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Editorial: Opportunities and challenges for nanotechnology in sustainable agri-food production

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Editorial on the Research Topic
Opportunities and challenges for nanotechnology in sustainable agri-food production

The United Nations has given 17 Sustainable Development Goals (SDG), and Goal 2 is about creating a world free of hunger by 2030. The rising population and climate changes may aggravate the problems of malnutrition, and burden the existing food production and distribution (Fróna et al., 2019). So, agricultural resources must be used wisely to increase crop production and provide sustainable, quality food to the global population. There is an immediate need to develop novel tools to assist current agriculture and food industry practices in achieving sustainability. The recent development in science and technologies based on nanomaterials has created a lot of interest and expectation in solving the existing problems in various fields. Nanotechnology deals with manipulating and using materials fabricated in nanometre regimes for their novel properties due to their small size. The application of engineered nanomaterials (ENM) has been researched for their role in futuristic agriculture and food production. The recent development of precision farming/site-specific crop management can benefit from nano-based technologies (Pudake et al., 2019; Otari et al., 2024). With the help of recent emerging tools such as artificial intelligence, efficient and sensitive nano biosensors can bring a new uprising in crop production by providing high-resolution and real-time tools to monitor spatial and temporal deviations in their health. Another aspect of precision farming is the targeted release or slow release of agri-inputs in the current cropping system to achieve its high-use efficiency. The emerging field of plant nanobionics is developing plants with novel supplemented functions for their better performance under adverse conditions or to play a new role in agriculture (Lew et al., 2020).

Nanotechnology has shown great potential for changing the food packaging industry for sustainability. The characteristics like barrier properties, antimicrobial packaging, and food quality sensing are some of the aspects being explored with the help of nanoscience. Active and intelligent packaging is the future of the food industry, and nano-enabled packaging materials have the potential to increase the shelf life of food (de Sousa et al., 2023). Another approach of ENM application in food improvement is as an ingredient or extended-release or preservation of nutraceuticals. As an ingredient, the nanomaterials can be used as food

anticaking agents, nano-additives in the form nutraceuticals, and other similar applications in processed food (Wasilewska et al., 2023).

So, nanomaterials' potential application in the agri-food industry makes them a resourceful tool for the future. However, its successful application for sustainable agriculture will require intensive research to overcome the unaddressed challenges. This "Research Topic" highlights the latest advances in nanotechnology for increasing plant production and sustainable use of agri-inputs. It also aims to cover research on various aspects of nanomaterials in the food industry.

Developing eco-friendly methodologies in nanomaterial synthesis is important in deciding its suitability in biological applications. Recently, several inorganic nanoparticles with definite chemical composition, size, and morphology have been synthesized by different bio-organisms or their extract/by-products. These bioinspired nanomaterials have shown promising results in many cutting-edge biological areas (Karunakaran et al., 2023). Deepa et al. demonstrated the biogenic synthesis of silver nanoparticles from potato peels as a promising strategy for producing antimicrobial agents. The authors found that an extract of potato peels can be used as a cheap, productive, and readily available source of biomolecules that are required for Ag precursor reduction and biosynthesis of NP. The disc diffusion technique was utilized to check the antimicrobial activity of AgNPs against both—Gram-positive bacteria, *Staphylococcus aureus* (ATCC 25923), and Gram-negative bacteria, *Escherichia coli* (ATCC 25922). The results have indicated that the antibacterial properties of AgNPs could be used in the food industry to avoid microbial contamination. It was evaluated for potential in the purification of industrial wastewater, and the results confirmed the excellent antibacterial ability of AgNPs. The results have the potential to add value to the farm waste and, therefore, can be an essential finding for sustainability in the agriculture and food industry. In continuation of this study, Flores-Contreras et al. have summarized the opportunities for the biosynthesis of nanomaterials by agricultural waste and its application as antimicrobials for food preservation. They have emphasized that this method of synthesis of ENMs is a sustainable and innovative alternative in the circular economy of recycling biowaste. This review provides evidence that summarises the usage of various agri-waste as a source for organic NPs as the top-down approach or assisting the synthesis of inorganic NPs by a bottom-up approach. These NPs have shown remarkable antimicrobial and antioxidant activities and can be used for manufacturing nanocomposites that are suitable for food preservation. This paper has also discussed the molecular mechanism of nanoparticles' antimicrobial action; like the production of reactive oxygen species (ROS), hindrance in metabolic pathways, inhibition of DNA replication, or cell wall/membrane damage are the mechanisms for NP toxicity. This is also true in the case of dose-dependent toxicity in humans, which is a main cause of concern for the safety of nanoparticles in the food industry. Authors suggest that extensive studies are needed to unravel the effects of NPs on human health.

Nanobiosensor deployment for pathogen detection in agriculture has become one of the fastest-growing nanotechnology applications in recent days (Ray et al., 2023). Nanobiosensors have physical transducer probes modified with NPs for a biological molecule or complete cell detection. An ideal biosensor should be economical, sensitive, easily portable, minimal or non-invasive, and rapid with real-time monitoring. Virk et al. have presented a perspective review emphasizing the role of nano biosensors in controlling plant diseases. The review discusses the types of nano biosensors, their application in disease management, and pesticide/toxin detection. Along with the summary of recent advancements in the field of nano biosensors in the agricultural and food industry, the challenges and the prospects are also highlighted to achieve the large-scale application. The major limitations of nano-based sensing devices are high cost and product sensitivity. Other limitations of biosensors are the energy requirement and their durability in harsh environmental conditions. So, developing energy-efficient and stable sensors is the future direction of research.

As mentioned earlier, modern-day agriculture relies on various agrochemicals to enhance crop production by providing nutrients and controlling crop pests. However, their indiscriminate use has currently caused several threats to human and environmental health. Dangerous consequences of this overexploitation on ecological balance and conservation of soil biodiversity are major focus areas for sustainable crop production in many countries (Andrade et al., 2021). The solution to this problem is using nanoscale agrochemicals such as nanofertilizers and nanopesticides that are more sustainable and efficient. Basak et al. have highlighted the advantages of Metal-organic Framework (MOF)s as nanocarriers of agrochemicals. MOFs are a class of porous polymers made of metal clusters and organic ligands. It is being used in various chemical and biological applications. Agricultural researchers are becoming increasingly interested in using MOF for agri-input delivery due to their biocompatibility and biodegradability. The synthesis methods and types of MOFs and the basics of their structure are discussed in detail in this review. Using traditional pesticides with MOF can result in the controlled release of agrochemicals and increase its bioavailability. It has been reported that MOFs are degraded by soil microbes and act as a source of plant nutrients due to their chemical composition.

Overall, the "Research Topic" represents the need for continued research required to understand the fundamental challenges—like cost and safety for the various applications of nanomaterials in the agriculture industry. Current updates and recent advances in nanomaterials and nanotechnology approaches can be explored for the NextGen revolution, and create a pool of knowledge to develop sustainable agriculture.

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