

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

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

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.

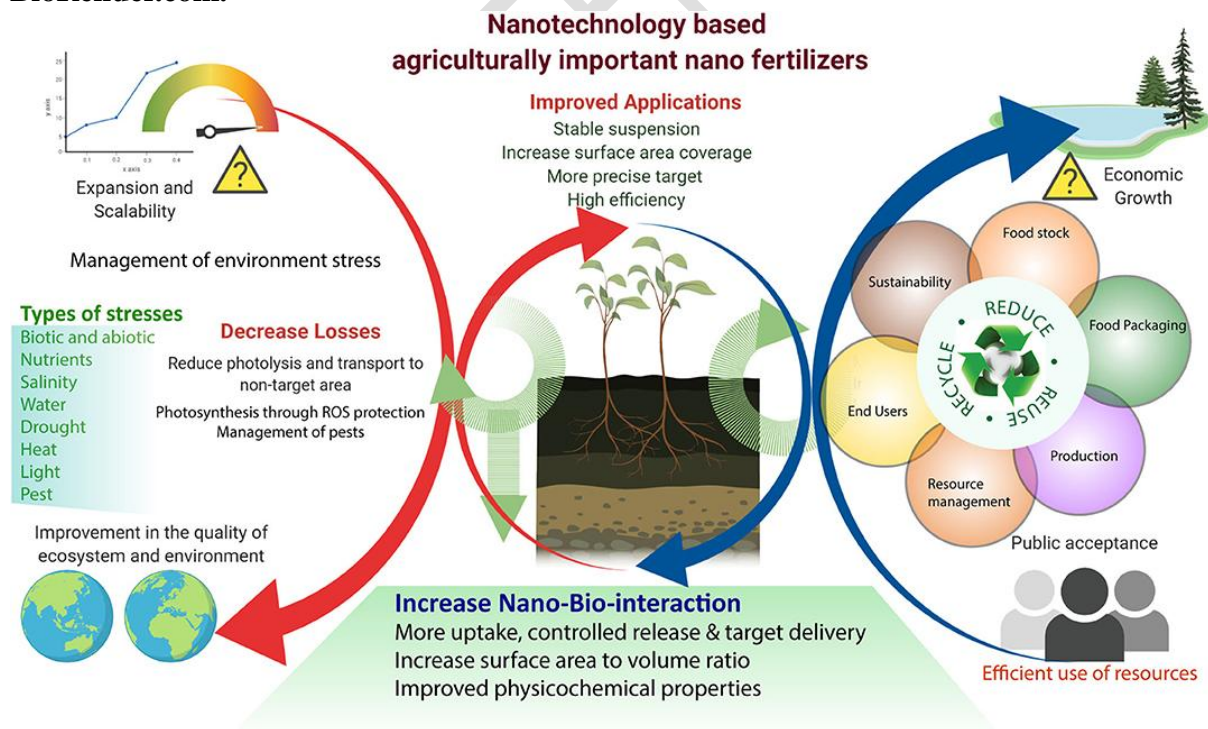
Nanotechnology has emerged as a pivotal platform providing novel solutions with potential to revolutionize nearly all facets of agriculture (3). Diverse engineered nanomaterials, fabrication techniques, and nano-enabled applications are being tailored to the agricultural sector (Figure 1). Nanotechnology 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.

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



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.

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.

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). 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). 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.

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 nanoprobe 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.

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.

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.

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). Aquaporin protein-embedded nanomembranes efficiently filtered sediments, bacteria, and salinity from wastewater for farm reuse following tomato and onion cultivation (48). Such nano-enabled filtration techniques can unlock unconventional water sources to expand agriculture in water-scarce regions.

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.

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.

Nanotechnology for Sustainable Livestock Production

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

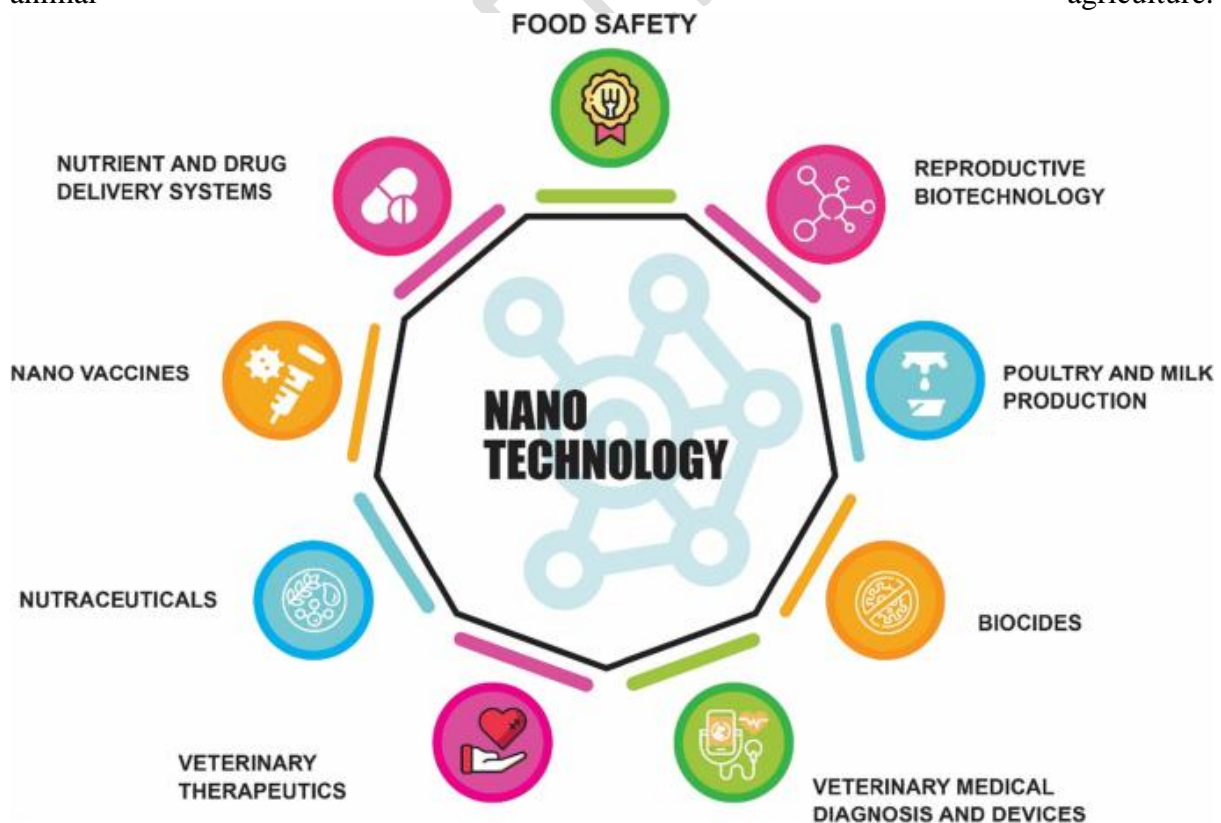


Fig. 2. Role of Nanotechnology for Sustainable Livestock Production

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.

Nanobiosensors for Animal Health Monitoring

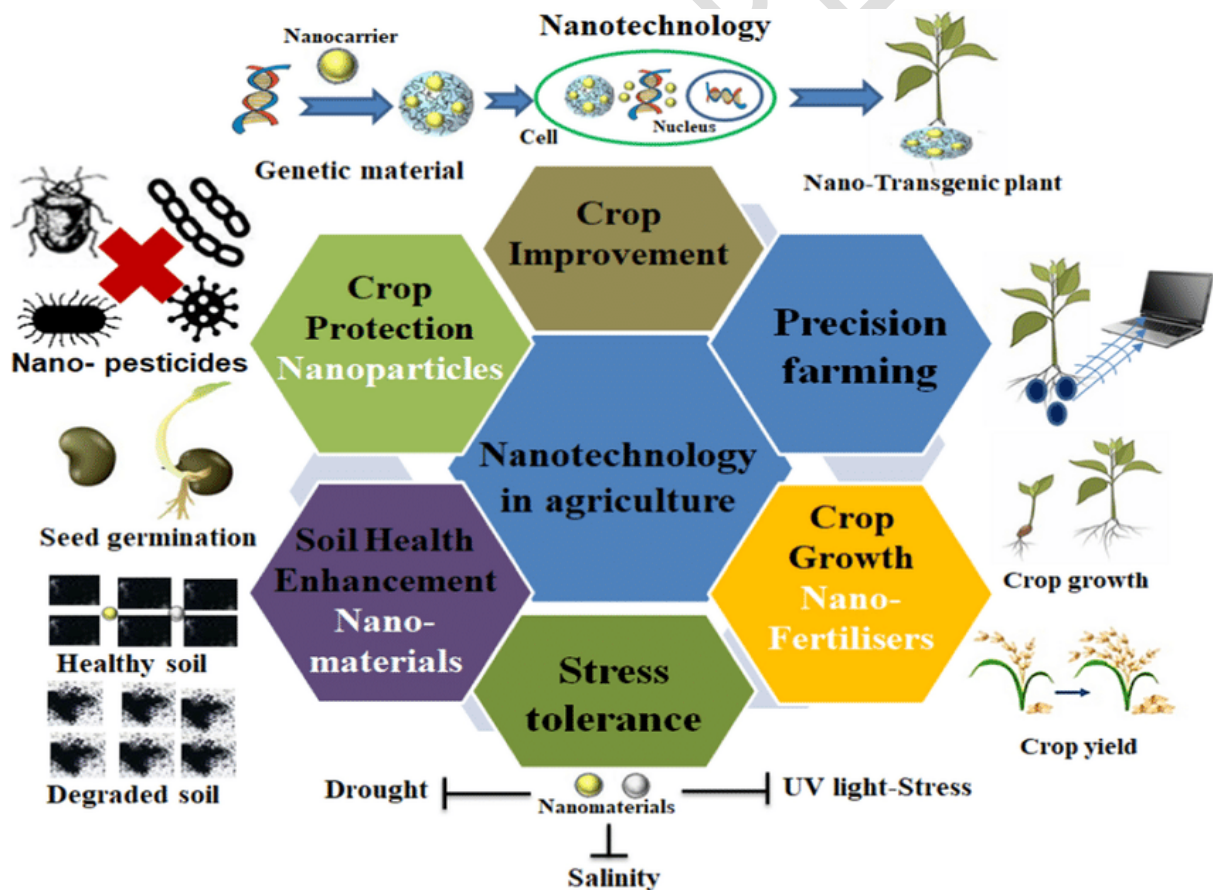
Implanted nanobiosensors and wearable nanotechnology devices allow continuous, real-time monitoring of physiological and biochemical parameters in livestock (62). Miniaturized electrochemical nanobiosensors measure pH and glucose levels for health evaluation when surgically inserted in the rumen or bloodstream (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.

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	Nanoclays, cellulose nanofibers,	Increased soil moisture retention;	53-

Application	Nanomaterial/Technology	Potential Benefits	Refs
conservation	nanogel polymers	reduced irrigation water needs	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 monitoring for physiological diagnosis/treatment	62-64

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



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.

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.

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.

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

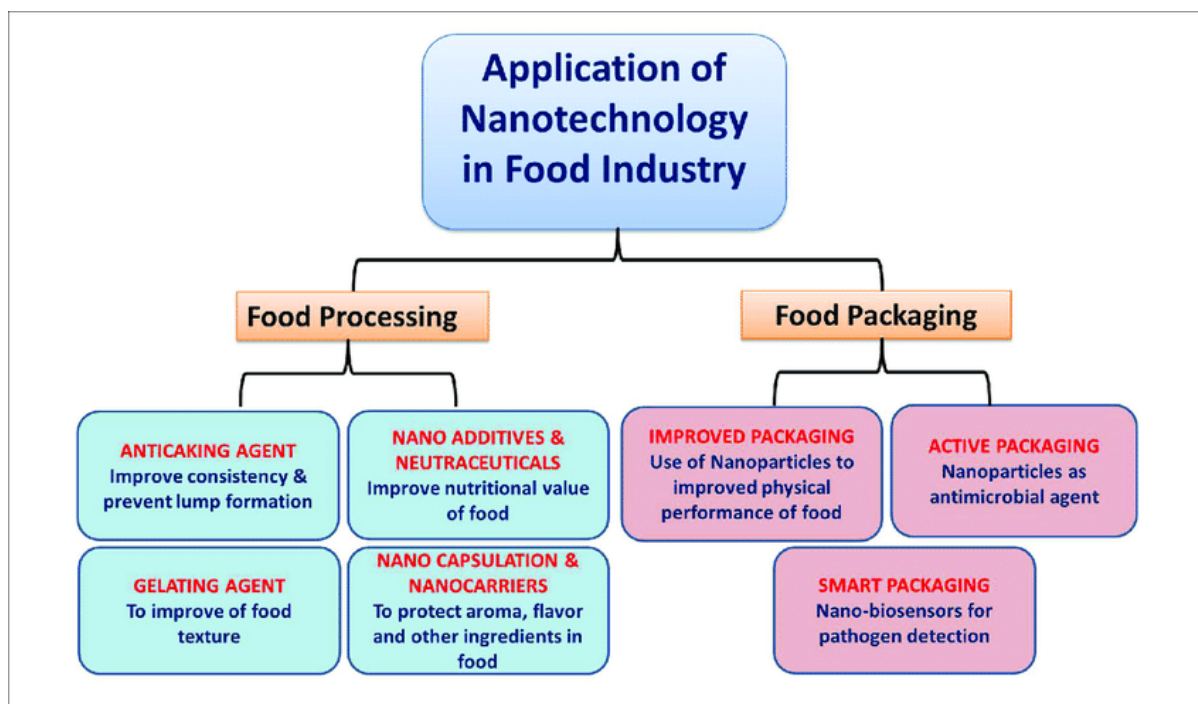


Fig. 4. Schematic showing potential nanotechnology applications for food quality, safety and security from production to consumption.

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	Porous nanosilicates	Reduced enteric methane	(Hristov et al.,

Application	Nanomaterial/Technology	Potential Benefits	References
emission mitigation		production in cattle	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 N ₂ O emissions from soil	(Cayuela et al., 2013) [93]
Carbon sequestration	Biochar nanoparticles	Enhanced crop residue carbon stabilization in soil	(Sohi, 2012) [94]

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.

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).

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.

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.

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 TiO₂ 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.

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-TiO₂ 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.

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.

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 nanoprobe measured plant nitrogen status and deficiency symptoms quickly and accurately in oilseed rape leaves (137). Multifunctional nanoprobe 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.

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.

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 nanoclays and cellulose nanoparticles formed biodegradable, non-toxic food packaging (160,161). Such smart nanotechnology packaging can enhance food security.

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.

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