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Nanoparticles in the food chain: Promises for safety and security with hidden risks

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Abstract
Nanotechnology, which involves manipulating matter at the nanoscale, has the potential to revolutionize food science. Nanomaterials (NMs), owing to their unique physicochemical properties, can significantly enhance food quality, safety, and shelf life. They enable more efficient detection of contaminants, improve the delivery of nutrients and bioactive compounds, and strengthen packaging systems. In agriculture, nano-based innovations such as nano-pesticides and nano-fertilizers offer solutions to food security challenges by boosting crop productivity and resilience. Despite these promising applications, concerns remain about the potential toxicity of NMs. Their small size and high reactivity may lead to oxidative stress and cellular damage. Factors such as composition, size, and surface charge influence their toxicological effects. Therefore, while nanomaterials hold transformative potential for the food sector, it is essential to develop a thorough understanding of how they interact with living organisms and the environment.

Keywords: Nanotechnology, nano-particles, food safety, food security, toxicity

Introduction
Nanotechnology is a multidisciplinary domain that employs various tools and techniques to engineer, alter, and manipulate matter at the nanoscale level (10^{-9} meters). Its applications span multiple sectors, including engineering, food technology, and the health sciences where nanomaterials play a key role in enhancing food safety, extending shelf life, and improving preservation methods (Hossain *et al*., 2021) [16]. The transformative impact of nanotechnology on industry has led to substantial investments by both developed and developing nations. Nanomaterials, typically less than 100 nano-meters in size, consist of particles, aggregates, or filaments. This advancement has facilitated the creation of diverse nanostructures such as nanoparticles, nano-dispersions, nanolaminates, nanotubes, nanowires, fullerenes (also known as buckyballs), and quantum dots, among other nanoscale configurations (Scrinis & Lyons, 2007) [38].

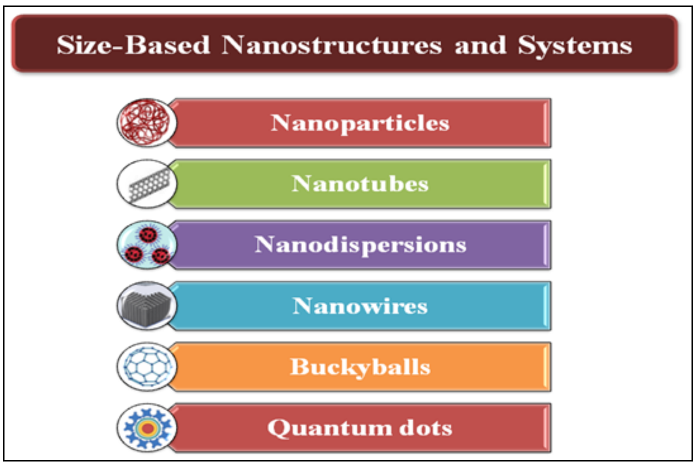

Fig 1: Types of nanomaterials

The rapid evolution of industrial development has ushered in the era of nanotechnology, attracting substantial investments from both developed and developing nations. This technology has found extensive applications across engineering, food science, and biomedical fields. The integration of nano-compounds plays a vital role in enhancing food safety, extending shelf life, and maintaining product quality. Nevertheless, contemporary lifestyle shifts, excessive pesticide use, and exposure to chemical and biological contaminants pose significant threats to the safety and nutritional value of food (Hossain *et al*., 2021) [16].

Nanomaterials (NMs) are emerging as transformative tools for enhancing food safety, prolonging shelf life, and elevating food quality. Owing to their distinct physicochemical properties, engineered NMs show immense potential across agrifood sectors such as production, packaging, processing, and safety regulation. Their nanoscale design with a high surface-area-to-volume ratio confers exceptional optical, electrical, mechanical, and functional attributes. This innovation underpins the current achievements and future prospects of nanotechnology in diverse application domains (Neethirajan & Jayas, 2011) [29].

The performance and utility of nanoparticles are largely determined by their unique attributes such as size, distribution, interfacial characteristics, grain boundaries, chemical makeup, and phase interactions. Due to their targeted delivery capabilities, these naturally occurring or synthetically engineered nanostructures are often dubbed "magic bullets" and are gaining traction in industries like food, textiles, and pharmaceuticals (Naseer *et al*., 2018) [28]. As a cross-disciplinary technological frontier, nanotechnology is reshaping the landscape of material science and driving revolutionary advances across numerous domains.

Addressing the challenges posed by a rising global population, environmental degradation, climate change, dwindling energy resources, and the shrinking availability of arable land demands the adoption of advanced technologies to enhance food production and quality. Nanotechnology has emerged as a cutting-edge solution, seamlessly integrating into various stages of the food and feed processing chain including manufacturing, packaging, storage, transportation, and value addition offering innovative pathways for improvement (Naseer *et al*., 2018) [28].

The strategic application of nanoparticles has revolutionized the agri-food sector by reducing dependence on harmful agrochemicals and enabling the targeted delivery of bio-actives, fertilizers, pesticides, and fungicides (Srilatha, 2011) [48]. Furthermore, their use facilitates early detection and control of crop diseases. Nanotechnology has also introduced innovative advancements such as nano-sensors for smart packaging and real-time transport monitoring, enzyme encapsulation to enhance biochemical efficiency, and nanoparticle-based detection systems for identifying food adulterants and contaminants (Srilatha, 2011) [48]. Collectively, these innovations reinforce the vital role of nanotechnology in advancing global food safety, efficiency, and sustainability (Roholla & Rezaei, 2011) [35].

Nanoparticles are broadly categorized into three types: carbon-based, inorganic, and organic. Organic nanoparticles also known as polymeric nanoparticles include structures such as ferritin, liposomes, dendrimers, and micelles. These nanostructures are well-suited for biomedical applications due to their inherent non-toxicity and biodegradability. Many of them, including micelles and liposomes, possess a hollow core known as a nano-capsule, which can respond to electromagnetic stimuli like heat and light. Their biocompatibility and controlled-release properties make them excellent candidates for targeted drug delivery systems (Ealia & Saravanakumar, 2017) [10].

Inorganic nanoparticles, also referred to as non-carbon-based nanoparticles, are primarily composed of metals or metal oxides. These materials are engineered to nanoscale dimensions through either top-down (destructive) or bottom-up (constructive) synthesis methods. Commonly utilized metals in nanoparticle production include aluminum (Al), cadmium (Cd), cobalt (Co), copper (Cu), gold (Au), iron (Fe), lead (Pb), silver (Ag), and zinc (Zn). When these metallic nanoparticles undergo chemical conversion into their metal oxide forms, their physicochemical properties are significantly enhanced, boosting both reactivity and efficiency. For example, iron (Fe) nanoparticles readily oxidize under atmospheric conditions to form iron oxide (FeO_3), which increases surface activity. Similarly, aluminum oxide (AlO_3) nanoparticles exhibit superior functional traits compared to their metallic counterparts (Ealia & Saravanakumar, 2017) [10].

Carbon-based nanoparticles, composed solely of carbon atoms, exhibit a wide range of structural forms. This category encompasses fullerenes, graphene, carbon nanotubes (CNTs), carbon nanofibers, carbon black, and, in some cases, nanoscale-activated carbon. Due to their outstanding mechanical strength, high electrical conductivity, and expansive surface area, these nanomaterials hold great promise in fields such as electronics, energy storage, and biomedical engineering (Ealia & Saravanakumar, 2017) [10].

Properties of nanoparticles

One of the defining features of nanoparticles is their exceptionally high surface-area-to-volume ratio, which markedly alters their physicochemical properties compared to their bulk forms. For instance, while bulk gold is largely inert, its nanoscale counterpart exhibits heightened reactivity along with unique optical and electrical characteristics (Daniel & Astruc, 2004) [4]. These nanoscale attributes make gold nanoparticles highly suitable for diverse biological applications, including biosensing, medical imaging, and targeted drug delivery.

Due to their high surface reactivity, nanoparticles readily interact with biological macromolecules such as proteins, lipids, and cellular structures. Their nanoscale dimensions enhance their ability to penetrate cellular membranes, facilitating accumulation in various organs and potentially triggering inflammatory or immune responses (Gojova *et al*., 2007; Geiser *et al*., 2005) [13, 12]. Additionally, their strong affinity for biomolecules prevents them from existing as bare particles within biological environments. Instead, they become coated with a layer of adsorbed proteins known as the protein corona which governs how nanoparticles interact with cells. This layer influences key processes such as cellular uptake, distribution within the body, organ-specific accumulation, and eventual clearance (Lynch & Dawson, 2008) [23].

Nanoparticles interact with biological membranes through both physical and chemical mechanisms. Physically, they can compromise membrane integrity, alter protein conformation, induce particle aggregation, and interfere with key cellular transport pathways (Deng *et al*., 2011) [6]. Chemically, they generate reactive oxygen species (ROS), which are primarily responsible for oxidative stress, DNA damage, and cytotoxic effects (Oberdörster *et al*., 2007) [31]. Additionally, environmental factors influence nanoparticle stability, toxicity, and aggregation behaviour, adding complexity to their risk assessment and biological impact evaluation (Ju-Nam & Lead, 2008) [18].

Metallic nanoparticles (MNPs) have garnered significant attention for their potent antimicrobial activity and their ability to extend the shelf life of perishable foods. Acting as effective preservatives, MNPs inhibit microbial growth, thereby reducing contamination and spoilage. When incorporated into biopolymer-based packaging materials, they enable the controlled release of antimicrobial agents, enhancing food safety and prolonging storage stability. Additionally, the fusion of natural bioactive compounds with metallic nanomaterials leads to the creation of hybrid nanocomposites multifunctional systems offering enhanced performance and biocompatibility (Santos *et al*., 2020) [7].

Beyond their industrial and biomedical applications, the versatility of metallic nanoparticles in food preservation underscores their transformative potential. However, ensuring their safe and effective implementation requires a comprehensive understanding of their interactions with both biological systems and the environment.

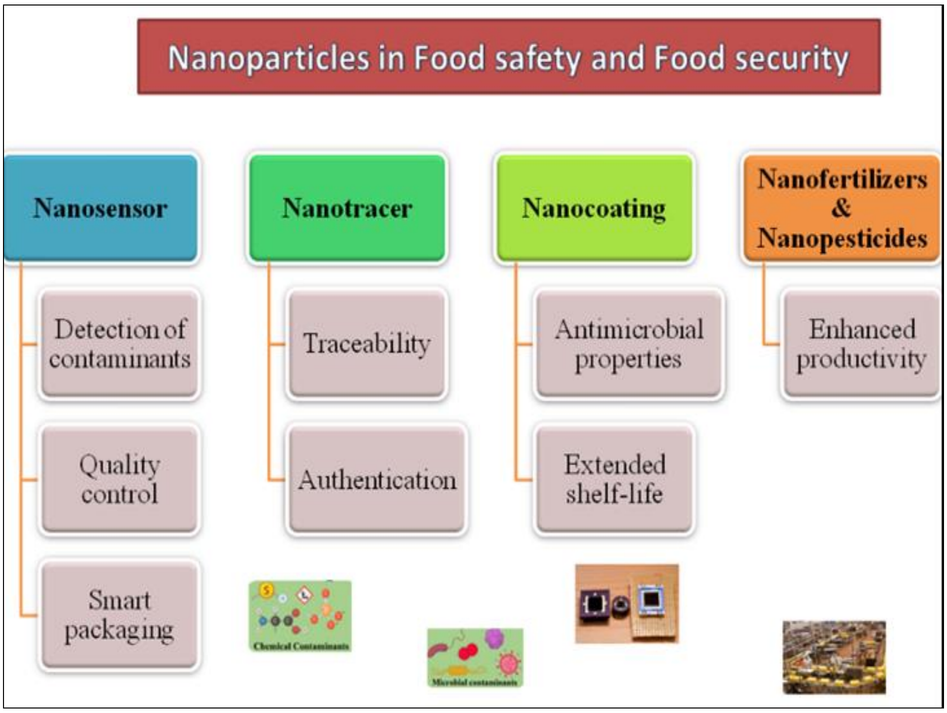

Fig 2: Role of various nanoparticles in food safety and food security

Application of nanoparticles in enhancing food safety

Food safety encompasses a range of practices and regulations designed to prevent harmful substances from contaminating food and posing risks to human health. The primary objective of these safety measures is to ensure that food is safe for consumption, thereby promoting overall public health and well-being. Reflecting this shared responsibility, the theme of World Food Safety Day *"Food safety is everyone's business"* underscores the vital role each individual plays in maintaining the integrity of the food supply (FAO, 1996) [11].

Food waste remains a critical global issue in the food industry, leading to substantial economic losses and inefficient use of resources. It is estimated that over 1.3 billion metric tons of food are discarded annually across various stages of the supply chain. This large-scale waste is primarily attributed to outdated postharvest practices, inadequate transportation infrastructure, traditional storage techniques, and delays in market accessibility (Tricco *et al*., 2019) [52]. Microbial contamination further exacerbates the problem by accelerating food spoilage, rendering it unsuitable for consumption. The absence of robust food safety regulations not only increases food loss but also contributes to persistent malnutrition, prolonged hunger, and entrenched poverty ultimately hampering societal progress. According to the World Health Organization (WHO, 2015) [56], foodborne illnesses are responsible for approximately 420,000 deaths each year, with children under five being among the most vulnerable populations.

If you'd like, I can adapt this content for use in a policy brief, presentation, or research paper this topic holds significant relevance and impact across multiple sectors.

With the global population rising and resource competition intensifying, minimizing food waste and promoting sustainable agricultural practices have become urgent priorities. Nanotechnology (NT) offers a transformative approach to these challenges by improving food preservation, optimizing storage conditions, and strengthening food security (Sperber & Doyle, 2009) [47]. The use of nanomaterials (NMs) in agriculture has demonstrated significant benefits, including increased crop yields, improved product quality, and enhanced food safety all essential for fostering healthier communities and resilient food systems (Duncana, 2011; Islam *et al*., 2019) [8, 17].

Nanotechnology offers several key advantages in agriculture, including enhanced food safety and quality, reduced dependence on synthetic agronomic inputs, and improved nutrient uptake by crops at the nanoscale level (Ameta *et al*., 2020) [3]. Nanomaterials (NMs) have demonstrated remarkable preservation capabilities, significantly extending the shelf life of perishable food items. For instance, the nanoencapsulation of quercetin in tomatoes has been shown to effectively delay spoilage and maintain nutritional value during storage (Yadav, 2017) [58]. Similarly, the application of NMs in the packaging and storage of various fruits and vegetables has played a crucial role in minimizing postharvest losses (Yadav, 2017) [58].

Table 1: Role of various nanomaterials in enhancing food safety and quality

Nanomaterials	Working principle	References
Carbon based Nanomaterials		
Graphene	Rapid detection of pollutants in food matrices by Nanoplate-based nanocomposites	Sundramoorthy and Gunasekaran, 2014 [50]
Carbon nanotubes (CNTs)	Thermal, mechanical, electrical, and optical conductivity	Yadav, 2017 [58]
Cellulose nanocrystals	High water absorption that is biocompatible	He *et al.* 2021 [15]
Organic Nanomaterials		
Chitosan	Antimicrobial properties	Xing *et al.* 2016 [57]
Polymeric nanoparticles	Use as an effective and antibacterial delivery system	Senapati *et al.* 2015 [41]
Nanolaminates	Nanolaminates enhance the texture of foods by acting as carriers	Acevedo-Fani *et al.* 2017 [2]
Inorganic Nanomaterials		
Gold nanoparticles (AuNPs)	Combines AuNPs with pathogen DNA, enzymes, or antibodies	Paul *et al.* 2017 [32]
Copper nanoparticles (CuNPs)	Surface water	Zhang *et al.* 2008 [60]
Iron oxide (Fe_2O_3) magnetic nanoparticles	Solution of acetate buffer	Wei and Wang, 2008 [60]
Zinc oxide (ZnO) nanoparticles	Reduces the oxygen flow within the overflowing containers	Zhao *et al.* 2008 [61]
Titanium dioxide (TiO_2) nanoparticles	Utilized in dairy products (such as milk and cheese) as a whitener.	Zhao *et al.* 2008 [61]
Aluminum oxide (Al_2O_3) nanoparticles	Contaminants oxidation	Thangavel and Thiruvengadam, 2014 [51]
Lanthanum nanoparticles (La)	Contaminants oxidation	Thangavel and Thiruvengadam, 2014 [51]
Metal-Composite Nanoparticles		
Silica-coated silver shells	Purification of water	Zhu *et al.* 2020 [62]
Silver zeolite (silver ions in zeolite structure)	Antimicrobial compound	Matsumura *et al.* 2003 [26]
CdTe quantum dots (QDs)	used in the food sector	Sonawane *et al.* 2014 [46]
CdSe@ZnS core-shell quantum dots	Antimicrobial compound	Matsumura *et al.* 2003 [26]

Nanoscale filtration technologies have significantly enhanced food safety by removing harmful microorganisms from milk, dairy products, water, and beverages such as beer without the need for heat-based treatments like boiling while also extending product shelf life (Nair *et al*., 2010) [27]. Engineered nanoparticles further contribute to food quality by neutralizing undesirable odours and off-flavours, and by improving the bioavailability, sensitivity, and stability of food components (Sekhon, 2010; Powers *et al*., 2006; Kang *et al*., 2007) [39, 33, 20]. Collectively, these innovations showcase nanotechnology's transformative role in advancing sustainable agricultural practices, minimizing food waste, and bolstering global food security.

Recent advancements in nanofabrication driven by mass and heat transfer principles have significantly enhanced the thermal durability of materials used in food packaging. Additionally, the integration of nanoscale enzyme reactors into food processing systems has facilitated the modification of nutritional profiles and the enhancement of flavour by regulating enzymatic activities, ultimately extending the shelf life of food products. These technological innovations are vital for preserving food consistency and quality, thereby enriching the overall consumer experience (Singh *et al*., 2021) [44].

Nanoencapsulation has emerged as a promising application of nanotechnology in food science, offering improvements in food preservation, sensory attributes, and nutritional bioavailability. The development of nano-capsules including those based on nanoceramic structures has revolutionized food processing by modifying nutrient absorption kinetics, reducing cooking time, and eliminating trans fats through the substitution of hydrogenated oils with plant-based alternatives. Furthermore, these engineered nano-capsules enhance the functional properties of processed foods by boosting the bio-efficacy of nutrient delivery (Khan *et al*., 2022) [21].

Beyond its role in preservation, nanoencapsulation enables precise interactions among active food components and effectively neutralizes undesirable odours. By delaying the premature release of bioactive compounds, this technology safeguards food from degradation caused by chemical reactions, moisture exposure, or microbial activity during storage and packaging (Singh *et al*., 2021) [44]. In addition, metallic oxides have been utilized as food-grade colorants; for instance, silicon dioxide (SiO_2) nanoparticles serve as carriers for aromatic agents, enhancing flavour stability and enabling controlled release in food products (Dekkers *et al*., 2011) [5]. These advancements highlight nanotechnology's pivotal role in elevating food safety, improving product quality, and extending shelf life.

Application of nanoparticles in ensuring food security

According to the FAO (1996) [11], food security is established when individuals reliably possess both physical and economic access to adequate, safe, and nutritious food that meets their dietary requirements and personal preferences to lead a healthy, active life. This concept is structured around three core pillars of the food system: Food availability, which includes the processes of production, distribution, and exchange. Food access, shaped by factors such as consumer choices, affordability, and fair allocation. Food utilization, which covers food safety, cultural appropriateness, and nutritional sufficiency (Gregory *et al*., 2005) [14]. A failure in any of these pillars can significantly undermine global well-being by heightening the threat of food insecurity.

The late 1980s witnessed a rise in incomes across certain socioeconomic groups, which led to increasingly diverse diets and spurred the production of protein-rich foods such as meat, milk, and eggs. This surge in per capita food availability instilled hope that India's food security issues could be addressed amidst growing population demands. Despite these early gains, by 2023 approximately 9.1% of the global population still experienced hunger a troubling statistic that has remained largely unchanged over the past three years. Sub-Saharan Africa continues to bear the brunt, with 20.4%

of its population suffering from undernourishment (Kumar, 2024) [22].

Agriculture faces mounting environmental challenges due to rapid population growth, climate change, and industrialization factors that collectively threaten global food security. To boost agricultural productivity, biomass accumulation, plant performance, and ultimately grain yield, it is crucial to optimize current fertilization practices. Yet, heavy dependence on chemical fertilizers presents significant threats to ecosystems, plant vitality, and the health of both humans and animals. In light of these concerns, nanotechnology is gaining recognition as a forward-thinking and sustainable approach, offering precise nutrient delivery and improved resource efficiency to strengthen and modernize agricultural systems (Seleiman *et al*., 2021) [40].

Nano fertilizers (NFs) are increasingly recognized as highly effective tools for enhancing resource efficiency, improving crop yields, and reducing environmental pollution. Serving as sustainable alternatives to traditional fertilizers, they play a vital role in boosting agricultural productivity and enhancing crop quality (Seleiman *et al*., 2021) [40]. Their adoption offers an innovative and forward-looking solution to the pressing challenges faced by modern agriculture. Additionally, the integration of nanotechnology-based solutions such as nano-pesticides, nano-fertilizers, and nano-sensors has transformed conventional farming practices by making them more precise, ecologically sound, and technologically sophisticated. These cutting-edge advancements are instrumental in advancing agricultural systems, as they help increase food output, lessen environmental degradation, and strengthen long-term food security (Usman *et al*., 2020) [53].

The integration of nanoparticles into agricultural practices marks a transformative advancement in addressing global food security by enhancing food production, optimizing input utilization, and promoting environmental sustainability. Beyond its agronomic benefits, nanotechnology holds substantial potential for increasing food availability and boosting agricultural efficiency. Its applications also extend into diverse fields such as water resource management, environmental protection, medicine, and public health. By embedding nanotechnology into contemporary farming systems, it is possible to cultivate sustainable, resilient, and highly productive agricultural techniques that reinforce long-term food security and ecological balance

Certain nanoparticles exhibit distinct physicochemical properties that significantly enhance plant growth and resilience (Saxena *et al*., 2016) [37]. In the field of nano-agriculture, biosynthesized nanoparticles are employed to mitigate the adverse effects of both biotic and abiotic stresses, offering a broad range of agronomic benefits. Research has demonstrated that nanoparticles play a vital role in stimulating plant development by promoting root elongation, accelerating seed germination, encouraging shoot proliferation, and increasing biomass accumulation. These promising findings underscore nanotechnology's transformative potential in sustainable agriculture. The demonstrated efficacy of nanoparticles in improving plant performance is expected to drive further research and facilitate the integration of nanotechnological innovations into modern agricultural practices (Abbasi Khalaki *et al*., 2021) [1].

Nanotechnology-based innovations have the potential to significantly strengthen the four core pillars of food security: agricultural productivity, soil health, water availability, and the storage and distribution of food. Nanocides support targeted pesticide delivery, thereby reducing ecological harm, while nano-emulsions enhance pesticide efficacy. Nanoparticles contribute to soil conservation and remediation, and nano fertilizers enable controlled nutrient release, improving plant uptake efficiency. In animal husbandry and aquaculture, nanotechnology allows for precise delivery of nutrients and medicines, optimizing health and productivity. Meanwhile, nano-sensors provide real-time monitoring of soil and crop health, and tools like nano-brushes and nano-filters assist in the purification of water and soil. Additionally, precision agriculture benefits from nanodevices that increase resource efficiency. In the realm of food processing and handling, nanocomposites and nano-biocomposites bolster packaging strength and shelf life, while antimicrobial nano-emulsions support hygienic food storage and decontamination practices (Sastry *et al*., 2011) [36].

Examples: Zinc Oxide (ZnO) Nanoparticles in Wheat improve crop yield and nutritional value by enhancing seed germination, root growth, and chlorophyll content. Plants produce reactive oxygen species (ROS) during abiotic stress, which may neutralize their innate enzymatic defense system. By regulating osmolytes, activating stress-related genes, and supplying vital minerals and amino acids, nanomaterials reduce this stress. Furthermore, anionic nanoparticles have superior uptake, translocation, and internalization because of the negative charge of plant cell walls, which increases their efficacy in nutrient delivery and stress management (Rajput *et al*., 2021) [34].

Titanium dioxide (TiO_2) nanoparticles have demonstrated significant benefits in tomato cultivation, notably enhancing fruit quality, photosynthetic efficiency, and ultraviolet protection factors that collectively contribute to higher crop yields. When applied to over 95% of plant species, these nanoparticles substantially improve photosynthetic activity and nitrogen metabolism, resulting in increased fresh and dry biomass. Improved plant growth and metabolic performance are further achieved through enhanced light energy conversion via photophosphorylation, stimulation of pigment biosynthesis, and intensified biological carbon sequestration through the Calvin cycle (Verma *et al*., 2022) [54].

Chitosan nanoparticles applied to fruits and vegetables serve as edible coatings that prevent microbial spoilage, thereby reducing post-harvest losses and extending shelf life (Sharma *et al*., 2025) [42]. In maize, the use of iron oxide (FeO_4) nanoparticles enhances iron absorption, mitigates crop-level iron deficiencies, and boosts overall nutritional value key factors in strengthening food security (Yousaf *et al*., 2023) [59]. For soybeans, carbon nanotubes have proven effective during drought conditions by enhancing the uptake of water and nutrients, thereby ensuring stable agricultural output (Sun *et al*., 2020) [49]. Collectively, these nanotechnology-based innovations play a pivotal role in improving crop resilience, optimizing production, and enhancing post-harvest management, thus contributing significantly to global food security.

Harmful effects of nanoparticles on humans and animals

Notwithstanding its many benefits, the use of nanotechnology in the food sector raises concerns about toxicity and may present environmental, social, and health risks because nanoparticles may infiltrate the ecosystem through processed food packaging and agricultural pesticide applications. Because of their increased reactivity and bioavailability, nanoengineered particles carry a heightened risk that could result in long-term pathological effects (Sastry *et al*., 2013) [19]. 1. Direct incorporation in new food systems as nano-emulsions, nano-capsules, and nano-antimicrobial films is how nanomaterials enter the food chain. 2. The use of nanolaminates, nano-sensors, and carbon nanotubes (CNTs) for improved functionality and safety in food processing, preservation, and monitoring.

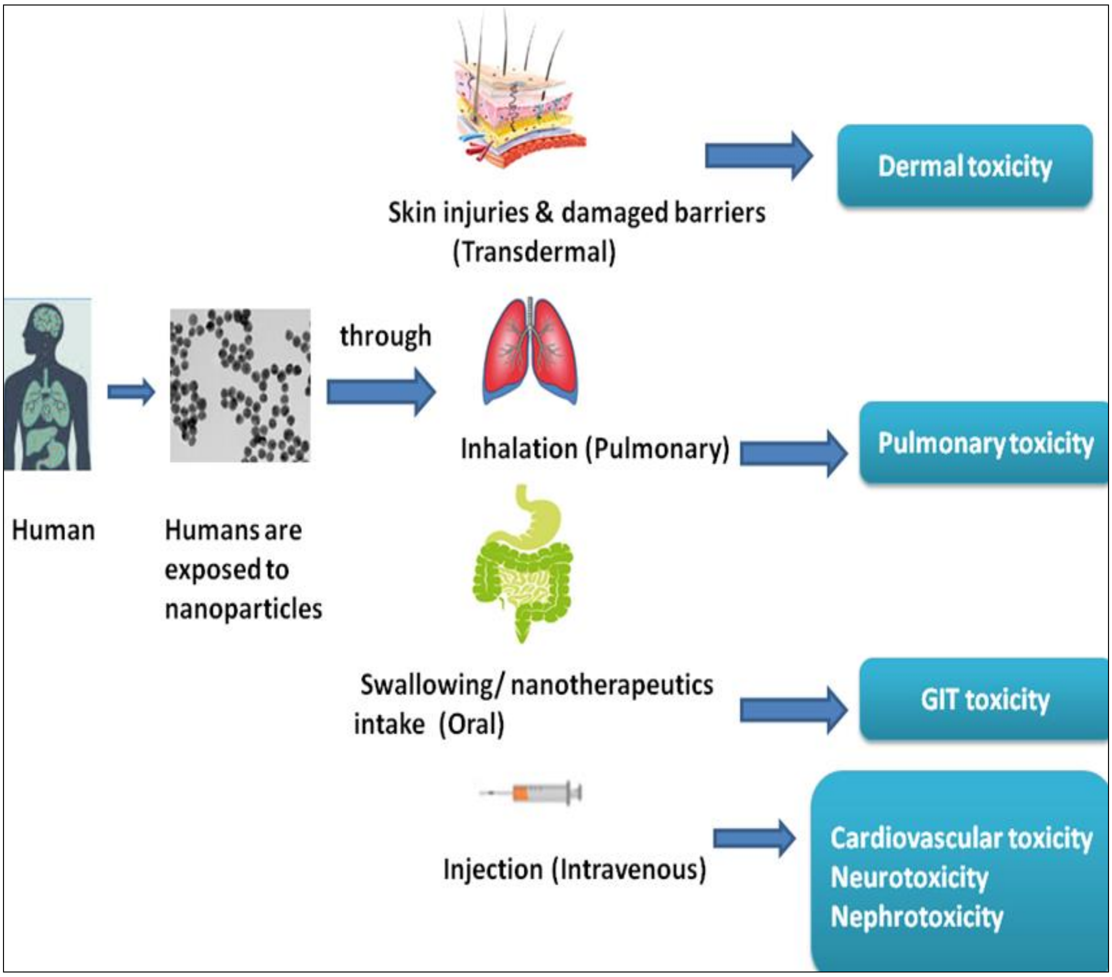

Fig. 3 Harmful effects of nanoparticles on the human body

Due to their minuscule size, nanoparticles can readily penetrate physiological barriers in living organisms, potentially triggering adverse biological responses. These particles may enter the body through the respiratory system, gastrointestinal tract, or skin, leading to health issues such as neurotoxicity, pulmonary inflammation, and cardiovascular complications (Oberdorster *et al*., 2005) [30]. Their unique physicochemical properties often result in oxidative stress and organ damage, which are common mechanisms underlying nanoparticle-induced cytotoxicity. Magrez *et al*. (2006) [24] demonstrated that in lung cancer cells, the size of carbon-based nanoparticles significantly influences their toxic effects. Furthermore, factors such as chemical composition, particle size, surface attributes, crystallinity, and aggregation behaviour are key determinants of nanoparticle toxicity (Mancuso *et al*., 2014) [25].

Nanotechnology especially the use of nanoparticles offers remarkable opportunities to enhance food safety and security. Innovations such as active packaging, rapid and precise pathogen detection, and extended product shelf life exemplify its transformative potential. However, concerns about nanoparticle toxicity and the unknowns regarding their long-term effects on biological systems, including human and animal health, call for cautious evaluation. To ensure the responsible and sustainable adoption of nanotechnology in the food and agricultural sectors, it is essential to conduct thorough and multidisciplinary research. Such efforts will help clarify the associated risks and guide the development of safe implementation strategies.

Conflict of Interest

Not available

Financial Support

Not available

Reference

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