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APPLICATIONS OF NANOTECHNOLOGY IN AGRICULTURE AND HEALTH CARE: A REVIEW

Ridhima Arya[1], Neha Negi[1*], Jag Mohan[1], Bharti Gautam[1], Babita Bharti[1] and Anil Kumar Sharma[2]
[1]Department of Agriculture, Maharishi Markandeshwar (Deemed to be University)
Mullana- Ambala, Haryana, India, 133207
[2]Department of Biotechnology, Amity University, Mohali-Punjab, India, 201313
*Corresponding author Email Id: nnegi531@gmail.com ;
ORCID Id- 0000-0002- 8453-1292
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ABSTRACT

Nanotechnology has shown promising potential to promote sustainable agriculture. Nanomaterials play an important role regarding the fate, mobility and toxicity of soil pollutants and are essential part of different biotic and abiotic remediation strategies. Nanomaterial has many potential applications in agriculture to enhance crop productivity and to improve the soil health. Nanotechnology is the rising technology of the current decade, which has also shown promising results in controlling excess agri-inputs and maintaining environmental balance. The characteristics of controlled release capacity and targeted delivery of nano fertilizer and nanopesticide showed high activity in comparison to conventional fertilizers and pesticides. Various types of nano tools such as nanomaterial, nano formulations, nanocomposite, nanoemulsion and nanoencapsulation based agri tools have been used to provide nutrition to plants and toxins to pests in a controlled manner. Nanotechnology can also reduce post-farming losses by increasing the shelf life with the aid of nanoparticles. Nanotechnology has extensive application as nanomedicine in the medical field. Some nanoparticles have possible applications in novel diagnostic instruments, imagery and methodologies, targeted medicinal products, pharmaceutical products, biomedical implants, and tissue engineering. Today treatments of high toxicity can be administered with improved safety using nanotechnology, such as chemotherapeutic cancer drugs. Nanotechnology has enormous potential to play an important and innovative role to secure the agri-production and food security.
***Keywords*:** Nanoparticles, agriculture, medicine, tools

Introduction

Nanotechnology is the science of manipulating matter at a very small scale. It has emerged as a cutting-edge field with transformative potential across various sectors, including agriculture and allied sciences. At the nanoscale, materials exhibit unique physical, chemical, and biological properties that are very different from their normal size. This unique behaviour arises due to quantum effects, surface area-to-volume ratios, and increased reactivity, among other factors. These properties enable nanomaterials to perform functions that are not achievable at larger scales, opening up new possibilities for innovation and applications. In the realm of agriculture and allied sciences, nanotechnology offers promising solutions to address a wide range of challenges faced by the industry. One of the key areas where nanotechnology holds immense potential is in crop production. Nanomaterial-based formulations, such as nano-fertilizers and nano-pesticides, offer targeted delivery of nutrients and agrochemicals to plants, thereby maximizing uptake efficiency and minimizing environmental losses (Khot *et al.*, 2012). These nanoscale formulations can be engineered to release nutrients and pesticides gradually, providing sustained benefits to crops while reducing the need for frequent applications (Giraldo and Landry, 2017). Additionally, nanotechnology enables the development of smart delivery systems that respond to environmental cues, ensuring precise and timely delivery of inputs to crops (Zhu *et al*., 2016).

In addition to improving crop yield and quality, nanotechnology plays a crucial role in pest management and disease control (Kah *et al*., 2013). Nanoparticles can be functionalized with specific compounds to target pests and pathogens selectively, minimizing the impact on beneficial organisms and reducing the risk of resistance development (Hernandez-Viezcas *et al*., 2013). Furthermore, nanoscale delivery systems enhance the bioavailability and efficacy of pesticides, allowing for lower application rates and reduced environmental contamination (Kole *et al*., 2013). Nanotechnology also offers innovative solutions for soil remediation and environmental sustainability in agriculture (Kah *et al*., 2019). Nanomaterials, such as nanoscale adsorbents and reactive nanoparticles, can effectively remove pollutants and contaminants from soil and water, thereby restoring ecosystem health and enhancing soil fertility (Unrine *et al*., 2012). Moreover, nanotechnology-based sensors enable real-time monitoring of soil quality, nutrient levels, and environmental parameters, facilitating precision agriculture practices and optimized resource management (Meng *et al*., 2017).

In the realm of food safety and quality assurance, nanotechnology plays a pivotal role in ensuring the safety, freshness, and shelf life of agricultural products (Rai *et al*., 2019). Nano biosensors enable rapid and sensitive detection of pathogens, toxins, and contaminants in food, enhancing food safety monitoring and regulatory compliance (Zhao *et al*., 2021). Additionally, nanomaterials can be incorporated into food packaging materials to provide antimicrobial properties, oxygen scavenging capabilities, and barrier properties, thereby extending the shelf life of perishable products and reducing food waste (Bumbudsanpharoke and Ko, 2015).

Overall, nanotechnology holds immense promise for transforming agriculture and allied sciences by offering innovative solutions to address pressing challenges and advance sustainability goals (Gogos *et al*., 2018). However, the widespread adoption of nanotechnology in agriculture requires interdisciplinary collaboration, regulatory oversight, and stakeholder engagement to ensure responsible innovation and mitigate potential risks (Sahoo *et al*., 2020). By leveraging the unique properties of nanomaterials, researchers, farmers, and policymakers can work together to create a more resilient, efficient and sustainable agricultural system for the future. The review will encompass diverse domains within nanotechnology relevant to agriculture, including nanomaterials, nanosensors, nanobiotechnology, and nanoscale delivery systems.

Agricultural Applications: It will explore a wide array of applications in agriculture, such as crop enhancement, disease management, soil remediation, food safety, and waste reduction.

Interdisciplinary Perspective: The scope extends beyond agriculture to allied sectors such as food processing, environmental science, biotechnology, and pharmaceuticals, embracing the interdisciplinary nature of nanotechnology.

Global Context: The review will consider global perspectives, incorporating studies and developments from various regions to provide a comprehensive overview of nanotechnology's impact on agriculture and allied sectors.

Application of Nanotechnology in Agriculture

Food production

Nanotechnology offers novel approaches to enhance food production by improving crop yield, quality, and resilience. Nano-enabled agricultural inputs, such as nano-fertilizers and nano-pesticides, facilitate targeted delivery of nutrients and agrochemicals to plants, ensuring efficient uptake and utilization while minimizing environmental impacts (Giraldo and Landry, 2017). These nanomaterial-based formulations can be designed to release nutrients gradually, providing sustained benefits to crops and reducing the need for frequent applications (Giraldo and Landry, 2017). Additionally, nanotechnology enables the development of smart delivery systems responsive to environmental cues, ensuring precise and effective delivery of inputs to crops (Zhu *et al*., 2016).

Environmental sustainability

Nanotechnology plays a crucial role in promoting environmental sustainability in agriculture through pollution mitigation, resource conservation, and reduced environmental footprints. Nanomaterial-based remediation technologies offer efficient and cost-effective solutions for soil and water remediation by capturing and degrading contaminants (Kah *et al*., 2019). Nanoscale adsorbents, reactive nanoparticles, and nanocomposites effectively remove pollutants like heavy metals, pesticides, and organic compounds, thereby restoring soil health and ecosystem balance (Kah *et al*., 2019). Furthermore, nanotechnology facilitates the development of nanosensors for real-time environmental monitoring, enabling early detection of pollution events and informed decision-making for sustainable resource management (Meng *et al.*, 2017).

Resource Management

Nanotechnology presents innovative solutions for optimizing resource management in agriculture, including water, energy, and land resources. Nanoscale sensors and monitoring devices provide real-time data on soil moisture, nutrient levels, and crop health, enabling precision agriculture practices. This information allows farmers to optimize irrigation, fertilization, and pest control practices, reducing resource inputs and maximizing crop yields (Meng *et al.*, 2017). Additionally, nanotechnology enables the development of nanomaterial-based membranes and filters for water purification and desalination, addressing challenges related to water scarcity and quality in agriculture (Kumar *et al.*, 2017).

Nanofertilizers

Nanofertilizers are a significant advancement in agricultural nanotechnology. These nutrient delivery systems are in nano-size and offer several advantages over traditional fertilizers. Nanoencapsulation techniques allow for the controlled release of nutrients, ensuring optimal uptake by plants while minimizing nutrient leaching and runoff. Furthermore, nanofertilizers can be engineered to target specific nutrient deficiencies, thereby optimizing plant growth and yield (Fernandez *et al.*, 2021).

Nano-enabled pesticide management

Nanotechnology has made significant improvements to pest management strategies in agriculture. By encapsulating pesticides at a nano-level, their efficacy is improved while reducing environmental contamination by minimizing off-target effects. Moreover, nanomaterials, such as nanoparticles and nanocapsules, can be functionalized to target specific pests, leading to increased pest control efficiency and reduced pesticide usage. These advancements promote sustainable pest management practices and minimize the negative impacts of chemical pesticides on ecosystems (Kah *et al.*, 2019).

Nanoscale delivery systems

Nanotechnology has facilitated the development of advanced delivery systems for agricultural inputs. Nanocarriers, such as nanoparticles and nanogels, provide a platform for targeted delivery of nutrients, pesticides, and growth regulators to plants. These nanoscale delivery systems enhance the bioavailability of active ingredients, improve uptake efficiency, and reduce environmental losses. Moreover, smart Nano delivery systems responsive to environmental stimuli enable controlled release of inputs, ensuring optimal efficacy and minimizing environmental impact (Zhao *et al.*, 2021).

Nanobiosensors for nutrient monitoring

Nanotechnology-based biosensors offer unprecedented capabilities for real-time monitoring of nutrient status and environmental stress in plants. These nanobiosensors can detect and quantify trace levels of nutrients, enabling precise nutrient management and optimization of fertilization practices. Integrated with data analytics and precision agriculture technologies, nanobiosensors provide valuable insights into crop health and facilitate data-driven decision-making for farmers. Furthermore, nanobiosensors contribute to sustainable agriculture by minimizing nutrient losses and optimizing resource utilization (Meng *et al.*, 2017).

Nanomaterials for Stress Tolerance

Nanotechnology has opened new avenues for enhancing plant stress tolerance to abiotic factors such as drought, salinity, and heat. Nanomaterials such as nanoclays, nanosilica, and carbon nanotubes improve soil structure, water retention, and nutrient availability, thereby mitigating the adverse effects of environmental stressors on plant growth and development. Nano-enabled foliar sprays and seed treatments activate stress response pathways in plants, enhancing their resilience to environmental stress and improving overall crop yield and quality (Kah *et al.*, 2019). Mechanism of Action: Nano encapsulated pesticides involve encapsulating pesticide molecules within nanoscale carriers, such as polymeric nanoparticles or lipid-based nanocapsules. These nanoencapsulated formulations protect the pesticide from environmental degradation, reduce off-target effects, and enhance its stability and efficacy. Upon application, the nanocarriers gradually release the encapsulated pesticide, ensuring sustained and targeted delivery to pests while minimizing environmental contamination.

Example: A study by Kah *et al.* (2019) demonstrated the effectiveness of nanoencapsulated insecticides for controlling agricultural pests. Polymeric nanoparticles loaded with insecticides exhibited prolonged release kinetics, leading to enhanced insecticidal activity and reduced environmental impact compared to conventional formulations.

Nanoparticle-Based Nutrient Delivery Systems

Mechanism of Action: Nanoparticle-based nutrient delivery systems involve the encapsulation or adsorption of essential nutrients onto nanoparticles, such as metal oxides or carbon-based nanomaterials. These nanoparticles serve as carriers for nutrient delivery to plants, improving nutrient uptake efficiency and reducing nutrient losses through leaching or volatilization. Additionally, nanomaterials can modify nutrient release kinetics and enhance nutrient availability in the rhizosphere, promoting plant growth and productivity.

Example: Research by DeRosa *et al.* (2010) explored the use of metal oxide nanoparticles, such as iron oxide and zinc oxide nanoparticles, for delivering micronutrients to crops. These nanoparticles effectively delivered micronutrients to plant roots, resulting in improved nutrient uptake and enhanced crop growth.

Nanostructured Fertilizers

Mechanism of Action: Nanostructured fertilizers involve the synthesis of fertilizer particles at the nanoscale, typically through techniques such as sol-gel processes or precipitation methods. These nanostructured fertilizers offer advantages such as controlled release, improved solubility, and increased nutrient availability. The nanoscale size and high surface area-to-volume ratio of these particles facilitate efficient nutrient absorption by plant roots, leading to enhanced nutrient utilization and crop yield.

Example: Studies by Fernandez *et al.* (2021) demonstrated the efficacy of nanostructured fertilizers in improving nutrient uptake and crop productivity. Nanostructured formulations of nitrogen, phosphorus, and potassium fertilizers exhibited prolonged release kinetics and enhanced nutrient availability in soil, resulting in increased crop yields compared to conventional fertilizers.

Nanoscale Soil Amendments

Mechanism of Action: Nanoscale soil amendments involve the application of nanomaterials, such as nanoclays or nanosilica, to improve soil properties and nutrient retention. These nanomaterials can enhance soil structure, water retention, and nutrient-holding capacity, thereby promoting root growth, nutrient uptake, and overall plant health. Additionally, nanomaterials can mitigate soil compaction, reduce erosion, and enhance soil microbial activity, leading to improved soil fertility and productivity.

Example: Research by Zhao *et al.* (2021) investigated the use of nanoscale soil amendments for improving soil quality and crop productivity. Nanoclays and nanosilica particles effectively improved soil structure, water infiltration, and nutrient retention, resulting in enhanced crop yields and sustainable agricultural practices.

Thus, nanomaterial-based formulations offer innovative solutions for enhancing agricultural productivity, nutrient management, and sustainability. These formulations leverage the unique properties of nanomaterials to improve the efficacy, stability, and targeted delivery of agricultural inputs, leading to more efficient resource utilize Nanoremediation is a soil remediation technique that involves the use of nanotechnology-driven approaches to tackle soil pollution effectively. It harnesses the unique properties of nanomaterials such as zero-valent iron nanoparticles, carbon nanotubes, and metal oxides, offering promising avenues for pollutant removal and transformation. This method can immobilize, degrade, or sequester contaminants through various mechanisms such as adsorption, chemical transformation, and enhanced mobility.

Nanoremediation has been successfully applied to heavy metal remediation, organic contaminant degradation, and even radioactive waste cleanup, making it a versatile and highly effective solution for soil contamination challenges. For instance, zero-valent iron nanoparticles have been used to remove arsenic, chromium, and lead from contaminated soils (Chowdhury *et al*., 2016). Carbon nanotubes have been shown to be effective in removing a wide range of organic pollutants, including pesticides, polycyclic aromatic hydrocarbons, and pharmaceuticals. Metal oxides such as titanium dioxide and iron oxide nanoparticles have been used to degrade persistent organic pollutants such as polychlorinated biphenyls (PCBs) and dioxins (Khodakovskaya *et al*., 2009).

Nanotechnology in Plant Medicine

A huge volume of plant viruses is non-enveloped and have RNA as genetic material. The symmetry of virus can be helical like tobacco mosaic virus or icosahedral like cowpea chlorotic mottle virus. The specific size as well as extremely symmetric nature of plant viruses makes them a potent tool for structural biology with the use of structural techniques like cryo-electron microscopy. The knowledge of the detailed 3D structure of virus particles has resulted in genetic modification of coat protein with the identification of their exposed loop part without disturbing the capsomeric interactions necessary for assembly. The plant viruses' features show promising nanotechnological applications. Kinked nano-boomerangs have been developed by using RNA molecules. Similar nanostructures showing highly exposed enzyme surfaces can be made. Nanostars have also been developed by using metal conjugates with nucleic acid of TMV. Similarly, nanonets have been developed by using large networks of Turnip Mosaic Virus bound to *Candida antarctica* Lipase B in catalytically dynamic supra molecular complexes.

Cargo particles can be trapped inside the viral capsomeres. The virus particles are made to swell so that pores may open and cargo may diffuse inside, then reversing the same closes the pores. Such a method has been used to trap ethidium bromide in Tombusviridae virions. Zeng *et al.* (2013) has also used this method to pack doxorubicin inside the cucumber particles.

The nematicide abamectin in viral particles through infusion by Cao *et al.* (1982) has been used in field. This encapsulated form of abamectin had similar bioavailability to nematodes as free form of the pesticide, making it more effective with improved soil mobility at protecting crop roots from nematode infection. In some cases, infusion does not even require swelling of the viral particles to allow ingress of cargo, which is possible to use the native nucleic acid content of the virions as an electrostatic sponge to attract and retain positively charged cargo. This is the strategy, which was used by Yildiz *et al*., (2013) as well as Wen *et al*., (2015) to load particles of CPMV with imaging agents and therapeutic molecules. This relies on the natural affinity for these molecules with nucleic acid, and these experiments demonstrate the potential to use infused CPMV particles as imaging and therapy vehicles. A similar method was employed to load the platinum-containing anti-cancerous drug candidate Phenanthriplatin in the channel of rod-shaped TMV through a one-step loading protocol, which also exploited the electrostatic interaction between the positively charged cargo and the negatively charged interior of the viral particle.

Nano sensors for precision Agriculture

Nano sensors for precision agriculture encompass a diverse array of sensing technologies tailored to meet the specific needs of modern farming. These sensors can detect a wide range of parameters vital for crop health and productivity, including soil moisture content, nutrient levels, pH, temperature, and the presence of pests or pathogens. The utilization of nanomaterials in sensor fabrication enhances their sensitivity, selectivity, and response time, enabling rapid and accurate measurements even at trace levels. For instance, carbon nanotubes and graphene-based nanosensors exhibit excellent electrical conductivity and surface-to-volume ratios, making them ideal for detecting changes in soil moisture and nutrient concentrations with high precision (Sharma *et al.*, 2020). Quantum dots, semiconductor nanoparticles with tunable optical properties, offer sensitive detection capabilities for environmental pollutants, pathogens, and pesticide residues (Gupta *et al*., 2021). Additionally, nanosensors can be integrated into various platforms, including wearable devices, drones, and autonomous vehicles, allowing for remote monitoring of agricultural fields and timely interventions based on real-time data analysis (Roduner, 2006). Moreover, the advent of Internet of Things (IoT) technology facilitates seamless communication between nanosensors and farm management systems, enabling farmers to access critical information and make data-driven decisions from anywhere in the world. Despite the significant advancements in nanosensor technology, challenges such as sensor miniaturization, power consumption, and long-term stability persist and require on-going research efforts to overcome (Su *et al*., 2020). Nonetheless, the integration of nanosensors into precision agriculture holds immense promise for revolutionizing farming practices, promoting sustainability, and ensuring global food security in the face of climate change and population growth.

Nanotechnology has become a crucial factor in ensuring food safety and quality assurance by providing innovative solutions for detecting, monitoring, and preserving food. Nanomaterials and nanodevices enable fast and precise detection of contaminants, pathogens, and adulterants in food products, which contribute to early warning systems and regulatory compliance (Zhao *et al*., 2021). Nanobiosensors use the unique properties of nanomaterials to provide real-time, label-free detection of foodborne pathogens and toxins with high specificity and sensitivity (Rai *et al*., 2019). Additionally, nanomaterials, such as nanoemulsions and nanocomposites, are used in food packaging materials to improve barrier properties, prolong shelf life, and prevent microbial growth. This helps reduce food spoilage and waste (Bumbudsanpharoke and Ko, 2015). Nanotechnology also allows for the development of nano-based delivery systems that can control the release of food additives, antioxidants, and antimicrobial agents, which enhances the safety and quality of food products throughout their shelf life (Zhao *et al*., 2021). Overall, nanotechnology offers a multifaceted approach to food safety and quality assurance, addressing challenges in detection, preservation, and regulatory compliance, thereby ensuring the delivery. Environmental and regulatory considerations play a crucial role in the development and application of nanotechnology. This is especially important because of the potential impact on ecosystems, human health, and regulatory frameworks governing their use. The primary environmental concern is the release of nanoparticles into the environment, which could pose risks due to their unique properties and interactions with living organisms and ecosystems. Nanoparticles can accumulate in soil, water, and air, leading to harmful effects on microbial communities, wildlife, and humans through bioaccumulation and toxicity. However, the fate and transport of nanoparticles in the environment remain poorly understood, making risk assessment and management difficult.

Application of Nanotechnology in Allied Sciences

Nanotechnology has been a promising therapeutic and scientific approach to effectively deal in healthcare with a potential to bring significant improvements in disease diagnosis and management. The existing drug regimen has become increasingly effective with the use of Nano medicines against many dreadful diseases. Nano medicines have shown promising attributes such as slow and sustained release, nominal side effects, low toxicity, and increased concentration of the drug at the target site along with increased life-span of the drug.

In Cancer Treatments

The conventional cancer medicines have the limitation but nanotechnology opened up a wide platform for cancer treatment. Although research has been done in the field of nano-medicines for cancer treatment, yet more-indulgent approach is required in biological nano-particle materials interaction, production and commercialization of nano-therapies. The nanoparticles used for cancer treatment are given in systemic manner, which accumulate in the cancer tissues. The first approved class of nanoparticles is liposomes in cancer therapy. The effectiveness of cancer nano-medicines depends upon the properties like geometry, elasticity, sixe, porosity, surface features, stiffness of the nanoparticles and the targeting ligand. In late 2016, the third phase trials of Vyxeos (liposomal cytarabine and daunorubicin) show higher overall survival rate in patients of acute myeloid leukaemia in a high-risk situation. The second commercialized class is nanoparticle alumin bound paclitaxel named Abraxane. It was found in literature studies-the number of research papers on nanoparticles on PubMed almost doubled every year from 2000 to 2014. Nanoparticles have also shown a promising capability in anticancerous drug delivery approaches. Research also has been going on for exploring inorganic nanoparticles like nanodiamond and graphene in various cancer therapies.

Malignant transformations of hematopoietic cells cause Acute Leukemias. Nanotechnology has diverse applications in acute leukemia therapies. There are new technologies like aptamer development, which helps in detection of malignant leukemias. A DNA based aptamer had been developed for the detection of acute leukemic cells by Hernandez-Viezcas *et al.* (2013). The sequence created was 88 nucleotides long and attached to fluorescent and magnetic nanoparticles. Food and Drug Administration had approved a number of nanoparticles-based approaches for various treatment strategies, out of which, some are in clinical trial phase also. An injection named Vincristine Sulfate Liposome Injection (VSLI) for the treatment of adult patients, which have relapse or progressive disease even after leukemia treatments earlier. The effect of Enhanced Permeability and Retention (EPR) in nanoparticles favoured their use in immuno-modulators. Lipid Coated Calcium Phosphate Nanoparticles (LCP-NP) have been used for delivering anti-inflammatory and down-regulatory molecules of immuno-system. Various NPs based combination therapies had shown improvised results in cancer treatments.

Nanotechnology in Non-Invasive Glucose Monitoring

Nanotechnology has shown keen possibilities in the monitoring of glucose in non-invasive manner. Improved nanosensors for glucose monitoring can be developed by exploiting the nanoscale properties like higher surface area to volume ratio enhanced catalytic and optical properties, which led to increased sensivity of the sensor. The sensors can be made as tattoos. The large scale production can be made cost effective. Innovations in nanotechnology based glucose sensors can revolutionize diabetic treatments. One of the examples is the use of nanotubes made of carbon with a diameter of few nm, which can be transplanted under the skin after wrapping inside a dialysis fibre. Carbon nanotubes fibres have been developed by using the bundles of two walled carbon nanotubes concentrically compressed into manifold films forming a nanoporous complex structure.

Conclusion

Despite its potential, nanoremediation faces some challenges that need to be addressed for its widespread adoption. These challenges include ensuring nanoparticle stability, evaluating environmental impacts, and establishing robust regulatory frameworks. Environmental impacts of nanoremediation also need to be evaluated to ensure that the technology does not cause unintended harm to soil or surrounding ecosystems. Additionally, regulatory frameworks need to be established to ensure that the use of nanomaterials in future research should aim to enhance our understanding of the interactions.

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Competing Interests

The authors declare no competing interests.

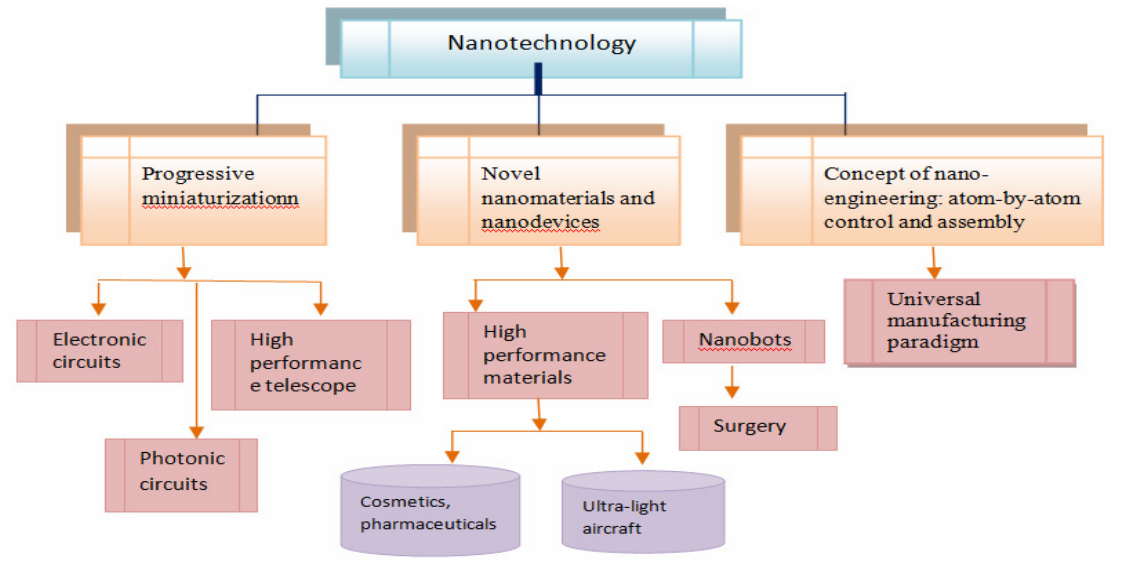

Fig. 1 : Applications of Nanotechnology in various thrust areas (Ramsden, 2015)

References

Bumbudsanpharoke, N., Ko, S. (2015). Nanotechnology in food packaging: A review. *Journal of Food Science and Technology,* **52**(12), 7594- 7614.

DeRosa, M. C., Monreal, C., Schnitzer, M., Walsh, R., Sultan, Y. (2010). Nanotechnology in fertilizers. *Nature Nanotechnology,* **5**(2), 91- 94.

Fernandez, M., Roco, M.C., Field, K. (2021). Nanotechnology: A global outlook 2021. Springer International Publishing.

Giraldo, J.P., Landry, M.P. (2017). Nanobiohybrids as delivery vehicles for agriculture. *Nature Nanotechnology,* **12**(4), 288- 290.

Gogos, A., Knauer, K., Bucheli, T. D., 2018. Nanomaterials in plant protection and fertilization: Current state, foreseen applications, and research priorities. *Journal of Agricultural and Food Chemistry*, **66**(20), 5082- 5090.

Gupta, S.K., Shukla, R. 2021. Applications of Nanotechnology for Wireless Sensor Networks. Review Article Journal of Nanomedicine & Nanotechnology Journal of Nanomedicine & Nanotechnology: *Journal of Nanomedicine and Nanotechnology* **12**(8):573- 578.

Hernandez-Viezcas, J. A., Castillo-Michel, H., Andrews, J. C., Cotte, M., Rico, C., Peralta-Videa, JR., Gardea-Torresdey, J. L., 2013. In situ synchrotron X-ray fluorescence mapping and speciation of CeO2 and ZnO nanoparticles in soil cultivated soybean (*Glycine max*). ACS Nano **7**(2), 1415- 1423.

Kah, M., Kookana, R. S., Gogos, A., Bucheli, T. D., 2019. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnology,* **14**(7), 627- 634.

Kah, M., Zhang, X., Jonker, M. T. O., 2013. Chronic nanosilver exposure results in size-dependent alterations in aquatic plants. *Environmental Toxicology and Chemistry*, **32**(8), 1936- 1942.

Khodakovskaya, M., Dervishi, E., Mahmood, M., Xu, Y., Li, Z., Watanabe, F., Biris, A.S. (2009). Carbon Nanotubes Are Able To Penetrate Plant Seed Coat and Dramatically Affect Seed Germination and Plant Growth A C S publications 3(10): 3221– 3227.

Khot, L.R., Sankaran, S., Maja, J.M., Ehsani, R., Schuster, E.W. (2012). Applications of nanomaterials in agricultural production and crop protection: A review. *Crop Protection* **35**, 64- 70.

Kole, C., Kole, P., Randunu, K. M., Choudhary, P., Podila, R., Ke, P. C., (2013). Nanobiotechnology can boost crop production and quality: First evidence from increased plant biomass, fruit yield and phytomedicine content in bitter melon (*Momordica charantia*). *BMC Biotechnology* **13**(37), 1- 10.

Kumar, V., Yadav, S. K., Yadav, S. C. (2017). Synergistic effect of nanofertilizers and bio-fertilizers on the growth and yield of wheat (*Triticum aestivum* L.). *Journal of Cleaner Production*, **140**, 890- 899.

Meng, X., Li, Y., Liu, S., Zhou, Z., Ding, W., Wu, L., (2017). Applications and research progress of nanotechnology in agriculture and food industry. *Nanoscience and Nanotechnology Letters* **9**(6), 757- 768.

Rai, M., Ingle, A. P., Yadav, A., Paralikar, P. (2019). Nanotechnology-based approaches in food and its safety. Nanotechnology in Food: Concepts and Applications 193-211.

Roduner, E. (2006). Size matters: Why nanomaterials are different. *Chemical Society Reviews,* **35**(7), 583-592.

Roychowdhury, S., McCullough, R.L., Garcia , C.S., Saikia, P., Alkhouri, N., Matloob, A., Pollard, K.A., McMullen, M.R., Croniger, C.M., Nagy, L.E. (2016). Effect of Nanoparticle Aggregation, Polydispersity, and Concentration on Transport of Surface Modified Nanoscale Zerovalent Iron (NZVI) Particles in Saturated Porous Media: *Epub* **64**(5):1518- 1533

Sahoo, S.K., Parhi, R., Biswas, A. (2020). Nanotechnology in agriculture: Opportunities, challenges, and applications. *Journal of Agricultural and Food Chemistry,* **68**(4), 875-877.

Sharma, P., Pandey, V., Mukut, M., Sharma, M., Patra, A., Singh, B., Mehta, S. Husen, A. (2021). A Review on biosensors and nanosensors application in agroecosystems: *Nanoscale Research letters*, **16**, 136-162.

Su, D., Han, X., Yan, X., Jin, R., Li, H., Kong, D., Gao, H., Liu, F., Sun, P., Lu, G. (2020). Smartphone-Assisted Robust Sensing Platform for On-Site Quantitation of 2,4-Dichlorophenoxyacetic Acid Using Red Emissive Carbon Dots. Analytical Chemistry 92 (18), 12716–12724.

Unrine, J. M., Colman, B. P., Bone, A. J., Gondikas, A. P., Matson, C.W. (2012). Biotic and abiotic interactions in aquatic microcosms determine fate and toxicity of Ag nanoparticles. Part 2. Effects of Ag nanoparticles and AgNO3 on macrophytes and algae. *Environmental Science & Technology* **46**(13), 7568- 7575.

Wen, A. M., Wang, Y. M., Jiang, K., Hsu, G. C., Gao H. Y., Lee K. L., Yang A. C., Yu X., Simon D. I., Steinmetz, N.F. (2015). Shaping bio-inspired nanotechnologies to target thrombosis for dual optical-magnetic resonance imaging. *Journal of Materials Chemistry,* B 3: 6037–6045.

Yildiz, I., Lee, K. L, Chen, K., Shukla, S., Steinmetz N.F. (2013). Infusion of imaging and therapeutic molecules into the plant virus-based carrier cowpea mosaic virus: cargo-loading and delivery. *Journal of Controlled Release,* **172**, 568–578.

Zhao, X., Liu, L., Gao, C., Li, L., Li, X. (2021). Nanotechnology and food safety: Opportunities and challenges. *Food Control,* **125**, 108003.

Zeng, Q., Wen, H., Wen, Q., Chen X., Wang, Y., Xuan W., Liang, J., Wan, S. (2013). Cucumber mosaic virus as drug delivery vehicle for doxorubicin. Biomaterials 34(19), 4632- 4642

Zhu, J., Bailly, A., Zwiewka, M., Sovero, V., Donato, M.D., Ge, P., Oehri, J., Aryal, B., Hao, P., Linnert, M., Burgardt, N.I., Lücke, C., Weiwad, M., Michel, M., Oliver., Weiergräber, Pollmann, S., Azzarello, E., Mancuso, S., Ferro, N., Fukao, Y., Hoffmann, C., Söldner, R.W., Friml, J.R., Thomas, C. and Geislera, M. (2016). Mediates the action of auxin transport inhibitors on actin cytoskeleton dynamics: *The Plant Cell.*, **28**: 930–948.