Animal Health Research Journal Vol. 10, No. 1, March 2025 pp. 107-118

ISSN: 2356-7767

Nanotechnology: Exploring Their Benefits and Potential Health Risk

Nariman, Abd Elhady; Mohamed, Nabil; Suzan, F. Elsisiy and Rehab, Gaafar
Food Hygiene Dept., Animal Health Research Institute-Benha Lab.,
Agricultural Research Center (ARC), Egypt

Review Article

Corresponding author:
Nariman, Abd Elhady
E. mail: narimanabdelhady@gmail.com

Received in 13/2/2025
Accepted in 18/3/2025

Abstract
Nanotechnology is revolutionizing the food sector by introducing innovative solutions that improve safety, quality, and food security. Advanced food items and packaging solutions can be developed because of this technology, which manipulates materials at the nanoscale (1 to 100 nanometers). Using nanoparticles for antibacterial purposes, extending food products' shelf lives, and boosting nutrient delivery through nano-encapsulation are some of the main uses. Strong antibacterial qualities are exhibited by nanomaterials like titanium dioxide, zinc oxide, and silver, which successfully stop the growth of bacteria and spoiling organisms. Nanosensors are also used to monitor food safety and quality in real time, enabling the early identification of pollutants and spoiling. Nanotechnology improves barrier qualities in food packaging, guaranteeing that food keeps its sensory qualities while being safe and fresh for extended periods of time. Despite the promising benefits, the application of nanotechnology in food production raises concerns regarding potential toxicity and environmental concerns, necessitating safety monitoring and regulatory ethics. As research progresses, the integration of nanotechnology in the nutrition field keeps the chance to significantly improve food security and sustainability, addressing global oppositions concerning the food safety and supply. This abstract highlights the transformative role of nanotechnology in the food production field, emphasizing its applications, convenience, and the challenges that must be labeled for its responsible use. This article mentioned also the concerns surrounding the application of nanotechnology in food, specifically focusing on the potential adverse effects of inorganic nanomaterials on consumer health, as highlighted by international authorities, agencies and the organizations concerned with food safety.

Keywords: *Food safety; Nanotechnology; Public health.*

Introduction

Organic nanotechnology using organic nanoparticles is increasingly recognized as a pivotal innovation in the food production sector, particularly in the fields of food preservation, processing, packaging, and antimicrobial applications. By manipulating materials at the nanoscale (1 to 100 nanometers), nanotechnology enhances the sensory and chemical valuables of food products, believed to be a new technology to improve safety, productivity, quality, and economy. This technology integrates various scientific disciplines, including physics, chemistry, and biology, to create nanomaterials that exhibit unique characteristics, such as increased surface area and enhanced reactivity, which are essential for effective food preservation **Biswas *et al.* (2022).**

Through manipulating the structure and qualities of materials at this length scale, the food industry can employ these new technologies to track safety, improve shelf life, enhance flavor, improve food quality, and increase nutritional advantages **Onyeaka *et al.* (2022).**

For satisfying the expanding food demands, there must be a significant increase in agricultural output worldwide. The need for more food is continuously growing, and some researchers are focusing on using nanotechnology from their observations and believing that it will boost agricultural produce in places where traditional approaches fall short **Mariyam *et al.* (2024).**

Moreover, the nanotechnology application in food production allows for the development of nanoemulsions and nanocapsules that improve the accessibility and nutrient supply and bioactive substances. These innovations not only enhance the nutritional profile of food products but also preserve their sensory qualities, such as taste and texture **Neme *et al.* (2021).**

In the realm of food packaging, nanotechnology offers solutions that create active packaging systems capable of interacting with the food environment. These systems can release antimicrobial agents or absorb spoilage gases, thereby maintaining the freshness of food items. The use of nanocomposite materials in packaging has proven effective in providing barriers against moisture and oxygen, which are critical factors in food degradation **Gupta *et al.* (2024)**

Because it improves the efficiency of food supply chains and reduces food waste, nanotechnology is thought to have numerous benefits when included into food systems. The significance of nanotechnology in resolving customer concerns about food safety and quality is expected to grow as public knowledge of these issues rises, opening the door for creative solutions in the food sector **Sadeghi *et al.* (2017).**

In food preservation, nanotechnology introduces advanced methods to hinder microbial multiplication and expand the storage time of perishable food items. Food packaging materials contain nanoparticles, like silver and zinc NPs, which have antibacterial properties and efficiently lower contamination and spoiling. These nanoparticles generate ROS, reactive oxygen species, that can break down the bacterial DNA and proteins, thereby preventing the proliferation of pathogens and enhancing food safety **Ansari (2023)**.

In conclusion, there are several benefits to using nanotechnology in food processing, preservation, and packaging, especially when it comes to improving antibacterial qualities and prolonging shelf life.

We would like to note the concerns of the European Food Safety Authority **EFSA (2021)** about the potential risk to the health and safety of consumers from consuming foods to which those inorganic nanoparticles are added which previously mentioned in this article and the requirements that would prove whether or not there is harm to consumer or not.

However, because nanoparticles may migrate into food, the safety of using nanotechnology in packaging is complicated. Both the environment and human health may be at risk from nanostructure. The laws pertaining to packaging for nanotechnology differ greatly between the consumer **Ganeson *et al.* (2023) and Singh *et al.* (2023).**

Nanotechnology for food security, safety and productivity

To guarantee global food security, technology that boosts productivity while reducing food waste is required. Lately, nanotechnology has enabled the production of new items that aid in agriculture and an increase in the availability of food. This is particularly deserving when it comes to optimizing food production through pest control, keeping nutritional value as well as lowering fertilizer losses **Sadeghi *et al.* (2017)**.

More food must be produced due to the global population expansion, which means food quality regulations must be tightened. Some of the quality control tests that are now in use suffer from low sensitivity and undesirable detection constraints, which calls for the development of novel solutions to these issues **FAO (2017)**.

While this phenomenon is common in some developing countries, the situation in Egypt, particularly in research centers, is distinct. These research centers, such as the Animal Health Research Institute, have the necessary capabilities and accredited according to ISO 17025 stanards for testing and calibration laboratories, ensuring the guaranteeing the quality and safety of their food testing procedures.

Additionally, it can be used to enhance food processing, offer nanotechnology-based techniques for detecting and averting food spoilage, enhance the flavor and taste of newly developed food products, and increase the shelf life of already existing food materials **Rizvi *et al.* (2022).**

Nowadays, nanotechnology is seen as a developing field in almost every aspect of science drawing and being used extensively. Some of the primary applications of nanotechnology include food with nanoparticles packaging processes, the use of nano biosensors to identify infections and toxins, and the modification of food-related surfaces in nanoscale dimensions to prevent pathogen adherence and contamination **Dadmehr *et al.* (2022).**

One of the major supplications of nanotechnology in agriculture industry is the development of nanofertilizers and nanopesticides. These innovations enable more efficient nutrient delivery and pest control, reducing the volume of chemicals required while maximizing their effectiveness. For instance, nanofertilizers can provide controlled and targeted release of nutrients, minimizing losses and enhancing crop uptake, which is essential for improving soil fitness and reducing adverse ecological impact. Similarly, nanopesticides can offer precise pest management control, thereby decreasing the reliance on conventional chemical pesticides that often lead to soil and water contamination **Xiaojia *et al.* (2019).**

In addition to enhancing productivity through better nutrient and pest management, nanotechnology also facilitates precision agriculture. This approach utilizes nanosensors to monitor soil conditions, crop health, and environmental parameters in real-time. By providing accurate data on moisture levels, nutrient availability, and pest infestations, these sensors enable farmers to make informed decisions, optimizing resource use and improving crop yields. Moreover, nanotechnology can aid in the genetic modification of crops, allowing for the development of varieties that are more resilient to diseases and environmental stressors **Zain *et al.* (2023).**

Although GMF has many benefits, potential risks had been recorded **Alliance for Biointegrity, key FDA documents (2004); Schmidt, (2005)** such as:

Allergic reactions: There is a concern that GM foods could introduce new allergens or transfer existing allergens to new foods, potentially triggering allergic or toxic reactions in sensitive individuals.

Gene transfer: Some worry that genes from GM crops could transfer to bacteria in the human gut, potentially leading to antibiotic resistance or other health problems.

Unknown long-term effects: Because GM technology is relatively new; there are concerns about potential long-term health effects that may not be immediately apparent.

Increased pesticide use: Some GM crops are engineered to be resistant to herbicides, leading to concerns about increase use of these chemicals and their potential impact on human health.

Cross-pollination between GM crops and conventional breeding is also an issue of debate.

Refining oil destroys DNA, the genetic material of plants. Therefore, the use of plant engineering is not detectable in oils after refinement.

Additionally, by lowering post-harvest losses, the use of nanotechnology in agriculture promotes food security. By extending the shelf life of food items, nanomaterials can be used in packaging solutions to reduce waste and provide a more dependable food supply. This is especially important in areas where food supply networks could be disrupted **Wahab *et al.* (2024).**

Despite the promising benefits, the adoption of nanotechnology in agriculture must be approached with caution. Concerns regarding the safety and environmental impact of nanomaterials necessitate thorough research and regulatory oversight to ensure that these technologies do not pose risks to human health or ecosystems **Dhall *et al.* (2024).**

On the other hand, one of the other goals of nanotechnology applications in animal nutrition is the formulation of nanofeed, which incorporates nanoparticles to enhance nutrient delivery and absorption. Nanoparticles can improve the bioavailability of essential minerals and vitamins, leading to better growth rates and overall health improvement of livestock. For example, nano-minerals have been shown to enhance digestive efficiency and immunity, resulting in keeping the quality of meat, milk, and eggs. This targeted approach allows for lower feed intake while maximizing their effectiveness, which is particularly beneficial for livestock and poultry production **Gelaye (2023)**.

Additionally, nanotechnology facilitates the development of nanosensors and nanobiosensors that can monitor animal health in real-time. These devices can detect pathogens, monitor vital signs, and assess environmental conditions, enabling farmers to make informed decisions and intervene promptly when health issues arise. This level of precision in monitoring contributes to better disease management and reduced mortality rates among livestock, ultimately enhancing food security by ensuring a stable supply of animal products **Miguel-Rojas and Pérez-de-Luque (2023)**.

Moreover, nanotechnology plays a critical role in disease prevention and treatment. Nanoparticles can be utilized in vaccines and drug delivery systems that target specific pathogens, improving the efficacy of treatments while minimizing side effects. For instance, silver nanoparticles have demonstrated antimicrobial properties that can be advantageous in reducing infections in poultry and other livestock. This capability is crucial for maintaining animal health and productivity, particularly in intensive farming systems where disease outbreaks can have devastating impacts on food supply **Patra *et al.* (2018)**.

Using nanotechnology in food processing

Many food sectors are searching for novel ways to enhance food safety, quality, and nutritional value. Nanotechnology, which includes NPs, nano-encapsulation, and nano-based food additives, is being teste for use in the processing and production of food **Singh *et al.* (2023)**.

Because it makes it possible to create nanostructured food ingredients that improve taste, texture, and nutritional value, nanotechnology is essential to food processing. For example, to better distribute bioactive chemicals and increase their stability and bioavailability, nano-encapsulation techniques are used. This process makes it possible for nutrients and additives to be released gradually, guaranteeing their effectiveness for the duration of the product's shelf life **(Chudasama and Goyary, 2024)**.

Additionally, nanomaterials can make the sensory parameters of food better, masking undesirable flavors or odors and enhancing overall consumer acceptance. For example, nanocomposite coatings can be used to create active packaging that not only extends the shelf life of food products but also provides real-time monitoring of freshness by changing color in response to temperature variations **(Onyeaka *et al.*, 2022)**.

One important technology is nano-encapsulation, which entails enclosing active substances in nanocarriers. This procedure improves the stability of delicate substances, like vitamins and antioxidants, shielding them from deterioration throughout storage and processing. Functional meals and nutraceuticals benefit greatly from the controlled release of the encapsulated chemicals, which enables the targeted distribution of components that promote health **(Biswas *et al.*, 2022)**.

For instance, it has been demonstrated that lipid-based nano-encapsulation programs, nanoliposomes, greatly increase the solubility and availability of many nutrients and active principles. To improve the functional performance of food items, these programs may also be made to release their contents in reaction to particular triggers, including temperature or pH changes **Ashfaq *et al.* (2023).**

Nano-based food additives are increasingly being comprised into food items to improve their safety and quality. These additives can include antimicrobial agents, antioxidants, and preservatives that are engineered at the nanoscale to improve their effectiveness. For example, Because of their well-known antibacterial qualities, silver nanoparticles are employed in food packaging to prevent the growth of infections and spoilage organisms, increasing the keeping quality of food items.

As previously mentioned, citing scientific references and the findings of technical committees of food safety organizations, there is a need for further studies on the risk assessment of using inorganic nanoparticles on human health before widespread use in food processing is approved.

Food packaging materials' barrier qualities can be improved by nanocoatings, which lower the permeability of moisture and gases like carbon dioxide and oxygen. By reducing spoilage and preserving freshness, this helps food products last longer on the market. Furthermore, the growth of bacteria, fungus, and viruses on food surfaces can be prevented by adding antimicrobial nanoparticles (such as silver, zinc oxide, and titanium dioxide) to food coatings. This lowers the chance of foodborne infections and enhances food safety **Ansari (2023)**.

An appropriate nanocomposite film for acidic food under higher pressure handling procedures was suggested by a study that examined the poly lactic acid films with migrating AgNPs into simulants of acidic food upon high -pressure food processing (200 and 400 MPa) **Zhu *et al.* (2021).**

A nanocomposite film consisting of chitosan and *Urtica dioica* leaf extract produced from ZnO and copper oxide was developed in order to extend the life of guava fruits in packaging. This movie demonstrated antibacterial and antioxidant properties, suggesting that it could be a useful way to prolong the shelf life of fruits **Kalia *et al.* (2021)**.

To intensify the amalgamation of meat-like process flavors, an inquiry was conducted to synthesize soybean protein isolate that has been enzymatically degraded into nanoparticles, SiO2 nanoparticles are used in food waste nanomaterials to impart scents to food items **Fadel *et al.* (2019).**

Moreover, the application of nanomaterials in food additives can upgrade the overall nutritional profile of food products without altering their taste or appearance. This is especially crucial when making functional food products that offer health advantages beyond simple nourishment **Zhang *et al.* (2020).**

The migration rate of nanostructured materials is a critical factor to consider when using packaging of coatings for food products. This evaluation must include a hazard assessment for each substance, considering factors like carcinogenicity, mutagenicity, reproductive toxicity, bioaccumulation, endocrine disruption (ED), and genotoxicity. Specially in case of using non-organic nanoparticles, such as TiO_2 NP, ZnO NPs, Ag NPs, CuO NPs, and SiO_2 NPs.

While there may be advantages to using these nanoparticles in food packaging, it is important to note that international organizations and bodies that are concerned with food safety have also recommended the need for comprehensive safety assessments to make sure there are no risks to the environment or human health. In light of this, the French Agency for Food, Environmental and Occupational Health and Safety (ANSES) released a statement in 2021 on the risk assessment associated with exposure to the food additive titanium dioxide (E 171). In this regard, ANSES suggested more research on in vivo genotoxicity; EFSA thought this suggestion need to be reexamined until the current endeavor to characterize the physico-chemical properties of the food additive titanium dioxide (E 171) is accomplished.

It is possible to create nano-coatings that can precisely encapsulate and release active ingredients including minerals, tastes, and antioxidants. This makes it possible to supply advantageous ingredients precisely to improve the nutritional content and quality of food products **Awuchi *et al.* (2022).**

Nano-coatings, also, can help maintain the physical characters of food items, such as concictency, color, and appearance, by preventing physical and chemical changes during storage. Some common types of nano-based food coatings include chitosan NPs, cellulose nanofibers, nano-emulsions, solid lipid NPs and protein-based NPs **Algarni *et al.* (2022); Lee *et al.* (2022)**

These nano-coatings have been successfully involved to various food products to elongate their storage time and maintain quality. However, before they are widely used, it is imperative to address safety concerns regarding the possible toxicity of nanoparticles and make sure that food coatings based on nanotechnology are properly assessed for safety and regulatory compliance **de Oliveira Filho *et al.* (2021).**

Innovative food coatings based on biopolymers and nanocomposite technology are created, and they have active and intelligent temperature sensing properties. These coatings change color at 8°C to a deep purple, acting as temperature indicators **Kritchenkov *et al.* (2021).**

Longer-lasting and used as antifouling agents are two benefits of nanocomposites, which created by adding nanomaterials to the main matrix at modest loadings have demonstrated remarkably strong antifouling properties especially in canning **Kamal *et al.* (2016)**.

Nanomaterials enable enhanced sensory properties, elevated bioavailability, antimicrobial characters, and the conveyance of bioactive substances for meat production and packaging **Ramachandraiah *et al.* (2015)**, such as the recorded results by **Ceylan *et al.* (2020)** who recorded that the growth of psychrotrophic bacteria was decreased in the nanofibers-treated meat samples, and had a better textural profile (springiness and cohesiveness) at 4°C than the control group.

The daily production is altered by the nano-filtration process, which removes salt from lactose, and the heat and mass transfer capabilities of the packages are improved by the nanofabrication technology **Dasgupta *et al.* (2015)**. Additionally, the process of nano-encapsulation enhances the active compounds' thermal stability and photo stability, protects them from heat, moisture, and chemicals, and helps manage and release them **Zhang *et al.* (2014)**.

<u>Nanotechnology for nutrient and drug delivery in food production</u>

One of the most worldwide methods of nanotechnology is the encapsulation of food additives and components. Customers can customize foods that use nano-encapsulation to fit their dietary requirements and preferences. Nutrients, supplements, and additives for water-insoluble food components that are nano-encapsulated provide enhanced dispensability, extended release, and protective barriers **Abbas *et al.* (2009)**.

One of the many transportation-related goals of the delivery method is the conveyance of basic substances to the proper intended point of action. The distribution approach has also shielded the functional components from deterioration brought on by chemical or biological processes, preserving their functionality. Furthermore, the receiving system may also be able to regulate the releasing rate and the particular environmental circumstances that initiate the distribution of the functional component **Thang *et al.* (2023)**.

Food can have its nutritional content increased by adding nanocapsules. It is possible to improve nutritional absorption by incorporating nanoparticles into different diets. Using additives to increase the food matrix's shelf life and make it easier for the body to absorb them is another important function **Singh *et al.* (2023)**.

Because they don't settle, colloids, emulsions, and packed nanocapsules formed of nanoparticles have longer shelf life and longer product stability. Ultrasonic emulsification modifies the characteristics of treated materials by applying a high-intensity ultrasonic pulse. high-pressure homogenization, which enhances emulsion stability by reducing fat globule size by the employment of extra compartments, by creating emulsions with more compartments to decrease size and enhance texture and mouthfeel, a process known as microfluidization and dry processing, which physically breaks down materials into coarse particles using mechanical energy **Pathakoti *et al.* (2017)**.

The distribution plan must also consider the other stages of manufacture as well as the final product's physicochemical properties, which include its texture, flavor, appearance, and shelf life. Delivery techniques have been changed to incorporate functional materials because of their significance **Chau *et al.* (2007)**.

Hydrolyzed milk proteins, such as α-lactalbumin, possess the capacity to self-assemble into nanotubes, suggesting that they could serve as a naturally occurring source for the nano-encapsulation of medications, vitamins, and minerals helps overcome challenges related to nutrient solubility and degradation, ensuring that these compounds are effectively absorbed by the body upon consumption. For instance, nano-encapsulated nutrients can protect sensitive ingredients from environmental factors such as light, heat, and oxygen, thereby maintaining their efficacy and extending the shelf life of food products **Graveland-Bikker and De Kruif (2006); Arshad *et al.* (2021).**

Nutrient Delivery

Additionally, the invention of nanofertilizers that improve agricultural nutrient absorption is made possible by nanotechnology. By controlling the delivery of nutrients, these fertilizers may be designed to increase efficiency and decrease waste. According to studies, nanoparticles can greatly increase the soil's nutrient availability, which will improve crop yields and create healthier plants **Haydar *et al.* (2024).**

Drug Delivery

Nanotechnology is essential for administering medications and probiotics in animal nutrition, in addition to delivering nutrients. By directly delivering vaccinations and drugs to specific locations within an animal's body, nanoparticles can increase therapeutic effectiveness while reducing adverse effects. Antibiotics that are nanoencapsulated, for instance, may be more effective against animal infections, lowering the need for larger dosages and lowering the possibility of antibiotic resistance **Youssef *et al.* (2019).**

Furthermore, nanosensors can be integrated into feed and food products to monitor health and nutritional status in real-time. These sensors can detect specific biomarkers related to animal health, allowing for timely interventions and optimized feeding strategies, thus enhancing overall productivity **Neethirajan (2017)**.

Benefits and Challenges

The benefits of using nanotechnology for nutrient and drug delivery in food producing animals are substantial. Improved nutrient bioavailability leads to enhanced food quality and safety, while targeted drug delivery can promote animal health and make less environmental hazards of agricultural practices. Additionally, the ability to encapsulate flavors and aromas using nanotechnology can enhance the sensory experience of food, making it more satisfactory to consumers **Neme *et al.* (2021).**

But there are drawbacks to using nanotechnology in food production as well. It is necessary to address worries about the long-term impacts of nanoparticles on the environment and human health, as well as their possible toxicity. Continuous research is necessary to assess the safety profiles of nanomaterials, and regulatory frameworks must be put in place to guarantee their safe usage in food systems **Xuan *et al.* (2023).**

Using Nanotechnology in Food Packaging:

In order to keep longer food freshness and avoid deteriorating, the food industry has lately enhanced several food packaging techniques. Food packaging is important to keep packed food safe from toxins in the environment and microbes while they are being stored and transported**.** Nanotechnology has been believed to be one of the best technologies. Using nanoparticles in food packaging to control water vapor permeability, offer antimicrobial protection, and enhance freshness is an easy and dependable method.

It's amazing to note that a study used a carboxymethyl cellulose (CMC) shell and chitosan NPs adsorbed in the core to generate a biodegradable, dual-purpose 3D printed cushioning and antibacterial package. Good resilience and cushioning qualities were shown by this packaging for *S. aureus* and *E. coli* **Zhou *et al.* (2021)**.

The thermal stability and antioxidant capacity of titanium dioxide (TiO2) nanoparticles in chitosan/tannic acid demonstrated their potential for application in active food packaging **Roy *et al.* (2021)**. To create bio-composite films, biosorbed-AgNPs were produced from plant extracts and combined with PVA or chitosan polymers. By reducing *Ps. fluorescens* growth and boosting tensile strength, nanoparticles demonstrated antibacterial activity; Because of these qualities, they can be used in active packaging **Wang *et al.* (2021)**.

Under 3D paper tubes, zinc oxide (ZnO) nanoparticles were developed as an absorbent pad to retain raw chicken meat. It was shown that absorbent pads inhibited Campylobacter jejuni in raw chicken meat by immobilizing zinc oxide nanoparticles with a regulated release of Zn^{2+} **Hakeem *et al.* (2020).**

The Food and Drug Administration (FDA) in the United States regulates food packaging that comes into contact with food. Whereas, the European Union's (EU) laws are seen to be stricter, whereas US regulations are often more lenient **Mitrano and Wohlleben (2020)**. The FDA has suggested that more research be done to look into possible long-term effects, such as cytotoxicity, endocrine activity, immunotoxicity and allergenicity, chronic toxicity and carcinogenicity, reproductive and developmental toxicity, neurotoxicity, and effects on the gut microbiome. Additionally, the guidelines stress the significance of risk characterization, uncertainty analysis, hazard identification and characterization, and exposure assessment **EFSA (2021).**

Food packaging is an essential component of the food manufacturing process because it protects the food from environmental elements such as temperature, humidity, microbiological infection, ambient gaseous mixtures, spill proofing, and tempering. Every stage of the food manufacturing process involves packaging, yet the permeability and porosity of conventional food packaging materials is a major drawback. Packing materials can allow the passage of ambient gasses including water vapor **Sharma *et al.* (2017).**

Nanotechnology in packaging prevents nutrient loss and degradation while extending shelf life, safeguarding food safety. It seems that active packaging serves as an inert barrier against external variables and is also crucial for food preservation.

Usually, packaging solutions are involved that can adjust to changing environmental conditions. They function by scavenging gases or generating advantageous compounds like antioxidants or antimicrobials. These interactions enhance food durability in several packaging technologies, including enzyme immobilization, O2 scavengers, and antimicrobials. Controlled-release packaging is another application for nanocomposites in active packaging. In this case, they might serve as a means of delivering healthy nutrients like vitamins, minerals, and probiotics to enhance their absorption during meals **Graveland-Bikker and De Kruif, (2006); Youssef and El-Sayed (2018)**.

Food safety is ensured and shelf life is prolonged by nanotechnology in packaging by preventing nutrient loss and degradation. Food preservation seems to be significantly impacted by active packaging, which also acts as an inert barrier against environmental factors. Packaging alternatives can release beneficial substances like antioxidants or antimicrobials to act as gas scavengers. As a result of these interactions, several packaging advances that improve food stability include O2 scavengers, antimicrobial medications, and enzyme immobilization techniques **de Sousa *et al.* (2023)**.

Eco-friendly packaging that uses plant extracts, nanocomposite materials, and biodegradable components can reduce the harm that artificial packaging causes to the environment. The use of nanotechnology in food packaging is constantly evolving because oxides of nanostructured metals and nonmetals can outperform their oxide equivalents **Pereda *et al.* (2019).**

Food packaging migration occurs when additives diffuse from the polymeric matrix of the film or coating into the food or a food simulant **EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP), (2020).** Migration can be advantageous in certain situations, such as in intelligent and active packaging, where the food is protected by the controlled release of an active ingredient **Souza *et al.* (2019).** However, it can also result in the migration of harmful compounds that are harmful to human health, therefore contaminating the food.

The following are some of the elements that affect the migration process:

Contact time: The duration of contact between the food and the packaging during storage.

Temperature: Storage temperature and any temperature changes during processing or heating.

Type of contact: The nature of the interaction between the food and the packaging material.

Migrant properties: Characteristics of the migrating substances, such as molecular weight, volatility, and polarity.

Food properties: Composition, fat content, and other characteristics of the food.

The degree of migration impacts the toxicity of nanostructures, as higher concentrations of nanoparticles are generally associated with more severe adverse effects **DeLoid *et al.* (2017).**

Antimicrobial activity of nanomaterials as food additives

In addition, organic nanoparticles, natural antimicrobial agents like organic oils and acids have been nanoencapsulated to reach the desirable stability and antimicrobial efficacy in food applications. Nanoencapsulation allows the incorporation of these sensitive compounds into food products without altering their sensory properties **Pateiro *et al.* (2021)**.

Despite the fact that antimicrobial nanoparticles can greatly improve the safety and quality of food, it is imperative to address any possible toxicity issues and guarantee their safe application as food additives. To weigh the benefits of these nanomaterials against any possible hazards to the environment and public health, further study and regulatory monitoring are required **Suvarna *et al.* (2022)**.

Conclusion

However, nanotechnology is a novel and developing food technology that has potent antioxidant and antibacterial properties. The use of non-organic nanotechnology, represented by nano-oxides [nano-zinc oxide (ZnO NPs), titanium dioxide (TiO2 NP, etc.], in the food industry has raised serious concerns and can pose serious risks to consumer health, according to the previously mentioned references and the recommendations of international committees concerned with food safety. The migration of these materials into food products has prompted calls for further research in this area whether used directly as food additive or used in packaging materials. These studies ought to concentrate on evaluating the hazards of non-organic nanomaterials, specifically their toxicity, possible interactions with different kinds of food, long-term chronic toxicity studies, and their capacity to react and change into crystalline substances in the intestinal tract. Furthermore, studies should be forward also to all factors that control these risks as temperature, humidity, hydrogen ion concentration, contact time, food properties and the concentration of non-organic nanoparticles in the food, so that the field is not open to use any random quantities of those oxides nanoparticles which may have a harmful effect on the health of the consumer on short or long term more than its benefits.

References

Abbas, K.; Saleh, A.; Mohamed, A. and MohdAzhan, N. (2009). The recent advances in the nanotechnology and its applications in food processing: a review. Food Agric. Environ. 7: 14–17.

Algarni, E.; Elnaggar, I.; Abd El-Wahed, A.; Taha, I.; Al-Jumayi, H.; Elhamamsy, S.; Mahmoud, S. and Fahmy, A. (2022). Effect of chitosan nanoparticles as edible coating on the storability and quality of apricot fruits. Polymers 14(11): 2227.

Alliance for Biointegrity (2004). Key FDA documents revealing (1) Hazards of genetically engineered foods and (2) Flaws with how the agency made its policy. Available on: http://www.biointegrity.org/list.html

Ansari, M.A. (2023). Nanotechnology in food and plant science: Challenges and future prospects. Plants 12: 2565.

Arshad, R.; Gulshad, L.; Haq, I.U.; Farooq, M.A.; Al-Farga, A.; Siddique, R.; Manzoor, M.F. and Karrar, E. (2021). Nanotechnology: A novel tool to enhance the bioavailability of micronutrients. Food Sci. Nutr. 9(6): 3354-3361.

Awuchi, C.; Morya, S.; Dendegh, T.; Okpala, C and Korzeniowska, M. (2022). Nanoencapsulation of food bioactive constituents and its associated processes: A revisit. Bioresource Technol. Rep. 19: 101088.

Biswas, R.; Alam, M.; Sarkar, A.; Haque, I.; Hasan, M. and Hoque, M. (2022). Application of nanotechnology in food: processing, preservation, packaging and safety assessment. Heliyon 8(11): 11795.

Ceylan, Z.; Meral, R.; Alav, A.; Karakas, C.Y. and Yilmaz, M.T. (2020). Determination of textural deterioration in fish meat processed with electrospun nanofibers. J. Texture Stud. 51: 917–924.

Chau, C.F.; Wu, S.H. and Yen, G.C. (2007). The development of regulations for food nanotechnology. Trends Food Sci. Technol. 18 (5): 269–280.

Chudasama, M. and Goyary, J. (2024). Nanostructured materials in food science: Current progress and future prospects. Next Materials 5: 100206.

de Oliveira Filho, J.; Miranda, M.; Ferreira, M. and Plotto, A. (2021). Nanoemulsions as edible coatings: A potential strategy for fresh fruits and vegetables preservation. Foods 10 (10): 2438.

de Sousa, M.S.; Schlogl, A.E.; Estanislau, F.R.; Souza, V.G.; dos Reis Coimbra, J.S. Santos, I.J. (2023). Nanotechnology in packaging for food industry: Past, present, and future. Coatings 13(8): 1411.

Deloid, G.M.; Wang, Y.; Kapronezai, K.; Lorente, L.R.; Zhang, R.; Pyrgiotakis, G.; Konduru, N.V.; Ericsson, M.; White, J.C. and De La Torre-Roche, R. (2017). An integrated methodology for assessing the impact of food matrix and gastrointestinal effects on the biokinetics and cellular toxicity of ingested engineered nanomaterials. Particle and Fibre Toxicol. 14: 1-17.

Dhall, S.; Nigam, A.; Harshavardhan, M.; Mukherjee, A. and Srivastava, P. (2024). A comprehensive overview of methods involved in nanomaterial production and waste disposal from research labs and industries and existing regulatory guidelines for handling engineered nanomaterials. Environ. Chem. Ecotoxicol. 6: 269-282.

EFSA (European Food Safety Authority) (2021). Guidance on risk assessment of nanoparticles to be applied in food and feed chain. Human and animal health, EFSA Journal. EFSA Scientific Committee, 2021.

EFSA Panel on Food Contact Materials, Enzymes and processing Aids (CEP). Silano, V.; Barat Bavicra, J.M.; Bolognesi, C.; Chesson, A.; Cocconcelli, P.S.; Crebelli, R.; Gott, D.M.; Grob, K. and Lambr, C. (2020). Review and priority setting for substances that are listed without a specific migration limit in Table 1 of Annex 1 of Regulation 10/2011 on plastic materials and articles intended to come into contact with food. EFSA Journal 18(6): 6124.

Fadel, H.; Mahmoud, K.; Saad, R.; Lotfy, S.; El-Aleem, F. and Ahmed, M. (2019). Nanotechnology for enhancing the production of meat-like flavour from enzymatic hydrolyzed soybean protein isolate. Acta Sci. Pol. Technol. Aliment. 18: 279–292.

FAO (2017). The future of food and agriculture: Trends and challenges. [online resource]. Available at https://openknowledge.fao.org/server/api/core/bitstreams/2e90c833-8e84-46f2-a675-ea2d7afa4e24/content. Retrieved on Sept., 2024.

Ganson, K.; Mouriya, G.K.; Bhubalan, K.; Razifah, M.R.; Jasmine, R.; Sowmiya, S.; Amirul, A.; Vigneswari, S. and Ramakrishna, S. (2023). Smart packaging- A pragmatic solution to approach sustainable food waste management. Food Packaging and Shelf Life, 36, 101044.

Gelaye, Y. (2023). Application of nanotechnology in animal nutrition: Bibliographic review. Cogent. Food & Agric., 10: 2290308.

Graveland-Bikker, J. and De Kruif, C. (2006). Unique milk protein based nanotubes: food and nanotechnology meet. Trends Food Sci. Technol. 17(5): 196–203.

Gupta, R.K.; Abd El Gawad, F.; Ali, E.; Karunanithi, S.; Yugiani, P. and Srivastav, P. (2024). Nanotechnology: Current applications and future scope in food packaging systems. Measurement: Food 13: 100131.

Hakeem, M.J.; Feng, J.; Nilghaz, A.; Ma, L.; Seah, H.C.; Konkel, M.E. and Lu, X. (2020). Active packaging of immobilized zinc oxide nanoparticles controls *Campylobacter jejuni* in raw chicken meat. Appl. Environ. Microbiol. 86: 1195-2000.

Haydar, S.; Ghosh, D. and Roy, S. (2024). Slow and controlled release nanofertilizers as an efficient tool for sustainable agriculture: Recent understanding and concerns. Plant Nano Biol. 7: 100058.

Kalia, A.; Kaur, M.; Shami, A.; Jawandha, S.K.; Alghuthaymi, M.; Thakur, A. and Abd-Elsalam, K. (2021). Nettle-leaf extract derived ZnO/CuO nanoparticle-biopolymer-based antioxidant and antimicrobial nanocomposite packaging films and their impact on extending the post-harvest shelf life of guava Fruit. Biomolecules 11: 224.

Kamal, T.; Ali, N.; Naseem, A.; Khan, S. and Asiri, A. (2016). Polymer nanocomposite membranes for antifouling nanofiltration. Recent Patents Nanotechnol. 10: 189–201.

Kritchenkov, A.S.; Egorov, A.R.; Volkova, O.V.; Artemjev, A.A.; Kurliuk, A.V.; Le, T.A.; Truong, H.H.; Le-Nhat-Thuy, G.; Thi, T.V. and Van Tuyen, N. (2021). Novel biopolymer-based nanocomposite food coatings that exhibit active and smart properties due to a single type of nanoparticles. Food Chem. 343: 128676.

Lee, D.; Shayan, M.; Gwon, J.; Picha, D. and Wu, Q. (2022). Effectiveness of cellulose and chitosan nanomaterial coatings with essential oil on postharvest strawberry quality. Carbohydrate Polymers 298: 120101.

Mariyam, S.; Upadhyay, S.; Chakraborty, K.; Verma, K.; Duhan, J.; Muneer, S.; Meena, M.; Sharma, R.; Ghodake, G. and Seth, C. (2024). Nanotechnology, a frontier in agricultural science, a novel approach in abiotic stress management and convergence with new age medicine-A review. Sci. Total Environ. 912: 169097.

Miguel-Rojas, C. and Pérez-de-Luque, A. (2023). Nanobiosensors and nanoformulations in agriculture: new advances and challenges for sustainable agriculture. Emerg. Top Life Sci. 7(2): 229-238.

Mitrano, D.M. and Wohlleben, W. (2020). Microplastic regulation should be more precise to incentivize both innovation and environmental safety. Nature Comm. 11(1): 5324.

Neethirajan, S. (2017). Recent advances in wearable sensors for animal health management. Sensing and Bio-Sensing Res. 12:15-29.

Neme, K.; Nafady, A.; Uddin, S. and Tola, Y.B. (2021). Application of nanotechnology in agriculture, postharvest loss reduction and food processing: food security implication and challenges. Heliyon 7: 8539.

Onyeaka, H.; Passaretti, P.; Miri, T. and Al-Sharify, Z. (2022). The safety of nanomaterials in food production and packaging. Curr. Res. Food Sci. 5: 763-774.

Pateiro, M.; Gómez, B.; Munekata, P.E.; Barba, F.J.; Putnik, P.; Kovačević, D.B. and Lorenzo, J.M. (2021). Nanoencapsulation of promising bioactive compounds to improve their absorption, stability, functionality and the appearance of the final food products. Molecules 26(6): 1547.

Pathakoti, K.; Manubolu, M. and Hwang, H.M. (2017). Nanostructures: current uses and future applications in food science. J. Food Drug Anal. 25(2): 245–253.

Patra, J.K.; Das, G. and Fraceto, L.F. (2018). Nano based drug delivery systems: recent developments and future prospects. J. Nanobiotechnol. 16: 71.

Pereda, M.; Marcovich, N. and Ansorena, M.R. (2019). In: Handbook of Ecomaterials. Martínez L.M.T., Kharissova O.V., Kharisov B.I., editors. Springer International Publishing; Cham: 2019. Nanotechnology in food packaging applications: barrier materials, antimicrobial agents, sensors, and safety assessment; pp. 2035–2056.

Ramachandraiah, K.; Han, S. and Chin, K. (2015). Nanotechnology in meat processing and packaging: Potential applications—A Review. Asian-Australas J. Anim. Sci. 28: 290–302.

Roy, S.; Zhai, L.; Kim, H.; Pham, D.; Alrobei, H. and Kim, J. (2021). Tannic-acid-cross-linked and TiO_2-nanoparticle-reinforced chitosan-based nanocomposite film. Polymers 13: 228.

Sadeghi, R.; Rodriguez, R.J.; Yao, Y. and Kokini, J.L. (2017). Advances in nanotechnology as they pertain to food and agriculture: Benefits and risks. Annu. Rev. Food Sci. Technol. 8: 467–492.

Sharma, C.; Dhiman, R.; Rokana, N. and Panwar, H. (2017). Nanotechnology: an untapped resource for food packaging. Front. Microbiol. 8: 1735.

Shmidt, C.W. (2005). Genetically modified foods: Breeding uncertainty. Env. Health Perspect. 113: 527-533.

Singh, R.; Dutt, S.; Sharma, P.; Sundramoorthy, A.K.; Dubey, A.; Singh, A. and Arya, S. (2023). Future of nanotechnology in food industry: Challenges in processing, packaging, and food safety. Glob. Chall. 7 (4): 2200209.

Souza, V.G.; Rodrigues, C.; Ferreira, L.; Pires, J.R.A.; Duarte, M.P.; Coelhoso, I. and Fernando, A.L. (2019). In vitro bioactivity of novel chitosan bionanocomposites incorporated with different essential oils. Industrial Crops and Products 140: 1 11563.

Suvarna, V.; Nair, A.; Mallya, R.; Khan, T. and Omri, A. (2022). Antimicrobial nanomaterials for food packaging. Antibiotics 11 (6): 729.

Thang, N.H.; Chien, T.B. and Cuong, D.X. (2023). Polymer-based hydrogels applied in drug delivery: An overview. Gels 9(7): 523.

Wahab, A.; Muhammad, M.; Shahid, U.; Gholamreza, A.; Ghulam, M.; Wajid, Z. and Ayaz, A. (2024). Agriculture and environmental management through nanotechnology: Eco-friendly nanomaterial synthesis for soil-plant systems, food safety, and sustainability. Sci. Total Environ. 926: 171862.

Wang, L.; Periyasami, G.; Aldalbahi, A. and Fogliano, V. (2021). The antimicrobial activity of silver nanoparticles biocomposite films depends on the silver ions release behaviour. Food Chem. 359: 129859.

Xiaojia, H.; Hua, D. and Huey-Min, H. (2019). The current application of nanotechnology in food and agriculture. J. Food Drug Anal. 27: 1-21.

Xuan, L.; Ju, Z.; Skonieczna, M.; Zhou, P.K. and Huang, R. (2023). Nanoparticles-induced potential toxicity on human health: Applications, toxicity mechanisms, and evaluation models. MedComm. 4(4): 327.

Youssef, A.M. and El-Sayed, S.M. (2018). Bionanocomposites materials for food packaging applications: concepts and future outlook. Carbohydr. Polym. 193: 19–27.

Youssef, F.S.; El-Banna, H.A.; Elzorba, H.Y. and Galal, A.M. (2019). Application of some nanoparticles in the field of veterinary medicine. Int. J. Vet. Sci. Med. 7(1): 78 -93.

Zain, M.; Ma, H.; Nuruzzaman, S.; Chaudhary, S.; Nadeem, M.; Shakoor, N.; Azeem, I.; Duan, A.; Sun, C. and Ahamad, T. (2023). Nanotechnology based precision agriculture for alleviating biotic and abiotic stress in plants. Plant Stress 10: 100239.

Zhang, J.; Hu, S.; Du, Y.; Cao, D.; Wang, G. and Yuan, Z. (2020). Improved food additive analysis by ever-increasing nanotechnology. J Food Drug Anal. 28(4): 622-640.

Zhang, T.; Lv, C.; Chen, L.; Bai, G.; Zhao, G. and Xu, C. (2014). Encapsulation of anthocyanin molecules within a ferritin nanocage increases their stability and cell uptake efficiency. Food Res. Int. 62: 183–192.

Zhou, W.; Fang, J.; Tang, S.; Wu, Z. and Wang, X. (2021). 3D-Printed nanocellulose-based cushioning–antibacterial dual-function food packaging aerogel. Molecules 26: 3543.

Zhu, B.; Fan, C.; Cheng, C.; Lan, T.; Li, L. and Qin, Y. (2021). Migration kinetic of silver from polylactic acid nanocomposite film into acidic food simulant after different high-pressure food processing. J. Food Sci. 86: 2481–2490.