brain, liver, spleen, and even the fetus [84].

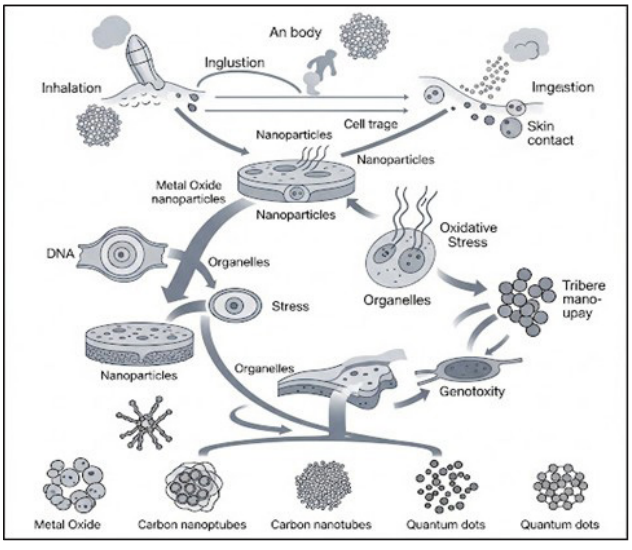

Figure 4: Toxicity and health impact of NPs.

Inhalation remains a primary concern, as airborne NPs

can induce pulmonary inflammation, fibrosis, and, in some cases, exhibit carcinogenic effects akin to asbestos or silica, as seen with carbon nanotubes and TiO_2 NPs, which have a higher mass-based potency than larger particles. These inhaled particles can also translocate into the bloodstream, leading to systemic effects, and may exacerbate pre-existing respiratory conditions. Beyond direct organ damage, a significant body of recent research continues to confirm that many NPs can generate reactive oxygen species (ROS) (Figure 4), leading to oxidative stress, inflammation, and damage to cellular components and DNA [85]. Emerging research is also exploring strategies to mitigate negative side effects associated with intravenously injected NPs in medical applications, such as immune system activation, by employing complement inhibitors.

The environmental implications of increasing nanoparticle production and release are equally significant. NPs can negatively impact diverse ecosystems and organisms. For instance, recent studies highlight increased cytotoxicity and oxidative stress in aquatic organisms due to metal-based NPs exposure. Furthermore, the accumulation of certain NPs in soil can reduce plant photosynthesis and transpiration rates, while also disrupting biological structures in organs like the kidney, heart, and liver of various organisms. Concerns persist regarding the potential for bioaccumulation and biomagnification of NPs within food chains [86].

Regulatory bodies are working to establish comprehensive guidelines to ensure the safe use of nanomaterials in food packaging (discussed in Section 6). By improving the efficiency and effectiveness of packaging, nanotechnology can contribute significantly to reducing food waste, enhancing food safety, and meeting the growing demand for sustainable food systems. But for the time being, the ability of the food industry to continue growing and advance toward commercialization is its biggest obstacle [87]. The cost economics pose a significant challenge in large scale adoption of the same [88]. Before any technology or product is introduced to the market, it is the result of numerous studies conducted by knowledgeable researchers. The development of nano-based technological features to be integrated with food like nano-encapsulated nutrients, nano-coatings etc., involve high investment costs for research and development and for involving the pioneering technology. Its limited expansion has led to a hike in the per-unit production costs making it expensive for both the manufacturers and consumers [89]. Moreover, brands have to invest extensively in detailed toxicological studies and safety assessments to meet the compliance standards issued by Food Safety and Standards Authority of India (FSSAI), Department of Biotechnology (DBT), and Ministry of Environment, Forest and Climate Change (MoEFCC). Since the regulations are still evolving for the use of nanomaterials in the food and agricultural industry, the companies aiming for global markets face additional obstructions in meeting un-harmonized standards of different countries and have to bear the extra expenses to meet the country-specific needs [90]. Moreover, there is a lack of bridge between the advanced technology and the accessibility of consumers to benefit from such innovations considerably due to higher costs. Further escalation in the logistical costs can be attributed to the poor infrastructural facilities and their restraints such as pilot-scale nanotech facilities, low access to nano-grade resources and the need of cold chain logistics for sensitive formulations [91].

Apart from this, the possible damage to the environment and the health of consumers is the other significant difficulty this industry faces. The main concerns with NPs or nanomaterials are about the health risks and increased exposure at each stage of consumption (digestion and intestinal tract absorption), as well as the effects and likelihood of their accumulation in the body. Numerous studies have examined the safety and toxicological implications of NPs [92]. NPs face major alterations and pose toxic interactions based on their physicochemical properties [93, 94]. Nanotoxicity is mainly caused by an overproduction of ROS, triggering oxidative stress that impairs proper cellular function causing DNA damage, abnormal cell signaling, cytotoxicity, apoptosis, and even cancer. NPs in food packaging like Ag and ZnO can leach into foods. Ag ions, for example, have leached into meat juices and orange juices, speeding up ascorbic acid degradation [95]. Furthermore, AgNPs incorporated starch-poly (adipate co-terephthalate butyl) migrated to the chicken sample, and the migration values exceeded the EFSA permissible limit [96]. These NPs tend to make easier interaction with cell organelles through improved permeability into cells causing cell destruction [97]. Substantial organ dispersal across blood, liver, spleen, testis, brain, heart, lungs etc., was observed by 10 nm gold nanoparticles while bigger NPs were only to be screened in blood, liver, spleen. Moreover, a higher tissue distribution causing hepatobiliary toxicity was attributed to 10 nm AgNPs than 40 and 100 nm ones [98]. Mobility of NPs in various organs can even lead to cancers, swelling and organ failure, protein denaturation and asthmatics attacks, etc. [99]. Bigger agglomerates of 17 nm TiO_2 produced more powerful toxicity reactions and DNA damage in monocytic cell lines than smaller agglomerates [100].

Apart from size, their shapes (spheres, ellipsoids, cylinders, sheets, cubes and rods) have evident effects on the toxicity [101]. Non-spherical ones penetrate through the cell membranes at a higher rate and quantity, aiding longer blood circulation and organ accumulation, compared to spherical ones [102]. Surface chemistry and chemical composition pose as other factors in their toxicological effects. For instance, negative zeta potential in NPs is less potent to cause toxicity [103, 104]. Different overlay materials like polylactic acid, polyethylene glycol, PLGA and others are generally used to alter the physicochemical properties metal-based nanoparticles [105, 106]. The NPs with similar chemical composition and different surface alteration exhibit differing intensities of pharmacokinetics and biodistribution of NPs [107].

Further, nanoclay being highly reactive because of its larger surface area raises concerns about the possibility of forming more toxic particles upon their use or production [108]. The migration of nanoclay and nano silica from LDPE composite to the food stimulants (distilled water, 3% acetic acid, and 95% ethanol) was found more in 95% ethanol than 3% acetic acid when examined upon 10 days storage period at 40 °C. Thus, highlighting the likelihood of migration of NPs to the high

fatty acid food items was higher as compared to the aqueous ones [109]. Furthermore, the emergence of new processing technologies like high-pressure, pulsed electric fields, and advanced heating can affect the potential release of montmorillonite [11].

Thus, apart from the encouraging benefits of nutrient delivery and improved food safety, the suitability of nanotechnology processed food products is a crucial concern because of the potential health hazards caused by the uptake of NPs. The potential effects are more observed in consumers with poor immunity and compromised detoxification systems, like infants and the old-aged. Infants or even young children are at a higher risk due to their underdeveloped gastrointestinal systems, potentially resulting in increased absorption of NPs and long-term health implications. Alongside, there is an increased rate of nanoparticle accumulation due to weakened organ function in the elderly, yielding gastrointestinal inflammation and organ toxicity [110]. In spite of the fact that nano-processed food helps counteract diseases like diabetes or obesity, their intracellular exchange remains unpredictable. Until thorough long-term toxicological evaluations are carried out, particularly stratified according to age groups, prudence is necessary. This involves observing dosage levels, types of NPs, and their performance in biological systems. Policy makers and researchers need to work together to put in place strict regulatory systems, open labeling, and strict safety testing before widely accepting nanotech-processed foods as safe across all age groups [63].

Regulatory Aspects of Nanomaterials in Food Products

Nanomaterials have brought a revolutionary change in the fields of agriculture and food industry. While their toxicity in the use is still prevalent, the majority of developed countries have regulatory control for them unlike developing countries. It is highly crucial to address the toxic effects of nanomaterials for their safe use and to minimize the risks on health and environment globally [111]. The U.S. FDA regulates nanomaterials in food contact substances under the Federal Food, Drug, and Cosmetic Act, requiring premarket notifications and safety assessments. Similarly, the EFSA has issued specific guidelines for risk assessment of engineered nanomaterials intended for use in food and feed, emphasizing the need for toxicological and physicochemical characterization. Additionally, the Codex Alimentarius Commission, established by the Food and Agriculture Organization and World Health Organization, has acknowledged the need for international harmonization of nanotechnology safety standards, particularly in the context of food additives and packaging. These global frameworks complement national regulations and foster cross-border safety assurance. The US Branch of Agriculture, in 2003, first proposed the applications of nanotechnology in the food and farming enterprises. With time, enough needed attention has been portrayed towards the assessment gatherings to address their regulations and guidelines, where a few models discussed such as - Nano Forum, Asia Nano Forum, and World Nano Conference [112].

With time, enough needed attention has been portrayed towards the assessment gatherings to address their regulations and guidelines, where a few models discussed such as - Nano Forum, Asia Nano Forum, and World Nano Conference [113, 114]. Regulatory acts in India regarding the use of nanomaterials in food and agricultural industries are concerned with ensuring support and yielding legal assurance in response to public raised concerns for their safety and status. As of 2015, the insecticides (Amendment) Bill introduced in Lok Sabha aided to regulate the registration of nano-insecticides, necessitating the in-depth examination and reporting of their potential risks to the health of humans and their effects on environment if any. To further reinforce the regulations, the Department of Science and Technology released a detailed document in 2016 mentioning good practices for safe handling, utilization and disposal of engineered nanomaterials in food sector in research and applications, as per the review from global agencies of International Organization for Standardization, Organization for Economic Co-operation and Development, National Institute for Occupational Safety and Health (USA), and Occupational Safety and Health Administration [112, 114].

Other agencies and legislative frameworks that governs such regulations in India are MoEFCC, FSSAI, and Indian Council of Agricultural Research (ICAR). Few laws and safety measures concerning the nanotechnology based agri-products in India as per dbtindia.gov.in are The Environment (Protection) Act, 1986 that authorizes MoEFCC for surveillance of production, utilization and handling of potential poisonous substances, including nanomaterials. The Hazardous Waste (Management, Handling, and Transboundary Movement) Rules, 2016 affirm the dispatch, disposal and management of hazardous waste safely, including nanomaterials. The Food safety and Standards Act, 2006 allows FSSAI to regulate food safety and has provided specific guidelines for the usage of nanotechnology in food. Coupled with other derivatives by Department of Biotechnology (2017) and ICAR (2010), these acts make up an evolving but disjointed framework, emphasizing the necessity of an integrated and more cohesive regulatory system in order to provide assurance for the safe application of nanotechnology in food and agriculture [115].

Public Perception

The commercial success of several industries is largely determined by public perception of the many applications of nanotechnologies. This also holds for its use in the food sector. As a result, when it comes to the meals and drinks they consume, consumer opinions are extremely sensitive. The public forms multiple opinions, both positive and negative, as a result of the knowledge gaps. The majority of these gaps are in consumer and environmental safety as well as application knowledge. These gaps are preventing market updates and regulations, necessitating additional study. The acceptability of nanotechnology uses in food is also influenced by trust, specifically confidence in food scientists, consumer organizations, and the food business and merchants. There are knowledge gaps in science as a result of the absence of a standard definition for nanomaterials and nanotechnologies. There are currently initiatives in place to establish a universally understood, more inclusive international definition.

To assess the present levels of knowledge and attitude of general Austrian public toward nanotechnology, as well as the potential effects of various sociodemographic characteristics, Joubert et al. [116] undertook an online survey utilizing a Citizen Science-guided Approach. A total of 1067 responses were gathered and subjected to quantitative analysis over 17 months. Although Austrians have a generally good attitude and hopeful perspective of nanotechnology, there are still unanswered questions regarding its safety and potential hazards. The participants indicated a strong desire for clear labeling and transparency of items containing NPs. Compared to females, males scored higher and showed more positive attitudes. However, female participants showed a stronger desire to know the field with greater transparency. It is interesting to note that individuals who had a bad attitude toward the nanotechnology field scored the lowest on the quiz and showed the least desire to learn more about it. People could therefore get an incorrect impression about nanotechnology if they lack clear facts. Being well-received by customers is crucial to utilizing this as one of the difficulties concerns at the greatest level first. To provide the public with accurate information, the media continues to play a crucial role as primary sources. It includes recognizing the advantages and disadvantages of using nanotechnology in culinary applications. The goal is to enlighten audiences about this technology and to let them know that while the benefits outweigh the risks, the risks are also acceptable. The media can have a significant impact on how people perceive emerging topics like food nanotechnology and the mental associations that form the basis of public opinion.

Thus, consumer preferences for adopting the newly integrated nanotechnology into the Food and Agro Industry can be challenging, especially for bringing the shift from traditional to innovative nano-based processed food products [117]. The prospective customer can be doubtful about acquiring nanotechnology due to unattended concerns about NPs and hesitation about possible health and environmental effects. Proactively addressing the concerns for the same by providing detailed technical assistance and support builds trust and credibility encourages better adoption of the applications of nanomaterial-based sensors into the food industry [118]. Streamlining the production process and launching an effective partnership with logistic workers reduces the high cost per consumption of the products and expands market reach [119]. Active packaging solutions that release beneficial active NPs or retract the undesirable ones strike a great influence on the shelf of the respective food products. Smart tracking and monitoring of interactions of several pesticides and food material due to the photocatalytic interactions during storage is a striking feature of Smart packaging nanosensors [62]. There is a significant rise in market demand with increasing unification of nanomaterials in goods for advanced and improved quality products. As per Joubert et al. [116], especially in the Food and Agro-product Sectors, the consumer preferences and needs are pushing the adaptation and scalability of nanotechnology, which is no longer an infancy to consumers.

Overall, public perception is still underwhelming for two major reasons- skepticism for health effects and unawareness, which makes it a necessity to bring transparency and widen the need for detailed support and marketing to make consumers informed and aware of this new age technology, which will encourage innovations and new products in the market. According to Lyu et al. [120], AgNPs have excellent antimicrobial characteristics that make their use essential in food packaging, but the pre-existing notions of health concerns alteration in gut health and disruptions in neurobehavior can pose challenges in consumer preferences. Access to information not only brings transparency but also makes consumers conscious and more questionable about the choices they make and the long-term effects of proximity to nanomaterials, essentially through ingestion. The global market reflects robust investments into research and development of this technology into functional food industries [68]. As highlighted by Kuang et al. [121], when presented with products like cherry tomatoes and chocolate ice creams, consumers preferred the ones with nanotechnology processing that has added benefits of probiotics and freshness, despite low awareness, preferring them in the packaging than in the product. These findings point to a cautious optimism trend-consumers embrace nanotechnology if it enhances quality and safety but expect openness and clear communication about its application.

Conclusion

The application of nanotechnology in the food sector is undergoing remarkable advancements, driven by innovative trends poised to significantly enhance food safety and quality. A prominent trend involves the development of smart nano-based delivery systems, capable of real-time monitoring of food product status during storage and transportation, and even autonomously initiating necessary actions, such as controlled release of antimicrobials or antioxidants. Concurrently, the utilization of nano sensors for real-time monitoring of food quality and safety is rapidly evolving, enabling precise and rapid detection of pathogens, toxins, and spoilage markers throughout the food supply chain, including advancements in multiplex nanosensors and integration with internet of things. Furthermore, the application of nanoencapsulation technologies for food fortification is advancing, enhancing the stability, solubility, and bioavailability of essential nutrients and bioactives in functional foods and dietary supplements. Beyond these, future research opportunities extend to developing advanced nano-enabled packaging with improved barrier properties and active antimicrobial functions, exploring the safe and effective use of nanofertilizers and nanopesticides for sustainable agriculture to reduce chemical usage and environmental impact, and investigating the full potential of NPs in preventing biofilm formation on food contact surfaces. Despite this promising potential, the integration of nanomaterials in the Agro-Food Sector faces ongoing challenges related to achieving comprehensive regulatory approval, fostering greater consumer acceptance through transparent communication, and ensuring robust environmental safety assessments. Continued research into long-term safety profiles, the establishment of harmonized global regulatory frameworks, and proactive public engagement are essential to address these challenges and fully harness the transformative benefits of nanotechnology for a safer, more sustainable, and higher-quality food supply.

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None.

Conflict of Interest

None.

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