Health Implications of Nanoparticles in Food: Safety Evaluation and Risks

Dr. Rashmi Manoj

Guru Nanak Girls' P G College, Udaipur-(Rajasthan), INDIA

---***---

Abstract - *Nanotechnology has revolutionized multiple sectors, notably food production and packaging, by integrating nanoparticles (NPs) to improve taste, texture, and shelf life. Despite these benefits, their distinct physicochemical properties raise concerns about potential health risks differing from conventional materials. This paper critically reviews current research on nanoparticle toxicity in food, focusing on exposure routes, toxic mechanisms, and regulatory perspectives. Key gaps in understanding are identified, urging further research to fill knowledge voids and refine safety assessment methodologies. Understanding these aspects is crucial for establishing comprehensive regulatory frameworks that ensure the safe integration of nanotechnology in food products while addressing public health concerns effectively.*

Keywords: Nanoparticles, Food safety, Toxicity, risk assessment, regulatory framework, health effects, nanotechnology

1. INTRODUCTION

Nanotechnology integrates various scientific disciplines to manipulate matter at the atomic and molecular levels, yielding materials with unique physicochemical properties distinct from bulk counterparts [1]. Nanoparticles, defined as particles with dimensions between 1-100 nm, exhibit enhanced reactivity, catalytic behavior, and biological activity due to their increased surface area and unique quantum effects [2]. These properties make them valuable across industries, including agriculture and food processing, where they improve food quality, stability, and nutrient bioavailability [3].

In the food sector, nanotechnology has revolutionized processing techniques, offering benefits such as improved sensory properties, enhanced nutrient delivery, and extended shelf life [4]. Nanomaterials play crucial roles in food safety, packaging development, and functional food production, with ongoing research exploring their potential to combat food-related diseases and design personalized nutrition regimens [5].

The application of nanotechnology in food systems also focuses on sustainability through innovations like nanoencapsulation for controlled nutrient release and fortification [6]. Despite these advancements, concerns persist regarding the safety and regulatory aspects of nanomaterials in food products, necessitating ongoing research to ensure their safe implementation and consumer acceptance [7]. Overall, nanotechnology offers promising opportunities to enhance the efficiency, safety, and sustainability of food production and processing, driving innovation in both industrial practices and consumer health solutions [8].

Nanotechnology plays a crucial role in enhancing food products through various applications such as food preservation, additives, packaging, and nanosensors for detecting food pathogens [9]. Nanoparticles like Cu/CuO, Ag, MgO, TiO_2, ZnO, carbon dots, and graphene are extensively used in food packaging due to their antimicrobial properties and ability to improve mechanical barriers and heat resistance compared to traditional methods [10]. Active packaging utilizing antimicrobial nanoparticles helps extend shelf life by inhibiting microbial growth and maintaining food freshness [11, 12]. Nanosensors are employed throughout the food supply chain to detect contamination and monitor food quality during processing, packaging, storage, and transportation [13, 14].

Despite these advancements, concerns arise regarding human exposure to nanoparticles through ingestion of nanoparticle-enhanced foods and migration from packaging materials. Studies indicate potential health risks including protein denaturation, oxidative stress, DNA damage, and gastrointestinal issues associated with oral exposure to nanoparticles [15]. This necessitates rigorous assessment of nanoparticle toxicity and safety in food applications to ensure consumer health and regulatory compliance [5]. While nanotechnology offers significant benefits in improving food quality and safety, careful consideration and comprehensive studies are essential to mitigate potential risks associated with the use of nanoparticles in food products. Regulatory frameworks and advanced techniques for toxicity assessment are crucial in ensuring the safe integration of nanotechnology into the food industry.

This study examines the current research on nanoparticles applied across various sectors of the food industry, investigates their potential toxicity, and assesses their safety implications in food applications.

2. HEALTH RISKS ASSOCIATED WITH TOXICITY AND SAFETY ASSESSMENT

Nanotechnology has revolutionized the food industry with its ability to enhance food quality and packaging capabilities. However, the integration of synthesized nanoparticles into food and food packaging raises significant health concerns due to potential exposure to harmful pollutants. Nanoparticles in food packaging, designed to improve barrier properties and provide active functionalities, can leach into food and subsequently into the human body, posing risks of toxicity and ecotoxicity [16]. These nanoparticles, despite their intended benefits such as antimicrobial and antioxidant properties, have been linked to oxidative stress, DNA damage, cell dysfunction, cytotoxicity, and even cancer formation.

The toxicity of nanoparticles depends on various factors including the type of nanoparticle, characteristics of the packaging matrix, migration extent, and absorption rates into specific food items [5]. Evidence suggests that nanoparticles can accumulate in organs such as the stomach, kidneys, liver, and lungs, potentially leading to organ damage and other health complications [17]. For instance, titanium dioxide nanoparticles have been implicated in adverse health effects upon ingestion and environmental contamination [14].

The risks associated with nanoparticle exposure necessitate thorough risk assessment and regulatory scrutiny to safeguard public health. More research is needed to understand the long-term health impacts of nanoparticles in food and packaging materials, particularly concerning their bioaccumulation and potential for systemic toxicity [18]. Addressing these concerns requires robust methodologies for toxicity testing and clear regulatory guidelines to mitigate risks associated with nanoparticle use in food products.

Research on the health impacts of nanoparticles in food is currently limited, highlighting significant gaps in understanding the risks associated with these materials. The risk profile of a nanomaterial depends on its chemical composition, physical properties, and interactions within biological tissues, coupled with exposure levels. Physicochemical characterization is essential to identify and classify substances as nanomaterials, ensuring accurate assessment of their unique properties and effects.

Nanomaterials intended for use in the food chain may pose safety concerns, particularly those capable of escaping the digestive system and potentially translocating to organs or causing local effects in the gastrointestinal tract [19]. Models simulating in vitro digestion have been pivotal in assessing the fate of nanoparticles in food matrices, from initial ingestion through the stomach to the intestines, providing insights into potential risks such as food contamination [20].

Despite regulatory efforts by organizations like the FAO, WHO, and EU to strengthen nanoparticle safety in food, critical gaps remain in understanding carcinogenic, genotoxic, and teratogenic risks associated with these materials [21]. The EFSA has revised its guidelines to include comprehensive assessments of nanomaterials in new foods, additives, and food contact materials, emphasizing physicochemical characterization, exposure assessment, and hazard identification [22]. Concerns persist regarding nanoparticle fractions and materials with nanoscale features that may pose risks to consumers, necessitating further research and stringent regulatory frameworks to ensure the safety of nanotechnology applications in the food industry.

The Scientific Committee on Consumer Safety (SCCS) issued a Consultation highlighting concerns regarding the safety characteristics of nanoparticles, urging rigorous risk assessment protocols (SCCS, 2019). These guidelines emphasize specific nano-specific features such as degradation, genotoxicity, accumulation, and immunotoxicity, which are critical in evaluating the hazard potential of nanomaterials [23]. Prior to integrating nanotechnology into the food industry, it is essential to standardize the identification, measurement, administration guidelines, and exposure limits of nanoparticles in food commodities [24].

Migration of nanoparticles from food packaging materials into food products is a significant concern but lacks comprehensive migration tests and risk assessments. Understanding nanoparticle migration involves studying diffusion processes using frameworks like Fick's second law to assess potential transfers of hazardous substances into food [25]. However, existing studies often fail to provide conclusive evidence due to limitations in analytical techniques for detecting nanoparticles, particularly those with lower concentrations and smaller diameters [8].

Engineered nano-objects (ENO) are widely utilized in the food industry for their antimicrobial properties and packaging enhancements, but their potential toxicity and environmental impact require further investigation [26]. Regulatory frameworks, such as those discussed by Gergely et al. (2010) and Hodge et al. (2014) need to establish safety thresholds and environmental disposal protocols for nanomaterials used in food applications [27, 28].

Advancing research is crucial to assess the safety and environmental implications of nanostructured materials in the food industry. Collaboration among food scientists, researchers, and regulatory bodies is essential to develop comprehensive guidelines and frameworks that ensure the safe implementation, consumption, and disposal of nanotechnology in food products.

3. FUTURE PERSPECTIVES AND CHALLENGES OF NANOTECHNOLOGY IN FOOD

The future of nanotechnology in the food industry holds immense promise for innovation in manufacturing processes and product development. However, several challenges must be addressed to ensure the safe and effective implementation of nanomaterials. Societal concerns regarding the safety of nano-enabled food products for human consumption continue to grow as scientific research progresses [29]. A comprehensive study of potential hazards to human health is essential before nano food products can be commercialized, yet there remains a lack of general guidelines for assessing the safety of nanomaterials in foodstuffs.

Key challenges include the development of cost-effective and safe edible delivery systems and understanding the migration and absorption of nanoparticles from packaging materials into food products [30]. Current understanding of nanoparticles at the nanoscale is limited, particularly in predicting their migration mechanisms, which involve complex processes beyond simple diffusion [31].

The physico-chemical characteristics of nanoparticles, such as morphology, composition, surface properties, charge, and aggregation state, significantly influence their gastrointestinal absorption and potential health risks. Comprehensive risk assessments are necessary to evaluate nanoparticle consequences, potential toxicological risks, and environmental impacts associated with their production and use in food processing, packaging, and consumption [17].

Furthermore, regulatory frameworks need to evolve to address public concerns and ensure biosafety in nano-based foodstuffs [32]. Research efforts should focus on understanding nanoparticle interactions with biological organisms through in vitro and in vivo studies to facilitate the safe development of antimicrobial nanoparticles and sustainable alternatives. Legislative bodies such as the Food and Drug Administration (FDA) and the European Commission have begun to outline regulatory frameworks for nanotechnology in food, emphasizing the need for safety assessments that consider the unique characteristics of nanomaterials. However, significant gaps remain, particularly in developing standardized safety evaluation methodologies specific to nano-based food products [33].

Moving forward, improving safety evaluations based on exposure and toxic response mechanisms is critical to addressing biological consequences such as oxidative stress, protein denaturation, and DNA damage associated with nanoparticle exposure in food [29]. Establishing consistent safety review methodologies and toxicity testing aligned with contemporary standards is essential for effective risk management and regulation of nanotechnology in the food processing sector.

In essence, while nanotechnology offers substantial opportunities for innovation in the food industry, ongoing research, regulatory development, and public engagement are essential to ensure its safe and sustainable integration into food production and consumption practices worldwide.

4. CONCLUSION

The integration of nanoparticles in the food industry presents significant advancements in food quality and packaging capabilities but raises concerns about potential health risks. Nanoparticles, utilized extensively in food preservation, additives, and packaging, offer benefits such as improved mechanical barriers and enhanced shelf life through antimicrobial properties. However, their ingestion through food or migration from packaging materials may lead to adverse health effects, including protein denaturation, oxidative stress, DNA damage, and gastrointestinal disturbances. To address these concerns, rigorous toxicity assessments and regulatory frameworks are essential. Current research underscores the importance of physicochemical characterization to understand nanoparticle behavior in food matrices and their potential impacts on human health. Models simulating digestion processes have provided insights into nanoparticle fate and bioavailability, highlighting the need for standardized testing methodologies.

Regulatory bodies like the FAO, WHO, and EU have initiated efforts to strengthen safety guidelines for nanomaterials in food, focusing on comprehensive risk assessments that encompass exposure levels, hazard identification, and toxicological endpoints. However, gaps remain in understanding long-term health implications, necessitating further research to evaluate carcinogenic, genotoxic, and teratogenic risks associated with nanoparticle exposure. Moving forward, collaboration among scientists, regulators, and industry stakeholders is crucial to develop robust safety protocols and ensure the responsible application of nanotechnology in food production and packaging. This multidisciplinary approach will support innovation while safeguarding consumer health and environmental sustainability in the evolving landscape of nanotechnology in food.

REFERENCES

[1] De Francisco, E. V., & García-Estepa, R. M. (2018). Nanotechnology in the agrofood industry. Journal of Food Engineering, 238, 1–11.

[2] Ozimek, L., Pospiech, E., & Narine, S. (2010). Nanotechnologies in food and meat processing. Acta

Scientiarum Polonorum Technologia Alimentaria, 9(4), 401–412.

[3] Patra, J. K., Shin, H.-S., & Paramithiotis, S. (2018). Application of nanotechnology in food science and food microbiology. Frontiers in Microbiology, 9, 714.

[4] Anandharamakrishnan, C., & Parthasarathi, S. (2019). Food nanotechnology: Principles and applications. CRC Press.

[5] Sahoo, M., Vishwakarma, S., Panigrahi, C., & Kumar, J. (2021). Nanotechnology: Current applications and future scope in food. Food Frontiers, 2(1), 3–22.

[6] Singh, T., Shukla, S., Kumar, P., Wahla, V., Bajpai, V. K., & Rather, I. A. (2017). Application of nanotechnology in food science: Perception and overview. Frontiers in Microbiology, 8, 1501.

[7] Bouwmeester, H., van der Zande, M., & Jepson, M. A. (2018). Effects of food-borne nanomaterials on gastrointestinal tissues and microbiota. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology, 10(1), e1481.

[8] López-Rubio, A., Fabra, M. J., & Martínez-Sanz, M. (2019). Food packaging based on nanomaterials. In Multidisciplinary Digital Publishing Institute.

[9] Bott, J., Störmer, A., & Franz, R. (2014). A comprehensive study into the migration potential of nano silver particles from food contact polyolefins. In Chemistry of food, food supplements, and food contact materials: From production to plate (pp. 51–70). ACS Publications.

[10] Omerovic, N., Djisalov, M., Živojevic, K., Mladenovic, M., Vunduk, J., Milenkovic, I., Knezevic, N. Z., Gadjanski, I., & Vidic, J. (2021). Antimicrobial nanoparticles and biodegradable polymer composites for active food packaging applications. Comprehensive Reviews in Food Science and Food Safety, 20(3), 2428–2454.

[11] Drago, E., Campardelli, R., Pettinato, M., & Perego, P. (2020). Innovations in smart packaging concepts for food: An extensive review. Foods, 9(11), 1628.

[12] Sharma, R., Jafari, S. M., & Sharma, S. (2020). Antimicrobial bio-nanocomposites and their potential applications in food packaging. Food Control, 112, 107086.

[13] Nile, S. H., & Kai, G. (2021). Recent clinical trials on natural products and traditional Chinese medicine combating the COVID-19. Indian Journal of Microbiology, 61(1), 10–15.

[14] Wang, M., Li, S., Chen, Z., Zhu, J., Hao, W., Jia, G., Chen, W., Zheng, Y., Qu, W., & Liu, Y. (2021). Safety assessment of nanoparticles in food: Current status and prospective. Nano Today, 39, 101169.

[15] Hong, F., Wu, N., Zhou, Y., Ji, L., Chen, T., & Wang, L. (2017). Gastric toxicity involving alterations of gastritis-related protein expression in mice following long-term exposure to nano TiO2. Food Research International, 95, 38–45.

[16] Dudefoi, W., Villares, A., Peyron, S., Moreau, C., Ropers, M.-H., Gontard, N., & Cathala, B. (2018). Nanoscience and nanotechnologies for biobased materials, packaging and food applications: New opportunities and concerns. Innovative Food Science and Emerging Technologies, 46, 107–121.

[17] McClements, D. J., & Xiao, H. (2017). Is nano safe in foods? Establishing the factors impacting the gastrointestinal fate and toxicity of organic and inorganic food-grade nanoparticles. NPJ Science of Food, 1(1), 1–13.

[18] He, X., & Hwang, H.-M. (2016). Nanotechnology in food science: Functionality, applicability, and safety assessment. Journal of Food and Drug Analysis, 24(4), 671–681.

[19] Dall'Asta, C., Falavigna, C., Galaverna, G., Dossena, A., & Marchelli, R. (2010). In vitro digestion assay for determination of hidden fumonisins in maize. Journal of Agricultural and Food Chemistry, 58(22), 12042–12047.

[20] Tydeman, E. A., Parker, M. L., Wickham, M. S. J., Rich, G. T., Faulks, R. M., Gidley, M. J., Fillery-Travis, A., & Waldron, K. W. (2010). Effect of carrot (Daucus carota) microstructure on carotene bioaccessibility in the upper gastrointestinal tract. 1. In vitro simulations of carrot digestion. Journal of Agricultural and Food Chemistry, 58(17), 9847–9854.

[21] Magnuson, B., Munro, I., Abbot, P., Baldwin, N., Lopez-Garcia, R., Ly, K., McGirr, L., Roberts, A., & Socolovsky, S. (2013). Review of the regulation and safety assessment of food substances in various countries and jurisdictions. Food Additives and Contaminants, 30(7), 1147–1220.

[22] Committee, E. S., More, S., Bampidis, V., Benford, D., Bragard, C., Halldorsson, T., Hernández-Jerez, A., Hougaard Bennekou, S., Koutsoumanis, K., Lambre,

C., Machera, K., Naegeli, H., Nielsen, S., Schlatter, J., Schrenk, D., Silano, V., Turck, D., Younes, M., Castenmiller, J., Chaudhry, Q., Cubadda, F., Franz, R., Gott, D., Mast, J., Mortensen, A., Oomen, A. G., Weigel, S., Barthelemy, E., Rincon, A., Tarazona, J., & Schoonjans, R. (2021). Guidance on risk assessment of nanomaterials to be applied in the food and feed chain: Human and animal health. EFSA Journal, 19(8), e06768.

[23] Dekkers, S., Oomen, A. G., Bleeker, E. A. J., Vandebriel, R. J., Micheletti, C., Cabellos, J., Janer, G., Fuentes, N., Vázquez-Campos, S., Borges, T., Silva, M. J., Prina-Mello, A., Movia, D., Nesslany, F., Ribeiro, A. R., Leite, P. E., Groenewold, M., Cassee, F. R., Sips, A. J. A. M., Dijkzeul, A., van Teunenbroek, T., & Wijnhoven, S. W. P. (2016). Towards a nanospecific approach for risk assessment. Regulatory Toxicology and Pharmacology, 80, 46–59.

[24] Brand, W., Van Kesteren, P., & Oomen, A. (2020). Potential health risks of nanomaterials in food: A methodology to identify signals and prioritize risks. In Mogelijke gezondheidsrisico's van nanomaterialen in voedsel: Een methode om risico's te signaleren en te prioriteren. Rijksinstituut voor Volksgezondheid en Milieu (RIVM).

[25] Souza, V. G. L., & Fernando, A. L. (2016). Nanoparticles in food packaging: Biodegradability and potential migration to food—a review. Food Packaging and Shelf Life, 8, 63–70.

[26] Ramakrishnan, S., Mahawer, S. K., Prasad, M., Chaudhary, M., Kumar, A., & Govindasamy, P. (2021). Nanomaterials in integrated methods for soil remediation (biological/physiological combination processes). In Nanomaterials for soil remediation (pp. 445–462). Elsevier.

[27] Gergely, G., Weber, F., Lukács, I., Illes, L., Toth, A., Horváth, Z., Mihaly, J., & Balazsi, C. (2010). Nano-hydroxyapatite preparation from biogenic raw materials. Open Chemistry, 8(2), 375–381.

[28] Hodge, G. A., Maynard, A. D., & Bowman, D. M. (2014). Nanotechnology: Rhetoric, risk and regulation. Science and Public Policy, 41(1), 1–14.

[29] Rastogi, I.D. (2012). Nanotechnology: Safety paradigms. Journal of Toxicology and Environmental Health Sciences, 4(1), 1–12.

[30] Dupas, C., & Lahmani, M. (2007). Nanoscience: Nanotechnologies and Nanophysics. Springer Science & Business Media.

[31] Jokar, M., Pedersen, G.A., & Loeschner, K. (2017). Six open questions about the migration of engineered nano-objects from polymer-based food-contact materials: A review. Food Additives & Contaminants: Part A, 34(3), 434–450.

[32] Bajpai, V.K., Kamle, M., Shukla, S., Mahato, D.K., Chandra, P., Hwang, S.K., Kumar, P., Huh, Y.S., & Han, Y.-K. (2018). Prospects of using nanotechnology for food preservation, safety, and security. Journal of Food and Drug Analysis, 26(4), 1201–1214.

[33] Jo, M.-R., Yu, J., Kim, H.-J., Song, J.H., Kim, K.-M., Oh, J.-M., & Choi, S.-J. (2016). Titanium dioxide nanoparticle-biomolecule interactions influence oral absorption. Nanomaterials, 6(12), 225.

BIOGRAPHY

Dr. Rashmi Manoj, Assistant Professor and Head at Guru Nanak Girls' P G College in Udaipur, Rajasthan, is a prolific writer with numerous research papers and four authored books. Her expertise spans community health in rural areas, nutrition, and sustainable development, showcased through presentations at national/ international conferences.