Applications of Zinc Oxide Nanoparticles in Food/Agriculture

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Zinc oxide nanoparticles (ZnO-NPs) have gained significant interest in the agricultural and food industry as a means of killing or reducing the activity of microorganisms. The antibacterial properties of ZnO-NPs may improve food quality, which has a direct impact on human health. ZnO-NPs are one of the most investigated inorganic nanoparticles and have been used in various related sectors, with the potential to rapidly gain attention and increase interest in the agriculture and food industries.

ZnO-NPs synthesis characterizations modifications

1. Role in Agriculture

We all know that agriculture is a basic necessity and the foundation of every nation's economy, but sadly, this industry is currently facing a number of global challenges, including urbanization, climate change, sustainable resource use, environmental issues, runoff, and the buildup of pesticides and fertilizers. Additionally, the world's population is expected to increase by a number that could be calculated on the basis of current trends [1]. According to research, applying ZnO-NPs to various plants at various stages of their development cycles accelerates plant production by supplementing them with micronutrients.

Significantly, research has shown that Zn is a crucial nutrient for living things. Nandhini et al., emphasized the beneficial effects of ZnO-NPs on pearl millet germination and development as well as the enhanced activity of the plant defense enzymes, such as lipoxygenase, phenylalanine, polyphenol oxidase, ammonia-lyase, and peroxidase [2]. Moreover, the production of chlorophyll pigment from maize and wheat plants was positively impacted by ZnO-NPs. The beneficial effects of ZnO-NP on quantitative, dietary, and physiological parameters of wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) were examined by Singh et al. In addition, these comprised the total protein, carbohydrate, and oil content [3].

In order to increase crop growth and production in global agriculture, and especially in food crops, the fertilizer application rate is very accumulated [4]. According to several studies, ZnO-NPs have the ability to increase food crop output, diversity, and promote healthy growth. Many studies have effectively demonstrated and suggested the use of ZnO-NPs as a foliar fertilizer in addition to a Zn fertilizer in the soil [3]. ZnO-NPs have been recommended as a crucial micronutrient and are intended as a cofactor for the mobilization and activation of nutrient enzymes due to their special characteristics [5].

Raliya et al., studied the influence of ZnO-NP (25 ± 3.5 nm) on the herb (tomato plant). They covered some parameters, such as the whole life cycle of the plant, flower, chlorophyl content, fruit yield, total biomass, and nutritional values. They studied plant development by an optimal concentration of ZnO-NPs, and reported no stimulation on the far side of the optimal concentration. The foliar application was more effective and simpler than the soil treatments. They ended with a maximum lycopene content and fruit yield of 100 mg kg^{-1}, and a concentration of 250 mg kg^{-1} was observed for the best stimulation of plant height, root length, and biomass and improved chlorophyl content at a concentration of 750 mg kg^{-1} [5].

In another study, ZnO-NPs were termed novel fertilizer nutrients for crops. In a greenhouse, the organic compound (urea) was coated with ZnO-NP (1%) or bulk ZnO (2%) and evaluated in wheat (*Triticum aestivum* L.) under drought (40% field moisture capacity; FMC) and non-drought conditions (80% FMC), compared to urea not coated with ZnO (control) and urea with separate ZnO-NP (1%) or bulk ZnO (2%) distinction. The crops were exposed to <2.2 mg/kg of ZnO NP and <4.4 mg/kg of bulk ZnO, indicating exposure to a better Zn rate of bulk ZnO (2%). ZnO-NP and bulk-ZnO showed similar vital efficiencies of urea coating of 74–75%. However, drought considerably (p < 0.05) exaggerated the time to panicle initiation, reduced grain yield, and inhibited the uptake of Zn, phosphorus (P) and nitrogen (N). Within the drought conditions, scientists noticed that ZnO-NPs remarkably reduced the average typical time to panicle initiation by five days, which was regardless of the coating, and relative to the management control. In distinction, bulk ZnO did not have an effect on time to panicle initiation. The grain yield was significantly exaggerated to 51 or 39%, with a ZnO-NP-coated or uncoated organic compound (urea), respectively, compared to the control. As balanced with both control and ZnO-NP treatments, the yield of bulk-ZnO-coated or uncoated urea increased insignificantly [6][7].

2. As Antimicrobial Agent against Food-Borne Pathogens

ZnO-NPs had a significant influence on the control of foodborne diseases. Foodborne infections are putting the entire planet in a dangerous situation. 20,000 people are hospitalized for foodborne illnesses each year in the United Kingdom, and 56 people die as a result, according to the UK Food Standards Agency (FSA). Foodborne illnesses cause a variety of challenges, including health concerns, poverty, and even economic problems [8][9][10]. ZnO-NPs are becoming more effective at combating hazardous microbes and preventing food contamination through adsorption-induced membrane damage and ROS-mediated cellular toxicity. The ZnO-NPs have been shown to be an effective antibacterial agent against harmful microorganisms found in food, including *Staphylococcus aureus*, *Escherichia coli*, *Bacillus subtilis*, *Pseudomonas vulgaris*, *Bacillus megaterium*, *Candida albicans*, *Klebsiella pneumonia*, *Aspergillus Niger* and so on [11][12][13][14]. Metal compound (oxide) particles have been studied to generate active oxygen species that could be the main mechanism of their antibacterial activity [15][16]. Firouzabadi et al. [17], studied the practical application of a ZnO suspension containing 0.3% citric acid at different concentrations (0, 1, 3, 5, 8 mM) in *Listeria monocytogenes*, *Escherichia coli*, *Staphylococcus aureus* and *Bacillus cereus*. It significantly inhibited the growth of all strains during 12 h of culture, and the suspension of ZnO with 5 mM and 8 mM citric acid was the most effective for all strains, and 5 mM and 8 mM ZnO were selected for further study in mango juice. The ZnO-NPs could reduce the initial growth count of all of the strains described above in the mango solution.

ZnO-NPs have direct interaction with cell surface poignant cell membranes, which subsequently ZnO-NPs enter and induce oxidative stress in microorganism cells, which results in inhibition of cell growth to cell death; Researchers recommends ZnO-NPs as a active antimicrobial agent within the food preservation field. ZnO-NPs are often used as a disinfecting and sterilizing agent for the types of equipment and containers utilized in the food industry against the strike and contamination with foodborne pathogenic microbes [18].

3. Role in Food Processing and Storage

ZnO-NPs have brought revolutionary advances to the food industry. In recent years, scientific researchers have shown great interest in the study of ZnO-NPs, along with other nanoparticles, in food processing and storage. These particles not only exhibit antimicrobial activity, as discussed previously, but also remain stable under adverse conditions, such as high temperature, extreme pH values, and more. Furthermore, they are considered “generally recognized as safe (GRAS)” by the US FDA for both human and animal consumption in their bulk form [19][20][21]. Biosensors of ZnO-NPs are being utilized successfully and greatly helped to detect the different pathogens and contaminants of food and water throughout storage [21]. Researchers are interested in enhancing the food processing and storage industry to extend the shelf life of processed food, control food-borne pathogens, and ensure food safety. Achieving these objectives entails improving the nutritional value, activity, and overall quality of food. These goals are critical for the food industry to meet [8][22]. Researchers are particularly concerned about the negative impact of pathogens on stored grain, which can also pose a risk to human health. ZnO-NPs have demonstrated antimicrobial activity and could play a significant role in controlling other important properties of food materials, such as moisture content, absorption, monolayer, solubility, and physical properties [23]. Therefore, reducing the chances of contamination by infectious agents and ensuring safe storage of products with an extended shelf life are critical objectives. To mitigate the risk of contamination or spoilage of food by microbes before or after processing, it is essential to understand the impact of storage time and temperature on microbial populations of minimally processed foods. ZnO-NPs have played a crucial role in protecting and preserving the freshness and nutritional value of food. Moreover, they could be used as a source of zinc supplements in functional foods for consumers [24][25][26]. Hakimian et al. [27], conducted a study on the use of ZnO-NPs (0, 0.1, 0.5, 1 g/kg) as a preservative to control microbial and physicochemical deterioration of mayonnaise during cold storage over a period of 6 months. The addition of ZnO-NPs to mayonnaise resulted in delayed growth of microorganisms, preservation of physical and chemical properties, and increased shelf life compared to the control (0 g/kg). In another study, Lili He and colleagues investigated the antifungal activity of ZnO-NPs against two postharvest fruit fungal diseases, *B. cinerea* and *P. expansum*. The mechanism of action of ZnO-NPs on the development of fungal hyphae was also examined. The results showed that a concentration of ZnO-NPs greater than 3 mmol L^{-1} significantly inhibited the growth of both *B. cinerea* and *P. expansum*. However, the nanoparticles were found to be more effective against *B. cinerea* than *P. expansum* [28].

4. Role in Food Packaging

A very important and in-demand area in the food sector may be related to the use of antibacterial agents in food packaging and with respect to foodborne pathogens [8]. Therefore, nanofood packaging technology is resulting in a brand new mode of safe, active, healthy, and intelligent food packaging. ZnO-NPs offer a safer and more cost-effective alternative compared to other metal oxides for pathogen-free food packaging and processed ingredients [21]. ZnO-NPs are utilized in processed food as a fount of metallic elements (Zn) that help play a crucial and important role in the growth, progress, and welfare of humans and animals. ZnO-NPs are an important antimicrobial supplement in food packaging to counter foodborne pathogens to increase shelf life, inhibit and inactivate or kill pathogens and reduce spoilage, contamination, post-harvest losses to maintain good quality and safety insurance of food products [29][30]. Safe, active, and smart food packaging aligns with customer's desires by enhancing safety and extending shelf life, while also providing a healthier solution [20]. ZnO-nanostructures could be used in the food packaging industry for the composition of filters that are efficient in maintaining microorganisms before packaging [31]. Food poisoning represents microbial contamination that causes significant health, social, and economic problems. Smart food packaging and similar preservative measures can prevent or inhibit the growth of microbials in food, as well as prevent their attachment, colonization, and spreading [24][26]. Microscopic and spectroscopic techniques, such as chemical analysis, can help create optimal food packaging materials to ensure the formation of a composite that enhances food safety and preservation [23].A group of researchers in China investigated the potential migration of ZnO-NPs from industrial products, which is often a mutual concern when it comes to their application in food packaging. They evaluated the migration of ZnO-NPs from polypropylene food containers to food-simulating solutions, taking into account various experimental factors, including the type of food simulant, storage time, and temperature. The experimental results showed significant migration of nano-sized zinc oxide into aqueous, oily, and acidic simulants. The quantity of migrated ZnO increased with storage time and temperature. However, it was observed that ZnO showed a sporadic tendency to migrate into food simulants [32]. Zafar et al. [33], have shown that the ZnO-2.5% composite membrane has strong antibacterial activity and high antioxidant activity against foodborne pathogenic bacteria, *Escherichia coli*, and *Lactobacillus mononucleus*. According to the results, compared to the CMC/GEL blend film, ZnO nanocomposite film could be used to prevent photooxidation, ensure food safety, and improve the shelf life of packaging products in active food packaging.

Using the solution casting method, Insoo Kim et al., created PLA/Zn-ONPs containing volatile oil in collaboration with *Menthe piperita* and *Zataria multiflora Boiss*. In comparison with five common foodborne bacteria including *Salmonella enterica*, *S. aureus*, *Pseudomonas aeruginosa*, *E. coli*, and *Bacillus cereus*, the nanocomposite film showed high antimicrobial activity. The PLA/ZnO-NP containing essential oil extended the shelf life of Otolithes ruber fish during storage. They jointly reported that Zn^{2+} migration was below the NIH limit for food contact material quality requirements [34].

Silvestre et al., introduced the utilization of compound nanotechnology (polymer) in food packaging that mainly meets the requirements of protection against bacteria to attain a completely unique method of packaging. Active packaging, smart packaging, and intelligent packaging are new materials with improved antimicrobial properties that jointly allow the trailing of food throughout storage and transfer [9].

5. Role in Food Flavor

Resaerachers aim to explain, discuss and analyze research works that have utilized ZnO-NPs for the improvement, enhancement, and protection of food flavor, an important ingredient in altering or enhancing the taste of any food. ZnO-NPs' mechanism of action and applications on food flavor are also discussed, particularly in relation to food packaging applications. As previously mentioned, ZnO-NPs are a highly intriguing inorganic compound that is considered safe, non-toxic, and has numerous functions. It is widely used in various industries, including cosmetics, pharmaceuticals, textiles, rubber, and medical fields. Therefore, it holds particular importance in the food and agricultural industry due to its numerous advantages [35]. Sensory quality via ZnO-NPs playing a significant role to make it toxin-free helps in influencing and increasing the interest in quality, stability, acceptability, consumption of different types of food-linked flavors [36][37]. As a result of its difficulty in controlling and stabilizing during the storage and production processes, ZnO-NPs help limit the deterioration or loss during processing and storage. It is advantageous to encapsulate flavors before using ZnO-NPs in food because it increases chemical stability and allows for regulated release. Protective carrier encapsulation prevents oxidation, reactions induced by light, and interactions between tastes. Biopolymers such as polysaccharides (starch, dextrose and maltodextrins), proteins (gelatine and whey proteins), gums (gum arabic, alginates and carrageenan), and chitosan are therefore preferred transporters [38][39]. Some other protein-based materials, e.g., soy protein, polypeptone, or gelatine derivatives, are considered to form stable emulsions with volatiles compounds [40][41].

Brian D. et al., conducted some experiments on diacetyl substitutes 2,3-heptanedione and 2,3-hexanedione. On the contrary, aldehydes seem to be omnipresent in food production, and almost in every sample acetaldehyde was detected and classified as a possible human carcinogen [36].

References

1. Van Der Spiegel, M.; Luning, P.; De Boer, W.; Ziggers, G.; Jongen, W. Measuring Effectiveness of Food Quality Management in the Bakery Sector. Total. Qual. Manag. Bus. Excel. 2006, 17, 691–708.
2. Nandhini, M.; Rajini, S.; Udayashankar, A.; Niranjana, S.; Lund, O.S.; Shetty, H.; Prakash, H. Biofabricated Zinc Oxide Nanoparticles as an Eco-Friendly Alternative for Growth Promotion and Management of Downy Mildew of Pearl Millet. Crop. Prot. 2019, 121, 103–112.
3. Singh, A.; Singh, N.B.; Afzal, S.; Singh, T.; Hussain, I. Zinc Oxide Nanoparticles: A Review of Their Biological Synthesis, Antimicrobial Activity, Uptake, Translocation and Biotransformation in Plants. J. Mater. Sci. 2018, 53, 185–201.
4. Xiao, L.; Wang, S.; Yang, D.; Zou, Z.; Li, J. Physiological Effects of Mgo and ZnO Nanoparticles on the Citrus Maxima. J. Wuhan Univ. Technol. 2019, 34, 243–253.

5. Raliya, R.; Nair, R.; Chavalmane, S.; Wang, W.-N.; Biswas, P. Mechanistic Evaluation of Translocation and Physiological Impact of Titanium Dioxide and Zinc Oxide Nanoparticles on the Tomato (Solanum lycopersicum L.) Plant. Metallomics 2015, 7, 1584–1594.
6. Dimkpa, C.O.; Andrews, J.; Fugice, J.; Singh, U.; Bindraban, P.S.; Elmer, W.H.; Gardea-Torresdey, J.L.; White, J.C. Facile Coating of Urea with Low-Dose ZnO Nanoparticles Promotes Wheat Performance and Enhances Zn Uptake under Drought Stress. Front. Plant Sci. 2020, 11, 168.
7. Dapkekar, A.; Deshpande, P.; Oak, M.D.; Paknikar, K.M.; Rajwade, J.M. Zinc Use Efficiency Is Enhanced in Wheat through Nanofertilization. Sci. Rep. 2018, 8, 6832.
8. Sirelkhatim, A.; Mahmud, S.; Seeni, A.; Kaus, N.H.M.; Ann, L.C.; Bakhori, S.K.M.; Hasan, H.; Mohamad, D. Review on Zinc Oxide Nanoparticles: Antibacterial Activity and Toxicity Mechanism. Nano-Micro Lett. 2015, 7, 219–242.
9. Silvestre, C.; Duraccio, D.; Cimmino, S. Food Packaging Based on Polymer Nanomaterials. Prog. Polym. Sci. 2011, 36, 1766–1782.
10. Yusof, H.M.; Mohamad, R.; Zaidan, U.H.; Rahman, N.A.A. Microbial Synthesis of Zinc Oxide Nanoparticles and Their Potential Application as an Antimicrobial Agent and a Feed Supplement in Animal Industry: A Review. J. Anim. Sci. Biotechnol. 2019, 10, 57.
11. Mirhosseini, M.; Firouzabadi, F.B. Antibacterial Activity of Zinc Oxide Nanoparticle Suspensions on Food-Borne Pathogens. Int. J. Dairy Technol. 2013, 66, 291–295.
12. Jin, S.-E.; Hwang, W.; Lee, H.J.; Jin, H.-E. Dual Uv Irradiation-Based Metal Oxide Nanoparticles for Enhanced Antimicrobial Activity in Escherichia coli and M13 Bacteriophage. Int. J. Nanomed. 2017, 12, 8057–8070.
13. Jalal, M.; Ansari, M.A.; Ali, S.G.; Khan, H.M.; Rehman, S. Anticandidal Activity of Bioinspired ZnO Nps: Effect on Growth, Cell Morphology and Key Virulence Attributes of Candida Species. Artif. Cells Nanomed. Biotechnol. 2018, 46, S912–S925.
14. Martínez-Carmona, M.; Gun’Ko, Y.; Vallet-Regí, M. ZnO Nanostructures for Drug Delivery and Theranostic Applications. Nanomaterials 2018, 8, 268.
15. Konduru, N.V.; Murdaugh, K.M.; Swami, A.; Jimenez, R.J.; Donaghey, T.C.; Demokritou, P.; Brain, J.D.; Molina, R.M. Surface Modification of Zinc Oxide Nanoparticles with Amorphous Silica Alters Their Fate in the Circulation. Nanotoxicology 2016, 10, 720–727.
16. Ye, H.; Yang, Z.; Khan, I.M.; Niazi, S.; Guo, Y.; Wang, Z.; Yang, H. Split Aptamer Acquisition Mechanisms and Current Application in Antibiotics Detection: A Short Review. Crit. Rev. Food Sci. 2022, 137, 108973.

17. Firouzabadi, F.B.; Noori, M.; Edalatpanah, Y.; Mirhosseini, M. ZnO Nanoparticle Suspensions Containing Citric Acid as Antimicrobial to Control Listeria Monocytogenes, Escherichia Coli, Staphylococcus Aureus and Bacillus Cereus in Mango Juice. Food Control 2014, 42, 310–314.

18. Joshi, H.; Dave, R.; Venugopalan, V.P. Pumping Iron to Keep Fit: Modulation of Siderophore Secretion Helps Efficient Aromatic Utilization in Pseudomonas Putida Kt2440. Microbiology 2014, 160, 1393–1400.

19. Simoncic, B.; Tomsic, B. Structures of Novel Antimicrobial Agents for Textiles—A Review. Text Res. J. 2010, 80, 1721–1737.

20. Duncan, T.V. Applications of Nanotechnology in Food Packaging and Food Safety: Barrier Materials, Antimicrobials and Sensors. J. Colloid Interf. Sci. 2011, 363, 1–24.

21. Sahani, S.; Sharma, Y.C. Advancements in Applications of Nanotechnology in Global Food Industry. Food Chem. 2021, 342, 128318.

22. Nile, S.H.; 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, 45.

23. Paul, S.K.; Dutta, H.; Sarkar, S.; Sethi, L.N.; Ghosh, S.K. Nanosized Zinc Oxide: Super-Functionalities, Present Scenario of Application, Safety Issues, and Future Prospects in Food Processing and Allied Industries. Food Rev. Int. 2019, 35, 505–535.

24. McClements, D.J.; Xiao, H. Is Nano Safe in Foods? Establishing the Factors Impacting the Gastrointestinal Fate and Toxicity of Organic and Inorganic Food-Grade Nanoparticles. NPJ Sci. Food. 2017, 1, 6.

25. Bari, L.; Grumezescu, A.; Ukuku, D.O.; Dey, G.; Miyaji, T. New Food Processing Technologies and Food Safety. J. Food Quality 2017, 2017, 3535917.

26. Martirosyan, A.; Schneider, Y.-J. Engineered Nanomaterials in Food: Implications for Food Safety and Consumer Health. Int. J. Environ. Res. Public Health 2014, 11, 5720–5750.

27. Hakimian, F.; Emamifar, A.; Karami, M. Evaluation of Microbial and Physicochemical Properties of Mayonnaise Containing Zinc Oxide Nanoparticles. LWT-Food Sci. Technol. 2022, 163, 113517.

28. He, L.; Liu, Y.; Mustapha, A.; Lin, M. Antifungal Activity of Zinc Oxide Nanoparticles against Botrytis cinerea and Penicillium expansum. Microbiol. Res. 2011, 166, 207–215.

29. Espitia, P.J.P.; de Fátima Ferreira Soares, N.; dos Reis Coimbra, J.S.; De Andrade, N.J.; Cruz, R.S.; Medeiros, E.A.A. Zinc Oxide Nanoparticles: Synthesis, Antimicrobial Activity and Food Packaging Applications. Food Bioprocess Tech. 2012, 5, 1447–1464.

30. Tayel, A.A.; Sorour, N.M.; El-Baz, A.F.; El-Tras, W.F. 14—Nanometals Appraisal in Food Preservation and Food-Related Activities. In Food Preservation; Grumezescu, A.M., Ed.; Academic Press: Cambridge, MA, USA, 2017; pp. 487–526.

31. Omerović, N.; Djisalov, M.; Živojević, K.; Mladenović, M.; Vunduk, J.; Milenković, I.; Knežević, N.; Gadjanski, I.; Vidić, J. Antimicrobial Nanoparticles and Biodegradable Polymer Composites for Active Food Packaging Applications. Compr. Rev. Food Sci. Food Saf. 2021, 20, 2428–2454.
32. Adeyeye, S.A.O.; Ashaolu, T.J. Applications of Nano-Materials in Food Packaging: A Review. J. Food Process. Eng. 2021, 44, e13708.
33. Zafar, A.; Khosa, M.K.; Noor, A.; Qayyum, S.; Saif, M.J. Carboxymethyl Cellulose/Gelatin Hydrogel Films Loaded with Zinc Oxide Nanoparticles for Sustainable Food Packaging Applications. Polymers 2022, 14, 5201.
34. Kim, I.; Viswanathan, K.; Kasi, G.; Thanakkasaranee, S.; Sadeghi, K.; Seo, J. ZnO Nanostructures in Active Antibacterial Food Packaging: Preparation Methods, Antimicrobial Mechanisms, Safety Issues, Future Prospects, and Challenges. Food Rev. Int. 2022, 38, 537–565.
35. Shafiq, M.; Anjum, S.; Hano, C.; Anjum, I.; Abbasi, B.H. An Overview of the Applications of Nanomaterials and Nanodevices in the Food Industry. Foods 2020, 9, 148.
36. Siddiqi, K.S.; Rahman, A.U.; Tajuddin; Husen, A. Properties of Zinc Oxide Nanoparticles and Their Activity against Microbes. Nanoscale Res. Lett. 2018, 13, 141.
37. Wu, D.; Zhang, M.; Xu, B.; Guo, Z. Fresh-Cut Orange Preservation Based on Nano-Zinc Oxide Combined with Pressurized Argon Treatment. LWT-Food Sci. Technol. 2021, 135, 110036.
38. Madene, A.; Jacquot, M.; Scher, J.; Desobry, S. Flavour Encapsulation and Controlled Release—A Review. Int. J. Food Sci. Tech. 2006, 41, 1–21.
39. Curwin, B.D.; Deddens, J.A.; McKernan, L.T. Flavoring Exposure in Food Manufacturing. J. Expo. Sci. Environ. Epidemiol. 2015, 25, 324–333.
40. Saffarionpour, S.; Ottens, M. Recent Advances in Techniques for Flavor Recovery in Liquid Food Processing. Food Eng. Rev. 2018, 10, 81–94.
41. Sahoo, M.; Vishwakarma, S.; Panigrahi, C.; Kumar, J. Nanotechnology: Current Applications and Future Scope in Food. Food Front. 2021, 2, 3–22.