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FOOD SCIENCE FOR THE FUTURE: TECHNOLOGY, SAFETY AND SUSTAINABILITY

Food Science for the Future:

TECHNOLOGY, SAFETY AND SUSTAINABILITY



Editors : -
Soumya Sucharita Sahoo
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Shreejaya Sivadas
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Preface

The global food industry is undergoing a transformative phase, driven by rapid advancements in technology, increasing concerns about food safety, and the urgent need for sustainable practices. *Food Science for the Future: Technology, Safety, and Sustainability* is a comprehensive exploration of these critical themes, offering insights into the innovative solutions shaping the future of food production, preservation, and consumption.

This book brings together contributions from leading experts in the field, covering a wide range of topics—from emerging non-thermal preservation technologies like cold plasma and pulsed light to the revolutionary applications of nanotechnology in food science. It also delves into the growing significance of functional foods and nutraceuticals, highlighting their role in promoting health and preventing diseases. Each chapter is meticulously researched, providing a blend of theoretical foundations, practical applications, and future directions.

The editors have carefully curated this volume to serve as a valuable resource for academics, researchers, industry professionals, and policymakers. Whether you are exploring novel food preservation techniques, investigating the safety and efficacy of nanomaterials, or analyzing market trends in functional foods, this book offers a holistic perspective on the challenges and opportunities in modern food science. We extend our gratitude to the contributors for their expertise and dedication, and we hope this work inspires further innovation and collaboration in the pursuit of safer, healthier, and more sustainable food systems.

Editors

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CHAPTER-2

ROLE OF NANOTECHNOLOGY IN FOOD SCIENCE: APPLICATION AND SAFETY CONSIDERATIONS

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Abstract

Nanotechnology plays a transformative role across food, medicine, and agriculture sectors by enabling the development of nanomaterials that improve the quality, safety, and shelf life of perishable and semi-perishable foods. Its advantages over conventional processing methods include enhanced preservation, contamination prevention, and the ability to produce healthier, safer, and high-quality functional foods with increased durability. This advanced technology supports sustainable development by reducing waste, extending product longevity, and ensuring better nutritional profiles, ultimately contributing to improved public health and food security. This book chapter highlights the promising advancements in nanotechnologies for functional food development, emphasizing how nanomaterials can improve bioavailability, taste, texture, and consistency through manipulation of particle size, clustering, and surface charge. It explores innovative applications such as nano delivery systems for nutraceuticals, nanomaterials' synergistic roles in food protection, and the integration of nanosensors in smart packaging for real-time quality monitoring. Additionally, it discusses current methodologies for evaluating the biological impacts of nanomaterials, underscoring their potential to revolutionize food safety, preservation, and personalized nutrition while also considering future directions and challenges in the field.

Keywords: Nanoparticles, Food processing, Active packaging, Smart packaging and Food safety.

Introduction

Nanotechnology's application in the food industry leverages the unique properties of nanomaterials, which due to their nanoscale dimensions (1-100 nm), exhibit enhanced strength, reactivity, and barrier properties. These advancements facilitate improved food packaging for better shelf life, targeted delivery of nutrients or antimicrobials, and innovative processing techniques that enhance food safety and quality. However, the integration of nanomaterials also necessitates careful assessment of safety and regulatory considerations to ensure consumer health and environmental protection. Nanomaterials' exceptional properties, driven by their high surface area-to-volume ratio and novel characteristics, are transforming sectors such as medicine, agriculture, and food by enabling the development of innovative systems and materials. The increasing investment in nanotechnology by both developed and developing countries highlights its vast potential to revolutionize industries through advancements like targeted drug delivery, enhanced crop protection, and improved food safety. This rapid growth underscores nanotechnology's role in creating sustainable, efficient, and groundbreaking solutions across various fields, promising significant societal and economic benefits (Rai *et al.*, 2018; Gupta *et al.*, 2016).

Nanoparticles are increasingly being explored by the food industry as a means to enhance food quality, leveraging their non-toxic nature and ability to incorporate beneficial components, although they may not directly boost nutritional content. Nanotechnology significantly advances food safety, quality, and health benefits by enabling the creation of innovative materials and solutions for food production, processing, and packaging, such as nanosensors for detecting contaminants, nanomaterials for improved food preservation, and packaging that extends shelf life and prevents spoilage, thereby ensuring safer and higher-quality food products for consumer (Roselli *et al.*, 2003; Dasgupta *et al.*, 2015).

Nanomaterials' stability under high temperatures and pressures has spurred their adoption in the food industry, primarily through two key applications: the development of food nanostructured ingredients, which can enhance texture, flavor, and nutritional content, and food nanosensing, which enables precise detection of contaminants, pathogens, and quality parameters, ultimately leading to safer, more innovative, and better-quality food products. Nanostructured food ingredients offer versatile benefits across the food industry, serving as processing aids such as additives and targeted nutrient delivery systems to enhance nutritional value and functionality, while also improving packaging through anti-caking and antimicrobial properties to extend shelf life and ensure safety. Additionally, food nanosensing technologies enable precise, real-time monitoring of quality and safety parameters during processing, facilitating early detection of contaminants or spoilage and thereby ensuring higher standards of food safety and quality control (Ezhilarasi *et al.*, 2013; Dasgupta *et al.*, 2015).

Definition

Richard Feynman's 1959 lecture *There's Plenty of Room at the Bottom* is widely regarded as the conceptual foundation of nanotechnology, as he envisioned the possibility of manipulating individual atoms and molecules, foreshadowing future advancements in controlling matter at the atomic level. Although he did not coin the term nanotechnology, his ideas sparked interest in the scientific community about the potential for precise atomic-scale engineering, leading to innovations in medicine, materials science, electronics, and beyond. This pioneering vision has since inspired decades of research and technological development in the nanoscale realm (Findik, 2021). Nanotechnology, which began in the 1980s with breakthroughs such as the invention of the Scanning Tunneling Microscope in 1981 and the discovery of fullerenes in 1985, involves controlling and manipulating matter at the nanoscale, leading to significant advancements like the creation of nanopowders used across various

industries. Recognized as a defining technology of the 21st century, it builds upon these foundational discoveries to enable innovations in materials science, medicine, electronics, and energy, highlighting its broad and transformative impact. These powders, a product of this advanced field, hold significant potential across numerous sectors (Afolalu *et al.*, 2019).

The term ‘nano’ originates from the Greek word ‘nanos,’ meaning dwarf or very small, and is used internationally as a prefix in the metric system to denote a factor of one billionth (10^{-9}) of a unit. For example, a nanometer is one billionth of a meter, a nanoliter is one billionth of a liter, and a nanokelvin is one billionth of a Kelvin, emphasizing the extremely small scale or quantity associated with this prefix. The prefix nano has experienced a significant surge in application across various scientific fields over the past decade, making it a prominent label in modern science and increasingly prevalent in scientific literature. At its core, the defining feature of nanoparticles, which fall within the 1 to 100 nanometer size range, is their nanoscale dimension, a critical attribute that imparts unique physical, chemical, and biological properties to these materials, thereby enabling diverse advancements in areas such as medicine, electronics, and material science (Afolalu *et al.*, 2019; Findik, 2021). Nanotechnology encompasses materials, systems, and structures with dimensions ranging from 1 to 100 nanometers. Advances in instrumentation and fabrication techniques enable the creation of intricate structures at the atomic and molecular levels. The advancements in nanotechnology, facilitated by specific techniques, have spurred the emergence of diverse interdisciplinary fields like nanobiotechnology and nanochemistry. These new materials have expanded applicability across numerous industries. While promising for various applications, the potential environmental and human health risks of nanoparticles, particularly those used in food and nutrition, are not fully understood. Further research is needed to assess the safety of these materials. The potential for nanomaterials to

penetrate the human body raises serious concerns about their safety. A British Royal Society report warns of a possible nanotoxicity catastrophe if the environmental and health effects of nanoparticle exposure aren't fully understood. This report suggests a cautious approach, advocating against the use of nanotechnology in products until the risks are better understood (Dowling *et al.*, 2006; Findik, 2021).

The primary concern regarding human exposure to nanoparticles is their potential for diverse entry routes into the body (skin, lungs, digestive tract), subsequent systemic transport, tissue accumulation (including the brain), and consequent immunological responses. Concerns exist regarding the potential health risks of food nanoparticles, prompting calls for safety evaluations before widespread commercialization. Some researchers link these particles to asbestos-like properties and suggest possible genetic modifications as a consequence. Advocacy groups like the ETC Group are urging a pause in nanotechnology product development until safety is definitively established. The public's demand for safety assurances regarding nanotechnology in food is growing due to its pervasive presence in food packaging, agriculture, processing, and the food itself, despite ongoing debates about its impact.

The burgeoning market for nanoproducts, particularly in agriculture and food processing, is driven by the unique properties of nanoparticles. The estimated USD 20 billion in 2006 food sector nanoproducts highlights the potential for enhanced food production, safety, nutrition, and quality, critical for meeting the needs of a growing global population (Joudeh and Linke, 2022). This discussion will explore the potential downsides of nanotechnology, including its effects on human health and the environment, alongside its applications in the food and other sectors.

Types and Classification of Nanomaterials in Food Industry

Generally, nanoparticles classified into two main groups on the basis of their origin *i.e.* natural and artificial nanoparticles.

Natural Nanoparticles

Natural nanomaterials are ubiquitous in nature and encompass a diverse range of forms such as viruses, protein molecules, clay minerals, natural colloids like milk and blood, aerosols like fog, gels like gelatin, mineralized structures like shells, corals, and bones, as well as biological and mineral-based materials like insect wings, opals, spider silk, lotus leaves, gecko feet, volcanic ash, and ocean spray, all exhibiting unique nanoscale features that contribute to their specific functions and properties (Zhang *et al.*, 2021).

Artificial nanoparticles

On the other hand, carbon nanotubes and quantum dots exemplify engineered nanomaterials intentionally synthesized with precise control over their size, shape, and properties through advanced manufacturing techniques. These artificial nanomaterials are categorized based on their structural composition into metal-based materials, dendrimers, or composites, reflecting their unique architectures and functionalities, which enable their widespread application in areas like electronics, medicine, and energy storage (Cho *et al.*, 2019; Zhang *et al.*, 2021).

Nanomaterials, which include powders and solutions, demonstrate unique chemical and physical properties at the nanoscale that differ significantly from their bulk counterparts, despite sharing the same chemical composition. This distinctive behaviour arises from their high surface area to volume ratio and quantum effects, enabling enhanced reactivity, strength, and functionality. In the food industry, these properties are exploited to improve product stability, bioavailability of nutrients, packaging, and safety. Nanomaterials are classified based on particle size, structure (such as spherical, fibrous, or tubular), and characteristics like surface charge or coating, which influence their specific applications and behaviors in various food-related processes (Chellaram *et al.*, 2014; Grumezescu and Holban, 2018).

- Nanoparticles,
- Nanocapsules,
- Nanoclays
- Nanoemulsions
- Nanotubes
- Nanofibers
- Nanolaminates

Nanomaterials offer diverse applications in the food industry, with preparation methods varying widely. Nanoparticles, with their size ranging from 1 to 100 nanometers, exhibit unique chemical, physical, and mechanical properties, leading to enhanced performance compared to their larger counterparts. Categorized by size, morphology, and composition, these nanoscale systems have garnered significant interest for their diverse applications (Saleh, 2020).

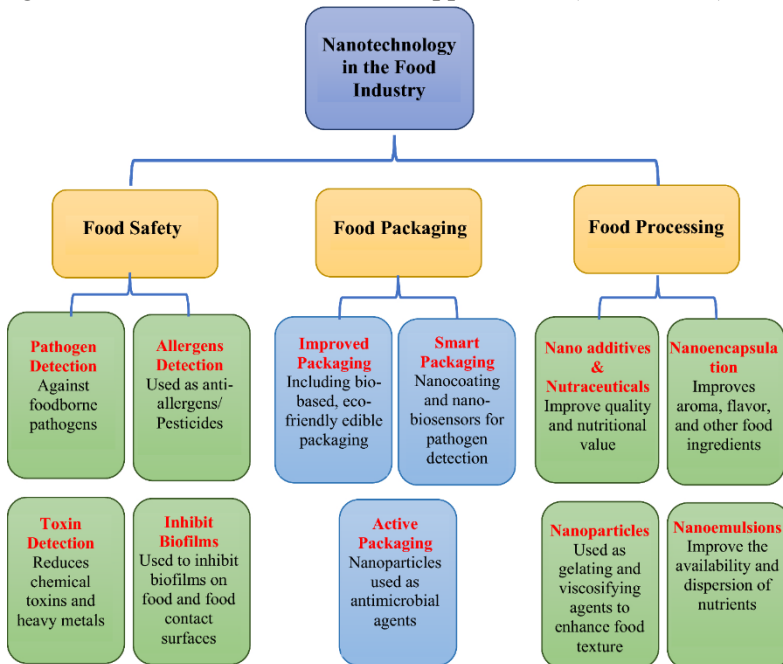


Figure 1: Nanotechnology in the food processing (Zahra *et al.*, 2022).

Biopolymeric nanoparticles

Biopolymeric nanoparticles, composed of food-grade protein and polysaccharide biopolymers, can be produced via various methods like emulsification, desolvation, coacervation, and electrospray drying. Coacervation, derived from the Latin *acervate* meaning heap, is a process similar to desolvation. It involves mixing a homogenous polymer solution with an organic solvent (like acetone) to create a concentrated polymer phase (coacervate). This nanomaterial is commonly used to encapsulate and deliver micronutrients like vitamins, iron, and proteins. Biodegradable nanoparticles derived from synthetic polymers (like PLGA) or natural polymers (like agarose, chitosan, collagen, and fibrin) are the prevalent carriers for this purpose. Nanoparticles enhance bio-nanosensors performance by providing a large surface area for enzyme immobilization, leading to improved enzyme efficiency and decreased substrate diffusion resistance. Their small size compared to bulk materials further contributes to these benefits (Yu *et al.*, 2018; Verma *et al.*, 2020).

Nanoemulsion

Nanoemulsions are a type of nanomaterial formed by dispersing small droplets (less than 500 nm) of one liquid within another immiscible liquid, like oil and water. Oil-in-water (o/w) emulsions result from oil droplets dispersed in water, while water-in-oil (w/o) emulsions feature water droplets in oil. Food nanoemulsions are valuable for delivering hydrophobic compounds like nutraceuticals, colorings, flavorings, and antimicrobials. These systems can also create biodegradable coatings and packaging films, enhancing food quality, nutritional value, and shelf life. Nanoclay, composed of layered silicate minerals, forms complex clay crystallites through the stacking of its layered structural units. Nanoclays, encompassing various types like montmorillonite and bentonite, are readily available, inexpensive, and environmentally benign materials. Their diverse applications are being explored across numerous fields due to their unique properties.

Nanoclay natural nanolayer structure effectively prevents gas and moisture penetration, making it a common additive in food packaging. Nanoclay-polymer composites, incorporating materials like polystyrene, polyamides, polyolefins, polyurethane, nylons, and epoxy resins with nanoclay, show promise for food packaging applications. These composites are potentially suitable for cheeses, confectioneries, processed meats, and cereal products, as well as for extrusion-coating fruit juices and liquid dairy products. Nanolaminates are coatings composed of multiple thin layers of food-grade materials; each less than 100 nanometers thick. However, Film thickness is dictated by the number of deposited layers, which can be assembled through various chemical interactions like electrostatic, hydrogen, hydrophobic, charge-transfer, and covalent bonding (Acevedo-Fani *et al.*, 2017).

Nanolaminates, composed of proteins, lipids, and polysaccharides, are increasingly used in food packaging and other food sector applications. Further research could lead to novel nanolaminate films with diverse applications in the food industry. Nanolaminates, a type of edible coating or film, can be applied to various food products, acting as barriers against moisture, gases, and lipids. They can also deliver functional components like flavors, colors, antimicrobial agents, and antioxidants. Nanocapsules, another emerging technique, encapsulate bioactive compounds within nanoscale structures, offering controlled release and enhanced stability. This nanotechnology promises significant benefits for the food industry by enabling the addition of nutrients without altering sensory or product quality. It facilitates the incorporation of novel or otherwise difficult-to-integrate nutrients, enhances nutrient absorption, and potentially extends shelf life. These improvements position nanoencapsulation as a valuable emerging technology (Ravichandran, 2010).

Nanotubes, derived from proteins like A-Lactalbumin, show promise in food applications, particularly for enzyme immobilization and as encapsulating agents. Their ability to withstand high pasteurization

temperatures (72°C for 40s) makes them potentially useful in various food processing methods. Nanofibers are nanomaterials with diameters between 10 and 1000 nanometers, often produced by electrospinning, a process where a polymer solution is forced through a small nozzle and subjected to an electric field to form thin, solid strands. Nanofibers are increasingly relevant in food packaging and artificial foods, offering potential as a platform for bacterial cultures. Their expanding use in the food industry is anticipated, given the growing applications of nanotechnology in this sector (Ameta *et al.*, 2020).

Role of Nanotechnology in Food Science

Nanotechnology is revolutionizing food science by improving food quality, extending shelf life, and enhancing food security through innovative processing techniques and packaging materials. Its application enables the detection of harmful pathogens like *E. coli* and *Salmonella*, as well as toxins and pesticides in food samples, thereby ensuring safer and more reliable food for consumers. Nanotechnology enhances food quality by improving sensory characteristics and consumer appeal, while also extending shelf life. It achieves this through methods like encapsulating nutrients for better absorption, using antimicrobial nanoparticles for preservation, and creating nanosensors to quickly detect contaminants (Zahra *et al.*, 2022).

Nanotechnology is being applied to food production, creating nanofood through its use in processing, packaging, and storage. This involves utilizing nanoparticles to improve various food characteristics, such as flow, flavor, stability, and color, and to increase shelf life. Nanotechnology offers enhanced food preservation by creating packaging materials that release antimicrobial agents and act as barriers against moisture and gas exchange. These materials must also provide protection, temperature resistance, and specific physical, chemical, and biological properties to ensure extended shelf life.

Application of Nanotechnology in Food

Food Processing

Nanotechnology offers promising solutions for extending food shelf life by incorporating antimicrobial packaging materials that prevent moisture and gas exchange. Enhanced protection, temperature resistance, and tailored physical, chemical, and biological properties in food packaging are crucial for successful application. Food processing encompasses methods for transforming raw ingredients into edible products. This involves various techniques like washing, slicing, cooking, heat treatments, fermentation, and freezing, all aimed at preserving and preparing food for consumption (Pradhan *et al.*, 2015). Food processing aims to extend shelf life, facilitate transport, and improve food quality through methods that inhibit microbial growth, remove toxins, and enhance uniformity. These processes allow for longer storage and wider distribution of food products compared to fresh counterparts (Chellaram *et al.*, 2014). These techniques improve food quality and safety by preserving sensory attributes and preventing spoilage-causing pathogens. However, processing and subsequent storage can lead to nutrient loss, and plastic containers effectively extend shelf life with minimal added weight (Pradhan *et al.*, 2015). Nanotechnology offers potential applications in food production, including enhancing food color and sensory qualities, improving bioavailability and absorption, and enhancing postharvest processing. These applications aim to increase food's nutritional value and sensory appeal (Faridi Esfanjani *et al.*, 2018).

➤ **Food Additives**

Anticaking Agents

Solidification or caking of food powders generally found during processing, handling and storage. This caking can decrease the functional properties and quality of food products due to the formation of lumps. In addition to, caking also affects the rehydration property of food, on the other hand, it also affects the sensory properties of food

and lower the shelf-life of food. This process triggered by environmental moisture in crystalline components, begins with the development of liquid bridges connecting the crystals, which occurs by partial diffusion or capillary condensation. Anticaking agents act by various processes, including bind the moisture content, with the host powder, create a protective layer from moisture on the surface of particles, providing smooth surfaces to reduce inter-particle friction, and prevent the crystal formation. SiO₂ (silicon dioxide) is used in non-food and food products as thickening agent (as an anticaking agent) and maintains the flow property in powdered products (e.g., salt, cornstarch, icing sugar, salts, milk powder, spices, and dry mixes). As an anticaking agent, synthetic amorphous silica has long been used without any health concern because, until recently, the nanoparticles were thought to be completely inert (Lipasek *et al.*, 2012).

However, there are many studies that describe the potential negative effects of nanoparticles and nanomaterials in the body at the molecular level (Winkler *et al.*, 2017). Currently, the safety and health concern are an active topic for food researchers and nanotechnologist. On the other hand, there is an increase the demand for reduction and improvement in risk assessment and regulation of those nanoparticles (McClements, 2017). Moreover, aluminum silicate, calcium aluminosilicate, sodium bicarbonate, sodium silicate and many more have also been used as additives in granular and powdered meals to reducing the caking (Samal, 2017).

Organoleptic Properties of Food

Nanotechnology has revolutionized the food industry by enabling nanoencapsulation techniques that enhance food quality, improve flavor and ensure flavor retention. These methods allow for targeted delivery of flavors and nutrients, leading to a more balanced culinary experience. By manipulating materials at the nanoscale, food scientists can create innovative solutions that not only optimize taste but also extend shelf life and improve overall nutritional value,

ultimately transforming how we perceive and enjoy food (Nakagawa, 2014). Nanoencapsulation techniques, such as using ferritin nanocages, have been shown to enhance the stability and solubility of reactive compounds like anthocyanins and rutin, thereby expanding their application in the food industry. This method not only improves the solubility of rutin, a flavonoid with notable pharmacological effects, but also increases its resistance to thermal and UV radiation, making it a more viable option for incorporation in food products. Metallic oxides like titanium dioxide and silicon dioxide serve important roles in the food industry, primarily as colorants or flow agents to enhance the appearance and texture of various food items. Additionally, silicon dioxide nanomaterials are highly valued for their ability to encapsulate fragrances and flavors, improving the delivery and stability of these sensory components in food products (Yang *et al.*, 2019).

Nutritional Value

Encapsulation of bioactive compounds using nanoparticles offers a promising solution to enhance the stability and bioavailability of sensitive nutrients such as lipids, proteins, carbohydrates, vitamins and antioxidants which can be adversely affected by the acidic environment and enzymatic activity in the stomach and duodenum. By improving the solubility and protecting these compounds, encapsulation facilitates their incorporation into food products, ensuring better assimilation and ultimately delivering significant health benefits through fortified daily nutrition. Polymeric nanoparticles are increasingly recognized for their ability to encapsulate bioactive compounds like flavonoids and vitamins, providing a protective environment that enhances their stability and bioavailability. This encapsulation allows for targeted delivery, ensuring that these compounds reach specific sites in the body where their health benefits can be maximized. By modifying the polymer properties and nanoparticle size, researchers can optimize the release profiles and improve the overall efficacy of the bioactive agents,

making polymeric nanoparticles a promising tool in drug delivery and nutraceutical applications (Devi *et al.*, 2021).

Preservation or Shelf-Life

Nanoencapsulation of bioactive components in functional foods significantly enhances their stability and shelf-life by protecting them from degradation in hostile environments. This technology not only preserves the integrity of these components until they reach their target site but also enables the use of edible nano-coatings that create barriers against moisture and gas exchange. These coatings can effectively deliver various beneficial substances such as colors, flavors, antioxidants, and enzymes, thereby improving the overall quality and longevity of food products, even post-packaging. Encapsulating functional components like curcumin extracted from turmeric (*Curcuma longa*) within droplets effectively enhances their stability and preserves their bioactivity by modifying the interfacial properties. This encapsulation not only protects curcumin from degradation during processes like pasteurization but also maintains its antioxidant activity across varying ionic strengths, illustrating a successful strategy for improving the longevity and efficacy of sensitive bioactive compounds (Sari *et al.*, 2015; Jagtiani, 2021).

Nanosensors for Pathogen Detection

Nanomaterials significantly enhance the performance of biosensors in food microbiology by providing improved sensitivity and specificity for pathogen detection, allowing for real-time monitoring of food safety. These nano biosensors enable rapid quantification of food constituents and can alert consumers and distributors about potential hazards, thereby facilitating safer food processing and distribution practices. Their unique properties, such as increased surface area and reactivity, make them invaluable tools in ensuring the integrity and quality of food products. Nanosensors serve as effective indicators for monitoring environmental changes, including humidity, temperature, microbial contamination, and product degradation. They utilize a range of nanostructures such as thin films, nanorods, nanoparticles,

and nanofibers, which have been extensively researched for their potential applications in the development of advanced biosensors. These materials enhance sensitivity and specificity, making them valuable tools for real-time detection in various industries.

Thin film-based optical immunosensors are advanced detection systems that utilize nanostructured films to immobilize specific antibodies, antigens, or proteins. When target molecules such as microbial substances or cells bind to these immobilized substances, the sensors emit detectable signals, enabling rapid and highly sensitive identification. These technologies enhance diagnostic capabilities and are pivotal in various fields, including healthcare and environmental monitoring. The integration of nanotechnology in food safety, exemplified by the development of a dimethyl siloxane microfluidic immunosensor for rapid detection of pathogens like *Escherichia coli* O157:H7 and *Staphylococcus aureus*, highlights its potential to enhance food quality monitoring (Tan *et al.*, 2011).

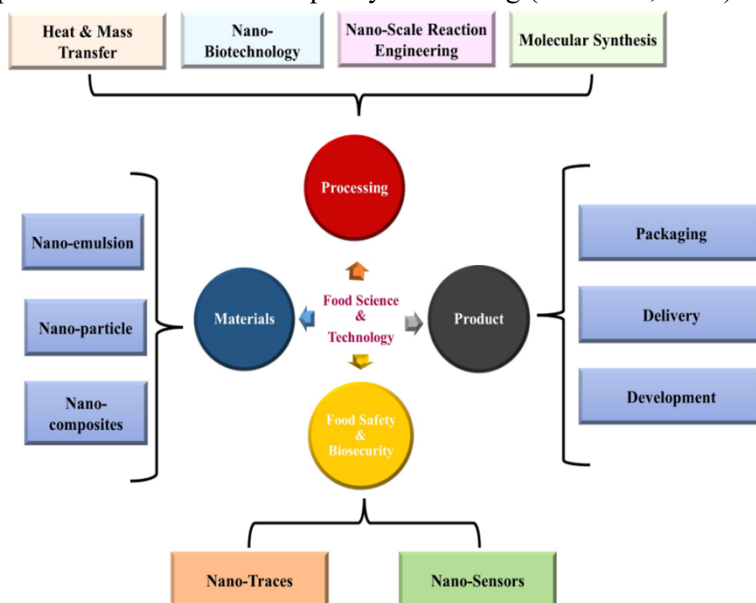


Figure 2: Application of nanotechnology in food industry (Zahra *et al.*, 2022).

Such innovations, along with the use of nanomaterials for detecting pesticides and toxins, significantly contribute to the efficiency of tracking and tracing in the food quality monitoring chain.

A dimethylsiloxane microfluidic immunosensor integrated with specific antibody immobilized on an alumina nanoporous membrane was developed for rapid detection of foodborne pathogens *Escherichia coli* O157:H7 and *Staphylococcus aureus* with electrochemical impedance spectrum. Nanotechnology plays a crucial role in ensuring food safety by enabling the detection of pesticides, pathogens, and toxins through advanced monitoring techniques, thereby enhancing the efficacy of the food quality tracking, tracing, and monitoring chain as highlighted by various studies (Inbaraj and Chen, 2016).

Food Packaging

The packaging industry plays a significant role in the global economy, with a considerable portion of its expenditure occurring in the food and beverage sector. In the USA, approximately 55–65% of the total \$130 billion spent on packaging highlights the critical importance of effective packaging solutions in enhancing product appeal, ensuring safety, and reducing waste, thereby showcasing the industry's overarching impact on economic and environmental sustainability. In recent years, the adoption of active and intelligent packaging systems for muscle-based food products, particularly in meat packaging, has surged significantly. These advanced packaging solutions aim to mitigate spoilage and contamination, improve tenderness through controlled enzymatic activity, reduce weight loss during storage, and help maintain the appealing cherry red color typically associated with fresh red meats. This innovative approach not only enhances food safety and quality but also contributes to a better consumer experience (Brody *et al.*, 2008). Nanosensors represent a significant advancement in food safety, as they can detect toxins, pesticides, and microbial contamination. These tiny devices enable real-time monitoring of food quality, alerting consumers to potential spoilage or

contamination and thereby enhancing food safety and reducing waste. By providing immediate feedback, nanosensors empower consumers to make informed decisions about the food they consume, ultimately contributing to better public health outcomes and more sustainable food practices. Nanoparticles in food packaging enhance food safety by exhibiting antimicrobial properties, often serving as carriers for antimicrobial polypeptides. Coatings made of starch colloids infused with these agents create an effective barrier against microbial spoilage by enabling the controlled release of antimicrobials, thereby prolonging shelf life and maintaining product quality (He *et al.*, 2019). Nanoparticles serve as effective carriers for delivering enzymes, antioxidants, anti-browning agents, flavors, and other bioactive compounds in food packaging, enhancing shelf life and maintaining quality even post-opening. By encapsulating these substances, nanoparticles can protect them from degradation, facilitate controlled release, and improve their stability, ultimately providing a way to extend the freshness of food and reduce spoilage. This innovative approach not only aids in preserving food quality but may also contribute to reducing food waste and enhancing consumer safety. Various metals and metal oxide nanoparticles, such as iron, silver, zinc oxide, magnesium oxide, titanium dioxide, and silicon dioxide, are increasingly used for their antimicrobial properties, and some are incorporated as food ingredients. Titanium dioxide, in particular, is noted for its ability to generate reactive oxygen species (ROS), which are harmful to pathogenic microbes, thus enhancing its effectiveness as an antimicrobial agent in food applications. Nanocomposites represent a significant advancement in material science, offering enhanced properties such as improved heat resistance, reduced weight, and superior mechanical strength, alongside greater barriers against gases like O₂ and CO₂, as well as moisture, UV radiation, and volatile substances. These characteristics make nanocomposites particularly valuable in packaging and coating applications, where performance and protection are paramount (Pinto et al 2013).

Incorporating nanoparticles like SiO₂ clay, carbon nanotubes, and graphene into a polymeric matrix enhances the material's lightweight characteristics while significantly improving its fire resistance, thermal stability, and gas impermeability. These advancements are achieved through the unique properties of the nanoparticles, which enhance the mechanical and thermal attributes of the composite material, making it suitable for a variety of applications in fields such as packaging, construction, and electronics (Mihindukulasuriya and Lim, 2014).

Nanoparticles, typically 100 nm or less, are incorporated into thermoplastic polymers to create polymer nanocomposites, which usually contain 2–8% of these nanoscale materials, such as carbon nanoparticles, nanoclays, or nanoscale metals and oxides. The enhanced properties of these materials stem from their significantly higher surface-to-volume ratio, resulting in increased reactivity and improved mechanical, thermal, and barrier properties compared to their bulk counterparts (Brody, 2006). The incorporation of carbon nanotubes in various applications not only aids in the removal of CO₂ and unpleasant odors but also enhances the functionality of nanocomposites like bentonite. This is particularly beneficial in food packaging, where the use of nanoclay significantly improves gas barrier properties, effectively preventing the diffusion of oxygen and moisture. As a result, these advanced materials help maintain the stability of beverages and prolong the shelf life of food products, contributing to better preservation and reduced spoilage.

The integration of active nanoparticles into polymer matrices significantly enhances the performance of food packaging materials by imparting beneficial properties like antioxidant, antimicrobial, and scavenging capabilities, which collectively contribute to extending the shelf life of packaged food products (He *et al.*, 2019). Nanocor is developed by nanocrystals for use in nanocomposite plastic beer bottles aims to enhance the bottles' barrier properties, effectively minimizing CO₂ loss and oxygen infiltration, thereby preserving the

beer's quality. This innovation parallels advancements in natural biopolymer-based nanocomposites, which also focus on improving the shelf life and freshness of packaged beverages (Nile *et al.*, 2019). The integration of clay nanoparticles into ethylene–vinyl alcohol copolymer and polylactic acid (PLA) biopolymer enhances their oxygen barrier properties, thereby extending the shelf life of food materials. The organically modified nanoclays not only impart mechanical strength to the polymer matrix but also effectively act as a barrier against gases, volatiles, and moisture, making these composites particularly suitable for food packaging applications. The enhanced biodegradation of PLA bionano-composites containing nanofillers compared to pure PLA can be attributed to several factors, including the increased surface area provided by the nanofillers, which may promote microbial activity, and potential disruptions in the polymer matrix that facilitate enzyme accessibility. These modifications can lead to improved interaction between the polymer and the surrounding environment, accelerating the breakdown process and enhancing the overall biodegradability of the composite material (Chaudhary *et al.*, 2008).

➤ **Active Food Packaging Systems**

Active packaging systems are designed to enhance the shelf life and quality of stored products by incorporating components like moisture regulators, CO₂ scavengers, oxygen scavengers, and antimicrobials, tailored to specific storage needs and conditions. These systems help maintain optimal internal environments, reducing spoilage and extending freshness in food and other perishable goods (Dias *et al.*, 2013). Overwrap packaging systems are ideal for short-term chilled storage, while long-term options like modified atmosphere packaging (MAP), vacuum packaging, and bulk gas flushing with 100% CO₂ provide extended shelf life. Low-density polyethylene (LDPE) and polypropylene (PP) are commonly used for these packaging solutions due to their inert nature, hydrophobic properties, and lower surface energy, making them effective barriers for moisture and oxygen

retention. Surface modifications featuring functional properties and polar groups are crucial for integrating antimicrobial substances, which play a vital role in preventing food spoilage, especially in processed meats. By addressing factors like lipid oxidation, dehydration, discoloration, and aroma loss, packaging systems can incorporate additives that significantly extend the shelf life and maintain the quality of meat products. These enhancements not only improve safety by reducing microbial growth but also preserve the sensory attributes crucial for consumer acceptance (Nile *et al.*, 2019). Modified Atmosphere Packaging (MAP) is crucial for preserving the quality and extending the shelf life of meat products by replacing air with specific gas mixtures, typically non-inert gases like oxygen (O₂) and carbon dioxide (CO₂). The composition of these gases can vary over time due to factors such as the type of meat, its respiration rate, packaging materials, pack size, storage conditions, and the integrity of the packaging.

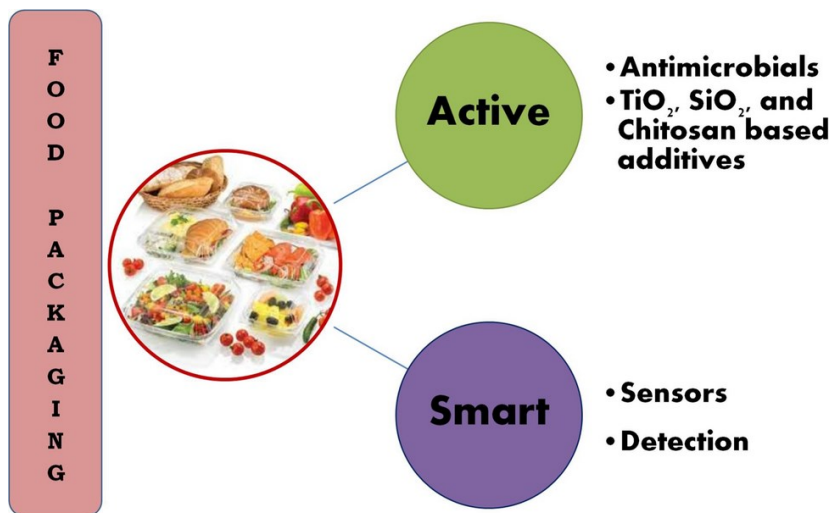


Figure 3: Types of Food Packaging by Nanotechnology (Zahra *et al.*, 2022).

This technology plays a significant role in maintaining cold chain logistics for meat distribution and storage (Morris *et al.*, 2017). The

use of clay nanoparticles in food packaging films, as developed by Bayer, enhances the barrier properties of the material, effectively preventing the permeation of gases and moisture that can spoil fresh meats and other foods. This innovation is supported by numerous patents across the USA, Europe, and Asia, highlighting the growing interest in nanomaterials-particularly nanoclays and nanosilver as a means to improve food preservation and safety in packaging applications (Drew *et al.*, 2016). The incorporation of allyl isothiocyanate and carbon nanotubes into active packaging systems effectively reduces microbial contamination, minimizes color changes, controls oxidation, and extends the shelf life of shredded, cooked chicken meat for up to 40 days (Dias *et al.*, 2013).

➤ **Smart/Intelligent Food Packaging Systems**

Smart packaging systems enhance food safety by utilizing responsive technologies, such as nanoparticles in nanosensors, to monitor and detect contaminants and pathogens. These custom-designed nanosensors play a crucial role in food analysis, ensuring quality by identifying flavors, colors, and even detecting toxins in drinking water and supporting clinical diagnostics, thereby advancing food safety and consumer protection (Li *et al.*, 2014). Nanosensors in food packaging significantly enhance food safety and quality monitoring by providing real-time detection of physical, chemical, and biological changes during processing. These smart packaging solutions are engineered to identify harmful substances like toxins and pathogens, enabling proactive measures in food management and reducing waste, ultimately improving consumer protection and food sustainability (Berekaa, 2015). Intelligent packaging systems equipped with sensors and indicators enhance the monitoring of food quality during storage and transportation, improving safety and minimizing waste. By incorporating functional nanomaterials as nanosensors and active packaging, these systems offer significant mechanical strength and barrier properties, while also serving as targeted nutrient delivery

mechanisms, ensuring that food remains fresh and retains its nutritional value throughout its shelf life (Nile *et al.*, 2019).

The integration of advanced sensors and smart packaging technologies in the meat industry significantly enhances food safety and quality by providing real-time monitoring of package integrity, product freshness, and time-temperature changes. These sensor-based indicators respond to environmental stimuli, enabling the detection of potential spoilage or quality degradation during distribution. By ensuring that meat products remain within safe parameters throughout their journey, these innovations contribute to extended shelf life and improved consumer confidence in food products. Nanobarcodes, enhanced by nanoparticles, serve as advanced ID tags that can be integrated into the production and distribution chain, enabling the monitoring of critical indicators that ensure product quality and extend shelf life. By providing detailed tracking information, these innovative barcodes help manufacturers maintain standards and optimize supply chain efficiency (Nile *et al.*, 2019).

Nanosensors in packaging enhance food safety by detecting enzymes released during the degradation of food compounds, indicating spoilage and making items unsuited for consumption. This innovative packaging solution not only improves shelf life by creating barriers against air and contaminants, thus reducing the need for artificial preservatives, but also effectively removes ethylene, a ripening hormone, further prolonging the freshness of food products. Nanosensors in smart packaging systems provide advanced detection capabilities for a range of factors such as gases, contaminants, and microbial activity, enhancing food safety and quality monitoring. While traditional analytical techniques like GC/MS and gas analysers can be valuable for assessing the gas composition in modified atmosphere packaging (MAP), they often have limitations regarding efficiency and practicality in real-time applications. In contrast, optical sensor-based approaches offer more effective solutions for

large-scale and real-time monitoring, making them preferable for contemporary packaging processes (Morris *et al.*, 2017).

The food industry faces significant challenges with food rotting, primarily caused by bacteria that emit unpleasant odors often undetectable by the human nose, potentially leading to food poisoning. To address this issue, the development of highly sensitive biosensors is crucial for reliably detecting the odors associated with food spoilage and ensuring food safety (Ditta *et al.*, 2012). The electronic nose, equipped with chemical sensors and a data processing system, emulates human olfaction and has demonstrated its versatility in analyzing the characteristics of various fruits like pears and strawberries. It effectively detects variations in aroma and quality during processes such as osmotic dehydration and milk processing, showcasing its potential applications in food quality assessment and management. The device you're referring to is likely a gas chromatograph, which is essential for analysing volatile compounds in food samples. It helps in quality control by ensuring that the levels of specific volatiles meet safety and quality standards, allowing for precise monitoring of flavour, aroma, and potential contaminants in food products (Dasgupta *et al.*, 2015).

Functions of Nanotechnology in Food

Antimicrobial

Microbial contamination during weaning food production, processing, transport, and storage significantly impacts nutritional value and safety, posing a serious public health concern due to the associated pathogenic infections and nutritional deficiencies. Recent studies indicate that novel nano-antimicrobials, particularly those derived from metal and metal oxide nanomaterials, exhibit significant potential in preventing food deterioration and extending shelf life. Their unique properties enable them to effectively inhibit microbial growth, thereby enhancing food safety and longevity. As interest in sustainable food preservation methods grows, these nanomaterials could play a crucial role in developing innovative solutions for food

storage and quality maintenance. The physicochemical properties of certain materials can lead to excessive reactive oxygen species (ROS), causing oxidative stress and cellular damage. Additionally, these materials can release metal ions that disrupt cell structure and function. Consequently, metal/metal oxide-based nanocomposites are explored for applications like food packaging and coatings, or even as food ingredients (Nile *et al.*, 2019).

Increase bioavailability

Some studies have reviewed the use of nanomaterials as delivery systems for bioactive compounds in nutritional supplements, aiming to enhance their bioavailability. Various bioactives, including CoQ10, vitamins, iron, calcium, and curcumin, have been extensively investigated for delivery using nanocarriers (Drew *et al.*, 2016; Morris *et al.*, 2017; Nile *et al.*, 2019). Various nano-delivery vehicles, including casein micelles, lipid-based nanocapsules, nanoemulsions, biopolymeric nanoparticles, nanolaminates, and nanofibers, have been extensively developed. Nanodelivery systems enhance bioavailability by improving drug solubility, targeting specific tissues, and protecting the bioactive from degradation, ultimately leading to higher drug concentrations at the desired site of action (Berekaa, 2015).

Antioxidants

Polymeric nanoparticles offer an innovative approach for delivering bioactive compounds like flavonoids and vitamins, particularly due to their potential to encapsulate these agents and release them in acidic environments, such as the stomach. This capability positions them as effective antioxidant carriers, contrasting with more reactive metal/metal oxide nanomaterials that can induce oxidative stress through the generation of reactive oxygen species (King *et al.*, 2018). SiO₂-gallic acid nanoparticles exhibit antioxidant properties, as evidenced by their ability to scavenge 2,2-diphenyl-1-picrylhydrazyl radicals (Khalaf *et al.*, 2013).

However, nanomaterials have potential applications, direct use as anti-browning agents is limited. One example, nano-ZnO-coated packaging, shows promise for extending the shelf life of fresh-cut apples (Zarei *et al.*, 2014). Nano-ZnO packaging significantly reduced the activity of polyphenol oxidase and pyrogallol peroxidase, effectively inhibiting browning in fresh-cut Fuji apples. The browning index was substantially lower in the nano-ZnO treated group compared to controls, indicating a preservation of the fruit's initial appearance. The treatment of fresh-cut Red Delicious apples with nanocapsules containing DL- α -tocopherol with a poly- ϵ -caprolactone biopolymer membrane significantly reduced the browning index (Zambrano-Zaragoza *et al.* 2014).

Flavour

Flavor enhancement is crucial in the food system, as it significantly impacts the overall sensory experience of eating. Recent advancements in nanoencapsulation techniques have proven effective in improving the release and retention of flavors, facilitating a more balanced culinary experience. Additionally, SiO₂ nanomaterials have emerged as promising carriers for fragrances and flavors, benefiting various food and non-food applications (Nakagawa *et al.*, 2014).

Additives (Color)

Food color additives must undergo rigorous approval processes by the U.S. FDA's Office of Cosmetics and Colors to ensure safety and compliance with specified uses. With advancements in nanotechnology, new nanoscale color additives are being explored and some have received approval due to their ability to enhance the visual appeal of food products, thereby significantly influencing consumer preferences. Titanium dioxide (TiO₂) is now approved as a food color additive by the U.S. FDA, limited to 1% by weight, and exempt from certification. Mixtures with TiO₂ may also include silica (SiO₂) and/or aluminum oxide (Al₂O₃) as dispersing aids, up to a maximum of 2% total. Importantly, carbon black is no longer permitted as a food color additive (Nile *et al.*, 2020).

Anticaking Agent

Silicon dioxide (SiO₂), commonly known as silica, is a versatile additive used to thicken pastes, prevent caking in powders, and act as a delivery agent for fragrances and flavors in various products. Silicon dioxide (E551), a widely used food additive, is often found in nano-sized form in powdered food products. This nano-scale silica is present in at least some portions of these materials. This suggests a potential pathway for E551 (nano-sized SiO₂) to interact with the gut lining, raising concerns about potential health effects due to direct exposure of the gut epithelium to this substance (Athinarayanan *et al.*, 2014).

Safety Considerations of Nanotechnology

This introductory outline highlights a critical environmental concern: the increasing release of nanoparticles into the environment due to widespread nanomaterial use. This raises significant risks requiring robust risk analysis and management strategies, particularly regarding nanoparticle accumulation in landfills and aquatic systems. Studies on the ecological risks of nanoparticles and their impact on human health are focusing on the safety evaluation of nanomaterials. A series of articles in toxicological sciences presented various techniques for characterizing nanoparticles and assessing their interactions with biological systems, highlighting important factors for safety assessment. Determining nanoparticle solubility, its health effects, and biological fate is crucial. Factors like aggregation, surface area, concentration, surface energy, and morphology significantly impact dissolution, and consequently, nanoparticle behavior within biological systems. This assessment highlights the potential for nanoparticle and nanostructure exposure through various bodily entry points, with the gastrointestinal tract, skin, and lungs being the most probable pathways.

The EFSA guidelines for assessing nanomaterial risk in food emphasize a tiered approach, considering the nanomaterial's state during production, use in food, toxicological testing, and presence

within biological samples. This multi-faceted evaluation aims to comprehensively understand and manage potential risks associated with metallic nanomaterials in commercial food products (Shankar *et al.*, 2015). While nanostructured materials may enhance absorption across the intestinal lining and potentially enter the circulatory system, extensive research on the systemic effects and long-term consequences of this potential route of invasion is lacking. A legal framework for governing nanomaterials in food applications is emerging, with the Organization for Economic Co-operation and Development (OECD) recommending standardized testing protocols for hazard assessment. This fosters a more consistent and reliable approach to ensuring the safety of nanomaterials used in food production and consumption. Nanotechnology holds significant potential in the food industry, enhancing everything from ingredients to packaging and quality analysis. However, the safety of nanoformulated products for human and animal health is a growing concern, as emerging research suggests potential toxicity to various organisms. Moreover, the absence of comprehensive regulatory frameworks governing the use of nanotechnology in food and agriculture exacerbates these risks, highlighting the need for stringent safety assessments and guidelines before widespread adoption.

Effective guidelines and policies are essential for the safe utilization of nanoparticles in the food industry to ensure consumer safety and public health. In the United States, the US FDA plays a crucial role in regulating nanofoods and food packaging, while in Australia, the Food Standards Australia and New Zealand (FSANZ) actively oversees the regulation of nanofood additives and ingredients under the Food Standards Code. These regulatory bodies are instrumental in establishing frameworks that address potential risks associated with nanotechnology in the food sector (Cubadda *et al.*, 2016).

The European Union employs the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) to assess nanotechnology risks. EU regulations mandate safety assessments for

nanotechnology-based food ingredients before they can be used in human food (Tinkle *et al.*, 2014). The nanofood or food ingredients are completely covered by the European Union Novel Foods Regulation (EC 258-97). The re-evaluation program by European Food Safety Authority (EFSA) suggested that the authorized nanoadditives before 2009 and food packaging materials should be treated as per the reevaluation program. While Japan and China are the major nanomaterial producing countries, they do not have proper nanotechnology specific regulations (Brien *et al.*, 2010). The absence of robust food regulations concerning nanomaterials stems from limited knowledge about their human exposure, availability, and toxicity. The emergence of nanofood products and associated regulatory challenges has prompted numerous countries to seek systems for managing risks associated with their use.

Comprehensive government regulations, including thorough toxicological assessments, are crucial for the safe and legal application of nanotechnology, especially in the food industry. A globally recognized regulatory framework is essential to ensure the responsible use of nanoparticles in food production and consumption (Nile *et al.*, 2020).

Toxicological Aspects of Nanomaterials in Food

Growing public concern about nanotechnology stems from the increasing recognition of potential nanoparticle toxicity and environmental impact. This toxicity is driven by complex factors including the particles' dynamic behavior, reactivity, and interaction with their surroundings, and how these factors influence their agglomeration and functionalization (Zou *et al.*, 2016). While nanoparticles on packaging are generally considered harmless, their potential uptake into food and subsequent translocation within the human body raises concerns about cytotoxicity and genotoxicity. Previous research has explored the mechanisms of nanoparticle entry, absorption, and distribution, highlighting the need for further investigation into the potential health impacts of this process.

Nanoparticles can enter the body through various routes, including skin absorption, ingestion, inhalation, injection, and implantation. Once inside, they interact with biological molecules. Toxicity often arises from their persistence, inability to dissolve, and resistance to breakdown, leading to problematic accumulation and potential adverse effects (Nile *et al.*, 2020). Insufficient consumer awareness, governmental guidelines, and robust detection methods for nanotechnology risk assessment highlight a critical need for improved understanding of nanomaterial toxicity.

Characterizing the toxicity of metal-based nanoparticles (NPs) and establishing effective regulatory processes are crucial, especially as the potential for toxicity increases with decreasing particle size (Cano *et al.*, 2018). Nanoparticles (NPs) exhibit unique reactivity and the ability to traverse biological membranes, leading to distinct toxicokinetic and toxicodynamic behaviors. Their interaction with proteins and enzymes can trigger the production of reactive oxygen species (ROS), leading to oxidative stress, which may cause mitochondrial degeneration and promote apoptotic pathways. Consequently, the accumulation of ROS poses significant risks for cellular health and contributes to various adverse biological effects.

The existing research indicates that nanoparticles (NP), particularly in animal studies, can cause significant toxicity to vital organs like the liver and kidneys, as well as negatively impact the immune system; however, there is a critical need for more comprehensive studies to evaluate their effects on human health. While silver nanoparticles are common in commercial products, the limited *in vivo* toxicological research involving mammalian models, such as mice and rats, underscores the necessity for further investigations to fully understand their safety and potential risks to humans (Mao *et al.*, 2016). Exposure to titanium dioxide nanoparticles (TiO₂ NPs) has been associated with tumor-like changes in human cells, as evidenced by observations in lung, gastrointestinal tract, and skin cell lines *in vitro* (Botelho *et al.*, 2014). The ICH (International Conference on Harmonization) and

OECD (Organization for Economic Co-operation and Development) have established widely adopted genotoxicity testing methods, encompassing assays for gene mutations (e.g., Ames test, mouse lymphoma), DNA damage (e.g., comet assay, micronucleus assay), and in vivo animal studies. These methods are crucial for assessing potential mutagenic and carcinogenic hazards of substances (Magdolenova *et al.*, 2014). Using bacterial enzymes to detect oxidized DNA bases and quantify oxidative DNA damage in comet assays offers a novel approach. However, the observed discrepancy between in vivo and in vitro results likely stems from the inherent DNA repair mechanisms present in animal models, which effectively mitigate damage in the living organism, leading to lower apparent levels of oxidative DNA damage compared to the in vitro setting where repair processes are absent (Magdolenova *et al.*, 2014).

However, Ames test and the chromosomal aberration tests are not reliable for the detection of nanoparticle related toxicity assessments. This research describes an in vitro cellular mutagenesis system investigating lung epithelial cells. Bronchoalveolar lavage fluid (BAL) is analyzed for neutrophil levels and DNA damage, assessed by comet assay and HPRT assay. Correlation between neutrophil content in BAL and DNA damage is explored. Moreover, In vivo micronucleus and comet assays are recognized by regulatory bodies as suitable tests for assessing the effects of exogenous materials, likely due to their ability to detect DNA damage in living organisms (Guo *et al.*, 2015).

Future Possibilities of Nanotechnology in Food

Nanotechnology significantly advances food science by enabling enhanced tracking, tracing, and monitoring for improved quality preservation and detection of contaminants like poisons, diseases, and pesticides. While the technology faces early-stage development hurdles for some nanocomponents, and associated costs, its potential for creating and preparing functional foods is promising. Effective regulations and laws addressing safety concerns are crucial for

nanotechnology to be widely adopted in food processing. This will foster public trust and acceptance, ensuring responsible development and application of nanomaterials in food production. Effective regulations and laws addressing safety concerns are crucial for nanotechnology to be widely adopted in food processing. This will foster public trust and acceptance, ensuring responsible development and application of nanomaterials in food production.

Conclusion

Nanotechnology significantly advances the food industry by enhancing food quality, safety, and storage through innovative processing, packaging, and detection methods. Nanomaterials and nanosensors provide consumers with real-time information about food freshness and nutritional content, while nanotechnology-based delivery systems improve the bioavailability and stability of hydrophobic bioactive compounds, targeting health benefits more effectively. However, these advancements pose regulatory and consumer acceptance challenges, requiring careful oversight and transparent communication to ensure trust in nanofoods. The active integration of nanocolloidal particles across various sectors quality control, safety, nutrition, and packaging continues to drive growth and innovation in the food industry. The properties and behaviour of colloidal particles, including nanoparticles, are vital for developing safer, healthier, and more sustainable food products, but the widespread application of nanotechnology in food faces regulatory, scientific, and safety challenges. While nanoparticles in packaging are considered less harmful than when used as food ingredients, concerns about environmental entry, potential DNA damage, and limited *in vivo* studies raise questions about their safety for human and animal health. Proper labelling, regulation, and further research are essential to ensure consumer acceptance and safety, but when managed responsibly, nanotechnologies hold significant promise for enhancing food processing and quality, ultimately benefiting public health and well-being.

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