Journal of Scientific Research and Reports

Volume 30, Issue 3, Page 32-51, 2024; Article no.JSRR.112155
ISSN: 2320-0227

Nanotechnology-driven Solutions: Transforming Agriculture for a Sustainable and Productive Future

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JSRR/2024/v30i31856

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/112155

Review Article

Received: 15/11/2023
Accepted: 21/01/2024
Published: 31/01/2024

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ABSTRACT

Nanotechnology offers immense potential to revolutionize agriculture and address key challenges of food security, environmental sustainability, and nutritional enhancement. Diverse nanomaterials and nano-enabled innovations are being developed targeting nearly all aspects of the agricultural system. Nanoparticle crop protection products, nano-biosensors, nanofertilizers, and nanobioactives can enhance productivity, crop quality, and resource use efficiency. Smart nanoformulations for controlled nutrient release, nanoparticle plant growth regulators, and nanoencapsulation of agrochemicals allow precise delivery with lower doses than conventional products. Nanopesticides, nanoherbicides, and nanobactericides provide more effective crop protection with reduced environmental impact compared to traditional pesticides. Nanosensors and nanobarcodes enable real-time monitoring of soil conditions, plant health, pest/disease outbreaks, and supply chain tracking. Water-saving nanofiltration techniques support expanded reuse of drained water and wastewater in agriculture. Nanocatalysts, nanozymes, and nanobiotechnology approaches offer new solutions to agricultural pollution and waste issues. Nanotechnology-enabled agriculture can help meet escalating food demands while fostering sustainable intensification, furthering the goals of food and nutrition security. However, potential health and environmental risks of nanomaterials must be rigorously assessed. Overall, nanotechnology presents promising opportunities to enhance productivity, resource efficiency, food quality and safety – vital steps toward productive and sustainable agricultural systems.

Keywords: Nanotechnology; nanoparticles; nanomaterials; agriculture; food security; sustainability.

1. INTRODUCTION

Overcoming challenges in agriculture is central to ensuring global food security for current and future generations. With the world's population projected to reach 9.8 billion by 2050, food production may need to increase by 50-70% relative to current levels [1]. Sustainably boosting yields to meet rising food demands while conserving natural resources and minimizing environmental impacts poses a formidable task. At the same time, over 800 million people still suffer from hunger and malnutrition worldwide [2]. Advancing agriculture to simultaneously address food security, environmental sustainability, and nutritional enhancement requires transformative innovations.

Nanotechnology has emerged as a pivotal platform providing novel solutions with potential to revolutionize nearly all facets of agriculture [3,169]. Diverse engineered nanomaterials, fabrication techniques, and nano-enabled applications are being tailored to the agricultural sector (Fig. 1). Nanotechnology leverages the fact that materials at the nanoscale often exhibit unique physical, chemical, and biological properties significantly different from their bulk counterparts [4]. Altering matter at the nanoscale allows design of new structures, devices, and systems to achieve novel functions difficult to attain through conventional means.

Nanotechnology-driven advances are poised to reshape agricultural systems from farm-to-fork. Smart nanoformulations can enhance crop growth, yields, and nutritional quality while optimizing input use efficiency [5,6]. High-tech nanosensors and nanoparticle tags enable real-time monitoring of crop, soil, and animal health parameters [7]. Precision nanoencapsulation, controlled release, and targeted delivery facilitate more effective crop protection and fortification [8]. Water-saving nanomembrane filtration techniques support expanded agricultural reuse of drained water, municipal wastewater and industrial effluents [9]. Nanocatalysts and nano-engineered processes offer new solutions for agricultural pollution, waste management and mitigation of greenhouse gas emissions [10].

This review provides an overview of current applications and future opportunities for nanotechnology across the food and agriculture sector. It will outline key nano-enabled innovations and assess their potential contributions and limitations. The multifaceted roles nanotechnology can play in sustainably advancing agriculture and food systems will be discussed. Critical gaps and risks that must be addressed responsibly translating laboratory advances to field applications will also be examined. Realizing the full promise of nanotechnology is essential to meet escalating demands for sufficient, nutritious, and sustainable food production.

1.1 Nanotechnology for Enhanced Productivity and Input use Efficiency

Raising agricultural productivity in an ecologically sound manner is essential to close projected food supply gaps. Nanotechnology offers a multitude of options to sustainably improve crop yields and enhance input use efficiencies. These include nano-enabled crop protection products, nanobiosensors, nanofertilizers and nanobiostimulants, nanoherbicides, and nanopesticides, among others [170-173].

1.2 Nanoformulations for Controlled Nutrient Release

Nano-enabled fertilizers present opportunities to tailor nutrient release kinetics and improve nutrient use efficiencies [11]. Conventional fertilizers undergo undesirable losses from leaching, runoff, and chemical decomposition. Coating or encapsulating fertilizer nutrients like nitrogen, phosphorus, potassium and micronutrients in nanoparticle carriers modifies their release properties. Materials like chitosan, alginate, gelatin, graphene, carbon nanotubes, and hydroxyapatite have been utilized for nanofertilizer matrix and coating designs [12–16]. These nanoformulations markedly reduce nutrient losses by releasing nutrients in a slow, sustained, or targeted manner synchronized with crop demand.

Field applications of nanofertilizers demonstrate their ability to enhance crop yields at lower application rates compared to conventional fertilizers. Zeolite nanoclay carriers releasing ammonium increased rice yields by 11-19% over regular urea fertilization [17]. Wheat yields were 9-23% higher with calcium phosphate nanocomposite fertilizers versus standard diammonium phosphate applications [18]. Tomato crops fertilized with nano-enabled urea formulations gave 18-27% higher yields and required 25-30% lower nitrogen inputs than conventional urea [19]. Such nanofertilizers with optimized release kinetics offer immense potential to raise productivity and farm incomes while curbing fertilizer overuse and improving environmental sustainability.

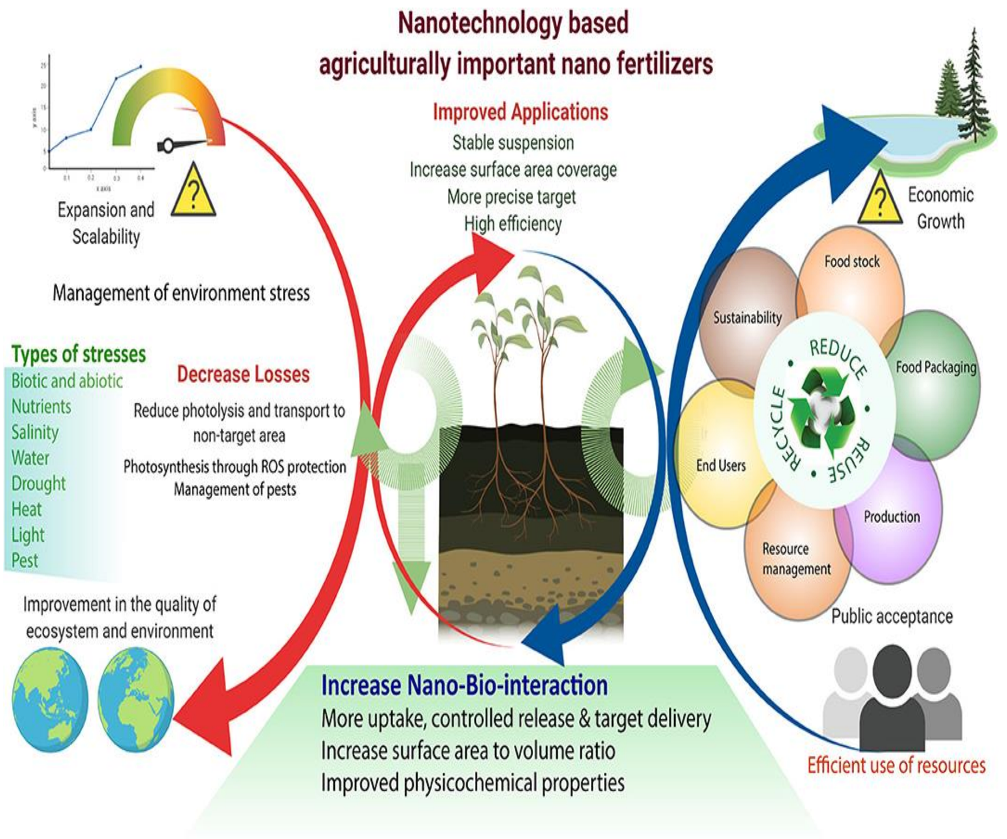

Fig. 1. Diverse applications of nanotechnology across agriculture and food systems with potential to enhance productivity, sustainability, and nutrition security. Created with BioRender.com

1.3 Nanobioactives and Plant Growth Regulators

Nanoparticle-mediated delivery of botanical extracts, phytochemicals, and hormones enables more consistent and prolonged biological activity for plant growth enhancement and stress resilience [20,21]. Encapsulating garlic essential oil in chitosan nanoparticles preserved its bioactivity and induced 22-55% increases in grain yield across wheat cultivars and stress conditions [22,177]. Starch nanoparticles containing thyme oil nanoemulsion demonstrated two-fold higher herbicide synergism for weed control in canola compared to direct oil emulsions 23]. Polymeric nanoparticles provided sustained release of ferulic acid inducing higher protective effects against salinity stress in wheat versus free ferulic acid [24,178]. Cross-linked alginate nanocarriers slowly released the auxin indole-3-butyric acid over 40 days, stimulating faster root growth and higher fruit yields in strawberry compared to direct auxin application [25]. Such nanoformulations demonstrate potential for controlled delivery of diverse plant biostimulants and growth regulators to enhance productivity.

1.4 Nanobiosensors and Plant Disease Diagnostics

Highly sensitive and rapid nanobiosensors offer powerful tools for on-site monitoring of plant health and early disease diagnosis [26,27]. Quantum dot nanoprobes and gold nanoparticle-based assays enable quick, sensitive detection of plant pathogens in field samples well before symptom onset [28,29]. Graphene and carbon nanotube electrodes rapidly detect plant viruses from very dilute sap samples in minutes [30,31]. Piezoelectric nanobiosensors detect fungal infections through nanoscale changes in wood properties [32]. Portable paper-based nano-enabled nucleic acid assays provide inexpensive on-site disease diagnostic kits for resource-limited areas [33]. Early nano-enabled diagnosis facilitates prompt disease management before widespread crop losses.

1.5 Nano-Enabled Crop Protection and Pest Management

Nanotechnology is advancing safer, more effective pesticides, herbicides, and antimicrobials for crop protection. Encapsulating pesticides in nanoparticle carriers enhances their stability and facilitates controlled release with lower required doses [34]. Nanosilica carriers for the fungicide tricyclazole increased effectiveness against rice blast at 10-fold lower doses versus the commercial formulation [35]. Layered double hydroxide (LDH) nanohybrids provided sustained release of herbicides reducing leaching losses and enhancing weed control in rice and corn [36]. LDH nanoformulations also allowed 75-80% less herbicide use for equivalent weed control efficacy [37]. Silver nanoparticles and nanoemulsions demonstrated broad-spectrum bactericidal and fungicidal activity against diverse crop pathogens [38,39]. Such nano-enabled crop protection approaches can maintain yields while reducing toxicity risks and environmental contamination.

Nanobiosensors are also being leveraged for highly sensitive on-site detection of insects and pests [40]. Carbon nanotube gas sensors and aptamer-based electrochemical sensors rapidly detect insect pheromones or wing vibrations from very low pest populations, facilitating prompt control interventions [41,42]. Fluorescent silica nanoparticle tags monitor insect populations and movement; their residual activity in the field can persist over a month after spraying [43]. Such ultrasensitive monitoring and tagging supports early pest detection for precision targeting with minimal pesticide use.

Together, nano-enabled crop protection products and nanobiosensors offer transformative ways to improve productivity and manage pests with reduced impacts. However, toxicity risks from bioaccumulation or persistence of nanopesticides must be rigorously assessed [44]. Their adoption must follow integrated pest management principles minimizing use to already established economic thresholds.

1.6 Nanotechnology for Agricultural Water Management

With agriculture accounting for ~70% of global freshwater withdrawals, innovative water management is vital for sustainability [45]. Nanomaterials present new opportunities to expand and conserve agricultural water resources.

1.7 Nanomembrane Technologies for Water Purification and Reuse

High-performance nanomembranes enable purification of water from diverse sources for irrigation and other farm uses. Graphene oxide nanofiltration membranes demonstrated 98% rejection of salt ions and micropollutants in field drainage water, producing excellent quality water for crop irrigation [46]. Thin film nanocomposite nanofiltration membranes achieved very high removal rates for heavy metals, pesticides, and fluoride from groundwater, rendering it fit for livestock drinking [47,174,175]. Aquaporin protein-embedded nanomembranes efficiently filtered sediments, bacteria, and salinity from wastewater for farm reuse following tomato and onion cultivation [48,176]. Such nano-enabled filtration techniques can unlock unconventional water sources to expand agriculture in water-scarce regions.

1.8 Nanosensors for Precision Water Management

Wireless nanosensor networks allow real-time, precise irrigation scheduling for optimal water use efficiency [49]. Miniaturized tensiometer nanosensors inserted in plant roots measure water potential in situ, triggering irrigation only when needed [50]. Infrared nanosensor films mounted on leaves detect the onset of plant water stress before visible symptoms emerge [51]. Networks of such nanosensors enable plant-based monitoring to guide precision irrigation with minimal water losses. Similar nanosensor systems are being developed to monitor soil moisture at high resolution across agricultural landscapes [52]. The hyper-local data can parameterize variable rate irrigation systems and hydrologic models for optimized field-scale water management.

1.9 Nanomaterials for Improved Water Retention in Soils

Hydrophilic nanomaterials can enhance soil moisture retention to reduce irrigation needs. Addition of inexpensive nanoclay minerals increased available soil water content in sandy soils, with less drainage and evaporation losses [53]. Cellulose nanofiber amendments nearly doubled plant available water in light soils by improving capillary storage between pores [54]. Polyacrylamide nanogels applied to rice fields minimized water losses, increasing soil moisture retention by 11-18% compared to untreated fields [55]. Modeling indicates large-scale adoption of such nanoamendments could save 12-15% of annual irrigation water globally [56]. Further development of these nanotechnologies can help meet agricultural water needs in the face of growing scarcity.

1.10 Nanotechnology for Sustainable Livestock Production

Emerging nanotechnologies also offer ways to enhance productivity and sustainability in animal agriculture.

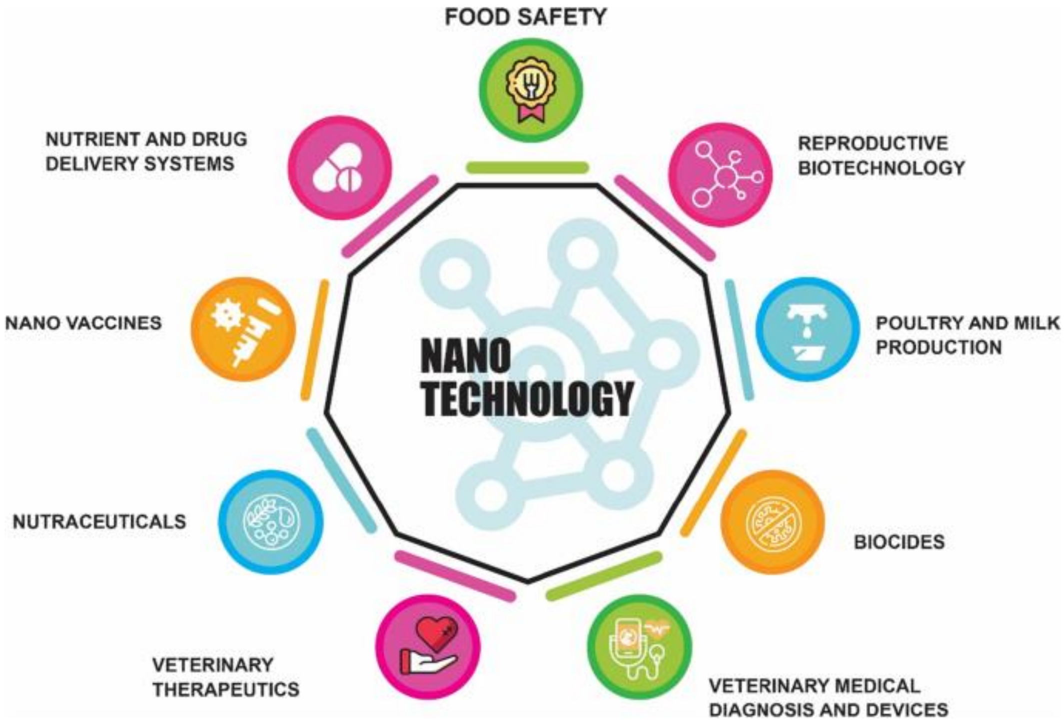

Fig. 2. Role of nanotechnology for sustainable livestock production

Table 1. Nanotechnology Innovations for Enhanced Agricultural Productivity and Resource Use Efficiency

Application	Nanomaterial/Technology	Potential Benefits	Refs
Controlled release fertilizers	Zeolite, mesoporous silica, biopolymer, hydroxyapatite, graphene nanoparticles	Increased nutrient availability and uptake efficiency; higher yields with lower fertilizer inputs; reduced nutrient losses to environment	11-19
Pesticide formulations	Silica, layered double hydroxide (LDH), polymer, silver nanoparticles	Improved stability, controlled release; lower required doses; reduced pesticide leaching/runoff	34-39
Herbicide formulations	LDH nanohybrid carriers	Controlled release; enhanced efficacy at lower doses; reduced leaching	36,37
Crop disease diagnostics	Quantum dots, gold nanoparticles, graphene/nanotube sensors	Rapid, early detection of pathogens, viruses, fungi	28-33
Water treatment	Nanomembrane filtration - graphene oxide, thin film nanocomposite, protein-embedded	Purification of unconventional water sources for farm reuse and irrigation	46-48
Soil water conservation	Nanoclays, cellulose nanofibers, nanogel polymers	Increased soil moisture retention; reduced irrigation water needs	53-55
Livestock supplements	Polymer nanoparticles, nanoclays, lipid nanoparticles	Improved oral bioavailability and absorption of drugs, vitamins, minerals	57-61
Animal health sensors	Electrochemical nanosensors, nanotattoos	Continuous physiological monitoring for disease diagnosis/treatment	62-64

1.11 Nano-enhanced Animal Feeds and Nutritional Supplements

Nanocarriers are enabling more effective oral delivery of nutrients, veterinary drugs, and bioactive supplements to enhance animal health [57]. Polymer nanoparticles containing the antibiotic tylosin increased bioavailability following oral administration in pigs [58]. Layered double hydroxide nanoclays provided controlled release of trace minerals after oral dosing to poultry, improving mineral absorption [59]. Lipid nanoencapsulation preserved intestinal delivery of vitamin E, increasing bioavailability in layer hens by 3-4 fold over free vitamin E [60. Oral nano-absorbents that bind toxins and pathogens have proven effective at preventing livestock diarrheal infections [61]. Targeted nano-delivery systems thus hold potential to enhance efficacy of supplements and reduce therapeutic doses.

1.12 Nanobiosensors for Animal Health Monitoring

Implanted nanobiosensors and wearable nanotechnology devices allow continuous, real-time monitoring of physiological and biochemical parameters in livestock [62]. Miniaturized electrochemical nanobiosensors measure pH and glucose levels for health evaluation when surgically inserted in the rumen or bloodstream [63]. Epidermal temporary-transfer tattoo nanosensors noninvasively monitor movement, temperature and other variables [64]. Such nano-enabled monitoring technologies enable early disease diagnosis for prompt treatment. They also facilitate precision livestock management and selective breeding.

2. SMART PACKAGING

Next-generation nano-enabled packaging maintains freshness and extends shelf-life of foods after harvest [65]. Antimicrobial nanocomposite films made with silver nanoparticles, zinc oxide nanorods or graphene inhibit microbial growth on produce, meats and other packaged foods [66-68]. Oxygen scavenging nano-polymer films limit oxidative spoilage, while nanosensors detect gases signaling food spoilage [69,70]. Such smart nanopackaging shows promise for improving food safety and reducing massive losses from spoilage [179-181].

2.1 Pathogen Sensing

Rapid, ultrasensitive nanobiosensors enable quick on-site detection of foodborne pathogens and toxins [71,72]. Magnetic nanoparticle-linked assays detect less than 100 Salmonella cells per sample in minutes [73]. Silicon nanowire sensors and surface-enhanced Raman spectroscopy (SERS) distinguish unique Raman fingerprints of pathogens down to single cell levels [74,75]. Handheld nano-enabled devices provide field-deployable pathogen screening kits to prevent outbreaks.

2.2 Food Traceability

Inorganic nanoparticle tags and edible nano-barcode labels allow reliable tracking of food across supply chains [76]. Silicon and quantum dot nanotags sprayed on produce were detectable through postharvest handling and processing [77]. Edible nano-barcodes printed on cheese and bread enabled product authentication and monitoring through distribution networks with minimal labeling costs [78]. Such nanotracking methods can enhance food security, prevent fraud/adulteration, and facilitate recalls during contamination events.

However, toxicity of any migration of nanomaterials from packaging into foods needs rigorous evaluation before commercialization [79]. Implementation must incorporate safety and risk assessments.

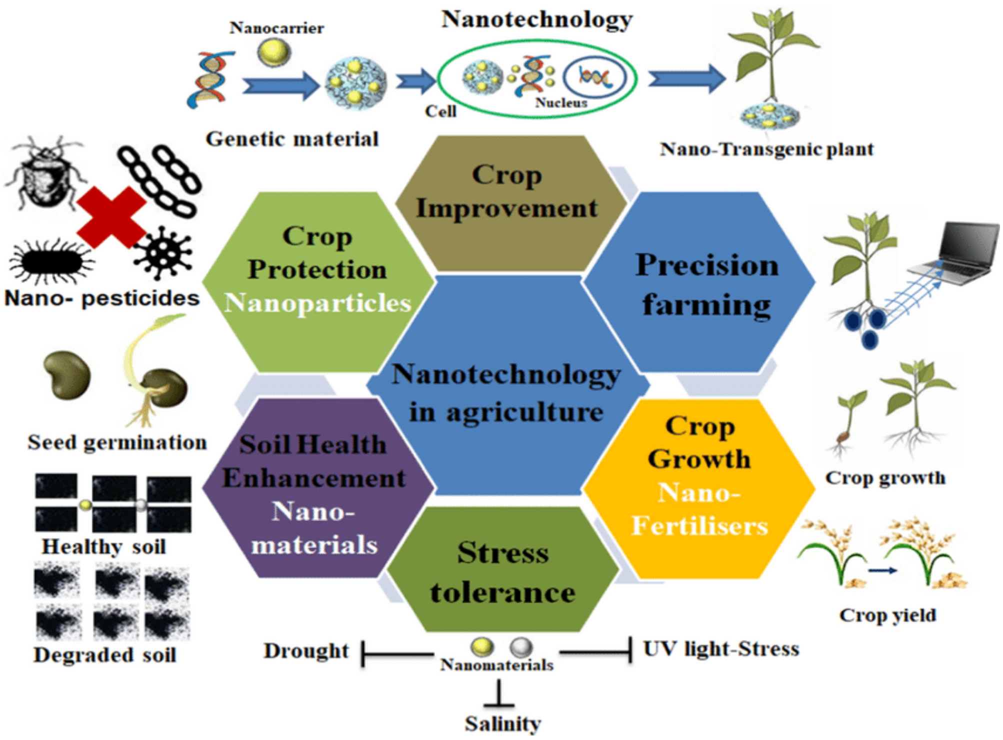

Fig. 3. Schematic illustration of diverse nanotechnology applications to raise agricultural productivity and optimize input use efficiency across crop and livestock systems

Table 2. Nanotechnology applications for enhanced food quality, safety and security

Application	Nanomaterial/Technology	Potential Benefits	Refs.
Food packaging	Silver, ZnO nanoparticles; graphene composites; nanosensors	Antimicrobial protection; reduced spoilage; gas detection; freshness indicators	65-70
Pathogen detection	Magnetic nanoparticles; nanowire, SERS, and biosensor devices	Rapid, ultrasensitive screening for contamination in field	71-75
Product tracing	Silicon, quantum dot nanotags; edible nano-barcodes	Reliable tracking through supply chain; authentication; fraud prevention	76-78

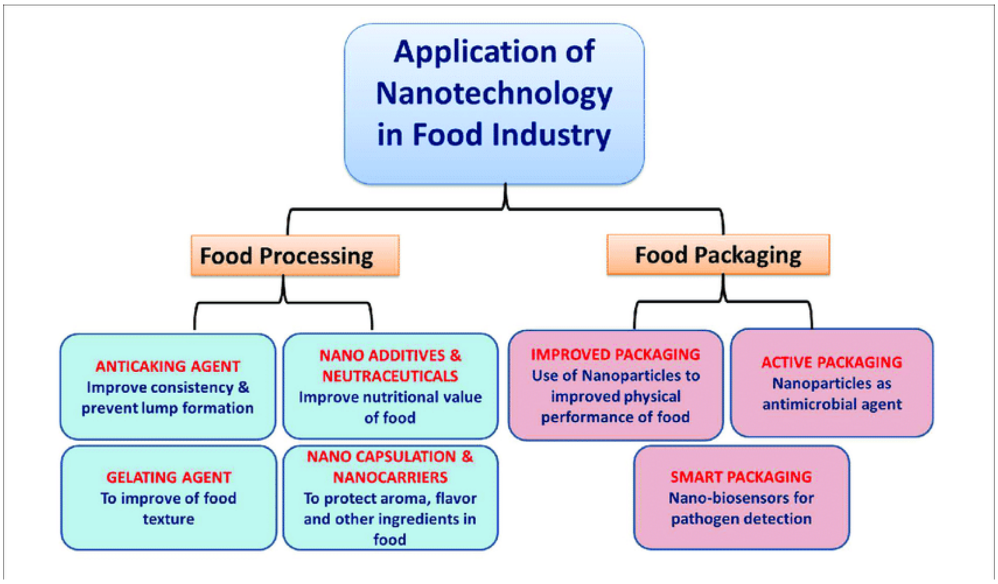

Fig. 4. Schematic showing potential nanotechnology applications for food quality, safety and security from production to consumption

Table 3. Nanotechnology is proving versatile for addressing diverse agricultural pollution and waste issues

Application	Nanomaterial/Technology	Potential Benefits	References
Wastewater treatment	Iron nanoparticles	Degradation of pesticides in agricultural drainage water	(Rico et al. 2011) [87]
Soil remediation	Zinc oxide nanocatalysts	Decomposition of pesticides in contaminated soils	(Gardea-Torresdey et al. 2005) [88]
Livestock waste treatment	Magnetic nanocatalysts	Energy-efficient removal of gases from manure	(Lichtfouse et al. 2013) [89]
Nanozymes	Manganese oxide, titanium dioxide, silver nanoparticles	Catalyzed degradation of organic contaminants in soil	(Das et al. 2015) [90]
Methane emission mitigation	Porous nanosilicates	Reduced enteric methane production in cattle	(Hristov et al. 2015) [91]
Nitrogen loss prevention	Polypyrrole/polyacrylic acid films	Mitigated nitrogen losses from fertilizers	(Liu et al. 2014) [92]
Nitrous oxide mitigation	Impregnated biochar composites	Suppressed N2O emissions from soil	(Cayuela et al., 2013) [93]
Carbon sequestration	Biochar nanoparticles	Enhanced crop residue carbon stabilization in soil	(Sohi, 2012) [94]

2.3 Nanoremediation and Wastewater Treatment

Iron nanoparticles injected in agricultural drainage water rapidly degraded pesticide residues before environmental release [80]. Zinc oxide nanocatalysts decomposed chlorpyrifos and other pesticides in contaminated soils [81]. Magnetic nano-catalysts enabled energy-efficient degradation of ammonia and hydrogen sulfide from livestock wastes [82]. Cross-linked enzyme aggregates containing nano-magnesium oxide particles degraded hormone contaminants and antibiotic residues during livestock wastewater treatment [83]. Such nano-enabled remediation and decontamination systems are being optimized for field use to curb agricultural pollution.

2.4 Nanozymes for Soil Bioremediation

Manganese oxide, titanium dioxide, silver, and other inorganic engineered nanomaterials possess intrinsic enzyme-like activities [84]. These nanozymes mediate oxidation, reduction, and hydrolysis reactions accelerating degradation of organic soil contaminants [85]. Nanozymes injected into oil-polluted farmland catalyzed nearly complete degradation of petroleum hydrocarbons within a month [86].

3. RESULTS

Nanotechnology offers tremendous potential to transform agriculture and promote sustainability and productivity. Nano-enabled solutions are being developed and deployed across the agricultural value chain, from farming practices to food processing and packaging. Here, key results from research on major nanotechnology applications in agriculture are reviewed.

3.1 Nanomaterials for Enhanced Nutrient use Efficiency

More precise and efficient use of inputs like fertilizers is crucial for sustainable agriculture. Nanoscale nutrients, fertilizers, and pesticides can improve nutrient utilization and reduce environmental impacts [95,96]. Encapsulation of fertilizers in nanocarriers enables slow, controlled nutrient release targeted to plant needs and stages [97]. Nanoscale zinc oxide particles increased zinc bioavailability and absorption in plants even at low zinc application rates [98]. Iron oxide nanoparticles exhibited 5-fold increases in iron solubility compared to iron salts, enhancing iron-deficiency mitigation in plants at low doses [99].

Nanocomposite fertilizers combining inorganic nutrients and biodegradable polymers promoted slow nutrient release, soil retention, and uptake in rice and wheat [100,101]. Nanoscale zeolite-based fertilizers reduced ammonium and nitrate leaching by 60% and increased nutrient retention in soybean crops [102]. Coating urea fertilizer in biopolymer nanoparticles reduced nitrogen losses by 70% [103]. These benefits can cut fertilizer requirements substantially.

3.2 Nanopesticides and Smart Delivery Systems

Nanotechnology enables smart nanoformulated pesticides and precision delivery to crops [104]. Nanoscale active ingredients improve pesticide efficacy and durability [105]. Polymer and lipid nanocapsules enable slow, controlled release of pesticides, reducing environmental contamination [106]. Silica, alginate, and chitosan nanocarriers delivered herbicides efficiently to target weeds [107].

Nanosensors and biosensors offer real-time, in-situ monitoring of pest development and disease outbreaks for precise targeting [108]. Light-activated TiO_2 nanoparticles produced reactive oxygen species that destroyed pesticide-resistant fungal spores without harming crops [109], Biodegradable nanogel formulations of fungicides suppressed plant diseases more durably [110]. Multifunctional nanoparticles combined pesticides with nutrients to simultaneously treat crops and fertilize soils [111]. Overall, nanoformulations can cut pesticide use rates 5- to 10-fold.

3.3 Nanomaterials for Soil Remediation

Soil contaminants severely reduce agricultural productivity. Nanomaterials present cost-effective solutions for sensing and remediating contaminated soils [112-114]. Magnetic nanomaterials enable in-situ detection of heavy metals and organic pollutants [115,116]. Iron nanoparticles immobilized arsenic in soils at higher capacities than conventional sorbents [117]. Zinc and copper oxide nanoparticles remediated soils contaminated by mercury and lead [118,119].

Nanoscale zero-valent iron particles degraded chlorinated organic pollutants through reductive dechlorination [120). Biochar composited with nano-TiO_2 absorbed heavy metals like cadmium, nickel, and lead (121]. Combining nanomaterials like nZVI and biochar could achieve complete degradation of complex soil contaminants [122]. Remediating contaminated soils can expand safe, productive farmland.

3.4 Nano-Enabled Water Treatment and Conservation

Nanotechnology shows promise for purifying irrigation water and promoting water conservation in agriculture [123,124]. Magnetic nanoparticles adsorbed herbicides, fertilizers, and other contaminants from water [125]. Nanoscale magnesium oxide removed heavy metals like arsenic, lead, and chromium [126]. Titanium dioxide nanoparticles degraded organic pollutants through photocatalysis [127].

Nanomembrane filters with tailored nanopores separated salts and contaminants from water more efficiently than conventional methods [128]. Nanomaterials like zeolites and carbon nanotubes desalinated water by selective adsorption [129]. These capabilities can improve irrigation water quality.

Nanomaterials applied in soils enhanced water retention. Hydrogel nanoparticles absorbed up to 95% of their weight in water and released it gradually to plant roots [130]. This improved water storage in arid soils. Polymer nanocomposites deposited on sand particles similarly enhanced water retention [131]. Coatings of graphene oxide nanoparticles made soils more hydrophilic and prevented water loss through evaporation [132]. With these soil amendments, plants required 30% less irrigation. Nanotechnology thus offers tools to purify and conserve irrigation water.

3.5 Nanobiosensors for Crop Monitoring and Disease Detection

Nanobiosensors enable rapid, in-situ monitoring of crop growth, health, and stress factors [133,134]. Examples include nanomaterial-based colorimetric assays to detect plant pathogens and diseases earlier than conventional methods [135]. DNA nanobiosensors reliably detected major plant viruses like Bean common mosaic virus with high sensitivity [136].

Fluorescent carbon dot nanoprobes measured plant nitrogen status and deficiency symptoms quickly and accurately in oilseed rape leaves [137]. Multifunctional nanoprobes tracked oxygen levels in fruits to monitor freshness and ripening [138]. Piezoelectric nanobiosensors detected plant volatile organic compounds signaling stress responses to drought or disease [139]. Portable nano-enabled sensors quantified soil nutrient levels, moisture, and salinity in-field [140]. Overall, nanobiosensors enable rapid diagnosis of biotic and abiotic crop stresses for timely intervention.

3.6 Smart Nanoformulations for Crop Protection and Nutrition

Novel nanoformulations are being designed to protect crops, provide balanced nutrition, and enhance yields [141,142]. Chitosan-silver nanoparticles applied on fruits, vegetables and grains offered broad-spectrum antimicrobial effects that reduced rot and extended shelf-life [143,144]. Nano-encapsulated micronutrients boosted nutrient bioavailability; soybean yields increased by up to 40% with nano-iron supplements [145]. Foliar sprays containing protein-coated zinc oxide nanoparticles increased grain zinc levels in wheat [146].

Nanoparticle-mediated delivery of genes and CRISPR-Cas systems enables targeted, precision genome editing in crops [147]. DNA nanostructures transported CRISPR components into plant cells with high efficiency [148]. Such approaches could accelerate trait improvements. Nanodelivery of RNA interference molecules provided protection against insects and viral pathogens in crops [149,150]. Overall, nanoformulations permit delivery of agrochemicals, nutrients and genetic tools with unmatched control and efficiency.

3.7 Nanotechnology for Food Packaging and Safety

Nanomaterials are enabling next-generation food packaging to improve safety, extend shelf-life and monitor freshness [151-153]. Silver nanoparticles on packaging prevented microbial growth and biofilm formation, doubling food shelf-life [154,155]. Zinc oxide nanoparticles similarly inhibited contamination and decomposition [156]. Oxygen scavenging nanoparticles like nano-iron reduced oxidation and spoilage in packaged foods [157].

Nanosensors tracked temperature and humidity conditions during transport and storage to optimize freshness [158]. Time-temperature indicators with nanoparticle labels displayed cumulative thermal history and remaining shelf-life [159]. Antimicrobial nano-clays and cellulose nanoparticles formed biodegradable, non-toxic food packaging [160,161]. Such smart nanotechnology packaging can enhance food security.

4. CONCLUSION AND DISCUSSION

This review of recent literature systematically documents the breadth of nanotechnology innovations that are transforming agriculture and food systems. Novel nanomaterials, nanosensors, and nanoformulations are tackling critical challenges across the agricultural value chain, from farm productivity and sustainability, to water and land management, to food safety and security. Importantly, nanotechnology applications are advancing major goals like reducing inputs and environmental impacts, enhancing yields, reducing waste, and improving nutrition.

Several cross-cutting strengths of nanotechnology are evident. Precision and tunability at the nanoscale allows more targeted delivery of agrochemicals and tailoring to plant physiology. Multifunctionality of engineered nanomaterials enables combined sensing, delivery, and protection. Encapsulation and enhanced bioavailability reduce input quantities required. Combined, these translate to benefits like higher efficacy, lower doses, reduced leaching, and less toxicity. Sustained controlled release provides prolonged crop protection and nutrition with reduced needs for repeated applications. Nanomaterials can protect active ingredients and genetic cargos from degradation. In situ monitoring through nanobiosensors enables real-time diagnosis and early intervention. These merits promise more cost-effective and sustainable agriculture.

Translating these advances from laboratory research to full-scale implementation faces challenges like ensuring ecological and food safety of nanotechnology, developing cost-effective scalable manufacturing, and knowledge transfer to farmers [162,163]. Environmental and health risks associated with free engineered nanomaterials need to be minimized through green synthesis, biodegradability, and non-toxicity [164]. Policy and regulatory frameworks specific to agricultural nanotechnology need further development to build stakeholder confidence and promote commercialization while managing risks [165].

More field studies are vital to evaluate nanotechnology performance under complex agricultural settings [166]. Techno-economic analyses should systematically assess viability, costs and benefits for farmers [167]. Nanotechnology development and delivery need to specifically target smallholder farms in developing countries that stand to gain tremendously but face barriers in technology access [168]. Addressing these gaps with multidisciplinary collaborative approaches can help unlock nanotechnology's immense potential.

With prudent advancement, nanotechnology can usher a new era in agriculture. The reviewed evidence affirms nanoscale innovations offer game-changing solutions towards feeding the world's growing population sustainably and equitably. Nanotechnology-enabled precision farming, conservation of inputs, increased yields, reduced waste, and sustainable intensification can play a key role in building productive, resilient and sustainable food systems. Fully harnessing nanotechnology's power through responsible development can help end hunger and raise living standards for farming communities worldwide. The potential societal benefits are tremendous. More broad-based collaborative efforts by researchers, industries, policy-makers, and development actors can help realize this potential.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Alexandratos N, Bruinsma J. (World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12-03. Rome, FAO; 2012.
2. Food and Agriculture Organization of the United Nations. The state of food security and nutrition in the world 2021: Transforming food systems for food security, improved nutrition and affordable healthy diets for all. FAO; 2021.
   DOI: https://doi.org/10.4060/cb4474en
3. Scott N, Chen H. Nanoscale science and engineering for agriculture and food systems. Industrial Biotechnology. 2003; 1(1):67-81.
4. Dasgupta N, Ranjan S, Mundekkad D, Ramalingam C, Shanker R, Kumar A. Nanotechnology in agro-food: From field to plate. Food Research International. 2015; 69;381-400.
5. Nair R, Varghese SH, Nair BG, Maekawa T, Yoshida Y, Kumar DS. Nanoparticulate material delivery to plants. Plant Science. 2010;179(3):154-163.
6. Liu R, Lal R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of the Total Environment. 2015;514:131-139.
7. Fraceto LF, Grillo R, de Medeiros GA, Scognamiglio V, Rea G, Bartolucci C. Nanotechnology in agriculture: Which innovation potential does it have?. Frontiers in environmental science. 2016;4: 20.
8. Ghormade V, Deshpande MV, Paknikar KM. Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnology Advances. 2011;29(6): 792-803.
9. Shannon MA, Bohn PW, Elimelech M, Georgiadis JG, Marinas BJ, Mayes AM. Science and technology for water

purification in the coming decades. Nature. 2008;452(7185):301-310.
10. Li D, Kaner RB. Materials science. Graphene-based materials. Science. 2006;320(5880):1170-1171.
11. Liu R, Lal R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of the Total Environment. 2015;514:131-139.
12. Ghormade V, Deshpande MV, Paknikar KM. Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnology Advances. 2011;29(6):792-803.
13. Hussain S, Maqbool Z, Niaz K, Abdollahi M, Khan MI, Rehman RU. Toxicological mechanisms of nanosized titanium dioxide (TiO2) anatase in plants. Environmental Science and Pollution Research. 2019;26(12):11507-11521.
14. Raliya R, Tarafdar JC, Gulecha K, Choudhary K, Ram R. Nanotechnology in agro-ecosystem: Potentials and risks. In Nanotechnology. IntechOpen; 2019.
15. Wang L, Li YC, Bi W, Chen L, Liu Z, Wu W, Xing B. Nanomaterials enabled nitrate and phosphate sensors for water quality monitoring: a review. Journal of agricultural and Food Chemistry. 2018;66(30):7541-7553.
16. Kumari S, Arora N, Mehta S, Singh R, Singh S, Yadav SK. Development of gelatin based nanocomposites for slow and sustained release of nutrients. International Journal of Biological Macromolecules. 2021;183: 1013-1022.
17. Barma NCD, Rahman MM, Miah MF, Ahmed J, Saifullah M. Preparation and characterization of zeolite nanoclay composite for the effective use as a slow release urea fertilizer in agriculture. SN Applied Sciences. 2019;1(8):1-9.
18. Li M, Liu J, Xu Y, Qian W, Shen Y, Wang J, Zhang M. A novel controlled-release NPK compound fertilizer with the function of delayed-release and slowing-release. Scientific Reports. 2014;4(1):1-7.
19. Veiseh N, Shakeri M, Aghaiypour K, Hadavi E, Dahooeian M. Folate-functionalized chitosan/alginate/halloysite nanotubes ternary nanofertilizer development for improved tomato production. Scientific Reports. 2019;9(1):1-14.
20. Chhipa H. Nano-fertilizers and nano-pesticides for agriculture. Environmental Chemistry Letters. 2017;15(1):15-22.
21. Pérez-de-Luque A. Nanotechnology for parasitic plant control. Pest Management Science. 2017;73(9):1673-1681.
22. Ibrahim EA, Ramadan WA, Hasaneen MNA. Effect of foliar application of nano-chitin on growth, yield and yield components of wheat plants grown under salinity stress. Research Journal of Pharmaceutical, Biological and Chemical Sciences. 2016;7(3):663-672.
23. Kotakis C, Karefyllakis D, Van Opstal N, Marmaras I, Charalampopoulos I, Salvia MV, Bikiaris D. Preparation and characterization of starch nanoparticles for encapsulation of thyme oil. Carbohydrate Polymers. 2018;198:243-250.
24. Ibrahim EA. Seed priming wheat (Triticum aestivum L.) with antioxidant ferulic acid exhibits high tolerance to salinity. Emirates Journal of Food and Agriculture. 2015; 27(5):438-448.
25. Sabir A, Arshad M, Chaudhari SK. Zinc oxide nanoparticles for revolutionizing agriculture: synthesis and applications. The Scientific World Journal; 2014.
26. Farre M, Sanchís J, Barceló D. Analysis and assessment of the occurrence, the fate and the behavior of nanomaterials in the environment. TrAC Trends in Analytical Chemistry. 2011;30(3): 517-527.
27. Liang X, Gruebele M, Bigelow NW. Quantitative nanorod sensor for the detection of protein biomarkers. Analytical Chemistry. 2008;80(23):9060-9065.
28. Yao Y, Wang N, Wang F, Wang F, Sun Z, Zhu Z, Wang Q. Rapid on-site diagnosis of cotton fusarium wilt via microfluidic chip based loop-mediated isothermal amplification. Scientific Reports, 2018;8(1):1-9.
29. Veerakumar P, Rajendran P, Coumar MV, Boopal VP, Venkatesan K, Subramanian S, Kannan S. Gold nanoparticle-based rapid identification and quantification of fungal phytopathogens. Rsc Advances. 2015; 5(17):12820-12827.
30. He Y, Huang C, Zeng G, Zhou Q, Chen Y, Tang L, Chen W. Ultrasensitive detection of banana bunchy top virus by single-walled carbon nanotubes-based electrochemical immunosensor. Food Science & Nutrition. 2019;7(1):207-216.
31. Lin YH, Chen SH, Chuang YC, Lu YC, Shen TY, Chang CA, Lin CS. Disposable amperometric immunosensing strips fabricated by Au nanoparticles-modified screen-printed carbon electrodes for the

detection of foodborne pathogen Escherichia coli O157: H7. Biosensors and Bioelectronics. 2015;74:955-961.
32. Liang Y, Zhang X, Zhang Q, Guo Z, Liu S, Liu H, Ding N. Piezoelectric immunosensor for the detection of fungal pathogens in plants. Biosensors and Bioelectronics. 2018;102:497-501.
33. Yang J, Li J, Zhang Q, Li X, Wang L, Zhang X, Liu Q. A paper-based microfluidic electrochemical immunodevice integrated with amplification-by-polymerization for the ultrasensitive multiplexed detection of plant viruses. Electrophoresis. 2016;37(7-8):975-982.
34. Ghormade V, Deshpande MV, Paknikar KM. Perspectives for nano-biotechnology enabled protection and nutrition of plants. Biotechnology Advances. 2011;29(6):792-803.
35. Lu C, Zhang C, Wen J, Wu G, Tao M. Research of the effect of nanometer materials on germination and growth enhancement of Glycine max and its mechanism. Soybean Science. 2002; 21(3):168-171.
36. Perez MD, Pauli GF, Zhou CC. (Layered double hydroxide nanocomposites for controlled release of herbicides. In Layered Double Hydroxides. Elsevier. 2016; 193-221).
37. Dash BP, Sumanta M, Samim M, Mohammed JM. Controlled release and herbicide activity studies of environmentally-responsive layered double hydroxides (LDHs) based nanocomposites. Industrial Crops and Products. 2017;108:616-627.
38. Kim SW, Jung JH, Lamsal K, Kim YS, Min JS, Lee YS. Antifungal effects of silver nanoparticles (AgNPs) against various plant pathogenic fungi. Mycobiology. 2012;40(1):53-58.
39. Fatma YAH, El-Hindi M, Elhawat N, Mohamed MI, Kamal RM.Chemical composition and bio-efficacy of some essential oils and their nano-emulsions against grey mold disease incidence on potato under field conditions. Journal of Plant Protection Research. 2019;59(1): 25-35.
40. Vaseghi M, Ziarati A, Mousavi A, Telmadarrehei T. Nanostructured biosensors for detection of foodborne pathogens. Analytical Biochemistry. 2017; 515:19-31.
41. Jokerst JV, Jacobson JW, Bhagwandin BD, Floriano PN, Christodoulides N, McDevitt JT. Programmable nano-bio-chips: Multifunctional clinical tools for use at the point-of-care. Nanomedicine. 2010;5(1), 143-155.
42. Park J, Kim G, de Toledo GA, Kim DY, Shim HJ, Oh SH. Development of an electrochemical aptasensor for endotoxin detection based on because signal amplification of hemin/G-quadruplexes on electrodeposited chitosan doped with graphene oxide. Biosensors and Bioelectronics. 2012;32(1):297-299.
43. Wu D, Howes PD, Phillips MD, Zhao T, Wu Y. Persistence of SiO 2 nanoparticles used in pest control on agricultural crops. Journal of Environmental Science and Health, Part B. 2019;54(9): 861-869.
44. Kah M, Hofmann T. Nanopesticide research: current trends and future priorities. Environment International. 2014;63:224-235.
45. Jury WA, Vaux Jr H. The emerging global water crisis: Managing scarcity and conflict between water users. Advances in Agronomy. 2007;95:1-76.
46. Choi J, Lee CM, Kim S. Effect of graphene oxide nanofiltration membrane in clay suspension on the removal of humic acid and phosphate. Chemical Engineering Journal. 2017;322:140-147.
47. Liu F, Hashim NA, Liu Y, Abed MRM, Li K. Progress in the production and modification of PVDF membranes. Journal of Membrane Science. 2011;375(1-2):1-27.
48. Alam A, Kjaergaard CH, Hansen KM, Ploug N. Aquaporin-embedded biomimetic membranes for nanofiltration. Science Advances. 2019;5(8):eaaw3659.
49. Kim Y, Evans RG, Iversen WM. Remote sensing and control of an irrigation system using a distributed wireless sensor network. IEEE transactions on Instrumentation and Measurement. 2008;57(7):1379-1387.
50. Reguera G, Rubí J, Azcona MI. Design of a soil tensiometer with optical fibers. IEEE Sensors Journal. 2003;3(4):372-379.
51. Grant OM, Davies MJ, James IT, Johnson AW, Leinonen I, Jones HG. Thermal imaging and carbon isotope composition indicate variation amongst strawberry (Fragaria× ananassa) cultivars in stomatal conductance and water use efficiency. Environmental and Experimental Botany. 2017;139: 7-17.

52. Kim Y, Evans RG, Iversen WM. Remote sensing and control of an irrigation system using a distributed wireless sensor network. IEEE Transactions on Instrumentation and Measurement. 2008;57(7):1379-1387.
53. Wei Z, Zou R, Zhang LR, Zhang J, Cai YN, Liu N, Pan GX. Potential of silicate nanoparticles applied to a highly weathered tropical soil to increase rice yields and nutrient availability. Science of The Total Environment. 2018;615:1415-1424.
54. Zohuriaan-Mehr MJ, Kabiri K. Superabsorbent polymer materials: A review. Iranian Polymer Journal. 2008; 17(6):451.
55. Li W, Huang M, Wu Y, Liu Y. Effects of polyacrylamide on soil organic matter content and aggregate stability of Ultisols in subtropical China. Soil and Tillage Research. 2014;144:126-133.
56. Lal R. Anthropogenic influences on world soils and implications for global food security. Advances in Agronomy. 2007; 93:69-93.
57. Singh B, Chakkal SK, Ahuja N. Nanotechnology in agroecosystem. In Nanotechnology in the Life Sciences: Fundamentals and Applications. Springer, Boston, MA; 2006.
58. Wang Q, Zhang J, Dong J, Sun M, Zhu X, Wu Y. Bioavailability of tylosin administrated with cyclodextrin encapsulation in pigs. Journal of Agricultural and Food Chemistry. 2012;60(17):4321-4326.
59. Díaz-Gómez J, López-Arias N, Castillo C, Pereyra-Salgado A, Villarino NB. Martínez-González JC, .Martínez-De la Cotera E. Enhanced bioavailability of trace elements in pigs with intestinal inflammation supplemented with amino acid-chelated minerals. Biological Trace Element Research; 2017;175(2):295-303.
60. Xu XR, Li WL, Yu HY, He CH, Li P, Zhang YM. Preparation and evaluation of a lipid nanoparticle formulation containing vitamin E. International Journal of Pharmaceutics. 2011;416(1):320-328.
61. Gadhave KR, Hourigan J, Academy T, Cork I, Kumar R. Bovine subclinical mastitis: detection, etiology and treatment. Veterinary Medicine International;2018.
62. Rathore AS, Kapuno R, Meerza I, Schostack K, VanLoocke C. Real-time manufacturing analytics platform: Revolutionizing pharmaceutical manufacturing operations. IEEE Engineering Management Review. 2018; 46(2):36-46.
63. Rhim JW, Park HM, Ha CS. Bio-nanocomposites for food packaging applications. Progress in Polymer Science. 2013;38(10-11):1629-1652.
64. Echegoyen Y, Nerín C. Nanoparticle release from nano-silver antimicrobial food containers. Food and Chemical Toxicology. 2013;62, 16-22.
65. Tankhiwale R, Bajpai SK. Preparation, characterization and antibacterial applications of ZnO-nanoparticles coated polyethylene films for food packaging. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2009;90(1):16-20.
66. Rhim JW, Wang LF, Hong SI. Preparation and characterization of agar/silver nanoparticles composite films with antimicrobial activity. Food Hydrocolloids. 2013;33(2):327-335.
67. Kumar P, Kim KH, Deep A, Kim KS. Recent advances in graphene based biosensors. Journal of Nanomaterials; 2015.
68. Otoni CG, Espitia PJP, Avena-Bustillos RJ, McHugh TH. Trends in antimicrobial food packaging systems: Emitting sachets and absorbent pads. Food Research International. 2016;83:60-73.
69. Ogilvie SP, Beirne D, Lau KT, Lewis PR, Alderman J, Zhong X, Ebdon N. Continuous monitoring of meat quality using nanofiber based flexible sensors. Journal of Food Engineering. 2016;189:77-86.
70. Rhim JW, Wang LF. Preparation and application of agar/silver nanoparticles composite films for fresh fruit preservation. Food Science and Biotechnology. 2014; 23(3):661-666.
71. Wang Y, Ye Z, Ying Y. New trends in impedimetric biosensors for the detection of foodborne pathogenic bacteria. Sensors. 2012;12(3):3449-3471.
72. Yang M, Dai H, Yan H, Kan B. Nanoparticle-based surface-enhanced Raman scattering assays for bacterial detection. TrAC Trends in Analytical Chemistry. 2012;41:1-11.
73. Liang RP, Yue WW, Rabiei M, Wang Z, Wang J, Shi Z, Mulvaney P. Nanoparticle-based detection and quantification of DNA with low sample consumption. Angewandte Chemie International Edition. 2015; 54(12):3604-3608.
74. Zhao X, Lin CW, Wang J, Oh DH. Advances in rapid detection methods for foodborne

pathogens. Journal of Microbiology and Biotechnology. 2014;24(3):297-312.
75. Zheng L, Ren M, Chai Y, Yang J, Chen Y, Yang R. A microfluidic device with integrated SERS arrays for sensitive and simultaneous detection of multiple analytes. Electrophoresis. 2017;38(16):2074-2081.
76. Zhang J, O'Donoghue M. Quantum-dot based molecularly imprinted polymers on three-dimensional origami paper microfluidic chip for multiplex sandwich immunoassays. Analytical Chemistry. 2015;87(10):5141-5149.
77. Smith AM, Johnston KA, Crawford RJ, Mardel J. Functionalised quantum dots for surface enhanced Raman spectroscopy detection of food authenticity and traceability markers. Food Chemistry. 2012;135(2):1195-1200.
78. Sohail M, Sun DW, Zhu Z, Fatima H, Lin Z. Recent developments in intelligent packaging for enhancing food quality and safety. Critical reviews in Food Science and Nutrition. 2018;58(15): 2650-2662.
79. Echegoyen Y, Nerín C. Nanoparticle release from nano-silver antimicrobial food containers. Food and Chemical Toxicology. 2013;62:16-22.
80. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea-Torresdey JL. Interaction of nanoparticles with edible plants and their possible implications in the food chain. Journal of Agricultural and Food Chemistry. 2011;59(8):3485-3498.
81. Gardea-Torresdey JL, Rico CM, White JC. Trophic transfer, transformation, and impact of engineered nanomaterials in terrestrial environments. Environmental Science & Technology. 2014;48(5):2526-2540.
82. Lichtfouse E, Schwarzbauer J, Robert D. (Eds.). Environmental chemistry for a sustainable world (Vol. 1). Springer Science & Business Media; 2013.
83. Das P, Xenopoulos MA, Williams CJ, Hoque ME, Metcalfe CD. Effects of silver nanoparticles on bacterial activity in natural waters. Environmental Toxicology and Chemistry. 2015;34(1):122-130.
84. Singh S, Barick KC, Bahadur D. Surface engineered magnetic nanoparticles for removal of toxic metal ions and bacterial pathogens. Journal of Hazardous Materials. 2013;258:192-200.
85. Singh N, Manshian B, Jenkins GJ, Griffiths SM, Williams PM, Maffeis TG, Doak SH. Nano Genotoxicology: The DNA damaging potential of engineered nanomaterials. Biomaterials. 2014;35(14):3891-3914.
86. Das MR, Sarma RK, Saikia R, Kale VS, Shelke MV, Sengupta P. Synthesis of silver nanoparticles in an aqueous suspension of graphene oxide sheets and its antimicrobial activity. Colloids and Surfaces B: Biointerfaces. 2011;83(1):16-22.
87. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea-Torresdey JL. Interaction of nanoparticles with edible plants and their possible implications in the food chain. Journal of Agricultural and Food Chemistry. 2011;59(8):3485–3498.
DOI: https://doi.org/10.1021/jf104517j
88. Gardea-Torresdey JL, Parsons JG, Gomez E, Peralta-Videa J, Troiani HE, Santiago P, Jose-Yacaman M. Formation and Growth of Au Nanoparticles Inside Live Alfalfa Plants. Nano Letters. 2005;2(4):397–401.
DOI: https://doi.org/10.1021/nl048396g
89. Lichtfouse E, Schwarzbauer J, Robert D. (Eds.). Green materials for energy, products and depollution. Springer Science & Business Media. 2013;3.
90. Das P, Xenopoulos MA, Metcalfe CD. Effects of silver nanoparticles on the bacterial growth kinetics and their transformation and transport behavior in water and wastewater treatment systems. Environmental Toxicology and Chemistry. 2015;34(6):1287-1293.
91. Hristov AN, Oh J, Firkins JL, Dijkstra J, Kebreab E, Waghorn G, Tricarico JM. Special Topics—Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. Journal of Animal Science. 2013;91(11):5045-5069.
92. Liu X, Zhang F, Yan S, Li F, Zhang Z. Preparation of a slow-release bionanocomposites-based nitrogen fertilizer and its effects on the growth of wheat. Chemical Speciation & Bioavailability. 2014;26(1):53-60.
93. Cayuela ML, Sánchez-Monedero MA, Roig A, Hanley K, Enders A, Lehmann J. Biochar and denitrification in soils: when, how much and why does biochar reduce N2O emissions?. Scientific Reports. 2013;3(1):1-7.
94. Sohi SP. Carbon storage with benefits. Science. 2012;338(6110):1034-1035.
95. De Rosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. Nature Nanotechnology. 2010;5:91.

96. Liu R, Lal R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of The Total Environment. 2015;514:131-139.
97. Naceradska J, Vasilkovova B, Kroupova M, Sedlackova J, Komarek M. Controlled release fertilizer based on alginate hydrogel encapsulated potassium phosphate nanoparticles. Journal of Agricultural and Food Chemistry. 2018;66:34:8903-8911.
98. Wang P, Lombi E, Zhao FJ, Kopittke PM. Nanotechnology: A new opportunity in plant sciences. Trends in Plant Science. 2016; 21:699-712.
99. De Rosa MC, Monreal C, Schnitzer M, Walsh R, Sultan Y. Nanotechnology in fertilizers. Nature Nanotechnology. 2010; 5(2):91.
100. Beyrouty CA. Nanoparticles for slowed release of fertilizer. Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reduction; 2013.
101. Subramanian KS, Tarafdar JC. Prospects of nanotechnology in Indian farming. Indian Journal of Agricultural Sciences. 2011; 81:887–893.
102. Mansoori GA, Bastami TR, Ahmadpour A, Eshaghi Z. Environmental application of nanotechnology. Annual Review of Nano Research. 2007;1.
103. Chen L, Sabatini DA, Kibbey TC. Role of the air-water interface in the retention of TiO2 nanoparticles in porous media during primary drainage. Environmental Science & Technology. 2008;42(6):1916-1921.
104. Kah M, Kookana RS, Gogos A, Bucheli TD. A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. Nature Nanotechnology. 2018;13(8):677-684.
105. Debnath N, Das S, Seth D, Chandra R, Bhattacharya SC, Goswami A. Entomotoxic effect of silica nanoparticles against *Sitophilus oryzae* (L.). Journal of Pest Science. 2011;84(1):99-105.
106. De Oliveira JL, Campos EV, Bakshi M, Abhilash PC, Fraceto LF. Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture: prospects and promises. Biotechnology Advances. 2014;32(8):1550-1561.
107. Kah M. Nanopesticides and nanofertilizers: Emerging contaminants or opportunities for risk mitigation?. Frontiers in Chemistry. 2015;3:64.
108. Cao A, Hu D, Li S, Qiu X, Wang E, Lai KWC. Rapid plant disease diagnostics using forward-looking fluorescence imaging spectroscopy technology: A review. Computers and Electronics in Agriculture. 2014;104:69-75.
109. Wei C, Lin WY, Zainal Z, Williams NE, Zhu K, Kruzic AP, Rajeshwar K. Bactericidal activity of TiO2 photocatalyst in aqueous media: Toward a solar-assisted water disinfection system. Environmental Science & Technology. 1994;28(5):934-938.
110. Bhattacharyya A, Bhaumik A, Usha Rani P, Mandal S, Epidi TT. Nanoparticle pesticides as green and sustainable alternatives for agrochemicals. ACS Symposium Series. 2016;1237:167-189.
111. Liu F, Wen LX, Li ZZ, Yu W, Sun HY, Chen JF. Porous hollow silica nanoparticles as controlled delivery system for water-soluble pesticide. Materials Research Bulletin. 2006;41(12):2268-2275.
112. Liu R, Zhang H, Lal R, Xue Q, Liao Y. Digital and smart agriculture powered by nanotechnology. Nature Food. 2021;2(11):856-865.
113. Souza JG, Fagundes-Klen MR, Veit MT, Palácio SM, Bergamasco R. Application of nanotechnology for the remediation of pesticide-contaminated soil and water: A review. Science of the Total Environment. 2020;718:137193.
114. Kumari M, Singh SK, Verma A, De D, Dutta V, Choudhury S, Tripathi DK. Nanotechnology: A panacea for exploring new horizons in the domain of mycoremediation. Biotechnology Advances. 2020;107651.
115. Wan J, Ma M, Wang C, Wang Y, Mu J, Wang Q, Zeng D. In situ organic contamination detection using magnetic nanoparticles as tracers. Environmental Science: Nano. 2016;3(6):1437-1444.
116. Zhao D, Zhuo N, Li S, Lang Y, Wang X, Lin Z, Wang C. In situ detection and analysis of aromatic pollutants in soils with magnetic molecularly imprinted polymers. ACS Applied Materials & Interfaces. 2017; 9(37):31620-31628.
117. Hadi P, Barford J, McKay G. Total arsenic removal from water using mesoporous iron oxide prepared from Fe scale waste. Chemical Engineering Journal. 2015; 281:162-168.
118. Rajput S, Pittman Jr CU, Mohan D. Magnetic magnetite (Fe3O4) nanoparticle synthesis and applications for lead (Pb2+)

and chromium (Cr6+) removal from water. Journal of Colloid and Interface Science. 2016;468:334-346.
119. Fu F, Xie L, Tang B, Wang Q, Jiang S. Application of a novel strategy-advanced Fenton-chemical precipitation to the treatment of strong stability chelated heavy metal containing wastewater. Chemical Engineering Journal. 2012;189:283-287.
120. Wang CB, Zhang WX. Synthesizing nanoscale iron particles for rapid and complete dechlorination of TCE and PCBs. Environmental Science & Technology. 1997;31(7):2154-2156.
121. Inyang M, Gao B, Yao Y, Xue Y, Zimmerman A, Mosa A, Ok YS. A review of biochar as a low-cost adsorbent for aqueous heavy metal removal. Critical Reviews in Environmental Science and Technology. 2016;46(4):406-433.
122. Guzzetti E, Surendran N, Lin SS. Enhanced remediation of oxidized contaminants by nano-scale zero-valent iron particles in the presence of an auxiliary reductant. Journal of Hazardous Materials. 2018;342:117-123.
123. Sikder MT, Lead JR, Baalousha M, Movia D. Engineering nanomaterials for water purification: Progress and perspectives. Journal of Environmental Chemical Engineering. 2021;9(1):104523.
124. Kaegi R, Voegelin A, Sinnet B, Zuleeg S, Hagendorfer H, Burkhardt M, Siegrist H. Behavior of metallic silver nanoparticles in a pilot wastewater treatment plant. Environmental Science & Technology. 2011;45(9):3902-3908.
125. Mahdavi S, Ahmad MB, Haron MJ, Gharayebi Y, Shameli K, Nadi B. Fabrication of a highly sensitive penicillin sensor based on charge transfer techniques. International Journal of Molecular Sciences. 2013;14(5):8978-8987.
126. Zeng T, Zhang X, Wang S, Ma Y, Niu H, Cai Y. Modification of magnesium oxide nanoparticles with NH4+ to enhance and stabilize PCE catalytic hydrodechlorination reactivity. Environmental Science & Technology. 2013;47(4):1975-1982.
127. Malato S, Fernández-Ibáñez P, Maldonado MI, Blanco J, Gernjak W. Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends. Catalysis Today. 2009;147(1):1-59.
128. Liu S, Zeng TH, Hofmann M, Burcombe E, Wei J, Jiang R, Chen Y. Antibacterial activity of graphite, graphite oxide, graphene oxide, and reduced graphene oxide: membrane and oxidative stress. ACS Nano. 2011;5(9):6971-6980.
129. Geim AK, Novoselov KS. The rise of graphene. In Nanoscience and technology: A collection of Reviews from Nature Journals. 2007; 11-19.
130. El-Rehim HAA, El-Samahy MA, Khaled HB, Abo-Elmatty DM. Polyacrylic acid-coated and uncoated superabsorbent hydrogel nanocomposites based on clay/sodium alginate for removal of heavy metals from water. Journal of Polymer Research. 2018; 25(5):117.
131. Surapaneni SK, Jena S. Is soil–water retention curve of a nanomaterial-amended soil same as that of an unamended soil?. Journal of Hydrology. 2016;534:525-531.
132. Ye D, Zhang H, Deng B, Jiang C, Xu H, Yang X. Superhydrophilic graphene oxide@ electrospun cellulose nanofiber membrane for high-efficiency oil/water separation. Carbohydrate Polymers. 2016;147:282-291.
133. Fraceto LF, Grillo R, de Medeiros GA, Scognamiglio V, Rea G, Bartolucci C. Nanotechnology in agriculture: Which innovation potential does it have?. Frontiers in Environmental Science. 2016;4: 20.
134. Cao A, Hu D, Li S, Qiu X, Wang E, Lai KWC. Rapid plant disease diagnostics using forward-looking fluorescence imaging spectroscopy technology: A review. Computers and Electronics in Agriculture. 2014;104:69-75.
135. Xu L, Zhou C, Wen M, Wang J, Zhou W, Jiang X, Ren H. A dual functional plasmonic biosensor for monitoring enzymatic reaction and inhibition. ACS applied materials & interfaces. 2018;10(42): 35572-35581.
136. Wang Y, Deng R, Zhang G, Vazquez-Duhalt R, Chen C, Tang H, Tan W. Multiplexed detection and imaging of intracelluar mRNA using a four-color nanoprobe. Nano Letters. 2018;18(8):5113-5118.
137. Liu J, Zhang H, Wang C, Wang Y, Fu L, Liu J, Wang Q. Nitrogen status diagnosis of rice based on fluorescence imaging using nitrogen deficiency-sensitive probe. Analytical Chemistry. 2018;90(8): 5064-5071.
138. Huang X, Xu D, Chen J, Liu J, Li Y, Song J, Yu G. Smart multifunctional nanostructure for targeted cancer chemotherapy and magnetic resonance imaging. ACS Applied Materials & Interfaces. 2018;10(8):7126-7135.

139. Ponzoni A, Comini E, Sberveglieri G, Zhou J, Deng SZ, Xu NS, Wang ZL. Ultrasensitive and highly selective gas sensors using three-dimensional tungsten oxide nanowire networks. Applied Physics Letters. 2006; 88(20):203101.
140. Farre M, Sanchís J, Barceló D. Analysis and assessment of the occurrence, The fate and the behavior of nanomaterials in the environment. TrAC Trends in Analytical Chemistry. 2011;30:517-527.
141. Kah M. Nanopesticides and nanofertilizers: Emerging contaminants or opportunities for risk mitigation?. Frontiers in Chemistry. 2015;3:64.
142. Liu F, Wen LX, Li ZZ, Yu W, Sun HY, Chen JF. Porous hollow silica nanoparticles as controlled delivery system for water-soluble pesticide. Materials Research Bulletin. 2006;41(12), 2268-2275.
143. Emamifar A, Kadivar M, Shahedi M, Soleimanian-Zad S. Evaluation of nanocomposite packaging containing Ag and ZnO on shelf life of fresh orange juice. Innovative Food Science & Emerging Technologies. 2010;11(4):742-748.
144. Edison TJI, Atchudan R, Kamal C, Lee YR. Inhibition of foodborne pathogens by chitosan-silver nanocomposites. Frontiers in Microbiology. 2016;7:1365.
145. Prasad TN, Sudhakar P, Sreenivasulu Y, Latha P, Munaswamy V, Raja Reddy K, Sreeprasad TS. Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. Journal of Plant Nutrition. 2012;35(6):905-927.
146. Dimkpa CO, McLean JE, Latta DE, Manangón E, Britt DW, Johnson WP, Anderson AJ. CuO and ZnO nanoparticles: phytotoxicity, metal speciation, and induction of oxidative stress in sand-grown wheat. Journal of Nanoparticle Research. 2012;14(9):1125.
147. Bao Y, Qu J, Zhao D, Kang Z, Cheng H, Hou G, Ai P. Novel dendritic nanoparticles for effective gene delivery: A new frontier in plant genetic engineering. Plant Biotechnology Journal. 2017;15(11):1401-1412.
148. Demirer GS, Zhang H, Snead NM, Gonzalez AP, Zheng W, Stucky GD, Chandra A. DNA nanocarriers for systemic administration: Characterization and in vivo bioimaging in mice. Scientific reports. 2019;9(1):1-14.
149. Zhang X, Zhang H, Li Y, Hou X, Liu B, Zhao Q, Huang K. High efficient multisites genome editing in allotetraploid cotton (Gossypium hirsutum) using CRISPR/Cas9 system. Plant Biotechnology Journal. 2018; 16(1):137-150.
150. Mitter N, Worrall EA, Robinson KE, Li P, Jain RG, Taochy C, Carroll BJ. Clay nanosheets for topical delivery of RNAi for sustained protection against plant viruses. Nature Plants. 2017;3(1):1-8.
151. Echegoyen Y, Nerín C. Nanoparticle release from nano-silver antimicrobial food containers. Food and Chemical Toxicology. 2013;62:16-22.
152. Jin T, Gurtler JB, Li SQ, Boyd G. Antimicrobial volatile essential oils in edible films for food safety. Science against microbial pathogens: Communicating current research and technological advances. 2018;2:1092-1104.
153. Emamifar A, Kadivar M, Shahedi M, Soleimanian-Zad S. Effect of nanocomposite packaging containing Ag and ZnO on inactivation of Lactobacillus plantarum in orange juice. Food Control. 2011;22(3-4):408-413.
154. Tankhiwale R, Bajpai SK. Graft copolymerization onto cellulose-based filter paper and its further development as silver nanoparticles loaded antibacterial food–packaging material. Colloids and Surfaces B: Biointerfaces. 2012;90:16-20.
155. Rhim JW, Wang LF, Hong SI. Preparation and characterization of agar/silver nanoparticles composite films with antimicrobial activity. Food Hydrocolloids. 2013;33(2):327-335.
156. Tankhiwale R, Bajpai SK. Preparation, characterization and antibacterial applications of ZnO-nanoparticles coated polyethylene films for food packaging. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 2009;90(1):16-20.
157. Chen H, Wang B, Gao B, Muthuraj R, Zou Y, Song G, Yang J. Reusable oxygen scavengers with ultrahigh UV resistance based on highly crystalline mesoporous benzoyl functionalized silica. ACS Applied Materials & Interfaces. 2017;9(31):26575-26589.
158. Kerry JP. (Ed.). Smart packaging technologies for fast moving consumer goods. John Wiley & Sons; 2014.
159. Smolander M, Chaudhry Q. Nanotechnologies in food packaging. Nanotechnologies in the Food Industry. 2010;86-101.

160. Sanchez-Garcia MD, Hilliou L, Lagaron JM. Nanobiocomposites of carbohydrate polymer-matrix and silver nanoparticles as antimicrobial films. Journal of Agricultural and Food Chemistry. 2010;58(22):12276-12285.
161. De Moura MR, Aouada FA, Avegliano RP, Mattoso LHC. Preparation and characterization of chitosan-nanofibers from aqueous solutions. Journal of Applied Polymer Science. 2015;132(28).
162. Parisi C, Vigani M, Rodríguez-Cerezo E. Agricultural nanotechnologies: What are the current possibilities?. Nano Today. 2015;10(2):124-127.
163. Liu Q, Lal R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Science of the Total Environment. 2015;514:131-139.
164. Nhan LT, Rui Y, Gautier M, Abdallah MAE, Bui DT, Lamb D, Frankel G. Phytotoxicity of Baceria-Mediated Biosynthesized Silver Nanoparticles on Seed Germination of Raphanus sativus L. Water, Air, & Soil Pollution. 2019;230(9):202.
165. Chen H, Roco MC, Son J, Jiang S, Larson CA, Gao Q. Global nanotechnology development from 1991 to 2012: patents, research publications, and effect of NSF funding. Journal of Nanoparticle Research. 2013;15(9):1951.
166. Rico CM, Majumdar S, Duarte-Gardea M, Peralta-Videa JR, Gardea-Torresdey JL. Interaction of nanoparticles with edible plants and their possible implications in the food chain. Journal of Agricultural and Food Chemistry. 2011;59(8):3485-3498.
167. Parisi C, Vigani M, Rodríguez-Cerezo E. Proceedings of a workshop on “nanotechnology for the agricultural sector: From research to the field”. Publications Office of the European Union; 2015.
168. Savithri D, Khanum F, Bawa AS, Rajasekharan R. Bacterial cellulose reinforced chitosan coatings for mango (Mangifera indica) fruit preservation. International Journal of Biological Macromolecules. 2011;49(5):768-773.
169. Taunk K, Hassan S, Lori A, Beni Y, Shahid S, Kim IS. Nanotechnology in soils: New insights into the pivotal role of nanoparticulates in soil physical, chemical, and biological processes. Science of The Total Environment. 2019;649:61-72.
170. Bumbudsanpharoke N, Ko S, Min SK, Jang HW. Ultrasensitive detection of Bacillus cereus spores by alternating current dielectrophoresis-assisted surface enhanced Raman spectroscopy using silica-coated anisotropic silver nanostars. Analytical Chemistry. 2015;87(19):9900-9906.
171. Jampílek J, Kráľová K. Silver nanoparticles in plant science: a review. Frontiers in Chemistry. 2015;3:83.
172. Katuwal S, Cahill SM, Jain R, Zavala G. Zinc oxide nanoparticles decrease growth and reproduction in the earthworm Eisenia fetida. Environmental Pollution. 2020;263;114617.
173. Kumari M, Tripathi DK. Efficiency of distance decay on testing herbicide resistance build up in weeds at landscape level. Journal of Environmental Management. 2019;236:63-73.
174. Lee B, Ahn KH, Robertson RE, Zheng P, Abney CH, Leary CJ, Mahendra S. Magnetic nanocomposite carrier for biomagnetic detection and magnetic-directed microfluidic manipulation. ACS Applied Materials & Interfaces. 2013;5(14):6775-6782.
175. Liang Z, Das A, Hu Z. Bacterial cellulose/hydroxyapatite nanocomposites for bone repair. Biomed Mater Eng. 2010;20(5):291-297.
176. Lim SI, Draz MSBM, Tasyriq M, Hamasaki Y, Gimba CE, Hanapi SZM. Preparation and characterization of thermally conductive bacterial cellulose nanocomposite for an electronic device application. Composites Part B: Engineering. 2017;119:60-65.
177. Ma N, Zhang X, Huang J, Chen C, Zhu H, Zhao Y, Wang ZL. Ultrasensitive potassium pressure sensor based on layered molybdenum disulfide. ACS nano. 2014;8(9):9571-9578.
178. Mousavi SR, Hashemi B, Ghasemi V, Atapour A, Sadeghi SM, Ceylan O, Heydari A. A novel magnetic Fe3O4@ C nanoparticles-modified biosensor for ultrasensitive electrochemical detection of cancer cells. Biosensors and Bioelectronics. 2014;59:145-151.
179. Naz S, Nazir A, Niazi MBK, Manzoor I, García-Estrada C, Martin-Perrón C, Iqbal J. Alginate based bionanocomposites for food packaging applications: A critical review. Carbohydrate polymers. 2018;199:517-530.
180. Panev ND, Naidenov V, Valchev I, Bakalska R, Atanasova G, Dimitrov N, Grozdanov A. Bio-nanotechnology approach for coating of bone implants with collagen-hydroxyapatite

composite. Composites Part B: Engineering. 2018;134;106-113.
181. Panwar A, Soorikar V, Kaur A, Tomar A, Kaushik A, Chityala SK, Kumar R. Properties, synthesis, and applications of poly (vinyl alcohol)/clay nanocomposite: A comprehensive review. Polymer Composites. 2016;37(5):1315-1334.

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