Development and Current State of Nanotechnology in the Agricultural and Food Sectors- A review

Abstract

The swift proliferation of nanotechnology is revolutionising the conventional sectors of food and agriculture, with remarkable innovations such as intelligent and responsive packaging, nanosensors, nano-based pesticides and fertilisers. An array of new nanomaterials are being developed to enhance food safety and quality, boost crop yields, and monitor environmental parameters. This review explores the most recent advancements in nanotechnology focusing on the pressing challenges and potential opportunities in the food and agriculture sectors, based on various contemporary studies. The review also delves into the basic toxicology and risk assessment of nanomaterials employed in these new-generation food and agriculture products. Significant emphasis is placed on the potential application of bio-synthesized and bio-inspired nanomaterials for sustainable development. Fundamental questions related to high-performance, low-toxicity nanomaterials need resolution to boost the active evolution and application of nanotechnology. Legislative measures and regulations are crucial to oversee the manufacturing, processing, application, and disposal of nanomaterials. There is a pressing need for initiatives to amplify public awareness and acceptance of these novel nano-enabled food and agriculture products. Concluding the introduction of nanotechnology food and agriculture sectors offers a multitude of opportunities and a sustainable path forward.

Keywords: *Nanotechnology, Agriculture, Food Safety, Regulation, Public Perception*

Introduction

The advent of nanotechnology, a field that manipulates matter on an atomic and molecular scale, has revolutionized various sectors, especially food and agriculture. The genesis of nanotechnology can be traced back to the visionary scientist Richard Feynman and his talk, "There's Plenty of Room at the Bottom" in 1959 [1]. Since then, the world has seen an exponential growth in this science's applications. Food and agriculture are sectors that have been immensely impacted by the emergence of nanotechnology. The properties of nanomaterials, which include higher surface area to volume ratio and unique optical, thermal, and mechanical properties [2], have opened up a plethora of opportunities to revolutionize these sectors. This includes enhancing food safety and quality, developing smart and active packaging, and improving agricultural practices through nanosensors, nanofertilisers, and Nano pesticides [3]. The development of nanotechnology in India has been rapid and multi-faceted. Following the global trend, India recognized the potential of nanotechnology early on. The launch of the "Nano Mission" by the Department of Science and Technology in 2007 marked the country's dedicated efforts towards research and development in this field [4]. The Indian government's investment in nanotechnology has since grown considerably, nurturing academic institutions, research laboratories, and industries associated with nanotechnology. The progress of nanotechnology in India is especially noteworthy in the food and agriculture sectors. For instance, the introduction of nanosensors has made it possible to monitor the quality and safety of food products more accurately and quickly [5]. Smart packaging, employing nanotechnology, has transformed the way food products are stored and transported, contributing to a significant reduction in food wastage [6]. In agriculture, the impact of nanotechnology is equally prominent. Nanopesticides and nanofertilisers, for instance, offer more efficient and targeted delivery, reducing environmental impact and increasing crop yield [7].. Nanotechnology has also made possible the use of agricultural waste in the production of nanoparticles, thereby promoting a circular economy [8]. The potential impacts of nanotechnology on food and agriculture sectors are wide-ranging. The increased efficiency in food production, processing, and storage can substantially address food security concerns. For instance, the utilisation of nanotechnology in food packaging can extend the shelf life of products, thereby reducing food waste and contributing towards solving hunger issues [9]. In agriculture, nanotechnology can help increase crop yield, optimise water usage, and improve pest and disease management. This can not only help feed the growing global population but also contribute towards sustainable agricultural practices [10]. Despite the many potential benefits, the introduction of nanotechnology in food and agriculture also raises certain concerns related to the environment and human health. Hence, the importance of rigorous research, appropriate regulation, and public awareness cannot be overstated [11].

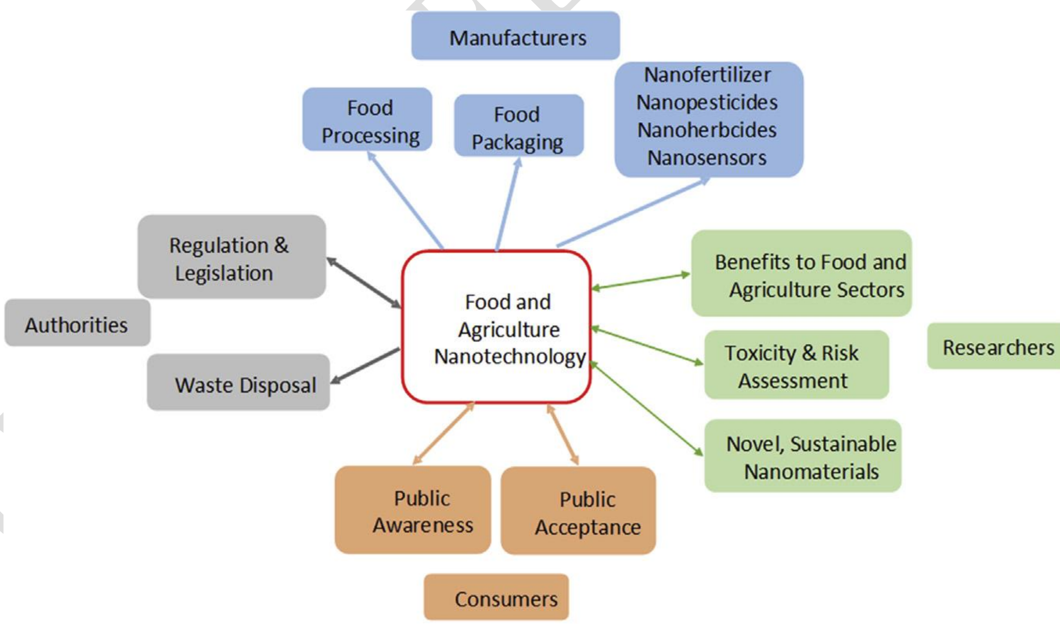

Image: Schematic illustration of food nanotechnology from scientific research to marketed product, and to consumer's plate.

Development and Application of Nanotechnology

In India, the progression of nanotechnology has been dynamic and comprehensive, marking its presence in various sectors, including electronics, health care, energy, and notably food and agriculture (Table 1). India's nanotechnology journey commenced with the inception of the "Nano Science and Technology Initiative" (NSTI) in 2001 [64]. This endeavour was followed by a more significant "Nano Mission" in 2007, which facilitated the integration of academic institutions, research laboratories, and industries to propel nanotechnology innovations (DST, 2007). India's emphasis on nanotechnology's development is reflected in its research output, with the country ranked 3rd globally in terms of the number of scientific publications in the nanotechnology domain [12]. Various academic and research institutions, such as the Indian Institute of Science (IISc), Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), and various IITs, are at the forefront of nanotechnology research in India [13]. The establishment of the Nano and Soft Matter Sciences unit by the Council of Scientific and Industrial Research (CSIR) exemplifies the country's dedicated research initiatives in this field [65].

Table 1: Current status of nanotechnology-enabled food products in India

Sector	Application	Nanomaterials	Manufacturer	Current status	Note	Reference
Food processing	Nanoemulsions in food products	Curcumin, Piperine	Various Indian Firms	Under research and development	Promotes bioavailability and stability of nutrients	[14]
Food packaging	Smart packaging	Silver nanoparticles, Clay Nanocomposites	Various Indian Firms	Under research and development	Enhances shelf life and monitors food quality	[15]
Agriculture	Nanopesticides	Copper nanoparticles, Silver nanoparticles	Various Indian Firms	Under research and development	Improves pest control and reduces environmental impacts	[16]
Agriculture	Nanofertilisers	Zinc Oxide, Iron Oxide	Various Indian Firms	Under research and development	Enhances nutrient absorption and reduces waste	[17]
Food Safety	Nanosensors	Gold nanoparticles, Quantum	Various Indian Firms	Under research and development	Monitors food contaminan	[18]

		dots			ts and pathogenic bacteria	

Nanotechnology's applications are particularly pronounced in food and agriculture sectors.

1. **Smart Packaging**: Nanotechnology in food packaging enhances the shelf life and safety of food products. Nanocomposite materials, such as silver nanoparticles embedded in polymer films, are used in packaging to impart antimicrobial properties, thus preventing microbial spoilage [19].

2. **Nanosensors**: Nanosensors are devices that detect and respond to a physical stimulus on the nanoscale. In the food industry, nanosensors can detect pathogens and toxins, thus improving food safety [20]. Furthermore, these nanosensors can monitor environmental conditions such as pH, temperature, and moisture content, essential for food quality [21]. Significant advancements in nanosensors have been made by the Central Food Technological Research Institute (CFTRI), where research is underway to develop nanosensors for the detection of food-borne pathogens [22].

3. **Nanopesticides and Nanofertilisers**: In agriculture, nanotechnology has enabled the development of nanopesticides and nanofertilisers, which offer more precise delivery, reducing environmental impact, and increasing crop yield [23]. Institutions like the Indian Agricultural Research Institute (IARI) have initiated research on nanoformulations of pesticides and fertilisers, offering the potential for more efficient nutrient utilisation and minimising environmental harm.

Case Studies of Recent Innovations in Nanotechnology

Nanotechnology has played a crucial role in the development of novel nanomaterials for the enhancement of food safety and quality, promotion of crop growth, and monitoring of environmental conditions. Several innovative studies elucidate these advancements.

1. **Nanomaterials for Food Safety and Quality**

A significant innovation in nanotechnology has been the development of nanosensors for improving food safety (Table 2). A study by the Central Food Technological Research Institute (CFTRI) in India demonstrated the development of a nanosensor to detect the foodborne pathogen, Salmonella [24]. The sensor was based on a nanocomposite of reduced graphene oxide and gold nanoparticles. The study presented a low-cost, rapid, and sensitive method for Salmonella detection, enhancing food safety measures. Study by the National Institute of Nutrition (NIN), Hyderabad, India, developed a nanosensor based on quantum dots for aflatoxin detection in food products [25]. Aflatoxin, a potent carcinogen, often contaminates various food products, and this study provided an effective tool for its detection, thus ensuring food safety. Nanotechnology also finds application in smart packaging to improve food quality. A study by the Indian Institute of Food Processing Technology (IIFPT) developed an antimicrobial food packaging system using silver nanoparticles [26]. The packaging displayed potent antimicrobial activity, ensuring longer shelf life and enhanced food quality.

Table 2: Current status of nanotechnology-enabled agriculture products in India

Application	Commercial names	Manufacturer	Current status and legislation compliance	Nanomaterial composition	Function of nanomaterials	Reference
Nanofertilizer	Nano-Grow, Nano-Zinc	Various Indian Firms	Under research and development	Zinc Oxide, Copper Oxide	Enhances nutrient absorption	[27]
Nanopesticides	N/A	N/A	Under research and development	Silver nanoparticles	Effective pest control with less environmental impacts	[28]
Nanoherbicides	N/A	N/A	Under research and development	Polymeric nanoparticles	Controlled release of herbicides	[29]
Nanosensors	N/A	N/A	Under research and development	Gold nanoparticles	Monitoring soil nutrients and contaminants	[30]

2. **Nanomaterials for Crop Growth**

Nanotechnology has revolutionised agriculture, notably through nanofertilisers. A study by the Indian Agricultural Research Institute (IARI) investigated the use of nanozeolite as a slow-release fertiliser for rice plants [31]. The study concluded that nanozeolite enhanced nutrient use efficiency and increased crop yield. A study by the University of Agricultural Sciences, Bangalore, India, used chitosan nanoparticles as a carrier for the controlled release of urea, a widely used fertiliser [32]. The results showed improved nutrient use efficiency and crop productivity, substantiating the potential of nanotechnology in improving agricultural practices.

3. **Nanomaterials for Monitoring Environmental Conditions**

Nanotechnology plays a crucial role in environmental monitoring, with several nanosensors developed for this purpose. A notable study by the Indian Institute of Science (IISc), Bangalore, India, demonstrated the development of a nanosensor based on gold nanoparticles for real-time monitoring of soil nutrients [33]. The nanosensor could detect trace amounts of nitrate, an essential plant nutrient, in soil, thus providing a tool for optimising fertiliser use and promoting sustainable agricultural practices.

Toxicology and Risk Assessment

As nanotechnology continues to permeate the food and agriculture sectors, it is crucial to consider the potential risks associated with the use of nanomaterials. The same properties that render nanomaterials desirable in these sectors can also result in unforeseen health and environmental implications. Therefore, a thorough understanding of the toxicological fundamentals related to nanomaterials is necessary.

1. Toxicological Fundamentals

Nanoparticles, due to their small size and high surface-to-volume ratio, possess unique physicochemical properties, which can influence their interaction with biological systems and the environment [34]. Depending on their composition, size, shape, and surface characteristics, nanoparticles can induce varying degrees of toxicity. Several studies have shown that nanoparticles can cross biological barriers and accumulate in various organs, such as the liver, spleen, lungs, and brain [35]. For instance, silver nanoparticles, commonly used in food packaging, have been shown to cross the gastrointestinal barrier and accumulate in various organs, potentially causing adverse effects [36]. Some nanomaterials can generate reactive oxygen species (ROS), leading to oxidative stress, inflammation, and DNA damage, potentially causing cytotoxicity and genotoxicity. Moreover, certain nanomaterials can interfere with nutrient absorption in plants, affecting plant growth and development [37].

2. Risk Assessment

Given the potential toxicity of nanomaterials, risk assessment is a critical component in the use of nanotechnology in the food and agriculture sectors. The process of risk assessment involves hazard identification, dose-response assessment, exposure assessment, and risk characterisation [38]. Several studies have highlighted potential risks associated with nanomaterial use in food and agriculture. A study by the National Institute of Nutrition, Hyderabad, India, investigated the toxicity of titanium dioxide nanoparticles, commonly used as a food additive. It was found that the nanoparticles caused DNA damage and inflammatory response in mice [39]. In agriculture, a study by the University of Calcutta, India, assessed the impact of zinc oxide nanoparticles on rice plants. It was observed that while low concentrations of the nanoparticles promoted plant growth, higher concentrations resulted in oxidative stress, negatively affecting plant health [40]. While nanotechnology presents numerous opportunities for improving food safety, quality, and agricultural efficiency, it is crucial to carefully balance the benefits with potential risks. As we continue to harness the potential of nanotechnology, it becomes imperative to adopt a 'safety by design' approach, where safety considerations are integrated at the design stage itself [41].

Bio-synthesised and Bio-inspired Nanomaterials for Sustainable Development

The convergence of nanotechnology with biology has facilitated the evolution of bio-synthesised and bio-inspired nanomaterials, offering sustainable solutions with potential applications in agriculture. This approach aligns with the principles of green chemistry, minimising environmental impacts, and promoting resource efficiency [42].

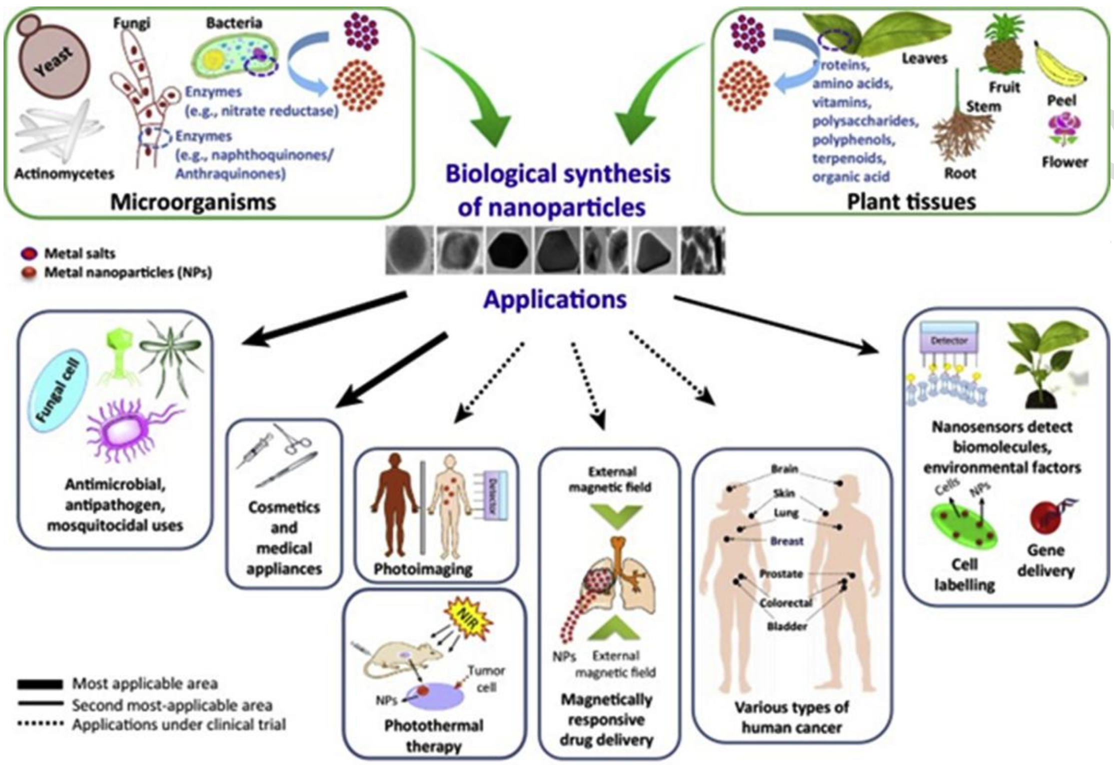

Figure 1: Biological snthesis and applications of nnoparticles. Reproduced with permission from Elsevier [43].

1. Potential and Applications in Indian Agriculture

Bio-synthesised nanomaterials, also known as 'green' nanomaterials, are produced using biological entities such as plants, microorganisms, or biomolecules. These methods are eco-friendly, cost-effective, and reduce the toxic impact associated with the conventional synthesis of nanomaterials [44]. India, with its rich biodiversity, presents vast potential for the bio-synthesis of nanomaterials. Studies have demonstrated the use of various plant extracts, such as neem (Azadirachta indica), for the green synthesis of nanoparticles like silver and gold nanoparticles [45]. These nanoparticles, when used in agriculture, can offer antimicrobial effects, enhancing plant resistance to various diseases. Bio-inspired nanomaterials, developed using principles learned from nature, offer innovative solutions for agriculture. For example, bio-inspired nanopesticides, mimicking natural pest defence mechanisms, can provide a more targeted approach to pest management, reducing environmental impacts [46]. Significant advancements in bio-synthesised and bio-inspired nanomaterials have been made. The Indian Agricultural

Research Institute (IARI) has developed bio-pesticides using nano-formulations of neem, offering a greener alternative to conventional chemical pesticides.

2. **Challenges and Questions**

While bio-synthesised and bio-inspired nanomaterials present significant potential, the development of high-performance, low-toxicity nanomaterials poses several challenges. Ensuring consistent quality and size distribution of bio-synthesised nanomaterials is a significant challenge, given the variability in biological synthesis methods [47]. While bio-synthesised nanomaterials are generally considered less toxic than their chemically synthesised counterparts, this assumption is not universally true. Studies have shown that bio-synthesised nanomaterials can still induce cytotoxicity and genotoxicity, and thus, comprehensive toxicological studies are still required [48]. Regulatory frameworks need to be in place to oversee the development and use of these nanomaterials. Regulatory agencies in India, like the Central Insecticides Board & Registration Committee (CIB&RC), need to establish clear guidelines to evaluate the safety and efficacy of bio-synthesised and bio-inspired nanomaterials used in agriculture.

Regulation and Legislation of Nanotechnology in India

As nanotechnology continues to revolutionise various sectors, including food and agriculture, there is a growing need for comprehensive regulation and legislation to oversee its applications. This section will discuss the current regulations and legislation pertaining to nanotechnology in India and evaluate their adequacy in ensuring safe manufacturing, processing, application, and disposal of nanomaterials.

1. **Current Regulations and Legislation**

In India, the regulation of nanotechnology is scattered across several departments and regulatory bodies, depending on the application of nanomaterials. For instance, the Food Safety and Standards Authority of India (FSSAI) is responsible for ensuring the safety of nanomaterials used in food products [49]. It has released guidelines for the testing of nanomaterials in food, requiring detailed information on their physicochemical properties, stability, and toxicity. For nanomaterials used in agriculture, the Central Insecticides Board & Registration Committee (CIB&RC) oversees their use. It mandates that any nanopesticides or nanofertilisers should be thoroughly tested for efficacy and safety before commercialization [50]. The Ministry of Environment, Forest and Climate Change (MoEF&CC) has issued guidelines for the safe handling and disposal of nanomaterials, emphasising the importance of minimising environmental impacts [51].

2. **Adequacy of Regulations**

While these regulations provide some degree of oversight, their adequacy in ensuring the safe use of nanotechnology is debatable. There are several gaps and challenges that need to be addressed. There is a lack of uniform, standardised methodologies for the risk assessment of nanomaterials. Current testing guidelines primarily rely on conventional methodologies, which may not be entirely applicable for nanomaterials due to their unique properties [52]. Therefore, there is a need for the development of specific, validated methodologies for the risk assessment of nanomaterials. There is a lack of transparency in the labelling of nano-enhanced products. In many cases, consumers are unaware that they are purchasing products containing nanomaterials, as there is no mandatory requirement for nano-labelling [53]. The disposal of nanomaterials is a significant concern. Current guidelines primarily emphasise safe handling but provide little direction on the safe disposal or recycling of nanomaterials [54]. There is a lack of regulatory harmonisation. The scattered nature of regulations, with different bodies overseeing different applications, can lead to inconsistencies and overlaps. There is a need for a central regulatory body to oversee all applications of nanotechnology, ensuring uniformity in regulation [55].

Public Awareness and Acceptance of Nanotechnology

The potential of nanotechnology to revolutionise various sectors, including food and agriculture, is significant. Its successful integration into society hinges on public awareness and acceptance. This section will analyse the current public perception of nanotechnology in India and discuss efforts and strategies to increase public awareness and acceptance of nano-enabled food and agriculture products.

1. **Current Public Perception**

Public perception of nanotechnology in India is influenced by various factors, including awareness, perceived benefits and risks, trust in regulation, and ethical considerations [56]. A survey conducted by the Centre for Study of Science, Technology and Policy (CSTEP) in India found that public awareness of nanotechnology was relatively low, with only around 25% of the respondents being aware of it [57]. Among those aware, there was a general perception that nanotechnology could offer significant benefits, particularly in healthcare and energy sectors. The perception of nanotechnology in food and agriculture was mixed. While some saw potential benefits in terms of improved food safety and agricultural productivity, concerns were raised about potential health risks and environmental [58].

2. **Increasing Public Awareness and Acceptance**

Increasing public awareness and acceptance of nanotechnology requires multifaceted strategies, focusing on education, transparency, and engagement. Educational campaigns can play a vital role in increasing awareness about nanotechnology. This can be achieved through the integration of nanoscience in school and university curricula, public lectures, and science exhibitions [59]. Transparency is crucial for building public trust. Clear labelling of nano-enabled products can help consumers make informed choices. Additionally, transparency in regulatory processes and in sharing results of safety assessments can improve public confidence ([60]. Engagement with the public through consultations and dialogue can also help shape the development of nanotechnology in a way that aligns with societal values and expectations. It can also help identify potential concerns and address them proactively [61]. Several initiatives in India are focusing on these strategies. The Nano Mission, launched by the Department of Science and Technology, India, includes public awareness programs as a key component [62]. The Indian Institute of Technology, Bombay, has been conducting nanoscience workshops for teachers and students, fostering curiosity and interest in nanotechnology [63].

Conclusion

Nanotechnology presents an immense potential to revolutionize the food and agriculture sectors in India, offering solutions like smart packaging, Nano sensors, nano-pesticides, and nano-fertilisers. Issues surrounding safety, environmental impact, regulation, and public acceptance pose significant challenges. Emphasis on green chemistry, bio-synthesized and bio-inspired nanomaterials can provide sustainable and environmentally friendly solutions. Strengthening the regulatory framework, enhancing public awareness and engagement, and carrying out comprehensive risk assessments are vital for harnessing the full potential of nanotechnology while ensuring public and environmental safety. In essence, nanotechnology in food and agriculture holds great promise if balanced with precaution and responsibility.

References

1. Junk, A., & Riess, F. (2006). From an idea to a vision: There's plenty of room at the bottom. *American Journal of Physics*, *74*(9), 825-830.
2. Hussain, C. M. (2016). Magnetic nanomaterials for environmental analysis.
3. Shende, S., Rajput, V. D., Gade, A., Minkina, T., Fedorov, Y., Sushkova, S., ... & Boldyreva, V. (2021). Metal-based green synthesized nanoparticles: Boon for sustainable agriculture and food security. *IEEE Transactions on NanoBioscience*, *21*(1), 44-54.
4. Kumar, A. (2014). Nanotechnology development in India: an overview. New Delhi: *Research and Information System for Developing Countries.*
5. Mohammadi, Z., & Jafari, S. M. (2020). Detection of food spoilage and adulteration by novel nanomaterial-based sensors. *Advances in Colloid and Interface Science*, *286*, 102297.
6. Poyatos-Racionero, E., Ros-Lis, J. V., Vivancos, J. L., & Martinez-Manez, R. (2018). Recent advances on intelligent packaging as tools to reduce food waste. *Journal of cleaner production*, *172*, 3398-3409.
7. Okey-Onyesolu, C. F., Hassanisaadi, M., Bilal, M., Barani, M., Rahdar, A., Iqbal, J., & Kyzas, G. Z. (2021). Nanomaterials as nanofertilizers and nanopesticides: An overview. *ChemistrySelect*, *6*(33), 8645-8663.
8. Mujtaba, M., Fraceto, L., Fazeli, M., Mukherjee, S., Savassa, S. M., de Medeiros, G. A., ... & Vilaplana, F. (2023). Lignocellulosic biomass from agricultural waste to the circular

economy: A review with focus on biofuels, biocomposites and bioplastics. *Journal of Cleaner Production*, 136815.

9. Ganeson, K., Mouriya, G. K., Bhubalan, K., Razifah, M. R., Jasmine, R., Sowmiya, S., ... & Ramakrishna, S. (2023). Smart packaging− A pragmatic solution to approach sustainable food waste management. *Food Packaging and Shelf Life*, *36*, 101044.
10. De Schutter, O., & Vanloqueren, G. (2011). The new green revolution: how twenty-first-century science can feed the world. *Solutions*, *2*(4), 33-44.
11. Landis, S. C., Amara, S. G., Asadullah, K., Austin, C. P., Blumenstein, R., Bradley, E. W., ... & Silberberg, S. D. (2012). A call for transparent reporting to optimize the predictive value of preclinical research. *Nature*, *490*(7419), 187-191.
12. Kay, L., & Shapira, P. (2009). Developing nanotechnology in Latin America. *Journal of Nanoparticle Research*, *11*, 259-278.
13. Mukunda, N. (1995). Jawaharlal Nehru Centre for Advanced Scientific Research–A tribute to the architect of modern Indian science. *Current Science*, *68*(6), 570-572.
14. Chauhan, N., Gupta, S., & Goyal, A. (2014). Nanoemulsion: An advanced mode of drug delivery system. *3 Biotech*, 4(2), 123-127.
15. Malik, S., Sharma, G., & Saini, K. S. (2021). Nanotechnology and its trend in the food industry: a review. *Journal of Food Science and Technology*, 58(3), 801-814.
16. Kah, M., Beulke, S., Tiede, K., & Hofmann, T. (2013). Nanopesticides: state of knowledge, environmental fate, and exposure modeling. Critical reviews in environmental science and technology, 43(16), 1823-1867.
17. Liu, R., & Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Science of the Total Environment*, 514, 131-139.
18. Ezhilarasi, A. A., Vijaya, J. J., Kaviyarasu, K., Maaza, M., & Ayeshamariam, A. (2020). Recent advances in gold nanoparticles for biomedical applications: from hybrid structures to multi-functionality. *Journal of Photochemistry and Photobiology B: Biology*, 207, 111891.
19. Deshmukh, S. P., Patil, S. M., Mullani, S. B., & Delekar, S. D. (2019). Silver nanoparticles as an effective disinfectant: A review. *Materials Science and Engineering: C*, *97*, 954-965.
20. Joyner, J. J., & Kumar, D. V. (2015). Nanosensors and their applications in food analysis: a review. *The International Journal of Science and Technoledge*, *3*(4), 80.
21. Fuertes, G., Soto, I., Carrasco, R., Vargas, M., Sabattin, J., & Lagos, C. (2016). Intelligent packaging systems: sensors and nanosensors to monitor food quality and safety. *Journal of Sensors*, *2016*.
22. Thakur, M. S., & Ragavan, K. V. (2013). Biosensors in food processing. *Journal of food science and technology*, *50*, 625-641.
23. Vasseghian, Y., Arunkumar, P., Joo, S. W., Gnanasekaran, L., Kamyab, H., Rajendran, S., ... & Klemeš, J. J. (2022). Metal-organic framework-enabled pesticides are an

emerging tool for sustainable cleaner production and environmental hazard reduction. *Journal of Cleaner Production*, 133966.

24. Ravichandran, R. (2010). Nanotechnology applications in food and food processing: innovative green approaches, opportunities and uncertainties for global market. *International Journal of Green Nanotechnology: Physics and Chemistry*, *1*(2), P72-P96.
25. Singh, R. L., & Mondal, S. (Eds.). (2019). *Food safety and human health*. Academic Press.
26. Anukiruthika, T., Sethupathy, P., Wilson, A., Kashampur, K., Moses, J. A., & Anandharamakrishnan, C. (2020). Multilayer packaging: Advances in preparation techniques and emerging food applications. *Comprehensive Reviews in Food Science and Food Safety*, *19*(3), 1156-1186.
27. Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Frontiers in microbiology*, 8, 1014.
28. Kah, M., Beulke, S., Tiede, K., & Hofmann, T. (2013). Nanopesticides: state of knowledge, environmental fate, and exposure modeling. *Critical reviews in environmental science and technology*, 43(16), 1823-1867.
29. Kookana, R. S., Boxall, A. B., Reeves, P. T., Ashauer, R., Beulke, S., Chaudhry, Q., ... & Romeis, J. (2014). Nanopesticides: guiding principles for regulatory evaluation of environmental risks. *Journal of Agricultural and Food Chemistry*, 62(19), 4227-4240.
30. Khan, I., Saeed, K., & Khan, I. (2019). Nanoparticles: Properties, applications and toxicities. *Arabian Journal of Chemistry*, 12(7), 908-931.
31. KS, S. (2019). Role of nano-fertilizer on Greenhouse Gas Emission in Rice Soil Ecosystem. *Madras Agricultural Journal*, *106*.
32. Koul, O. (Ed.). (2019). *Nano-biopesticides today and future perspectives*. Academic Press.
33. Sekhon, B. S. (2014). Nanotechnology in agri-food production: an overview. *Nanotechnology, science and applications*, 31-53.
34. Navya, P. N., & Daima, H. K. (2016). Rational engineering of physicochemical properties of nanomaterials for biomedical applications with nanotoxicological perspectives. *Nano Convergence*, *3*, 1-14.
35. Wu, T., & Tang, M. (2018). Review of the effects of manufactured nanoparticles on mammalian target organs. *Journal of Applied Toxicology*, *38*(1), 25-40.
36. Panyala, N. R., Peña-Méndez, E. M., & Havel, J. (2008). Silver or silver nanoparticles: a hazardous threat to the environment and human health?. *Journal of applied biomedicine*, *6*(3).
37. Verma, S. K., Das, A. K., Patel, M. K., Shah, A., Kumar, V., & Gantait, S. (2018). Engineered nanomaterials for plant growth and development: a perspective analysis. *Science of the Total Environment*, *630*, 1413-1435.

38. Coleman, M. E., & Marks, H. M. (1999). Qualitative and quantitative risk assessment. *Food Control*, *10*(4-5), 289-297.
39. Shukla, R. K., Kumar, A., Gurbani, D., Pandey, A. K., Singh, S., & Dhawan, A. (2013). TiO2 nanoparticles induce oxidative DNA damage and apoptosis in human liver cells. *Nanotoxicology*, *7*(1), 48-60.
40. Gong, X., Huang, D., Liu, Y., Zeng, G., Wang, R., Wan, J., ... & Xue, W. (2017). Stabilized nanoscale zerovalent iron mediated cadmium accumulation and oxidative damage of Boehmeria nivea (L.) Gaudich cultivated in cadmium contaminated sediments. *Environmental science & technology*, *51*(19), 11308-11316.
41. Shandilya, N., Marcoulaki, E., Barruetabena, L., Llopis, I. R., Noorlander, C., Jiménez, A. S., ... & Fransman, W. (2020). Perspective on a risk-based roadmap towards the implementation of the safe innovation approach for industry. *NanoImpact*, *20*, 100258.
42. Axon, S., & James, D. (2018). The UN Sustainable Development Goals: How can sustainable chemistry contribute? A view from the chemical industry. *Current Opinion in Green and Sustainable Chemistry*, *13*, 140-145.
43. Singh P, Kim YJ, Zhang D, Yang DC. Biological synthesis of nanoparticles from plants and microorganisms. *Trends Biotechnol* 2016;34:588e99.
44. Rani, N., Singh, P., Kumar, S., Kumar, P., Bhankar, V., & Kumar, K. (2023). Plant-Mediated Synthesis of Nanoparticles and Their Applications: A Review. *Materials Research Bulletin*, 112233.
45. Nazeruddin, G. M., Prasad, N. R., Waghmare, S. R., Garadkar, K. M., & Mulla, I. S. (2014). Extracellular biosynthesis of silver nanoparticle using Azadirachta indica leaf extract and its anti-microbial activity. *Journal of Alloys and Compounds*, *583*, 272-277.
46. Bahrulolum, H., Nooraei, S., Javanshir, N., Tarrahimofrad, H., Mirbagheri, V. S., Easton, A. J., & Ahmadian, G. (2021). Green synthesis of metal nanoparticles using microorganisms and their application in the agrifood sector. *Journal of Nanobiotechnology*, *19*(1), 1-26.
47. Rosman, N. S. R., Harun, N. A., Idris, I., & Wan Ismail, W. I. (2021). Nanobiotechnology: Nature-inspired silver nanoparticles towards green synthesis. *Energy & Environment*, *32*(7), 1183-1206.
48. Ong, W. T. J., & Nyam, K. L. (2022). Evaluation of silver nanoparticles in cosmeceutical and potential biosafety complications. *Saudi Journal of Biological Sciences*.
49. Kumari, R., Suman, K., Karmakar, S., Lakra, S. G., Saurav, G. K., & Mahto, B. K. (2023). Regulation and Safety Measures for Nanotechnology-based Agri-Products. *Frontiers in Genome Editing*, *5*, 1200987.
50. Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N. A., & Munné-Bosch, S. (2019). Nanofertilizer use for sustainable agriculture: Advantages and limitations. *Plant Science*, 289, 110270.
51. Change, C. (2020). The Ministry of Environment, Forest and Climate Change (MoEFCC).

52. Oberdörster, G., Maynard, A., Donaldson, K., Castranova, V., Fitzpatrick, J., Ausman, K., ... & Yang, H. (2005). Principles for characterizing the potential human health effects from exposure to nanomaterials: elements of a screening strategy. *Particle and fibre toxicology*, 2(1), 1-35.
53. Paull, J., & Lyons, K. (2008). Nanotechnology: the next challenge for organics. *Journal of Organic Systems*, *3*(1), 3-22.
54. Gupta, V., Mohapatra, S., Mishra, H., Farooq, U., Kumar, K., Ansari, M. J., ... & Iqbal, Z. (2022). Nanotechnology in cosmetics and cosmeceuticals-A review of latest advancements. *Gels*, 8(3), 173.
55. Chowdhury, N. (2010). Regulation of nanomedicines in the EU: distilling lessons from the pediatric and the advanced therapy medicinal products approaches. *Nanomedicine*, *5*(1), 135-142.
56. Rathore, A., & Mahesh, G. (2021). Public perception of nanotechnology: A contrast between developed and developing countries. *Technology in Society*, *67*, 101751.
57. McGann, J. G. (2020). 2019 Global Go To Think Tank Index Report.
58. Dibden, J., Gibbs, D., & Cocklin, C. (2013). Framing GM crops as a food security solution. *Journal of Rural studies*, *29*, 59-70.
59. Yu, H. P., & Jen, E. (2020). Integrating nanotechnology in the science curriculum for elementary high-ability students in Taiwan: Evidenced-based lessons. *Roeper Review*, *42*(1), 38-48.
60. Frewer, L., Lassen, J., Kettlitz, B., Scholderer, J., Beekman, V., & Berdal, K. G. (2004). Societal aspects of genetically modified foods. *Food and Chemical toxicology*, *42*(7), 1181-1193.
61. Challagalla, G., Venkatesh, R., & Kohli, A. K. (2009). Proactive postsales service: When and why does it pay off?. *Journal of Marketing*, *73*(2), 70-87.
62. Kumar, A. (2014). Nanotechnology development in India: an overview. New Delhi: *Research and Information System for Developing Countries.*
63. Kurup, A., Dixit, S., Ashwini, K., & Arora, S. (2019). Challenges of Nurturing the Gifted and Talented in Developing Countries: *Experiences from Rural and Urban India* (NIAS/SSc/EDU/U/PR/18/2019).
64. Deshpande Sarma, S., & Anand, M. (2012). Status of nano science and technology in India. Proceedings of the National Academy of Sciences, India Section B: *Biological Sciences*, 82, 99-126.
65. Krishna, V. V. (2012). Erawatch Country Reports 2012: India. *ERAWATCH Network-Jawaharlal Nehru University.-2013.-57 p*.