Nanotechnology in Agriculture and Food Science

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Abstract

Nanotechnology is gaining significant attention in agriculture and food science due to its potential to improve efficiency, sustainability, and food quality. Applications such as nano fertilizers, nano-pesticides, and nano-sensors enhance crop productivity and resource utilization, while nanotechnology in food science supports better processing, packaging, preservation, and safety. This review summarises recent advancements, key applications, and safety considerations of nanotechnology, highlighting its role in sustainable agriculture and improved food systems.

Keywords

Nanotechnology, Agriculture, Food Science, Nano-fertilizers, Food Safety, Sustainable Agriculture.

Introduction

Nanotechnology has grown in popularity in recent decades as a promising technology that has altered the food industry. In order to create and utilize materials with distinctive properties, this nanometer-scale technology works with atoms, molecules, or macromolecules that range in size from 1 to 100 nm [1]. The created nano materials enable for nano scale observation and manipulation since they contain one or more outward dimensions and an internal structure on a size between 1 and 100 nanometers. Due to the high surface to volume ratio and other novel physicochemical features as colour, solubility, strength, diffusivity, toxicity, magnetic, optical, and thermodynamic [2], these materials are observed to have distinct properties unlike their macro scale counterparts. Nanotechnology has ushered in a new era of industrialization, with both developed and emerging countries keen to invest more in this technology [3]. As a result, nanotechnology opens up a vast range of possibilities for the development and use of novel structures, materials, and systems in fields such as agriculture, food, and medical [4].

Nanomaterials are typically characterized as materials with a surface area of less than 100 nano meters and possess unique qualities when compared to their macro scale equivalents, such as colour, solubility, and thermodynamics [5]. These unique features provide possibilities for improving food sensory attributes like flavour, texture, and colour. Furthermore, nanoparticles can be used to improve food protection measures [6]. Microbial contamination, hazardous chemicals, and pesticides may all be detected quickly, sensitively, and reliably using nano sensors and nano packaging materials. Nano encapsulation techniques could be used to enhance food processing by adding bioactive ingredients to boost food bioavailability [7,8].

Food nanostructured components and food nano sensing are the two primary groups of nanotechnology applications in the food industry. Food nanostructured components are used in a variety of applications, ranging from food processing to food packaging. These nanostructures can be used as food additives, carriers for smart nutrient delivery, anti-caking agents, antimicrobial agents, fillers to improve the mechanical strength and durability of packaging materials, and so on in the food processing industry, whereas food nano sensing can be used to improve food quality and safety evaluation [9]. When compared to its usage in drug delivery and pharmaceuticals, nanotechnology's application in agriculture and food is relatively new [10]. Nanotechnology can be used to protect plants, track plant growth, detect plant and animal diseases, increase the world's food supply, enhance food quality, and cut down on waste for sustainable intensification [11]. The manufacturing of food and agricultural products is one of the most significant applications of nanotechnology. In this chapter, we discussed some of the drawbacks of nanotechnology as well as its significance in food science and agriculture.

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Agriculture and Nanotechnology

One of the most intriguing new fields of study, nanotechnology has great potential to address many of the urgent needs in the food and agriculture sectors [12]. The food business needs new technologies and solutions to produce high-quality, fresh, convenient, and delicious food products. With the main objective of improving food quality, nanotechnology seems to have the ability to completely transform the agri-food industry. It has the potential to improve present agri-food practices by offering new pathways for food production, manufacturing, and packaging, as well as plant cropping, animal production, and fisheries, making food and agriculture the most important field of nanotechnology application (Figure 1) [13].
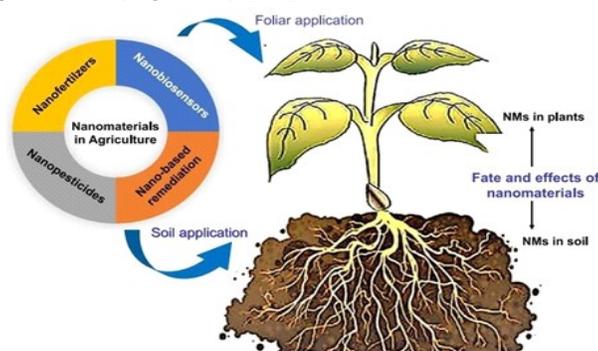

Figure. 1 Applications of nanotechnology in the agriculture industry [4]

Nanotechnology has a lot of potential in the food industry to improve food functionality and quality. Nano agrochemicals such as nano fertilizers, herbicides, nano pesticides, nano biosensors, nanomaterials for food processing and storage, food packaging and labelling, fruit preservation, food quality (nutritional supplement and nutritional drinks), plant growth promoters, crop improvement (nanoparticles-mediated gene transfer), nanocarriers in nitric oxide delivery, nano-enhanced biotreatment for agricultural wastewater, and so on are some of the applications in agriculture [14].

Nanofertilizers

An huge increase in agricultural yields, particularly grain yields, has played a vital role in providing the world's nutritional needs over the last five decades. In this context, increased usage of chemical fertilisers is one of the key contributors to increased crop productivity. Chemical fertiliser use has increased as a result of fertilizer-responsive crop types. Chemical fertilisers, on the other hand, have a low use efficiency due to fertiliser loss (through volatilization and leaching), which pollutes the environment and raises production costs [15]. Conventional fertilisers, for example, lose 50–70% of the nitrogen

they apply to the environment. As a result, the scientific community is paying close attention to the development of alternative ways to assure the long-term utilisation of nutrients. Nanotechnology is being employed in this setting to reduce mobile nutrient losses, develop slow-release fertilisers, and improve the accessibility of nutrients that are currently unavailable. Nano-fertilizers are nanomaterials that operate as carriers/additives for nutrients (e.g., by compositing with minerals) or as nutrients themselves (micro- or macronutrients) [16]. Encapsulating nutrients inside nanomaterials can also be used to create nano fertilizers.

Nanotechnology in agriculture environment

To boost food production, herbicides and fertilisers are used, which results in an unregulated release of unwanted compounds into the environment. Nanotechnology is now a viable option for increasing agricultural production and cleaning up contaminated soil and groundwater. Researchers discussed current nanotechnology uses in agro environmental investigations, with a focus on the destiny of nanomaterials once they are introduced into water and soil. They revealed that nanoparticles improved environmental quality and assisted in the detection and remediation of polluted locations; however, only a small number of nanomaterials exhibited possible harmful consequences [17]. The influence of iron nanoparticles on terrestrial plants found that root systems of all plant species from different families evaluated generated orange–brown complexes/plaques that were made up of iron nanoparticles. Furthermore, the creation of iron nanoparticles/ nanocomplexes has been described as an optimal homeostasis mechanism created by plants to adjust ionic iron intake at desired levels.

Nanotechnology in organic agriculture

The use of nanotechnology and nanomaterials in organic agriculture was rejected in an International Federation of Organic Agriculture Movements Position Paper on the Use of Nanotechnologies and Nanomaterials in Organic Agriculture [Figure 2]. Nano Green Sciences, Inc., on the other hand, sells an organic nano-pesticide [18].

Figure 2. Nanotechnology in organic agriculture

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Nanotechnology in food processing

Through the use of nano sensors and indicators to detect viruses and contaminants, the encapsulation of nutrients, and the development of new functional goods, nanotechnology plays a crucial role in delivering safe and high-quality food items [19]. The use of nanotechnology in this industry can improve food taste, flavour, colour, texture, and consistency, as well as increase nutraceutical and health supplement absorption and bioavailability. Nano carrier systems are increasingly employed to deliver food additives in various food products without causing any significant modification to the product's original structure or appearance.Because only sub micron nanoparticles may be absorbed well in some cell lines but not bigger size microparticles, particle size may have a direct impact on the distribution of any bioactive substance to diverse places inside the body [20]. Nanotechnology, when used in the creation of encapsulation, emulsions, biopolymer matrices, simple solutions, and association colloids, provides effective delivery systems with all of the features listed above. In food packaging, nano polymers are attempting to replace traditional materials. Food pollutants, mycotoxins, and microbes can all be detected with nano sensors [21].

Nanotechnology in food Packaging

In addition to the basic properties of packaging materials such as mechanical, optical, and thermal properties, the food package should prevent moisture loss, prevent microbial contamination, and act as a barrier against permeation of water vapour, oxygen, carbon dioxide, and other volatile compounds such as flavours and taints. Furthermore, the purpose of the food packaging system is to prevent, minimise, or postpone undesired changes in the appearance, sensory properties such as flavour, odour, and texture. The packaging of the future will almost certainly be more than just a physical container that protects food from the elements. Nano packaging must be further subdivided into packaging that allows nanoparticles to migrate into food on purpose and packaging that does not allow nanoparticles to migrate [23]. Using nanotechnologies to improve packaging materials is expected to be highly expensive, and it will not be implemented until procedures have been optimised, and outcomes have been proven to be consistent and cost-effective [Figure 3].
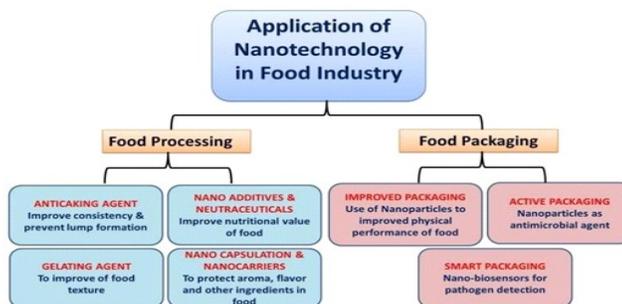

Figure 3. Application of nanotechnology in food processing

Antimicrobial Nano-Packaging

Nanotechnology in food packaging extends beyond the antimicrobial action of nanoparticles. Advanced materials such as nano-composites and nano-laminates are increasingly used to enhance packaging performance by providing effective barriers against elevated temperatures and mechanical stress, thereby contributing to extended food shelf life. The incorporation of nanoparticles into packaging matrices improves food quality preservation by reducing spoilage and degradation over time. Polymer- based nano-composites have been specifically developed to achieve superior mechanical strength and enhanced thermal stability compared to conventional packaging materials. To further improve the functional properties of these polymer composites, a wide range of inorganic and organic fillers are incorporated, resulting in packaging systems with improved durability, safety, and performance.

Conclusion

Nanotechnology offers a broad spectrum of applications with significant potential benefits across agriculture and food systems. Its integration into precision farming aims to enhance productivity by optimising resource use and improving crop monitoring, thereby enabling higher yields with reduced inputs. Through nanoscale interventions, plants can utilise water, fertilisers, and pesticides more efficiently, leading to improved agricultural sustainability. The adoption of nanotechnology also presents opportunities for farmers and the food industry through the development of innovative approaches in food processing, preservation, and packaging. At present, most applications in food and agriculture emphasise minimizing the adverse environmental and health impacts of agrochemicals rather than directly enhancing their performance in crop and livestock production. Consequently, the anticipated advantages of nanotechnology in agriculture, fisheries, and aquaculture must be carefully balanced against potential risks to soil quality, water resources, ecosystems, and occupational health. Notably, encouraging results have been reported in food preservation, where nano-materials act as protective barriers against moisture, lipids, gases, undesirable flavours, and aromas. Additionally, nanotechnology enables efficient and targeted delivery of bioactive compounds to specific tissues. Despite rapid advancements opening new technological pathways, several challenges remain, including the need for improved material design, regulatory clarity, and assessment of long- term implications. Addressing these concerns is essential to enhance technological performance and to build consumer confidence in nanotechnology-based food and agricultural applications.

Acknowledgement

References

1. Rai, M., Yadav, A., and Gade, A. (2009). Silver nanoparticles as a new generation of antimicrobials. Biotechnol. Adv. 27, 76–83.

2. Sorrentino, A., Gorrasi, G., and Vittoria, V. (2007). Potential perspectives of bio nanocomposites for food packaging applications. Trends Food Sci. Technol. 18, 84– 95.

3. Sorrentino, A., Gorrasi, G., and Vittoria, V. (2007). Potential perspectives of bio nanocomposites for food packaging applications. Trends Food Sci. Technol. 18, 84– 95.

4. Qureshi, A. M., Swaminathan, K., Karthikeyan, P., Ahmed, K. P., Sudhir, and Mishra, U. K. (2012). Application of nanotechnology in food and dairy processing: an overview. Pak. J. Food Sci. 22, 23–31.

5. M. Fathi, M.-R. Mozafari, and M. Mohebbi, "Nanoencapsulation of food ingredients using lipid based delivery systems," Trends in Food Science Technology, vol. 23, no. 1, pp. 13–27, 2012.

6. M. Zhu, G. Nie, H. Meng, T. Xia, A. Nel, and Y. Zhao, "Physicochemical properties determine nanomaterial cellular uptake, transport, and fate," Accounts of Chemical Research, vol. 46, no. 3, pp. 622–631, 2012.

7. T. Singh, S. Shukla, P. Kumar, V. Wahla, V. K. Bajpai, and I. A. Rather, "Application of nanotechnology in food science: perception and overview," Frontiers in Microbiology, vol. 8, p. 1501, 2017.

8. Q. Chaudhry, M. Scotter, J. Blackburn et al., "Applications and implications of nanotechnologies for the food sector," Food Additives and Contaminants, vol. 25, no. 3, pp. 241–258, 2008.

9. Ezhilarasi, P. N., Karthik, P., Chhanwal, N., and Anandharamakrishnan, C. (2013). Nanoencapsulation techniques for food bioactive components: a review. Food Bioprocess Technol. 6, 628–647.

10. Garcia M, Forbe T, Gonzalez E. Potential applications of nanotechnology in the agro- food sector. Food Science and Technology (Campinas). 2010;30(3):573–581.

11. Gruère G, Narrod C, Abbott L. Agriculture, Food, and Water Nanotechnologies for the Poor: Opportunities and Constraints. Policy Brief 19. Washington, DC: International Food Policy Research Institute; 2011.

12. Santos, A., Firak, D.S., Emmel, A., Siedlecki, K., Lopes, A., Peralta-Zamora, P., 2018. Evaluation of the Fenton process effectiveness in the remediation of soils contaminated by gasoline: effect of soil physicochemical properties. Chemosphere 207, 154–161.

13. Mura, S., Greppi, G., Roggero, P.P., Musu, E., Pittalis, D., Carletti, A., Ghiglieri,

G., Irudayaraj, J., 2015. Functionalized gold nanoparticles for the detection of nitrates in water. Int. J. Environ. Sci. Technol. 12, 1021–1028.

14. Shoults-Wilson, W.A., Reinsch, B.C., Tsyusko, O.V., Bertsch, P.M., Lowry, G.V., Unrine, J.M., 2011. Effect of silver nanoparticle surface coating on bioaccumulation and reproductive toxicity in earthworms (Eisenia fetida). Nanotoxicology 5, 432– 444.

15. Feizi, H., Amirmoradi, S., Abdollahi, F., Pour, S.J., 2013. Comparative effects of nanosized and bulk titanium dioxide concentrations on medicinal plant Salvia officinalis L. Annu. Res. Rev. Biol. 3, 814–824.

16. Doshi, R., Braida, W., Christodoulatos, C., Wazne, M., O'Connor, G., 2008. Nano-aluminum: transport through sand columns and environmental effects on plants and soil communities. Environ. Res. 106, 296–303.

17. Mura S, Seddaiu G, Bacchini F, Roggero PP, Greppi GF. Advances of nanotechnology in agro-environmental studies. Italian Journal of Agronomy. 2013;8(3):e18.

18. Witanachchi S., Merlak M., Mahawela P. Nanotechnology solutions to greenhouse and urban agriculture. Technol Innov. 2012;14(2): 209–217.

19. Cientifica Report (2006). Nanotechnologies in the Food Industry, Published August 2006.

20. Pradhan, N., Singh, S., Ojha, N., Srivastava, A., Barla, A., Rai, V., et al. (2015). Facets of nanotechnology as seen in food processing, packaging, and preservation industry.

21. Ezhilarasi, P. N., Karthik, P., Chhanwal, N., and Anandharamakrishnan, C. (2013). Nanoencapsulation techniques for food bioactive components: a review. Food Bioprocess Technol. 6, 628–647.

22. Rhim J.W., Park H. M., HA CH.S.2013. Bio-nanocomposites for food packaging applications, Progress in Polymer Science, 38, 1629–1652.

23. Roberts L., Lines, R.,Reddy, S., Hay, J. 2011. Investigation of polyviologens as oxygen indicators in food packaging. Sensors and Actuators B: Chemical, 152(1), 63–67.

24. Sorrentino, A., Gorrasi, G., and Vittoria, V. (2007). Potential perspectives of bio nanocomposites for food packaging applications. Trends Food Sci. Technol. 18, 84– 95.

25. Duncan, T. V. (2011). Applications of nanotechnology in food packaging and food safety: barrier materials, antimicrobials and sensors. J. Colloid Interface Sci. 363, 1– 24