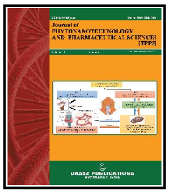
Journal of Phytonanotechnology and Pharmaceutical Sciences 3(4): 15-23, 2023

Online ISSN:2583-0376

http://jpps.ukaazpublications.com

DOI: http://dx.doi.org/10.54085/jpps.2023.3.4.3

Journal of Phytonanotechnology and Pharmaceutical Sciences



Review Article : Open Access

Comprehending fundamental concepts and applications of nanotechnology in food processing: Current overview and future perspectives

Manvik Joshi and Kamalesh Kumar Meena*◆

Department of Dairy and Food Chemistry, Maharana Pratap University of Agriculture and Technology, Udaipur-313001, Rajasthan, India
**Department of Dairy and Food Microbiology, Maharana Pratap University of Agriculture and Technology, Udaipur-313001, Rajasthan, India*

Article Info

Article history
Received 5 November 2023
Revised 14 December 2023
Accepted 15 December 2023
Published Online 30 December 2023

Keywords
Nanotechnology
Nanomaterials
Food packaging
Food safety
Food quality

Abstract

Nanotechnology is undoubtedly a cutting-edge multidisciplinary approach. It has revolutionized the world of the food industry by advancing organic materials and manipulating them on a molecular scale. With the help of nanomaterials, it plays a pivotal role in enhancing food safety by detecting pathogens and toxins, and providing insights into nutritional content. Its application in food packaging holds the potential to revolutionize food safety, quality, and shelf-life extension. However, limited customer acceptance persists due to ethical concerns and insufficient information. Raising awareness about the potential uses and benefits of nanotechnology in both industry and consumer health is crucial. Regulatory measures by government food administration departments are essential to ensure the correct and safe commercialization of nanofoods. Further research is needed to develop safer methods for incorporating nanotechnology into the food industry, addressing concerns and ensuring responsible use.

1. Introduction

With advancement in knowledge, various new technologies have emerged which are helpful for food processing. The evolution of a number of new scientific fields and technologies has revolutionized the food industry during the last few decades. Nanotechnology is a novel, multidisciplinary approach that entails the progress of organic materials, as well as the conversion of these materials on molecular size. It involves the examination and control of matter at molecular levels. This technique produce nanomaterials with altered physico-chemical and biological properties (Francisco and García-estepa, 2018). When particle size is reduced to nanometer, the resultant develops physicochemical properties that differ greatly from the features of macroscale materials composed of the same ingredient (Chellaram *et al.*, 2014). In modern scenario, nanotechnology plays a crucial role in improving the safety of food products by facilitating the detection of pathogens and toxins, as well as offering insights into nutritional status. The application of nanotechnology in food packaging has the potential to revolutionize the packaging of food items. Consequently, the promising applications of nanotechnology in food packaging have the capability to elevate food safety, quality, and prolong the shelf-life of food products (Rajamalar *et al.*, 2011).

Thus, nanotechnology is an advancement in technology with incredible potential various sectors of the food industry. This review highlights the significant impact of nanotechnology on the food industry, emphasizing its role in safety, quality monitoring, and packaging efficiency. Nanotechnology in food packaging holds immense potential for enhancing safety, quality, and shelf-life. Additionally, its incorporation into nutritional supplements improves drug delivery and offers a range of nutraceuticals. Despite challenges like limited customer acceptance, addressing ethical concerns and raising awareness is crucial. Ongoing research has transformative potential, necessitating regulatory measures for safe commercialization. While concerns about nanoparticle-cell interactions exist, recognizing nanotechnology's vast potential in the food sector is essential. Further research is needed for safer integration methods and exploration of its advantages in nutritional content, packaging, and sensing capabilities.

Corresponding author: Dr. Kamalesh Kumar Meena,
Assistant Professor, Department of Dairy and Food Microbiology, College of Dairy and Food Technology, MPUAT, Udaipur-313001, Rajasthan, India
E-mail: kamleshrj14@gmail.com
Tel.: +91-9680184316

2. Nanomaterials

Various types of nanoparticles are used in the food business for a variety of applications. Nanomaterials have different properties than their macro counterparts. They behave as cohesive units in terms of transport and qualities, are classified according to their properties, size, and structures (Sahoo *et al.*, 2007). The area of nanomaterials approaches nanotechnology from a materials science perspective, researching the properties of materials at the nanoscale and creating them in novel ways. Nanoparticles emerge as a result of processing methods like homogenization and milling. Additionally, there is a possibility that ingredients may spontaneously self-assemble into structures such as micelles and nanofibers. This phenomenon brings innovations in structural, physical and chemical properties. Apart from this, these nanaoparticles also provides better shelf life of food product. Consequently, nanotechnology has the capacity to revolutionize the food processing industries and positively influence the field of food science (Biswas *et al.*, 2022).

3. Types of nanomaterials

Some foods include nanoscale elements distinct from artificially manufactured nanomaterials. Within the realm of food, notable nanomaterials consist of biopolymeric nanoparticles, which can be classified in the following forms:

(i) Nanoparticles (size: 20-200 nm): Composed of biodegradable polymers for antioxidant release. (ii) Liposomes (size: 100-400 nm): Small sized, spherical synthetic vesicles mainly composed of lipid bilayers. (iii) Micelles (size: 10-100 nm): Self-assembling particles amphiphilic in nature which can encapsulate lipophilic as well as lipophobic substances. (iv) Nanocapsules (size: 10-1000 nm): Encapsulate nucleic acids, like DNA, microRNA, and siRNA. (v) Nanoconjugates: Polymers covalently bonded with medicinal molecules. (vi) Dendrimers (size: 3-20 nm): Monodisperse macromolecules that can encapsulate medications and targeting moieties (Mohammad *et al.*, 2022).

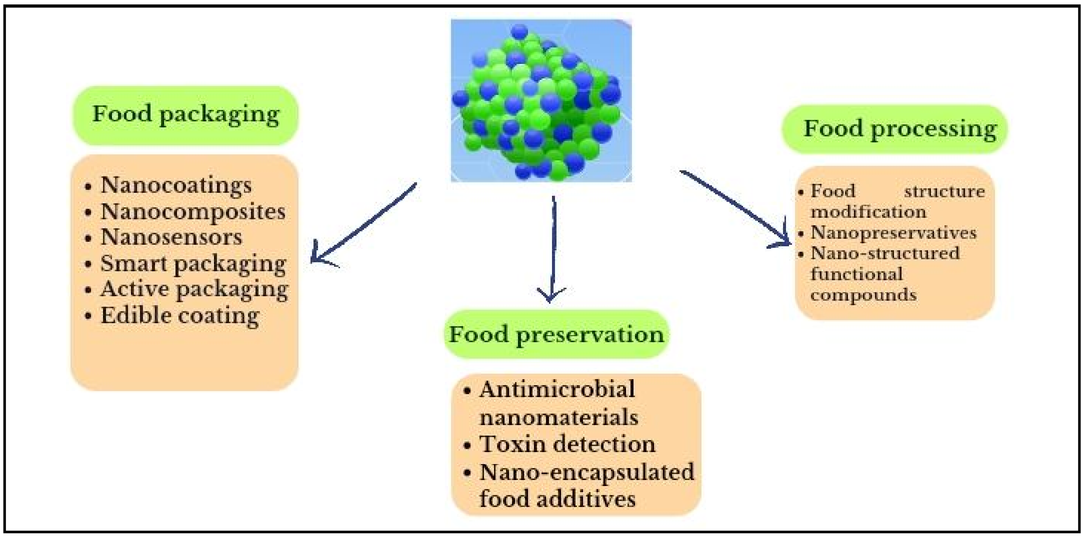


Figure 1: The application of nanotechnology in food processing, preservation and packaging.

Table 1: Techniques along with mechanism and applications of nanomaterials in food processing unit operation.

S. No.	Techniques	Nanomaterials	Mechanism	Application in various unit operation	References
1.	Nano-emulsion	Vegetable oil, sucroseand ester gum	Enhancing nutrient composition of food products, stabilizing properties and reducing creaming.	Homogenization Emulsification Encapsulation, Food additives Nutritional enrichment Fortification	Biswas *et al.*, 2022
2.		Carbohydrates and proteins like alginate, xanthan gum, guar gum, pectin, carra-geenan and starch	Aid in improving the texture and uniformity of ice creams.	Emulsifiers Stabilizers	Mohammed *et al.*, 2020
3.	Nanoen-capsulation	Nano capsules	Enhanced oxidation resistance, stability, and preservation of volatile elements; trapping of odor and undesirable food constituents. Controlled release resulted from pH; controlled release influenced by flavor and moisture	Encapsulation, Food additives Flavour enhancer Food preservation	Boonlao *et al.*, 2022
4.		Nano-cuticles	Utilized to nanocapsule nano-clusters which helps to increase the flavor of the drink without the addition of sugar.	Flavour enhancer Food additives	J *et al.*, 2022
5.		Nanoliposomes	Liposomes composed from zein fibres and gallic acid	Homogenization, Nutritional supplementation Food additives Emulsification	Thakur *et al.*, 2021

Table 2: Application of various nanomaterials with their working mechanism and applications in food industry

S.No.	Nanomaterials	Mechanism	Applications	References
1.	Zinc oxide	Potent antibacterial substance; exposure to UV-A had no impact on the structural properties of the generated nanomaterial; materials designed to scavenge activated oxygen.	Antimicrobial effects, prolong the freshness of perishable items.	Mizieliñska *et al.*, 2018
2.	Silver-based	Enhanced barrier properties and mechanical strength; reduced yellowness in food products, and improved heat stability; increased antioxidant efficacy; effective antibacterial activity.	Food preservation by extending the shelf life and controlling growth of pathogens.	Ramachandraiah *et al.*, 2017
3.	Titanium dioxide	Cost-effective, nontoxic, and resistant to photodegradation; antibacterial properties, and self-cleaning surfaces; heightened antibacterial activity; improved mechanical strength of polymer nanocomposites; milk and cheese.	Extending the shelf-life and controlling growth of pathogens.	Roilo *et al.*, 2018
4.	Polymer and nanoparticles	Gas barrier properties.	Antimicrobial properties	Yotova *et al.*, 2013
5.	Nano-clay and silicate	Antimicrobial activity; elevated levels of total volatiles, antioxidant capability, and organic acids.	Food packaging designed to extend the shelf-life of food and manage pathogenic and spoilage microorganisms/bacteria.	López-Rubio *et al.*, 2019
6.	Polymer-based: PHBV (3- hydroxy butyrate-co-3-hydro xyvalerate)	Thermal stability, and rheological performance have been improved, resulting in enhanced thermal characteristics and water barrier.	Active packaging for preserving food to extend its shelf-life and regulate the growth of patho-genic and spoilage micro-organisms/bacteria.	López-Rubio *et al.*, 2019
7.	Chitosan based polysaccharides	Incorporated with nanocapsules containing epicatechin gallate.	Extending shelf-life and controll-ing growth of pathogens.	Liang *et al.*, 2017
8.	Cellulose and starch (bio-nanocomposites)	Substances deposited for packaging purposes have demonstrated efficacy.	Enhanced composition for food packaging with unique features.	Pradhan *et al.*, 2015
9.	Imperm (nylon)	Scavenging oxygen.	Enhanced composition for food packaging with unique features.	Thirumurugan *et al.*, 2013
10.	Nano-smart dust	Investigating environment pollutants.	Intelligent food packaging designed to extend shelf life and identify, as well as control pathogens.	Coles and Frewer, 2013
11.	Durethan (polyamide)	Offers structural strength to paper containers for fruit juice.	Antimicrobial properties.	Dasari *et al.*, 2013
12.	Nano barcodes	Quality assessment	Intelligent food packaging (extending shelf-life and control as well as identify pathogens).	Coles and Frewer, 2013
13.	Metal-based (platinum, palladium, and gold), nano sensors	Monitoring and converting light, humidity, heat, gas, and chemical variations into electrical signals; detecting any irregularities in the color of food; detecting toxins such as aflatoxin B1 in milk; identifying any gases produced due to deterioration.	Intelligent packaging.	Meetoo, 2011
14.	Plasmon-coupled emission biosensors on the surface (with Au)	Identification of pathogens	Intelligent food packaging (extending shelf-life and control as well as identify pathogens).	Nile *et al.*, 2020
15.	Polyaniline with carbon black	Detection of pathogens; diagnosing infections transmitted through food; detecting carcinogens in food products.	Intelligent food packaging (extending shelf-life and control as well as identify pathogens).	Li *et al.*, 2005

16.	Integrator iSTrip (Time-temperature indicator)	Detection of pathogens and spoilage causing microbes using temperature.	Smart packaging	Li *et al.*, 2005
17.	DS13 top screen and guard in fresh	Scavenge ethylene to enhance ripening of fruits.	Antifungal properties; improved food packaging.	Ghosh *et al.*, 2022
18.	Nanolaminates	Coating of bakery foods, cheese, vegetables, meat and fruits.	Antimicrobial properties.	
19.	Garlic oil nano-composites	Eliminate common insect infestations in packaged food items at stores and shops.	Active packageing	Miranda *et al.*, 2022
20.	Zein-based nano-particles	Enhanced mechanical strength and water moisture barrier properties without affecting film elongation; reduced hydrophilicity, control bacterial; exhibited increased tensile strength, decreased elasticity.	Food preservation; extending the shelf-life of food and controlling the growth of spoilage microorganisms.	López-Rubio *et al.*, 2019
21.	Interferometry with reflections	*E. coli* detected from food stuff.	Intelligent food packaging designed to extend shelf life and to monitor, control, and identify pathogenic and spoilage bacteria.	Bashir *et al.*, 2022

4. Role of nanotechnology in enhancing food safety

Despite technological advancements in food preservation, sanitation, and regulations, the issue of food safety remains a significant concern globally. Foodborne illnesses caused by pathogens and toxins pose serious risks to human health. The scientific community and researchers prioritize the development of cost-effective, precise, and easily deployable contaminant detection methods for the food industry. Traditional detection techniques and rapid molecular methods are expensive, time-consuming, and labor-intensive, with potential inaccuracies and self-contamination risks (Dudefoi *et al.*, 2018). Nanotechnology emerges as a promising solution to address food safety challenges, offering tools and techniques for microbial and toxin detection, extending shelf-life, and enhancing food packaging. The focus is on leveraging the antimicrobial properties of nanoparticles and nano-sensors for detecting foodborne pathogens and contaminants. The increasing attention from researchers, the food industry, and the public underscores the importance of nanotechnology applications in food safety.

Nanotechnology-based detection methods outperform conventional and molecular techniques by providing faster, more accurate, and cost-effective results. These techniques significantly reduce incubation and measurement times while ensuring high sensitivity and accuracy. For instance, a study demonstrated the isolation of 88% of *E. coli* in just a 45 min incubation using nanosized magnetic iron oxide particles with sugar molecules (Biswas *et al.*, 2022). The culmination of nanotechnology into food safety practices holds great promise, addressing issues of accuracy and time constraints. This technological advancement empowers the food industry to deliver safer, healthier, and higher-quality food products.

5. Nanotechnology and safety concerns

The emergence and rapid usage of nanotechnology in modern era have sparked public apprehension regarding its safety and potential impact on human health. Due to the unique properties of nanomaterials, such as a large surface area, concerns arise about their potential toxicity to the human body, given the differences from their bulk materials (Krishna *et al.*, 2022). Notably, the ability of nanoparticles to traverse cellular and membrane barriers at the nanoscale raises concerns. Despite increasing concerns about potential negative impacts on human health, the widespread commercial adoption of nanotechnology persists. For example, nanomaterials integrated into food packaging are generally considered non-harmful to human health, although some risks may arise when they are used in conjunction with food products (Karthik *et al.*, 2013). Since applications of nanotechnology are chemical-based, they do not inherently contain toxins or pose adverse effects on human health (Chaudhry *et al.*, 2008). Nevertheless, additional research is needed to assess the impact of nanotechnology on both the environment and human health (Biswas *et al.*, 2022).

6. Nanotechnology in food packaging

Applications of nanotechnology in food packaging can be divided into two broad groups; firstly smart packaging and secondly active packaging. Factors like oxygen, water permeability, and ethylene are responsible for post-harvest deterioration of fruits and vegetables and thus significantly affect food quality. Effective food packaging plays a pivotal role in addressing such losses (Fuertes *et al.*, 2016). The principal objective of packaging is to control spoilage and contamination of pathogens, providing protection against temperature variations and external shocks, vibrations. It functions as a barrier to prevent the ingress of oxygen and gases responsible for spoilage, thus preserving the quality of the food products (Horner *et al.*, 2006). Incorporation of nanoparticles and polymer-based composites in food packaging, emerged as a highly effective solution in addressing these challenges (Mohammad *et al.*, 2022).

6.1 Smart packaging

Unlocking the potential of nanotechnology in the food industry, smart packaging systems primarily employ nanosensors for the detection of food contaminants, with nanoparticles playing a crucial role in their development. Nanoparticle-based nanosensors demonstrate significant promise in monitoring chemical, physical, and biological modifications throughout food processing and preservation. The integration of these sensors into smart packaging facilitates the detection of chemicals, toxins, and food pathogens (Nile *et al.*, 2020).

Furthermore, smart packaging equipped with nanosensors and indicators enables seamless tracking of information related to the quality of packaged food products during transportation and storage. Notably, the utilization of smart packaging contributes to maintaining food quality during distribution, as the embedded sensors document all responses associated with internal or external environmental stimuli (Krishna *et al.*, 2022). Various indicators are commonly incorporated into food packaging applications to assess packaging integrity, freshness, and changes dependent on time and temperature. The ongoing monitoring of changes in food products during production and the supply chain, facilitated by indicators, proves instrumental in preserving quality and extending the product shelf-life (Kumar *et al.*, 2021). Additionally, nanoparticle-based nano-barcodes serve as identity tags for smart packaging, enhancing traceability and further advancing the capabilities of nanotechnology in the food industry (Branton *et al.*, 2008).

6.2 Active packaging

Active packaging typically extends the shelf-life and enhances the quality of packaged food, with the design of active packaging systems being closely aligned with specific food storage objectives (Dias *et al.*, 2013). These intentionally crafted packaging systems integrate components capable of absorbing oxygen or releasing antimicrobials or antioxidant agents into or from the packaged food. The integration of active compounds, such as nanoparticles, antimicrobials, water vapor, and oxygen absorbers, into the packaging, enhances its resistance and effectiveness in preserving the shelf-life and quality of the packaged food. Various types of metal and metal oxide nanoparticles, including zinc, gold, silver, zinc oxide, titanium dioxide, and silicon oxide, have been extensively employed in different applications of active packaging (Sharma *et al.*, 2017). These nanoparticles can either act through direct contact or gradually migrate and react with organics present in the food. Silver nanoparticles, in particular, are widely utilized due to their established antimicrobial potential against pathogenic strains, as well as their inhibitory effects on viruses and fungi (such as Monkeypox and fungi) (Duncan, 2011). Mohammad *et al.* (2022) incorporated silver nanoparticles into sodium alginate films for food packaging, reporting significant antibacterial effects against *E. coli* and *Staphyloccus aureus*.

Figure 2: Active packaging.

6.3 Application of nanoparticles in nano packaging

Integrating nanoparticles into food packaging enhances the effectiveness of food packages, leading to extended shelf-life and improved food quality. In recent years, diverse nanoparticles have been developed and utilized in the food industry due to their capacity to encapsulate active compounds and enhance the functionality, stability, and bioavailability of packaging. A wide range of nanoparticles is known to possess antimicrobial properties, presenting significant potential for food packaging applications. For instance, silver nanoparticles, renowned for their high antimicrobial activity, are commonly employed as an active system in food packaging. Additionally, other nanoparticles like zinc oxide, titanium oxide, and silicate nanoparticles are incorporated into plastic films to minimize oxygen permeation within the packaging, thereby preserving the freshness of the food for an extended duration and preventing moisture leakage (Sharma *et al.*, 2017).

According to the standards set by the Food and Drug Administration (FDA), the utilization of silver as a food ingredient within certain limits is safe and does not pose a significant threat to biological systems. In recent years, silver nanoparticles have gained preference over other available antimicrobial nanoparticles in the market due to their ease of incorporation into packaging materials (Ramanathan *et al.*, 2008). Numerous studies have indicated that silver, due to its limited filtration within microbial systems, induces alterations in ribosomal activity, thereby inhibiting the production of various enzymes. Silver nanoparticles exhibit favorable bactericidal effects against both Gram-positive and Gram-negative bacteria, with observations suggesting higher activity against Gram-negative bacteria (Zhao *et al.*, 2008). Moreover, silver nanoparticles have demonstrated their effectiveness in prolonging the shelf-life of fruits and vegetables by absorbing and decomposing ethylene. Another noteworthy nanoparticle is zinc oxide, recognized as "Generally Recognized as Safe" (GRAS) by the FDA, allowing its use as a food additive or ingredient in everyday applications.

6.4 Use of chitosan in nano packaging

Chitosan, characterized by its high molecular weight and polycationic heteropolysaccharide nature, is renowned for its biodegradability, biocompatibility, and metal complexation. Its broad-spectrum antimicrobial activity is primarily attributed to its polycationic properties. Chitosan finds diverse applications in various realms, including food sciences, biological and chemical systems, as well as the food and pharmaceutical industries (Arora *et al.*, 2016).

Chitosan having positive charge, binds to negatively charged cell walls, which increases permeability and disrupts the cell wall integrity. The formation of chitosan based nanoparticles occurs through ionic gelation, where the positively charged amino groups of chitosan interact electrostatically with polyanions serving as cross-linkers (Acosta, 2009). Chitosan-based films exhibit antimicrobial and antioxidant activities, owing them as viable alternatives to synthetic chemicals in food packaging. Furthermore, chitosan-based films offer a superior solution for improving shelf-life of food product without compromising sensory properties. Various studies in the literature have highlighted the use of chitosan-based derivatives in preserving beverages. Researchers have also explored the combination of various nanomaterials in food packaging and preservation, resulting in effective thermal and barrier properties at a lower cost.

Edible coatings with nanomaterials, particularly chitosan, demonstrate significant benefits during the food storage. These coatings ensure food safety without causing physical damage during transportation, and thus maintaining overall quality. Chitosan is considered as one of the best edible and biologically safe coatings, exhibits biodegradable, biochemical, antimicrobial, and film-forming properties, along with a lack of toxicity (Yuan *et al.*, 2016). For fresh fruits, chitosan stands out as an amazing edible coating. Notably, chitosan has been found effective in controlling various pre- and post-harvest diseases of fruits and vegetables. Increasing the concentration of chitosan coating up to a certain limit has been observed to amplify its positive effects on shelf-life and food quality. The untreated fruit and fruit treated with 0.5% chitosan ripened within three weeks of storage, after which decomposition commenced. In contrast, fruit treated with 2.0% chitosan did not undergo proper ripening even after five weeks of storage in cold conditions. As a result, it is recommended to apply an edible coating of 1.5% chitosan to papaya fruit to uphold product quality and prolong shelf -life (Ali *et al.*, 2011).

7. Application of nanotechnology in improving food ingredients and additives

One of the principals focuses in contemporary nanotechnology applications within the food industry revolves around the development of nanostructured food ingredients and delivery systems for nutrients and supplements. Various techniques are employed for this purpose, including nano-emulsions, surfactant micelles, emulsion bilayers, and reverse micelles (Weiss *et al.*, 2006). The design of these nanostructured food ingredients is based on the premise that they can provide an improved taste, texture, and consistency. For example, low-fat nanostructured products such as mayonnaise, spreads, and ice creams claim to deliver the same "creamy" quality as their full-fat counterparts, presenting a healthier option for consumers.

8. Future perspective of nanotechnology in food

While great progress has been made in applying nanotechnology to many sectors of the food business, success in nanotechnology connected with nanostructures has been rather restricted. Despite the potential for bringing novel goods and processes in the food business, various problems must be addressed. As food nanotechnology research advances, societal worries about the safety of nanotechnology products meant for human consumption and usage grow. As a result, before nano food products can be commercially marketed, a thorough assessment of possible dangers to human health is required. There is currently no comprehensive guideline for evaluating the safety of nanomaterials in food. The key problem is to provide cost-effective and secure edible delivery systems (Ishan Das Rastogi, 2012).

To ensure food safety, a fundamental obstacle must be addressed: The migration and absorption of nanoparticles from packaging materials into food products. Materials display diverse behaviors at the nanoscale, but we still do not know how to examine these features properly. A deeper understanding of nanoscale functionalities and toxicity of nanomaterials is critical for increasing safety requirements in their practical application. The difficulties in forecasting nanoparticle migrations using models based purely on diffusion has made determining release mechanisms problematic (Sahoo *et al.*, 2007).

Moreover, there is a notable lack of understanding regarding the potential release mechanisms of identified nanoparticles. The intricacies of gastrointestinal absorption, shaped by factors like morphology, composition, surface properties, charge, aggregation state, and functional ingredients, add complexity to evaluating consumer risks associated with migrating nanoparticles in food packaging, surpassing the challenges of other considerations. Hence, these aspects warrant deeper exploration in future research (McClements and Xiao, 2017). It is critical to address nanoparticle effects, possible hazards, toxicological risks, and environmental concerns. Notably, nanoparticles have been discovered to cross biological barriers, allowing them to infiltrate cells and organs.

Food nanoparticles can cause biological effects such as oxidative stress, protein denaturation, and DNA damage. There is currently no global uniform safety review approach for nanoparticles, particularly for nanotechnology in food. It is critical to develop laws for the use of nanoparticles in food, including risk assessments and safety management approaches that are in line with the toxicity testing aims and objectives of the twenty-first century (Jokar *et al.*, 2017).

9. Technological limitations and challenges ahead

While nanotechnology holds significant potential for creating innovative products and processes in the food industry, there are numerous challenges (Ishan Das Rastogi, 2012). One major hurdle is the development of edible delivery systems using cost-effective processing methods and formulations that are safe for human consumption (Dupas *et al.*, 2007). Ensuring the wholesomeness of foods is a primary concern, particularly regarding the migration and leaching of nanoparticles from packaging materials into food products. Nanoscale materials, whether added directly or indirectly, sometimes result from migration from various sources (Hannon *et al.*, 2015). The behavior of materials at the nanoscale is distinct, and our technical knowledge of their analysis remains limited.

A comprehensive understanding of the nanoscale functionalities and toxicities of nanomaterials is crucial for advancing practical applications and safety regulations. The synthesis of nanoparticles using chemical methods can not only have adverse effects but also produce non-environmentally friendly by-products that can contribute to severe environmental pollution (Singh, 2016). Therefore, beyond popularity, technical benefits and public demand, comprehensive risk assessment programs, strict regulatory policies, biosafety considerations, and public health concerns must be taken into account during the processing of nanotechnology based food and dairy products (Bajpai *et al.*, 2018). Additionally, *in vitro* as well as *in vivo* studies examining nanoparticle interactions with living organisms are mandatory before commercial application. This needs especial attention in the production of eco-friendly antimicrobial nanoparticles (Das *et al.*, 2011). Further extensive research is to be done in multiple areas to ensure widespread application, and safety aspects and challenges should be considered simultaneously.

10. Conclusion

Nanotechnology has had a high impact on the food business and trading in a multiple field. Nanotechnology applications in food industry involves safety and quality monitoring. In resent scenario, nanotechnology in the food sector helps to improve food characteristics, extending shelf-life by efficient packaging and detecting spoilage causing microbes and pathogens.

The application of nanotechnology in food packaging has the remarkable potential to bring new era of change existing packaging methods, providing promising avenues to improve food safety, quality, and product shelf-life. The inclusion of nanotechnology into nutritional supplements improves drug delivery, resulting in the availability of a wide range of commercial nutraceuticals. These supplements have a strong interaction with cells and are beneficial. Despite the implementation of nanotechnology by food companies, customer acceptance remains restricted due to ethical issues and a lack of information. It is critical to raise awareness of the potential uses and benefits of nanotechnology in both industry and consumer health. Ongoing research in nanotechnology for the food business has the potential to transform the food industry landscape. Regulatory measures implemented by government food administration departments are also critical to ensuring the correct and safe commercialization of nano foods.

Concerns have been raised about the interaction of nanoparticles with cells; however, it is crucial to recognize the vast potential of nanotechnology in the food sector as a whole. Its advantages, such as improved nutritional content, high-quality packaging, and smart sensing capabilities, should be examined. More research is needed to develop safer methods for incorporating nanotechnology into the food business.

Conflict of interest

The authors declare no conflicts of interest relevant to this article.

References

Acosta, E. (2009). Bioavailability of nanoparticles in nutrient and nutraceutical delivery. Current Opinion in Colloid and Interface Science, **14**:1-21. doi: 10.1016/j.cocis.2008.01.002.

Ali, A.; Muhammad, M. T. M.; Sijam, K. and Siddiqui, Y. (2011). Effect of chitosan coatings on the physicochemical characteristics of Eksotika II papaya (*Carica papaya* L.) fruit during cold storage. Food Chemistry, **124**:620-626. doi: 10.1016/j.foodchem.2010.06.085.

Arora, D.; Sharma, N.; Sharma, V.; Abrol, V.; Shankar, R. and Jaglan, S. (2016). An update on polysaccharide-based nanomaterials for antimicrobial applications. Applied Microbiology and Biotechnology, **100**:321-327. doi: 10.1007/s00253-016-7315-0.

Bajpai, V. K.; Kamle, M.; Shukla, S.; Mahato, D. K.; Chandra, P.; Hwang, S. K.; Kumar, P.; Huh, Y. S. and Han, Y. K. (2018). Prospects of using nanotechnology for food preservation, safety, and security. Journal of Food and Drug Analysis, **26**:101-108. doi: 10.1016/j.jfda.2018.06.011.

Bashir, O.; Bhat, S. A.; Basharat, A.; Qamar, M.; Qamar, S. A.; Bilal, M. and Iqbal, H. M. N. (2022). Nano-engineered materials for sensing food pollutants: Technological advancements and safety issues. Chemosphere, **292**:1-11. doi: 10.1016/j.chemosphere. 2021.13 3320.

Biswas, R.; Alam, M.; Sarkar, A.; Haque, M. I.; Hasan, M. M. and Hoque, M. (2022). Application of nanotechnology in food: processing, preservation, packaging and safety assessment. Heliyon, **8**:413-424. doi: 10.1016/j.heliyon.2022.e11795.

Boonlao, N.; Ruktanonchai, U. R. and Anal, A. K. (2022). Enhancing bioaccessibility and bioavailability of carotenoids using emulsion-based delivery systems. Colloids and Surfaces B: Biointerfaces, **209**: 112211. doi: 10.1016/J.COLSURFB.2021.112211.

Branton, D.; Deamer, D. W.; Marziali, A.; Bayley, H.; Benner, S. A.; Butler, T.; Di Ventra, M.; Garaj, S.; Hibbs, A.; Huang, X.; Jovanovich, S. B.; Krstic, P. S.; Lindsay, S.; Ling, X. S.; Mastrangelo, C. H.; Meller, A.; Oliver, J. S.; Pershin, Y. V.; Ramsey, J. M.; Riehn, R.; Soni, G. V.; Tabard-Cossa, V.; Wanunu, M.; Wiggin, M. and Schloss, J. A. (2008). The potential and challenges of nanopore sequencing. Nature Biotechnology, **26**:1146-1153. doi: 10.1038/nbt.1495.

Chaudhry, Q.; Scotter, M.; Blackburn, J.; Ross, B.; Boxall, A.; Castle, L.; Aitken, R. and Watkins, R. (2008). Applications and implications of nanotechnologies for the food sector. Food Additives and Contaminants - Part A, **25**:241-258. doi: 10.1080/02652030 701744538.

Chellaram, C.; Murugaboopathi, G.; John, A. A.; Sivakumar, R. and Ganesan, S. (2014). Significance of nanotechnology in food industry. Procedia - Social and Behavioral Sciences, **8**:109-113. doi: 10.1016/j.apcbee.2014.03.010.

Coles, D. and Frewer, L. J. (2013). Nanotechnology applied to European food production: A review of ethical and regulatory issues. Trends in Food Science and Technology, **34**:32-43. doi: 10.1016/j.tifs.2013.08.006.

Damm, C.; Münstedt, H. and Rösch, A. (2008). The antimicrobial efficacy of polyamide 6/silver-nano- and microcomposites. Materials Chemistry and Physics, **108**:61-66. doi: 10.1016/J.MAT CHEMPHYS.2007.09.002.

Das, S.; Jagan, L.; Isiah, R.; Rajesh, B.; Backianathan, S. and Subhashini, J. (2011). Nanotechnology in oncology: Characterization and *in vitro* release kinetics of cisplatin-loaded albumin nanoparticles: Implications in anticancer drug delivery. Indian Journal of Pharmacology, **43**:409-413. doi: 10.4103/0253-7613.83111.

Dasari, T. P.; Pathakoti, K. and Hwang, H. M. (2013). Determination of the mechanism of photoinduced toxicity of selected metal oxide nanoparticles (ZnO, CuO, Co3O4 and TiO2) to *E. coli* bacteria. Journal of Environmental Sciences (China), **25**:882-888. doi: 10.1016/S1001-0742(12)60152-1.

Dias, M. V.; De Fátima F. Soares, N.; Borges, S. V.; De Sousa, M. M.; Nunes, C. A.; De Oliveira, I. R. N. and Medeiros, E. A. A. (2013). Use of allyl isothiocyanate and carbon nanotubes in an antimicrobial film to package shredded, cooked chicken meat. Food Chemistry, **141**:3160-3166. doi: 10.1016/j.foodchem.2013.05.148.

Dudefoi, W.; Villares, A.; Peyron, S.; Moreau, C.; Ropers, M. H.; Gontard, N. and Cathala, B. (2018). Nanoscience and nanotechnologies for biobased materials, packaging and food applications: New opportunities and concerns. Innovative Food Science and Emerging Technologies, **46**:107-121. doi: 10.1016/j.ifset.2017.09.007.

Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety: Barrier materials, antimicrobials and sensors. Journal of Colloid and Interface Science, 363:327-331. doi: 10.1016/j.jcis.2011.07.017.

Dupas, C.; Houdy, P. and Lahmani, M. (2007). Nanoscience: Nanotechnologies and nanophysics. doi: 10.1007/978-3-540-28617-2.

Francisco, E. V. De and García-estepa, R. M. (2018). Nanotechnology in the agrofood industry. Journal of Food Engineering, 238:1-11. doi: 10.1016/j.jfoodeng.2018.05.024.

Fuertes, G.; Soto, I.; Carrasco, R.; Vargas, M.; Sabattin, J. and Lagos, C. (2016). Intelligent packaging systems: Sensors and nanosensors to monitor food quality and safety. Journal of Sensors, 16:333-346. doi: 10.1155/2016/4046061.

Ghosh, A.; Saha, I.; Fujita, M.; Debnath, S. C.; Hazra, A. K.; Adak, M. K. and Hasanuzzaman, M. (2022). Photoactivated TiO2 nanocomposite delays the postharvest ripening phenomenon through ethylene metabolism and related physiological changes in capsicum fruit. Plants, 11:1-13. doi: 10.3390/plants11040513.

Hannon, J. C.; Kerry, J. P.; Cruz-Romero, M.; Azlin-Hasim, S.; Morris, M. and Cummins, E. (2015). Assessment of the migration potential of nanosilver from nanoparticle-coated low-density polyethylene food packaging into food simulants. Food Additives and Contaminants - Part A Chemistry, Analysis, Control, Exposure and Risk Assessment, 33:167-178. doi: 10.1080/19440049.2015.1114184.

Horner, S. R.; Mace, C. R.; Rothberg, L. J. and Miller, B. L. (2006). A proteomic biosensor for enteropathogenic *E. coli*. Biosensors and Bioelectronics, 21:1659-1663. doi: 10.1016/j.bios.2005.07.019.

Ishan Das Rastogi (2012). Nanotechnology: Safety paradigms. Journal of Toxicology and Environmental Health Sciences, 4:1-12. doi: 10.5897/jtehs11.071.

J, M. I. S.; S, S.; Senthil Kumar, P. and K, V. G. (2022). New analytical strategies amplified with carbon-based nanomaterial for sensing food pollutants. Chemosphere, 295:1-13. doi: 10.1016/J.CHEMOSPHERE.2022.133847.

Jokar, M.; Pedersen, G. A. and Loeschner, K. (2017). Six open questions about the migration of engineered nano-objects from polymer-based food-contact materials: A review. Food Additives and Contaminants - Part A Chemistry, Analysis, Control, Exposure and Risk Assessment, 34:434-450. doi: 10.1080/19440049.2016.1271462.

Karthik, P.; Chhanwal, N.; Specialities, C. and Chinnaswamy, A. (2013). Nanoencapsulation techniques for food bioactive components : A review nanoencapsulation techniques for food bioactive components: A review. Food Bioprocess Technology, 1:628-647. doi: 10.1007/s11947-012-0944-0.

Krishna, A. R.; Gurumoorthy, S.; Elayappan, P.; Sakthivadivel, P.; Kumaran, S. and Pushparaj, P. (2022). A review on the application of nanotechnology in food Industries. Current Research in Nutrition and Food Science, 10:871-883. doi: 10.12944/CRNFSJ.10.3.5.

Kumar, A.; Pratush, A. and Bera, S. (2021). Significance of nanoscience in food microbiology: Current Trend and Future Prospects. pp:249-267. doi: 10.1007/978-981-15-9916-3_10.

Li, Y.; Cu, Y. T. H. and Luo, D. (2005). Multiplexed detection of pathogen DNA with DNA-based fluorescence nanobarcodes. Nature Biotechnology, 23:885-889. doi: 10.1038/nbt1106.

Liang, J.; Yan, H.; Zhang, J.; Dai, W.; Gao, X.; Zhou, Y.; Wan, X. and Puligundla, P. (2017). Preparation and characterization of antioxidant edible chitosan films incorporated with epigallocatechin gallate nanocapsules. Carbohydrate Polymers, 171:300-306. doi: 10.1016/j.carbpol.2017.04.081.

López-Rubio, A.; Fabra, M. J. and Martínez-Sanz, M. (2019). Food packaging based on nanomaterials. Nanomaterials, 9:3-5. doi: 10.3390/nano9091224.

McClements, D. J. and Xiao, H. (2017). Is nano safe in foods? Establishing the factors impacting the gastrointestinal fate and toxicity of organic and inorganic food-grade nanoparticles. Science of Food, 1:1-13. doi: 10.1038/S41538-017-0005-1.

Meetoo, D. D. (2011). Nanotechnology and the food sector: From the farm to the table. Emirates Journal of Food and Agriculture, 23:1-13.

Miranda, M.; Sun, X.; Marín, A.; dos Santos, L. C.; Plotto, A.; Bai, J.; Benedito Garrido Assis, O.; David Ferreira, M. and Baldwin, E. (2022). Nano- and micro-sized carnauba wax emulsions-based coatings incorporated with ginger essential oil and hydroxypropyl methylcellulose on papaya: Preservation of quality and delay of post-harvest fruit decay. Food Chemistry: X, 13:1-13. doi: 10.1016/j.fochx.2022.100249.

Mizielińska, M.; Kowalska, U.; Jarosz, M. and Sumińska, P. (2018). A comparison of the effects of packaging containing nano ZnO or polylysine on the microbial purity and texture of cod (*Gadus morhua*) fillets. Nanomaterials, 8:1-13. doi: 10.3390/nano8030158.

Mohammad, Z. H.; Ahmad, F.; Ibrahim, S. A. and Zaidi, S. (2022). Application of nanotechnology in different aspects of the food industry. Discover Food, 2:1-21. doi: 10.1007/s44187-022-00013-9.

Mohammed, N. K.; Muhialdin, B. J. and Meor Hussin, A. S. (2020). Characterization of nanoemulsion of *Nigella sativa* oil and its application in ice cream. Food Science and Nutrition, 8:2608-2618. doi: 10.1002/fsn3.1500.

Nile, S. H.; Baskar, V.; Selvaraj, D.; Nile, A.; Xiao, J. and Kai, G. (2020). Nanotechnologies in Food Science: Applications, Recent Trends, and future perspectives. Springer Singapore doi: 10.1007/s40820-020-0383-9.

Pradhan, N.; Singh, S.; Ojha, N.; Shrivastava, A.; Barla, A.; Rai, V. and Bose, S. (2015). Facets of nanotechnology as seen in food processing, packaging, and preservation industry. Bio. Med. Research International, 15:1-17. doi: 10.1155/2015/365672.

Rajamalar, C. G.; Chandrika, M. and Chellaram, D. C. (2011). Chemical synthesis and structural elucidation of novel compounds - Schiff bases. Biometrics and Bioinformatics, 3:468-472.

Ramachandraiah, K.; Gnoc, N. T. B. and Chin, K. B. (2017). Biosynthesis of silver nanoparticles from persimmon by products and incorporation in biodegradable sodium alginate thin film. Journal of Food Science, 82:2329-2336. doi: 10.1111/1750-3841.13865.

Ramanathan, T.; Abdala, A. A.; Stankovich, S.; Dikin, D. A.; Herrera-Alonso, M.; Piner, R. D.; Adamson, D. H.; Schniepp, H. C.; Chen, X.; Ruoff, R. S.; Nguyen, S. T.; Aksay, I. A.; Prud'Homme, R. K. and Brinson, L. C. (2008). Functionalized graphene sheets for polymer nanocomposites. Nature Nanotechnology, 3:204-213. doi: 10.1038/nnano.2008.96.

Roilo, D.; Maestri, C. A.; Scarpa, M.; Bettotti, P. and Checchetto, R. (2018). Gas barrier and optical properties of cellulose nanofiber coatings with dispersed TiO2 nanoparticles. Surface and Coatings Technology, 343:21844-21853. doi: 10.1016/j.surfcoat.2017.10.015.

Sahoo, M.; Vishwakarma, S.; Panigrahi, C. and Kumar, J. (2007). Nanotechnology: Current applications and future scope in food. In Nanoscience: Nanotechnologies and Nanophysics, pp:3-22. doi: 10.1002/fft2.58.

Sharma, C.; Dhiman, R.; Rokana, N. and Panwar, H. (2017). Nanotechnology: An untapped resource for food packaging. Frontiers in Microbiology, 8:236-247. doi: 10.3389/fmicb.2017.01735.

Singh, H. (2016). Nanotechnology applications in functional foods; Opportunities and challenges. Preventive Nutrition and Food Science, 21:1-8. doi: 10.3746/pnf.2016.21.1.1.

Thakur, R. K.; Prasad, P.; Savadi, S.; Bhardwaj, S. C.; Gangwar, O. P. and Kumar, S. (2021). Nanotechnology for Agricultural and Environmental Sustainability. In Survival Strategies in Coldadapted Microorganisms, doi: 10.1007/978-981-16-2625-8_18.

Thirumurugan, A.; Ramachandran, S. and Shiamala Gowri, A. (2013). Combined effect of bacteriocin with gold nanoparticles against food spoiling bacteria - an approach for food packaging material preparation. International Food Research Journal, 20:50-54.

Weiss, J.; Takhistov, P. and McClements, D. J. (2006). Functional materials in food nanotechnology. Journal of Food Science, 71:107-116. doi: 10.1111/j.1750-3841.2006.00195.x.

Yotova, L.; Yaneva, S. and Marinkova, D. (2013). Biomimetic nanosensors for determination of toxic compounds in food and agricultural products (review). Journal of the University of Chemical Technology and Metallurgy, 48:215-227.

Yuan, G.; Chen, X. and Li, D. (2016). Chitosan films and coatings containing essential oils: The antioxidant and antimicrobial activity, and application in food systems. Elsevier B.V. doi: 10.1016/j.foodres.2016.10.004.

Zhao, R.; Torley, P. and Halley, P. J. (2008). Emerging biodegradable materials: Starch- and protein-based bio-nanocomposites. Journal of Materials Science, 43:3058-3071. doi: 10.1007/s10853-007-2434-8.

Citation **Manvik Joshi and Kamalesh Kumar Meena (2023). Comprehending fundamental concepts and applications of nanotechnology in food processing: Current overview and future perspectives. J. Phytonanotech. Pharmaceut. Sci., 3(4):15-23. http://dx.doi.org/10.54085/jpps.2023.3.4.3**