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Exploring The Nexus of Food Science and Nanotechnology: Applications, Innovations and Future Perspectives

Nitan Kaur[1]*, Preeti[1], Preeti[1], Vishakha Saini[1], Jagdeep Singh[1], Ashwani K. Dhingra[1].

[1] Global Research Institute of Pharmacy, Radaur, Yamuna Nagar-135133, Haryana.

* Correspondence: nitankaur55@gmail.com

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Abstract: Nanotechnology has emerged as a groundbreaking tool in food science, offering transformative solutions across various domains The integration of nanotechnology offers numerous benefits such as improved food quality and safety, extended shelf life, improved sensory attributes, and enhanced nutritional value. Innovation in nanotechnology has sparked numerous advancements in the food industry. Functional foods with improved nutritional profiles and novel textures are developed using nanoscale materials. Smart packaging solutions equipped with nanotechnology monitor food freshness in real time, contributing to reduced food waste and enhanced consumer satisfaction. Nanoparticles are utilised to extend the shelf life of food products and prevent contamination, while nanoencapsulation techniques enable targeted nutrient delivery, resulting in fortified and healthier food products. Nanosensors facilitate rapid detection of pathogens and contaminants, ensuring food safety. Despite its promise, the integration of nanotechnology in food science presents challenges. Concerns about the health and environmental impacts of nanoparticles require thorough testing and evaluation. Regulatory compliance, scalability, and cost-effectiveness are also significant hurdles to widespread adoption. Looking ahead, nanotechnology in food science holds great promise. Continued research is expected to lead to personalized nutrition solutions and innovations in addressing global food security challenges. Nanorobotics may revolutionize food processing, improving efficiency and sustainability. The integration of nanotechnology into food science offers opportunities for enhanced quality, safety, and sustainability, although challenges must be addressed. Ongoing innovation in this field has the potential to reshape the future of food production and consumption.

Keywords: Nanotechnology; Nanoparticles; Nanoencapsulation; Nanosensor; Food safety; Innovative solutions; Improved nutritional profiles.

1. Introduction

The term "nano" originates from the Greek word meaning "dwarf." A nanometer represents one billionth of a meter. Nanoparticles are typically defined as particles with sizes smaller than 100 nanometers, where distinctive phenomena allow for innovative applications and advantages. Most research in nanotechnology focuses on nanomaterials, which are typically powders composed of nanoparticles [1]. Since the previous few decennary, this concept has gained growing significance as a promising technology within the food industry. Nanotechnology encompasses various technological fields and functions as a means to generate, explore phenomena, or control materials at nanoscale dimensions [2]. Nanotechnology involves grasping and regulating matter within the nanometer range where exceptional phenomenon produces cutting-edge implementations. It spans nanoscale science, engineering, and technology, encompassing activities such as visualization, quantifying, representing, and altering at this dimension [3]. Due to their distinctive characteristics, along with their significant surface-to-volume ratio and modified solubility and toxicity compared to larger-scale counterparts, engineered nanoparticles have garnered increased interest in various fields such as medicine, agro-food sectors, sewage water treatments, and other industries. Various sizes of nanoparticles are employed in the realm of food science nanotechnologies to explore their potential in the creation and processing of foods that are not only healthier and safer but also of higher quality [4].

These novel characteristics offer avenues for enhancing the perceptual aspects of food, including palate, quality and chroma. Moreover, it presents opportunities to bolster food protection measures. By employing nanosensors and nanopackaging materials, it becomes possible to swiftly and accurately detect pathogenic microbe presence, hazardous substances, and agrochemicals. The Nanocarrier technology system holds promise in refining food manufacturing by facilitating the delivery of biologically active ingredients thereby improving their utilization efficiency in food products [5]. Nanomaterials are commonly used in addressing a wide array of pathogenic microorganisms owing to their outstanding antibacterial features and physicochemical properties. Research has shown that employing these nanoparticles effectively heightens food protection by boosting the healthful value, efficacy, and longevity of food items. Designing affordable processing techniques that prioritize safety for human utilization poses a crucial challenge for nanotechnologies. To tackle these growing concerns, experts suggest producing safe, non-toxic, and biocompatible nanostructures using accessible, cost-efficient, and environmentally friendly techniques, using materials suitable for food applications. Another viewpoint involves leveraging nanotechnology to enhance the bioavailability and absorption of supplements and vitamins within the body. Nanocarriers and nanocapsules, nanosensors, nanopackaging, and nanotubes serve as delivery systems for nanoparticles [6].

2. Applications

Nanotechnology is becoming increasingly important worldwide as a key tool for the food and bioprocessing industry to cope with the growing global need driven by population expansion and rising incomes in developing nations. It holds potential applications across the entire feeding hierarchy along with conservation, quality auditing, food manufacturing, encasing, taste and texture enhancement, flavour improvement, improved nutrient assimilation, better enveloping methods, and more effective microbial identification systems. The potential of nanotechnology in food quality monitoring through the use of nanosensors, food packaging and encapsulation, and ensuring the safety of food products during delivery [7-8] as shown in **Figure 1**.

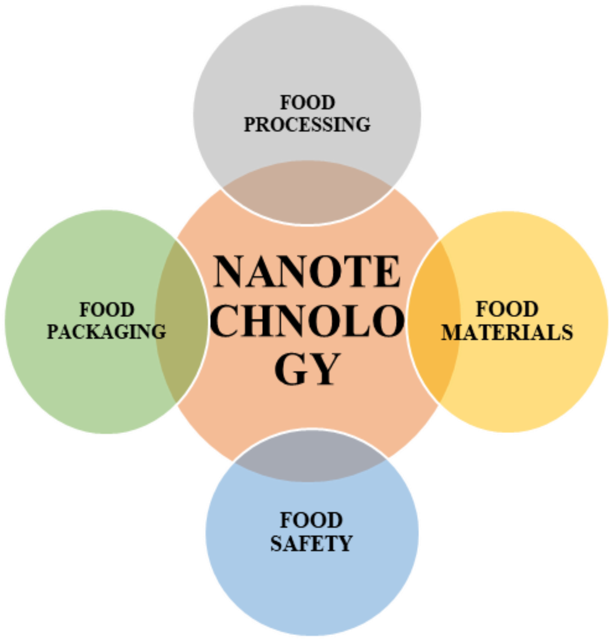

Figure 1: Application of nanotechnology in food quality monitoring.

2.1 Food Processing

A flawless delivery system should demonstrate the given qualities: (i) precise delivery of the active substance to its intended destination, (ii) assurance of procurement according to specified timing and dosage, and (iii) effectiveness in preserving active compounds at optimal levels for prolonged periods, particularly during storage. Leveraging nanotechnology in crafting encapsulation, emulsions, biopolymer matrices, basic solutions, and association colloids provides effective delivery systems embodying the mentioned characteristics. Applying nanotechnology in the development of encapsulation, emulsions, biopolymer matrices, simple solutions, and association colloids offers efficient delivery systems with the aforementioned attributes [9]. Enzymes are utilized in certain food manufacturing techniques to alter food constituents, thus improving taste, nourishing content, and positive well-being effects. This is achieved through their effective dispersion within food matrices and their large surface-to-volume ratios in comparison to conventional macro-scale support materials. For instance, nano-silicon dioxide particles exhibit efficient hydrolysis of olive oil, demonstrating modified stability, adaptability, and reusability [10].

Food technologists have long been accustomed to microencapsulating food ingredients, but they are now shifting towards nanoencapsulation methods like nano-emulsions, liposomes, micelles, colloidosomes, nanolimates, and nanocochleates. Advocates of nanoencapsulation argue that it offers significant advancements over microencapsulation. They claim that nanoencapsulation techniques provide superior protection for bioactive compounds, enhancing targeting within the body. Additionally, they facilitate better integration of nutrients into food and beverage matrices and aid in the development of more bioavailable nutrient additives [11-13]. Nanotechnologies offer avenues for enhancing the nutritional and medicinal attributes of food through improved solubility and dispersion of food additives, as well as by concealing undesirable flavors and textures linked to these additives. Ongoing research is focused on crafting nanocapsules and nanoemulsions capable of controlled release, facilitating the targeted delivery of vitamins, nutrients, and probiotic bacteria to specific cells or tissues. Additionally, lipid-based nanoencapsulation systems are being developed to encapsulate multiple materials with diverse solubilities [14].

2.2 Food Packaging

Food packaging stands as a critical measure in safeguarding food safety. Its key aims include thwarting deterioration and adulteration, enhancing susceptibility through biochemical function and curbing excess weight reduction. Nevertheless, in functional foods, the bioactive elements frequently undergo degradation and become inactive due to adverse environmental conditions, consequently shortening the product's shelf life. The utilization of nanostructured or nanomodified materials emerges as an encouraging avenue for prolonging and ensuring food item stability duration [15]. Further different methods that are implemented for the packaging of food are discussed below:

2.2.1 Antimicrobial Active Packaging

Antimicrobial packaging serves the dual purpose of preserving foods and prolonging their stability duration by hindering the production of microorganisms. It can be accomplished by integrating an active substance onto the packaging material or adding a protective layer inside. Because of variations in physiology, antimicrobial agents exhibit differing effects depending on the specific pathogenic microorganism [16]. Nanomaterials are frequently utilized to enhance the attributes of food protection due to their ability to inhibit microbial growth, UV protection capabilities, and potential to prevent rancidity. Nanoparticles like silver (Ag), titanium dioxide (TiO2), zinc oxide (ZnO), and magnesium oxide (MgO) are highly suitable for antimicrobial active packaging systems due to their potent antimicrobial activity. TiO2 nanoparticles, recognized for their safety for organism consumption and approval as food additives and for food storage materials, are commonly integrated into food wrapping. Nonetheless, additional investigation into their after-metabolism effects and absorption in the body is imperative to ensure their sheltered application in the food industry. Metal nanocrystals, serving as active entities, are frequently combined with other antimicrobial compounds and various metal nanoparticles to enhance their effectiveness [17-19].

2.2.2 Bioactive Polymers for Packaging

Bioactive polymers offer versatile solutions for food packaging, exhibiting antimicrobial, antioxidant, and barrier properties against water and oxygen. Through the integration of supplementary components, their effectiveness in prolonging shelf life while minimizing food degradation can be enhanced. Among these polymers, chitosan stands out as a particularly promising candidate due to its expanding utility across various sectors, including medicine and food packaging, all compliant with regulatory standards for food contact materials [20].

2.2.3 Nanostructured Polymers

Polymer nanocomposites (PNCs) have garnered significant attention because, in addition to inherent bioactivity, their composite structure often yields enhanced characteristics in contrast with their elements.

Nanostructured polymers are garnering increasing attention due to their size-dependent properties. Typically, branched polymers exhibit smaller dimensions compared to linear polymers of equivalent molecular weight. This innovative approach holds promise in revolutionizing food packaging by preserving food quality and safety while extending shelf life. Typically, nanocomposite packaging materials comprise a polymer matrix, nanofillers, plasticizers, and compatibilizers, each playing a crucial role in their performance [21].

2.2.4 Metal Oxide Nanoparticles

Metal oxide nanoparticles possess a larger surface area owing to their reduced dimensions, rendering them valuable across a range of applications including biosensors, bio-nanotechnology, and nanomedicine. Their heightened reactivity stems from the abundance of surface atoms. Various characteristics, including crystallinity, size, composition, and morphology, contribute to their distinct properties. Their small size facilitates penetration into cellular structures, enabling interactions with biomolecules within cells [22].

Examples of some nanoparticles used in food packaging-

- Zinc Oxide (ZnO) Nanoparticles for Food Packaging
- Titanium dioxide (TiO2) Nanoparticles for Food Packaging
- Copper Oxide (CuO) Nanoparticles for Food Packaging
- Silicon dioxide (SiO2) Nanoparticles for Food Packaging

2.3 Nanofood Materials

Nanofood materials represent a revolutionary approach to enhancing food quality, safety, and functionality. By leveraging the unique properties of nanomaterials, the food industry can develop innovative products that meet consumer demands for healthier, safer, and more sustainable food options. As research and technology advance, nanofood materials will likely play an increasingly vital role in the future of food science. Various types of nanofood materials are depicted in **Figure 2**.

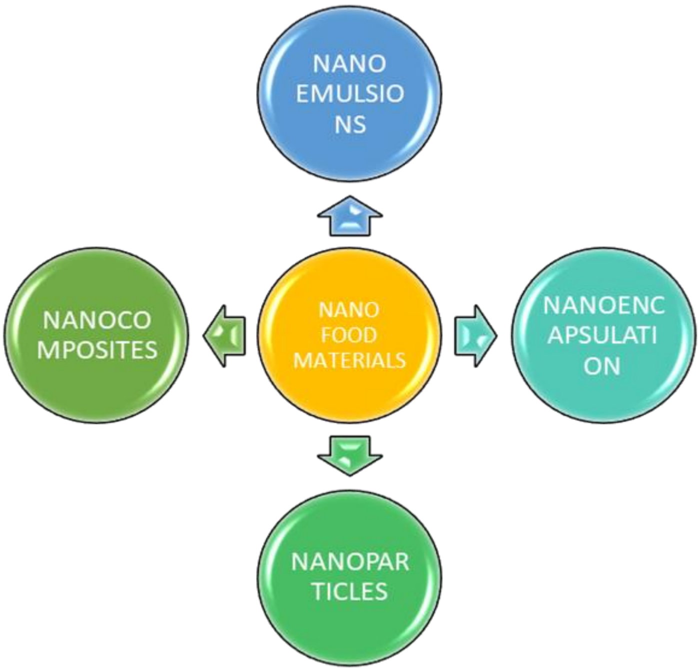

Figure 2: Various types of nanofood materials.

2.3.1 Nanoemulsions

Nanoemulsions offer versatile applications, including equipment decontamination and enhancing clarity without compromising product appearance or taste. Functional nanoemulsified and encapsulated compounds, such as lutein, lycopene, β-carotene, vitamins A, D, and E, coenzyme Q10, and omega-3 fatty acids, are utilized for targeted delivery. For instance, capsaicin-loaded nanoemulsions are stabilized with natural polymers like chitosan and alginate. Regular incorporation of components from functional meals into droplets can delay chemical breakdown processes by modifying the properties of the surrounding interfacial layer. Moreover, nanoemulsions are employed to produce bottled milk and water enriched with vitamins, antioxidants, and minerals [23].

2.3.2 Nanoencapsulation

Nanoencapsulation of probiotics aims to create specialized formulations prepared from microorganisms that can be effectively delivered to targeted areas of the gastrointestinal domain, enhancing their interaction with specific receptors. By encapsulating probiotics at the nano level, it becomes feasible to prolong the stability duration of substances while also improving their ability to survive harsh digestive conditions. This process opens up the potential for these designer probiotic formulations to serve as innovative tools for modulating immune responses and potentially acting akin to vaccines [6].

2.3.3 Nanoparticles

Nanoparticles offer a myriad of advantages when employed in food enhancement and processing. Their distinctive characteristics, including a high surface area to-volume ratio and customizable surface chemistry, render them highly sought-after for diverse applications within the food industry. These properties enhancement contribute to elevated sensory attributes and nutritional value. Additionally, nanomaterials can function as efficient carriers for preservatives, permitting controlled release and prolonged shelf life of food items. In the realm of animal nutrition, nanostructured feed additives have the potential to enhance nutrient absorption and foster animal health and growth, thereby benefiting both livestock and consumers [24].

2.3.4 Nanocomposites

Polymer nanocomposites (PNCs) in the form of packaging materials are emerging as promising alternatives to intricate multilayered polymer structures. There's a growing interest in utilizing nanocomposites for food packaging purposes. By incorporating small amounts of nanofillers, various physical and chemical characteristics can be improved. Nanocomposites offer a fresh alternative to traditional methods for enhancing polymer properties. They boast enhanced barrier properties, heightened mechanical strength, and superior heat resistance in comparison to both neat polymers and conventional composites. Additionally, antimicrobial and antioxidant characteristics can be integrated, which are highly beneficial for food packaging needs [25].

2.4 Food Safety

Food safety has become a pressing global public health issue, with its primary objective being to safeguard consumers from any harm arising during food preparation and consumption. Throughout processing, handling, and distribution, it's imperative to shield food from physical, chemical, and biological contaminants. The dynamic evolution of food recipes and consumption habits underscores the significance of this concern. Disease-causing agents, hazardous substances, and other contaminants pose significant risks to human health. Traditional detection methods for disease-causing agents, and hazardous substances are both laborious and time-intensive. The emergence of nanotechnology has revolutionized efforts to address food safety concerns, facilitating enhanced detection of microbial contaminants and toxins, as well as improving shelf-life and packaging strategies. The swift and accurate identification of pathogenic bacteria holds paramount importance in assuring food stability and early detection of diseases and infectious agents [26, 15].

2.4.1 Nanosensors

Nanosensors represent bioanalytical devices crafted using diverse nanostructured materials and biological receptors, integrated into a cohesive system design. Their importance in the food industry has surged recently owing to their rapid detection capabilities, reliability, and cost-effectiveness. With their heightened sensitivity and specificity, nanosensors hold promise for integration with a wide range of analytes. The remarkable sensing capabilities and advantageous characteristics of nanomaterials position them as ideal candidates for biosensors. Nanosensors or nano biosensors play crucial roles in quantifying food constituents, detecting pathogens in food and agriculture, and alerting distributors and consumers about the safety of food products. Utilizing quartz crystal surfaces has proven effective in detecting a range of functional groups or biological residues, including enzymes, lipid molecules, amines, and various polymers.

By merging biology and nanoscale technology, the development of sensors is poised to significantly decrease response times in identifying potential hazards. They are also employed in monitoring food freshness and ensuring food packaging integrity [27-29]. Nanomaterials utilized in nano biosensors are poised to detect pesticides, pathogens, and toxins, thereby improving the tracking, tracing, and monitoring of food quality throughout the supply chain. Nanomaterials are used in nano bioanalytical devices for estimating food allergens and in biosensors designed for detecting both food-borne pathogens and allergens. Furthermore, there have been documented instances of nano biosensors developed specifically for estimating and managing food allergens [30]. Various applications of nanosensors in the food industry:

- Nanosensors in the Detection of Toxins
- Nanosensors in the Detection of Food Pathogens
- Nanosensors in Sensing Chemicals and Pesticides in Food
- Nanosensors in Sensing the Quality of Key Food Ingredients

3. Challenges and Future Prospects

While the benefits of nanotechnology are vast, its adoption in food science is not without challenges. Concerns regarding the potential toxicity and environmental impact of nanomaterials, as well as regulatory and ethical issues, must be addressed. Comprehensive research and clear guidelines are essential to ensure the safe application of nanotechnology. Despite these challenges, the future of nanotechnology in food science is promising. Continued innovation holds the potential to shape a more sustainable and efficient food production system, meeting the demands of a growing global population while enhancing the quality, safety, and nutritional value of food. In conclusion, nanotechnology is poised to revolutionize the food industry by offering cutting-edge solutions that address existing challenges while opening up new possibilities. Its integration into food science represents a pathway to a more sustainable and innovative future for food production and consumption.

4. Conclusion

Nanotechnology is emerging as a transformative force in food production and food science, offering the potential to revolutionize traditional practices and address contemporary challenges through innovative solutions that enhance efficiency, safety, and sustainability in the food industry. It introduces advanced techniques for plant cultivation and conservation, enabling farmers and scientists to employ nanomaterials for precise environmental detection and bioremediation, thereby optimizing soil and crop conditions. In food storage and packaging, nanotechnology plays a pivotal role by incorporating nanosized materials that protect products from environmental factors like moisture, oxygen, and microbial contamination. Nano-preservatives and nanosensors further enhance monitoring capabilities, enabling real-time detection of spoilage and pathogens, which improves food safety and reduces waste. Its contributions to food safety extend to the isolation and detection of harmful microbes, toxins, and contaminants with unprecedented accuracy, fostering consumer confidence through stringent quality standards. Furthermore, nanotechnology facilitates the incorporation of nutritional and functional supplements into food products by encapsulating bioactive compounds such as polyphenols, vitamins, antioxidants, and fatty acids, improving stability, bioavailability, and health benefits to meet the growing demand for functional foods. Direct applications include the use of nano-based coloring agents, fragrances, and preservatives to enhance sensory and aesthetic qualities, while indirect applications involve nanosized materials in packaging and catalysts in fat hydrogenation processes, improving packaging durability and recyclability. These advancements collectively demonstrate the immense potential of nanotechnology to transform food science, providing innovative solutions for a more sustainable and efficient future.

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Conflict of interest

It was declared to be none.

Reference

1. Yang H, Wang Y, Lai S, An H, Li Y, Chen F. Application of atomic force microscopy as a nanotechnology tool in food science. J Food Sci, 2007;72(4):R65-75.
2. Primožič M, Knez Ž, Leitgeb M. (Bio) Nanotechnology in food science—food packaging. Nanomaterials, 2021;11(2):292.
3. Weiss J, Takhistov P, McClements DJ. Functional materials in food nanotechnology. J Food Sci, 2006;71(9):R107-16.
4. Nile SH, Baskar V, Selvaraj D, Nile A, Xiao J, Kai G. Nanotechnologies in food science: applications, recent trends, and future perspectives. Nano-Micro Lett, 2020;12:1-34.
5. Yu H, Park JY, Kwon CW, Hong SC, Park KM, Chang PS. An overview of nanotechnology in food science: preparative methods, practical applications, and safety. J Chem, 2018;2018.
6. Jagtiani E. Advancements in nanotechnology for food science and industry. Food Front, 2022;3(1):56-82.
7. Aigbogun IE, Mohammed SS, Orukotan AA, Tanko JD. The role of nanotechnology in food industries-a review. J Adv Microbiol, 2017;7(4):1-9.
8. Chen H, Weiss J, Shahidi F. Nanotechnology in nutraceuticals and functional foods. Food Technol, 2006;60(3):30-6.
9. Singh T, Shukla S, Kumar P, Wahla V, Bajpai VK, Rather IA. Application of nanotechnology in food science: perception and overview. Front Microbiol, 2017;8:268461.
10. Dera MW, Teseme WB, Mulugeta Wegari Dera WB. Review on the application of food nanotechnology in food processing. Am J Eng Technol Manag, 2020;5:41-7.
11. Gouin S. Microencapsulation: industrial appraisal of existing technologies and trends. Trends Food Sci Technol, 2004;15:330-47.
12. Flanagan J, Singh H. Microemulsions: a potential delivery system for bioactives in foods. Crit Rev Food Sci Nutr, 2006;46:221-37.
13. Tan CP, Nakajima M. b-Carotene nanodispersions: preparation, characterization and stability evaluation. Food Chem, 2005;92:661-71.
14. Powell M, Colin M. Nanotechnology and food safety: potential benefits, possible risks. CABI Rev, 2008;16:16.
15. Bajpai VK, Kamle M, Shukla S, Mahato DK, Chandra P, Hwang SK, et al. Prospects of using nanotechnology for food preservation, safety, and security. J Food Drug Anal, 2018;26:1201-14.
16. Mustafa F, Andreescu S. Nanotechnology-based approaches for food sensing and packaging applications. RSC Adv, 2020;10:19309-36.
17. Becerril R, Nerín C, Silva F. Encapsulation systems for antimicrobial food packaging components: an update. Molecules, 2020;25:1134.
18. Chaudhary P, Fatima F, Kumar A. Relevance of nanomaterials in food packaging and its advanced future prospects. J Inorg Organomet Polym, 2020;30:5180-92.
19. Neethirajan S, Ragavan V, Weng X, Chand R. Biosensors for sustainable food engineering: challenges and perspectives. Biosensors, 2018;8:23.
20. Tripathi S, Mehrotra GK, Dutta PK. Chitosan-based antimicrobial films for food packaging applications. E Polym, 2008;8.
21. Motelica L, Ficai D, Oprea OC, Ficai A, Andronescu E. Smart food packaging designed by nanotechnological and drug delivery approaches. Coatings, 2020;10(9):806.
22. Dash KK, Deka P, Bangar SP, Chaudhary V, Trif M, Rusu A. Applications of inorganic nanoparticles in food packaging: A comprehensive review. Polymers, 2022;14(3):521.
23. Sekhon BS. Food nanotechnology–an overview. Nanotechnol Sci Appl, 2010;3:1-5.
24. Siddiqui S, Alrumman SA. Influence of nanoparticles on food: An analytical assessment. J King Saud Univ Sci, 2021;33(6):101530.
25. Sarfraz J, Gulin-Sarfraz T, Nilsen-Nygaard J, Pettersen MK. Nanocomposites for food packaging applications: An overview. Nanomaterials, 2020;11(1):10.
26. Inbaraj BS, Chen BH. Nanomaterial-based sensors for detection of foodborne bacterial pathogens and toxins as well as pork adulteration in meat products. J Food Drug Anal, 2016;24(1):15-28.

27. Shafiq M, Anjum S, Hano C, Anjum I, Abbasi BH. An overview of the applications of nanomaterials and nanodevices in the food industry. Foods, 2020;9(2):148.
28. Joshi N, Da Silva LF, Jadhav H, M'Peko JC, Torres BB, Aguir K, Mastelaro VR, Oliveira ON. One-step approach for preparing ozone gas sensors based on hierarchical $NiCo_2O_4$ structures. RSC Adv, 2016;6(95):92655-62.
29. Joshi N, Da Silva LF, Jadhav HS, Shimizu FM, Suman PH, M'Peko JC, Orlandi MO, Seo JG, Mastelaro VR, Oliveira Jr ON. Yolk-shelled $ZnCo_2O_4$ microspheres: Surface properties and gas sensing application. Sens Actuators B Chem, 2018;257:906-15.
30. Singh RP. Utility of nanomaterials in food safety. In: Food Safety and Human Health. Academic Press; 2019. p. 285-318.

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