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REVIEW

Nanotechnology and Plant Biostimulants for Sustainable Agriculture: A Systematic Review and Future Perspectives

Sumit Sow[1,#], Alkajyoti Sharma[2,#], Mainak Ghosh[3,*], Nintu Mandal[4], Sanjay Kumar[2], Shivani Ranjan[5,*], Souvik Sadhu[6], Dibyajyoti Nath[7], Harun Gitari[8] and Rakesh Panday[9]

[1]Department of Agronomy, PGCA, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India
[2]Department of Agronomy, Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India
[3]ICAR-Agricultural Technology Application Research Institute, Zone-VII, Umiam (Barapani), Meghalaya, India
[4]School of Edaphic Stress Management, ICAR-National Institute of Abiotic Stress Management, Malegaon, Baramati, Maharashtra, India
[5]Department of Agronomy, Tirhut College of Agriculture, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India
[6]Department of Soil Science and Agricultural Chemistry, Bihar Agricultural University, Sabour, Bhagalpur, Bihar, India
[7]Department of Soil Science, PGCA, Dr. Rajendra Prasad Central Agricultural University, Pusa, Samastipur, Bihar, India
[8]Department of Agricultural Science and Technology, School of Agriculture and Environmental Studies, Kenyatta University, Nairobi, Kenya
[9]Department of Silviculture and Agroforestry, Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh, India
*Corresponding Authors: Mainak Ghosh. Email: mainakghosh999@gmail.com;
Shivani Ranjan. Email: ranjanshivani54@gmail.com
#These authors contributed equally to this work

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ABSTRACT: Increasing population pressure and growing constraints on cultivable land and water resources necessitate improving resource use efficiency through the adoption of advanced and efficient agricultural technologies. With finite resources and a growing global population, agriculture has become increasingly essential as a source of food, fiber, and livestock. Due to their eco-friendly nature, the integration of crop improvement strategies with nanotechnology and plant biostimulants (PB) plays an important role in the development of smart and sustainable agriculture. Improved agricultural techniques have the potential to transform agricultural systems, and as a result, could be a viable option to increase crop yields. The use of advanced technologies such as nanosensors and nanofertilizers derived from nanotechnology has offered promising ways to modernize the farming sector. The usage of nano products might be a reliable answer to increase crop yield to ensure food security. Due to its advantages over conventional agriculture in terms of being safer and healthier for humans, organic farming has attracted a great deal of interest from both consumers and experts. In addition, PB can boost plant resilience and optimize nutrient uptake efficiency, helping to reduce the yield gap between conventional and organic farming. This study investigates the role of nanotechnology and biostimulants in promoting sustainable agriculture and improving crop management practices at the field level. Researchers can use these to grasp the importance of nanotechnology and PB analyse future conditions, and develop strategies to maintain food and nutritional security. This review uniquely integrates nanotechnology and biostimulants within a unified mechanistic framework. We propose a conceptual framework describing how nanocarriers enhance biostimulant stability, signaling, nutrient uptake, and stress resilience, offering a new direction for nano-bioformulation design.

KEYWORDS: Food security; nanosensors; nanofertilizers; organic farming; plant biostimulants; resource use efficiency; sustainable agriculture

1 Introduction

More than 60% of the people living in developing nations depend on agriculture and related activities for their livelihood. Agriculture is a critical sector which is essential for supplying balanced nutrition and maintaining food security. However, the main focus is on sustainability and economic viability. Addressing food security challenges in agriculture—driven by a growing population and unpredictable climate shifts—demands innovative solutions such as nanotechnology-enabled inputs, PB, precision nutrient management, and climate-smart agronomic practices to support the development of climate-resilient farming systems [1]. The shrinkage of agricultural land, labour shortages, and increased urbanization are only few of the policy issues that have changed as a result of the changing environment and hindering the targeted production and productivity. Globally, governments and international organizations are increasingly prioritizing investments in agriculture to enhance food security, improve resource use efficiency, and address constraints related to limited land and water resources [2]. The greenhouse effect is intensified by anthropogenic changes in land cover, which alter the biophysical energy dynamics of the Earth's surface and contribute to increasingly unpredictable and extreme climate events. These transformations in both the landscape and atmosphere continue to disrupt ecological interactions, notably affecting the carbon cycle. As a result, agriculture faces mounting challenges, including climate variability, soil degradation, declining soil fertility, water scarcity, nutrient losses, increasing pest and disease pressure, and greenhouse gas emissions, in addition to pressures from global food supply chains, market competition, and industrial demands, while striving to enhance productivity [3]. In this context, the sector must balance economic profitability with environmental sustainability. In this context, the sector must navigate the delicate balance between achieving economic profitability and minimizing environmental harm. A redefined vision of sustainable agriculture is essential—one that can nourish a growing global population, sustain farmers' livelihoods, and safeguard natural ecosystems [4]. The implementation of smart and labour-saving crop production technologies is required to feed the world's expanding population. PB and nanotechnology play a crucial role in enhancing food production by improving resource use efficiency and ensuring economically viable and cost-effective agricultural outputs.

In recent years, there has been a growing emphasis on organic and natural farming approaches to produce high-quality agricultural products while maintaining long-term sustainability and environmental health. Due to the increasing focus on high quality agro-products, scientists over the past two decades have successfully promoted organic vegetables [5]. More than 87 countries are currently adopting organic agriculture [6]. However, compared to conventional agriculture, the biggest disadvantage of organic farming is its lower production [7]. Organic farming typically produces 5–34% lower yields compared to conventional agriculture [8]. One major limitation in organic systems is the restricted availability of macronutrients, as applying sufficient organic fertilizers to replace synthetic inputs can be economically unfeasible [9]. Moreover, the timing of nitrogen (N) and phosphorus (P) release from organic sources like manure often does not align with the crop's nutrient requirements, resulting in uptake inefficiencies [10,11]. To bridge the yield gap between organic and conventional farming, it is crucial to develop strategies that enhance nutrient availability in sync with crop needs, uptake, and assimilation [12]. A significant advancement toward sustainable modern agriculture has been the introduction of PB in crop cultivation. Naturally derived PB are a promising tool and sustainable approach for crop production, which is gaining widespread adoption globally [13]. PB are substances or microorganisms applied to crops to boost quality traits, enhance nutrient use efficiency, and improve tolerance to environmental stresses [14]. Derived from both microbial and non-microbial sources, these natural products contain bioactive compounds that stimulate plant physiological and metabolic processes, helping reduce dependence on chemical inputs [15]. While biostimulants demonstrate high efficacy even in small quantities and can be produced from diverse sources including waste materials, they suffer from short-lived effectiveness and rapid environmental degradation. These limitations suggest that biostimulants alone may be insufficient to address contemporary agricultural challenges. Nanotechnology potentially offers a promising solution to overcome these constraints by enhancing the delivery, stability, and efficacy of biostimulants, thereby extending their effectiveness while preserving their sustainability benefits in modern farming practices [16].

Taking into account climatic factors, nanotechnology offers promising potential to sustainably improve agricultural productivity [17]. Nanotechnology in agriculture has sparked a significant advancement, improving traditional farming approaches across crop production, pest management, and resource utilization. The use of NMs has shown notable effectiveness, primarily because their nanoscale size and large surface area enable more efficient delivery of fertilizers and pesticides. This advancement has significantly improved agricultural productivity while simultaneously reducing environmental impacts, making nanotechnology a promising solution for modern farming challenges [18]. In agriculture, the application of nanotechnology aims to increase production, reduce loss of fertilizer nutrients, and use fewer agrochemicals for the protection of plants [19]. Food production at the global level and food quality can be improved by nanotechnology through improved plant protection, disease detection, growth monitoring, and waste reduction for more sustainable agriculture [20]. Furthermore, nanotechnology enables precise fertilizer delivery and soil quality monitoring, which contribute to increased crop productivity [21,22]. The research findings on NM as fertilizers are mixed; some studies report superior performance compared to conventional fertilizers, while others observe no significant advantage or even reduced effectiveness [23]. Although agricultural nanotechnology has made encouraging progress, substantial research gaps remain concerning the long-term sustainability, large-scale applicability, and cost-effectiveness of NMs in practical farming environments. This review addresses these knowledge deficiencies through a comprehensive investigation of practical applications of NM, examining their effects on crop yield, environmental sustainability, and resource efficiency. Ongoing research and innovation in nanotechnology have the potential to revolutionize agriculture, making it more efficient and eco-friendly while addressing the pressing issues of global food security and environmental sustainability [24].

Nanotechnology integrated with biostimulants presents a strategic approach to enhance plant metabolic efficiency, strengthen stress resilience, and sustain crop productivity under climate pressures. Their combined use enables more precise, resource-efficient farming while minimizing environmental impacts and maintaining yield quality. Although numerous reviews have independently assessed nanotechnology or biostimulants, very few have evaluated their synergistic interactions, co-formulations, or nano-enabled biostimulants as an integrated strategy. Existing reviews either (i) focus only on nanofertilizers, (ii) discuss biostimulants in isolation, or (iii) mention nano-bio interactions only superficially. This review provides a new synthesis by proposing a conceptual framework describing how NMs influence biostimulant stability, delivery efficiency, and plant signaling pathways which is an aspect not covered comprehensively in previous literature.

Distinct Contribution of This Review Compared to Existing Literature

Although several reviews exist on nanotechnology or biostimulants individually, they generally lack mechanistic integration between the two domains. Table 1 summarizes major reviews published in the last decade and highlights gaps that remain unresolved particularly the absence of a unified mechanistic framework explaining how NMs interact with microbial and non-microbial biostimulants at cellular, biochemical, and physiological levels. The unique contribution of this review is the development of a conceptual, mechanism-based model that predicts synergistic nano biostimulant interactions. This synthesis provides new insights into nanocarrier-assisted delivery, molecular signalling enhancement, oxidative regulation, nutrient mobilization, and stress-response pathways perspectives not previously consolidated in any existing review.

Table 1: Critical comparison of existing review literature on nanotechnology and PB, highlighting research gaps and the novel contribution of the present review.

Review Title	Year	Focus Area	Limitation in Existing Review	Unique Contribution of Present Review	References
Advancing the impact of PB to sustainable agriculture through nanotechnologies	2023	Nanotechnology & PB	Mentions synergy but no mechanistic conceptual model	Provides full mechanistic framework + predictive interactions	[4]
PB: definition, concept, categories	2022	PB only	Does not discuss NMs or nano-delivery	Integrates PB pathways with nanocarrier-enhanced delivery	[14]
Synergistic biostimulatory action	2021	PB synergy	Covers PB–PB synergy only; no nano-enabled formulations	Adds nano-enabled synergy + signalling enhancement	[25]
Biobased biostimulants and biogenic nanoparticles enter the scene	2023	Nano-biogenic materials	Lacks a predictive model for NM–PB interactions	Introduces first unified conceptual model for NM–PB synergy	[16]
Nanotechnology: an innovative tool to enhance crop production	2020	Nanotechnology	No PB discussion; no synergy analysis	Combines nanotechnology with biostimulant signalling	[2]
Arbuscular mycorrhizal fungi as biostimulants	2019	Microbial biostimulants	No nano interactions; no mechanistic integration	Predictive framework for PGPR/AMF × NM interactions	[26]

2 Methodology

This review followed a systematic methodology to identify, select, and evaluate key literature on the application of nanotechnology and biostimulants to improve crop productivity. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was used to maintain transparency and methodological rigor throughout the process [27].

2.1 Literature Search Strategy

An extensive and systematic literature search was performed using five major scientific databases: Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. The search encompassed publications from 1999 to 2025, capturing the evolution of nanotechnology and biostimulants applications in agriculture from its early conceptualization to current innovations. The search strategy employed Boolean operators and utilized the following keyword combinations:

- Primary terms: ‘nanotechnology’ AND ‘agriculture’, ‘nanofertilizers’ AND ‘crop productivity’

- Secondary terms: 'nanomaterials in agriculture' OR 'nano-bioformulations', 'biostimulants', 'nano-biostimulant for food security" AND 'sustainable agriculture'
- Tertiary terms: 'abiotic stress' AND 'nanotechnology', 'climate resilience' AND 'nanomaterials', 'humic acid' AND 'nanomaterials', 'seaweed extract' AND 'nanomaterials', 'nanosensors' AND 'plant biostimulants'.

Additional grey literature was identified through reference tracking and citation analysis of seminal papers to ensure comprehensive coverage of the field.

2.2 Database Retrieval Counts and Search Timeline

Database-wise records retrieved were: Scopus (n = 210), Web of Science (n = 185), PubMed (n = 96), ScienceDirect (n = 198), and Google Scholar (n = 168; first 200 most relevant results were screened). In total, 857 records were identified. After removal of duplicates, 540 records remained. Prior to screening, 60 records were removed due to irrelevance, conference abstracts without full text, and studies outside the scope of nanotechnology–biostimulant interactions. Consequently, 480 records were subjected to title and abstract screening.

2.3 Inclusion and Exclusion Criteria

Inclusion criteria were: (1) Peer-reviewed articles, systematic reviews, meta-analyses, and authoritative book chapters published in English; (2) Original research studies that address the role of NMs and/or biostimulants in improving crop growth, improving yield, stress tolerance mechanisms, or optimizing soil health; (3) Research conducted under controlled laboratory conditions, greenhouse trials, or field experiments with appropriate controls; (4) Studies providing quantitative data on agricultural performance metrics or mechanistic insights into nano-bio interactions. However, exclusion criteria were: (1) Studies focusing solely on nanotechnology applications outside agricultural contexts; (2) Manuscripts lacking empirical data, statistical analysis, or theoretical frameworks relevant to agricultural sustainability; (3) Conference abstracts, opinion pieces, and non-peer-reviewed publications; (4) Duplicate publications and non-English language articles; (5) Studies with insufficient methodological detail or unclear experimental design. A quality assessment scoring matrix (experimental design, replication strength, analytical rigor, and reporting clarity) was applied. Studies with low methodological transparency or inadequate quantitative data were excluded.

2.4 Screening and Selection Process

An initial pool of 857 articles was identified, and duplicate records were removed.

Subsequently, titles and abstracts were screened for relevance, resulting in the selection of 212 articles for full-text review. During this stage, the studies were critically assessed based on the following criteria: (a) Quality of the experimental design, statistical power, and reproducibility; (b) Direct contribution to understanding nanotechnology-biostimulant synergies; and (c) Complete reporting and transparency of the results. The initial count of 857 records is relatively low because the search strings were intentionally restricted to agricultural applications of nanotechnology and biostimulants, excluding broader nanoscience topics that inflate record numbers. This rigorous evaluation process yielded a final corpus of 141 high-quality studies that form the foundation of this review.

The selection procedure is illustrated in the PRISMA flow diagram (Fig. 1), which details the number of records identified, screened, evaluated for eligibility, and finally included in the review.

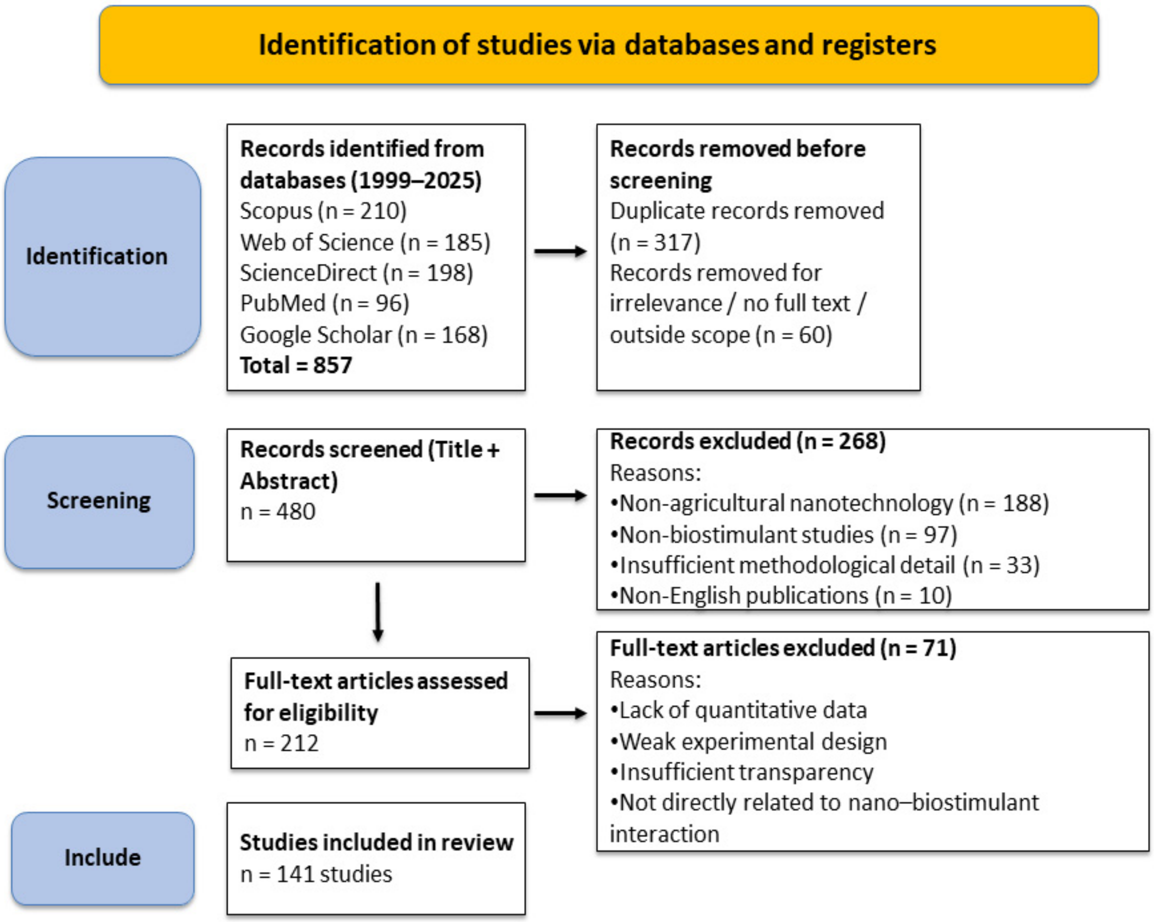

Figure 1: Review methodology workflow using PRISMA.

3 Nanomaterials

NMs are materials with at least one dimension measuring between 1–100 nm, exhibiting unique physicochemical properties that differ significantly from their bulk counterparts, including high surface-area-to-volume ratios, enhanced reactivity, and distinctive optical, electrical, and mechanical characteristics. Most engineered NMs used in agriculture are primarily composed of silicon- and carbon-based materials, and due to their unique physicochemical properties, they have emerged as transformative tools for improving food security, resource use efficiency, and environmental sustainability [22,28]. Agricultural NMs can be broadly classified based on composition, structure, and origin (Fig. 2). Based on composition, NMs include organic carbon-based materials such as carbon nanotubes (CNTs), fullerenes, graphene oxide, and single-layer graphene, which function as carriers, sensors, and structural scaffolds under biotic and abiotic stress conditions; inorganic NMs comprising metal (Ag, Au, Cu), metal oxide (ZnO, Fe_2O_3, TiO_2, CeO_2), and silica-based nanoparticles known for their bioactivity, biocompatibility, and antimicrobial properties; and hybrid or biodegradable NMs such as dendrimers, liposomes, peptide–polymer nanostructures, and starch- or cellulose-derived materials [29–31]. Structurally, NMs are categorized as zero-dimensional (0D; quantum dots), one-dimensional (1D; nanotubes, nanorods), two-dimensional (2D; nanosheets, nanofilms), and three-dimensional (3D; nanocomposites, nanoflowers), while based on origin they are grouped as engineered, naturally occurring, or incidental NMs [11,28]. In agriculture, nanotechnology enables precise nutrient and pesticide delivery, enhanced soil water retention, gene delivery for plant biotechnology, and environmental remediation. Due to their high surface-area-to-volume ratio and strong sorption capacity, NMs function as smart carriers that protect active ingredients from leaching, volatilization, and degradation, thereby improving nutrient use efficiency and plant uptake [22]. Mesoporous aluminosilicate nanoparticles have shown promising potential for controlled nutrient release, while nanopesticides provide targeted pest management with reduced environmental toxicity through controlled release mechanisms [30,32]. Additionally, nanosensors facilitate real-time monitoring of soil nutrients, pathogens, and environmental stresses for precision agriculture, and nanostructures such as CNTs serve as effective carriers for gene transfer in crop improvement programmes [29,33]. Furthermore, biodegradable NMs including silica- and clay-based particles contribute to sustainable soil management and water retention, highlighting the diverse functional roles of NMs in improving crop productivity, resource efficiency, and long-term sustainability of agricultural systems [11,22,29,31].

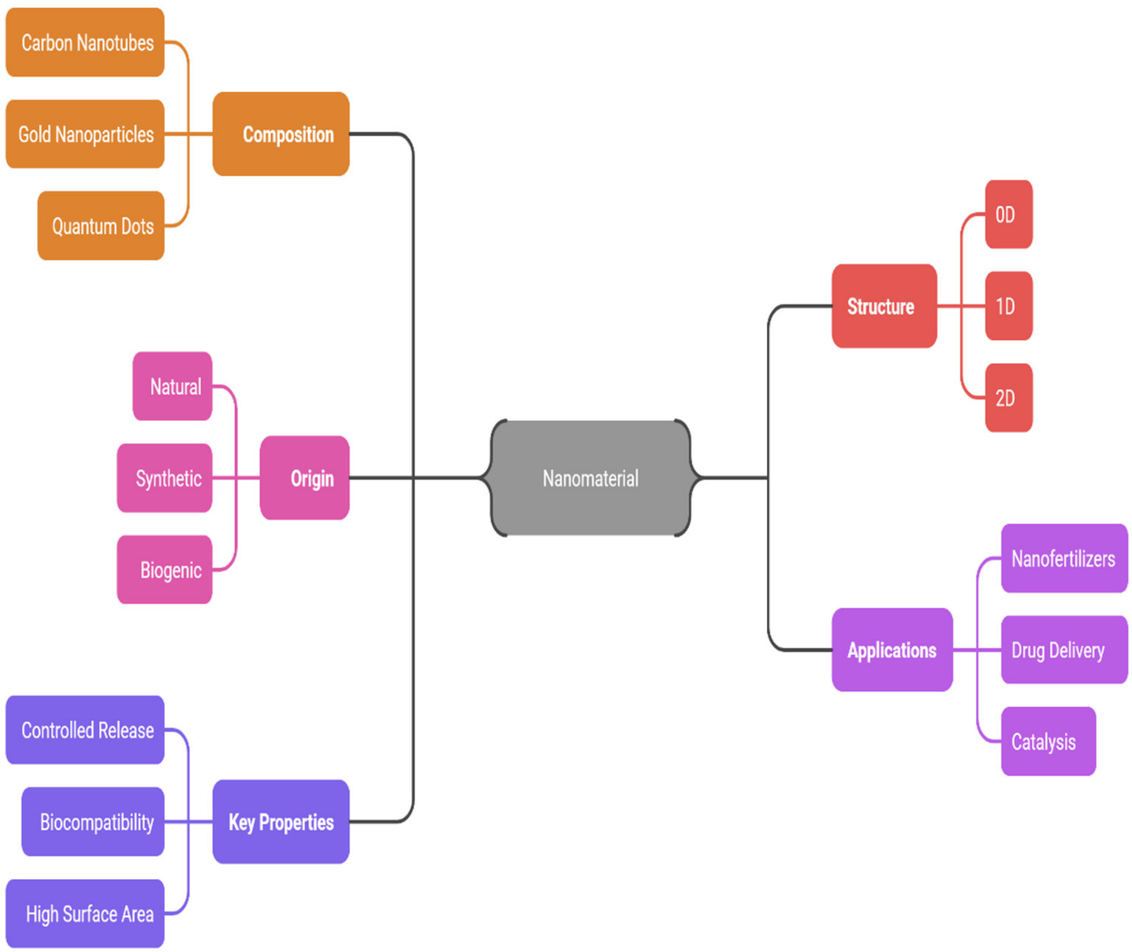

Figure 2: Nanomaterials in agriculture: classification, key properties, and applications.

4 Effect of Various Nanotechnology-Derived Products in Agriculture

4.1 Overview of Nanotechnology Applications in Agriculture

Nanotechnology has brought forth diverse innovations in agriculture, offering transformative solutions across multiple domains including enhanced crop production, pathogen detection, food preservation, wastewater treatment, contaminated soil remediation, and precision resource management, with advanced tools such as pathogen-sensing devices demonstrating significant potential for improved crop yields. To enhance their application in agriculture, numerous scientists have investigated how NMs affect plant germination and growth. ENMs can be broadly categorized into metal, non-metal, and metal oxide nanoparticles, with nano-ferrous/ferric oxides [34], nano-silver [35], nano-gold [36], and nano-copper [37] being the most widely investigated ENMs. The implementation of these nanotechnology-derived products has shown promising results in improving plant growth, enhancing nutrient uptake efficiency, protecting crops from pathogens, and enabling sustainable farming practices through controlled delivery systems and real-time monitoring capabilities.

4.2 Influence of Nanomaterials on Seed Germination and Plant Growth

An essential factor in determining how different NMs may affect plant's later developmental phases is the rate at which seeds germinate, with the onset of seed germination and seedling growth signaled by the appearance of the radicle and plumule. Silver NMs have unique uses in enhancing agricultural output and significantly influence plant growth by inducing physiological and molecular changes, such as reducing the abscission of reproductive organs and enhancing chlorophyll content [38]. According to Razzaq et al. [35], soil application of SNMs positively impacted wheat growth and yield, with treatments of 25–50 ppm of SNMs resulting in increased plant height and greater fresh and dry biomass compared to untreated controls. Shah and Belozerova [39] reported that nanoparticles positively influenced lettuce seed germination and seedling development, with low concentrations of palladium (Pd) and gold (Au), and higher levels of silicon (Si) and copper (Cu), as well as gold-copper (Au-Cu) combinations, showing beneficial effects. NMs also affect metabolic pathways involved in nutrient assimilation in plants, and the use of ENMs is particularly important for boosting the synthesis of key medicinal compounds in plants. Raliya and Tarafdar [40] suggested that improved growth traits and gum content may result from NMs adhering to plant surfaces and entering through nano- or micro-scale pores. Additionally, Joel et al. [41] demonstrated that co-application of ENMs and arbuscular mycorrhizal fungi has a synergistic effect on the soil microbiome, enhancing plant resilience to abiotic stress conditions.

4.3 Role of Nanofertilizers in Enhancing Nutrient Use Efficiency

Notably, nanofertilizers have attracted considerable attention for their ability to greatly improve nutrient uptake efficiency, and these fertilizers typically enhance nutrient delivery by employing one of three methods: encapsulating nutrients within nanoporous structures, coating them with thin polymeric films, or delivering them as nanoscale particles or suspensions [42–44]. The small size of nanoscale fertilizers grants them unique advantages, such as enhanced access to plant surfaces and internal transport channels, ultimately making nutrient delivery more effective [45]. Hydroxyapatite nanoparticles have shown particular promise for phosphorus delivery, while zeolite-based formulations and chitosan nanoparticles are effective for delivering micronutrients such as zinc, iron, and manganese. Studies by Chhipa [46] and Liu and Lal [47] have demonstrated that nano-fertilizers can increase nutrient use efficiency by 30–40% compared to conventional fertilizers, leading to reduced application rates, lower costs for farmers, and decreased environmental pollution from nutrient runoff.

4.4 Nanotechnology in Food Preservation

Beyond on-farm applications, nanotechnology plays an increasingly important role in post-harvest management and food preservation, helping to reduce the substantial losses that occur between harvest and consumption. Nanotechnology has transformed food preservation through the use of edible nano-coatings that serve as protective barriers against gas and moisture transfer, while also delivering additives such as flavors, colors, enzymes, antioxidants, and anti-browning agents effectively prolonging the shelf life of processed foods [48,49]. Nano-packaging materials incorporating silver or zinc oxide nanoparticles provide antimicrobial properties that extend the shelf life of fresh produce by inhibiting the growth of spoilage organisms. Nanosensors embedded in packaging can detect chemical markers of spoilage or ripeness, enabling better quality control and inventory management throughout the supply chain. Nano-coatings applied directly to fruits and vegetables create invisible barriers that reduce respiration rates, moisture loss, and microbial contamination without affecting appearance or taste. Dasgupta et al. [50] estimated that these nano-enabled post-harvest technologies can reduce losses by 30–50%, significantly improving food security and the economic returns for farmers while reducing the environmental burden of food waste.

4.5 Nanotechnology for Pathogen Detection and Disease Management

Nanotechnology has advanced the field of pathogen detection, with biosensors based on carbon nanotubes being effectively applied for quick, user-friendly, and cost-efficient identification of microbes, toxins, and other metabolites in food and beverages [51]. Additionally, silver NMs have demonstrated strong antimicrobial activity; for instance, colloidal nano-silver solutions have shown effective antifungal action against powdery mildew caused by *Sphaerotheca pannosa* var. rosae [52,53]. Kah et al. [54] indicates that nano-pesticides can reduce overall pesticide usage by up to 90% while maintaining or even improving efficacy against target pests and pathogens, representing a significant step toward reducing the environmental footprint of chemical pest control.

4.6 Nanoparticles for Controlled Delivery and Genetic Enhancement in Agriculture

One of the most promising applications of nanotechnology in agriculture is the development of nano-fertilizers that enable controlled and targeted nutrient delivery to plants. These nano-fertilizers encapsulate essential nutrients like nitrogen, phosphorus, and potassium within nanoparticles made from polymers, nanoclays, or other materials, allowing for slow and sustained release that matches plant uptake patterns. Smart, stimuli-responsive nanoparticles are now being directly applied to soils to enable precise, controlled release of fertilizers, fungicides, herbicides, and plant growth regulators, and this targeted delivery approach presents a promising strategy for boosting crop yields sustainably and efficiently [18,55]. Furthermore, nanotechnology has revolutionized plant genetic engineering by providing novel methods for delivering genetic material into plant cells without the need for traditional transformation techniques [56]. Functionalized nanoparticles, including carbon nanotubes, mesoporous silica nanoparticles, and gold nanoparticles, can carry DNA, RNA, or proteins directly into plant cells through the cell wall and membrane barriers that normally restrict uptake. This approach enables transient gene expression or even stable transformation without the integration of foreign DNA into the plant genome, potentially addressing some public concerns about genetically modified organisms. Demirer et al. [57] demonstrated that high aspect ratio NMs can deliver functional genetic material into mature plants without DNA integration, opening possibilities for rapid crop improvement and the development of plants with enhanced stress tolerance, disease resistance, or nutritional quality.

4.7 Nanosensors for Precision Agriculture

The integration of nanosensors into agricultural systems has opened new possibilities for real-time monitoring and precision management of crops and environmental conditions. Carbon nanotube-based sensors can detect specific pathogens, nutrient deficiencies, and biochemical markers in both soil and plants with extraordinary sensitivity and selectivity. Quantum dot sensors enable the monitoring of plant stress responses by detecting changes in fluorescence patterns, while nanobiosensors can continuously measure soil moisture, pH, and nutrient availability. Optical nanosensors have been developed to detect plant hormones and metabolites that indicate disease or stress before visible symptoms appear. As described by Giraldo et al. [58], these nanosensing technologies enable farmers to make data-driven decisions about irrigation, fertilization, and pest management, optimizing resource use and improving crop yields while reducing waste and environmental impact.

4.8 Nano-Enabled Water Management

Water scarcity is one of the most pressing challenges facing global agriculture, and nanotechnology offers several innovative solutions for improving water use efficiency. Nano-clay composites can be incorporated into soil to enhance water retention capacity, reducing irrigation requirements in arid regions. Carbon nanotubes and advanced nanomembranes show promise for water purification and desalination, potentially making brackish or contaminated water sources suitable for agricultural use. Nanoparticle-enhanced hydrogels can absorb and retain large quantities of water, releasing it slowly to plant roots during periods of drought stress. According to Pérez-de-Luque [59], these nano-enabled water management technologies can reduce agricultural water consumption by 20–30% while maintaining or improving crop productivity, which is crucial for sustainable agriculture in water-limited environments.

4.9 Nanomaterials for Soil Remediation and Health

The application of NMs for soil remediation represents an important strategy for restoring degraded agricultural lands and removing contaminants that threaten food safety and environmental health. Zero-valent iron nanoparticles have proven highly effective for immobilizing or removing heavy metals such as lead, cadmium, and arsenic from contaminated soils. Titanium dioxide nanoparticles can catalyze the photodegradation of persistent pesticide residues under sunlight, while nano-biochar improves soil carbon sequestration and fertility. Magnetic nanoparticles offer the unique advantage of being recoverable after use, allowing for the extraction of pollutants from soil with minimal disruption to soil structure. Research by Kah et al. [60] has shown that these NMs can effectively restore contaminated soils to productive use while improving overall soil health through enhanced microbial activity and nutrient cycling.

5 Biostimulants

PB are materials or microorganisms applied to crops to enhance nutrient efficiency, stress tolerance, and overall crop quality—regardless of their direct nutrient content. Even under nutrient-deficient conditions, biostimulants can support sustainable plant growth, making them especially valuable in organic farming systems. Microbial-based biostimulants function through several key mechanisms: (1) supplying nitrogen through biological nitrogen fixation [61], (2) improving the availability of nutrients by solubilizing mineral phosphates and other nutrients through the production of enzymes like phosphatases and compounds such as organic acids and siderophores [62], and (3) expanding the root access to the soil, allowing better nutrient uptake [63].

5.1 Usage Guidelines for Microbial Biostimulants

Plant growth-promoting bacteria, non-pathogenic fungi, arbuscular mycorrhizal fungi, protozoa, and nematodes are all examples of microbial biostimulants. It is necessary to follow the manufacturer's use instructions related to application methods, soil physical and chemical properties, microbial competition, and crop-specific compatibility with extreme caution (Table 2), when biostimulants are applied.

Table 2: Key environmental and management factors influencing the effectiveness of biostimulants and microbial inoculants in agricultural systems.

Parameter/Condition	Practical Consideration for Application	Effect on Biostimulant Performance
Production, storage, and application process	Follow manufacturer-recommended storage temperature, shelf-life, and application protocol	Improper storage or handling may reduce viability and efficacy of active compounds or microorganisms
Soil water potential, temperature, and clay content	Avoid extreme moisture stress, temperature fluctuations, and excessive clay content	Unfavourable soil physical conditions reduce microbial survival, colonization, and nutrient availability
Soil chemical properties (pH, nutrient availability)	Conduct soil testing before application if soil chemical status is unknown	Soil pH and nutrient status influence microbial activity, nutrient solubility, and plant response
Competition with native soil microorganisms	Ensure proper dose and compatible formulation	Native microbial populations may suppress introduced beneficial strains, affecting inoculant efficiency
Crop species and agronomic management practices	Select crop-specific formulations and integrate with appropriate nutrient management practices	Plant genotype and agronomic inputs influence compatibility, colonization efficiency, and overall effectiveness

5.2 Different Types of Plant Biostimulants and Their Impact

5.2.1 Microbial Inoculants

Inoculants are beneficial microorganisms that are applied to the soil or in plants to increase productivity and crop health. Several natural products are increasingly utilized for pest management and for improving soil fertility and crop quality, ultimately contributing to enhanced agricultural sustainability and food safety. In the past twenty years, microbial inoculants have become more popular in horticulture in addition to biostimulants. The most widely used microbial inoculants include plant growth-promoting rhizobacteria (PGPR) and endophytic fungi such as arbuscular mycorrhizal fungi (AMF) and *Trichoderma* species [13,61,63]. Taie et al. [64] reported a 75% increase in phenolic acid production in soybean seedlings inoculated with rhizobacteria. Similarly, Karthikeyan et al. [65] found that treating *Catharanthus roseus* with *Pseudomonas fluorescens* and *Bacillus megaterium* significantly enhanced alkaloid content. Biofertilizers also improve the nutritional quality of fresh vegetables by increasing antioxidant activity, total phenolics, and chlorophyll content. For instance, spinach treated with biofertilizers showed 58.7% and 51.4% higher total phenolic levels compared to untreated controls [66]. In lettuce, inoculation with *Azotobacter chroococcum* and *Glomus fasciculatum* led to elevated levels of total phenolics, anthocyanins, and carotenoids [67].

5.2.2 Protein hydrolysates

Protein hydrolysates (PH) are composed of polypeptides, oligopeptides, and amino acids obtained from the breakdown of protein-based materials. Plant- and animal-derived PH is used in the manufacture of a number of commercial products. Crop yields and quality characteristics have shown varying, but generally significant improvements in the past few decades in agricultural and horticultural crops [61]. Recent research has evaluated the safety of animal-derived hydrolyzed proteins using yeast and plant models, finding no signs of genotoxicity, ecotoxicity, or phytotoxicity. Nevertheless, concerns are growing over the inclusion of protein hydrolysates from animal by-products within the food chain, particularly because current regulations such as the European Commission Regulation (EC) No 1069/2009 impose strict guidelines on the processing, use, and safety of animal-by-product–derived materials to prevent risks associated with food safety and public health.

Matsumiya and Kubo [68] identified a short bioactive peptide, termed a "root hair promoting peptide", in soybean-derived protein hydrolysate (PH). This peptide enhanced the formation of adventitious roots in tomato cuttings and increased the development of root hair in *Brassica rapa*. Ertani et al. [69] discovered that two PHs stimulated nitrate assimilation by increasing nitrate reductase activity, glutamine synthetase activity, and the high induction of glutamine synthetase isoforms in leaves and roots of corn seedlings. Furthermore, Forde and Lea [70] demonstrated that even at very low doses, glutamate significantly modifies root architecture by reducing the growth of the main root and promoting branching close to the root apex. Similarly,

5.2.3 Humic Acids

Humic substances (HS) include three main components: humin, which is water-insoluble at all pH levels; fulvic acid (FA), soluble in water across all pH ranges; and humic acid (HA), which dissolves in water under alkaline conditions. According to Huang and Hardie [71], HA appears dark brown to black and precipitates at low pH, becoming soluble as pH increases. Both HA and FA act as weak acid polyelectrolytes in aqueous solutions, capable of buffering across a wide pH spectrum [72]. HA plays a vital role in supporting plant growth by improving soil structure, fertility, and moisture retention [73]. Moreover, it improves soil microbial activity [74]. Although not as effective as synthetic chelating agents, HA also has the capacity to bind metal ions and micronutrients, making it a beneficial input in agriculture [75]. When HS was made of compost or vermicompost compared to those made from brown coal, the former appeared to be more efficient and had a nonlinear impact on growth response [76].

5.2.4 Seaweed Extract

A complex of polysaccharides, fatty acids, vitamins, phytohormones, and minerals is one of the bioactive substances found in seaweed extract (SWE) [77]. Several studies have shown that the application of SWE to cuttings or plants stimulates the development of roots and histogenesis [78]. Vernieri et al. [79] reported that supplementing nutrient solutions with seaweed extract (SWE) significantly increased root biomass in hydroponically grown rocket plants, especially under conditions limited by nutrients. Similarly, Hernández-Herrera et al. [80] observed that extracts rich in polysaccharides greatly enhanced root development. Their findings suggest that oligosaccharides may function as signaling molecules, influencing internal phytohormone pathways by selectively modulating the expression of genes involved in phytohormone metabolism.

Seaweed extracts, particularly from brown algae species such as *Ascophyllum nodosum*, have demonstrated significant biostimulant effects in agricultural applications through multiple physiological mechanisms. Foliar application of *Ascophyllum nodosum* extract at 0.2% concentration increased tomato yield by 15–20% and enhanced fruit quality parameters including total soluble solids and lycopene content by 12–18% compared to untreated controls [38]. The biostimulant effect is mainly attributed to bioactive constituents, including alginates, fucoidans, laminarins, and phytohormone-like compounds. Application of Ecklonia maxima extract at 2.5 L ha^{-1} increased lettuce fresh weight by 41% and enhanced nitrogen uptake efficiency by 28%. The treatment also mitigated transplant shock and accelerated root establishment by 5–7 days [81]. Seaweed extracts also demonstrate plant defense priming capabilities, with *Sargassum* extract application at 3% concentration reducing powdery mildew incidence in cucumber by 62% through enhanced accumulation of defense-related enzymes including peroxidase and polyphenol oxidase [82].

5.2.5 Chitosan

Chitosan, a deacetylated derivative of chitin, is widely used in agriculture due to its strong elicitor activity. Its polycationic nature enables interaction with plant cell receptors, triggering defense-related signaling such as hydrogen peroxide generation and Ca^{2+} influx. These responses activate pathways that strengthen plant immunity and regulate stress signaling [83]. Beyond antifungal action, chitosan enhances tolerance to drought, salinity, and cold, and improves key physiological and metabolic traits that contribute to better crop growth and quality [84].

5.3 Interactive Effects among Different Biostimulants

In several crops, the effects of microbial and non-microbial biostimulants are synergistic or additive [85]. The application of HA and SWE led to notable improvements in groundnut plant height and branching—by 34.5% and 33% for HA, and 17.2% and 60% for SWE, respectively, compared to untreated controls. When applied together, these two biostimulants enhanced height and branching by 65% and 100%, respectively [86]. Giordano et al. [87] assessed the impact of two plant-derived biostimulants: PE and PH. These products contain various levels of free amino acids, peptides, carbohydrates, and mineral elements, with PE also including phytohormones and vitamins. The study showed that PE exhibited hormone-like effects and improved plant tolerance to environmental stresses, while PH boosted photosynthetic activity and nitrogen metabolism across various horticultural crops.

Scaglia et al. [88], discovered that a number of tiny chemical molecules, including amino acids, carboxylic linear acids, and aromatic carboxylic acids, have the ability to cause auxin-like reactions in a plant, such as the stimulation of root growth, which possibly include the chemical compounds that give humic acids their auxin-like properties. Furthermore, according to Zandonadi et al. [89], HS increased the synthesis, activity, and expression of plasma membrane H^+-ATPase, promoting lateral root induction and root hair growth. In addition, it promoted the expression of IAA5 and IAA19, two early auxin-responsive genes.

Various techniques—including microarrays, metabolomics, proteomics, and transcriptomics—have been employed to identify the active components of biostimulants. These approaches have been instrumental in the examination of changes in gene expression after the application of biostimulants [90,91]. The application of biostimulant chemicals can improve nutrient uptake and assimilation, according to several experiments conducted in greenhouses and open fields [92]. Higher soil enzymatic and microbial activity, changes in root architecture, and improved micronutrient mobility and solubility have been associated with increased plant nutrient uptake [69,93,94]. *Bacillus mucilaginous* and *Bacillus megaterium* were two strains of PGPR that, in addition to P, were able to increase K availability and release K from immobile forms in the soil [95–97]. Additionally, by creating siderophores, PGPR and *Trichoderma atroviride* can increase iron solubility, enhancing plant uptake and translocation. AMFs, which are defined as advantageous associations between soil fungi and plant roots, can also increase the availability of P in organic farming systems with nutrient deficiency/availability [98–100]. The development of soluble HS complexes with micronutrients is another significant benefit of HS on the availability of soil nutrients for plant uptake (i.e., iron). Intact complexes of cation-FA micronutrients appeared to be absorbed by plants because FAs have small molecules that can easily enter plant cells and the plasmalemma [101]. In contrast, humic acids have large molecules that cannot enter plant cells and can only interact with the cell wall [102,103].

6 Conceptual Mechanistic Framework for Nano–Biostimulant Synergy

This review proposes a unified mechanistic model describing how NMs enhance the stability, mobility, and efficacy of biostimulants at multiple biological scales. The conceptual framework integrates five mechanistic pillars:

a. Nanocarrier-enabled protection and controlled release

NMs protect labile biostimulant molecules (enzymes, peptides, PGPR metabolites) from UV degradation, oxidation, and soil adsorption, enabling sustained availability [104].

b. Enhanced root-zone delivery and uptake

Nano-sizing increases mobility in rhizosphere pores, improving biostimulant access to root mucilage and enhancing colonization/absorption pathways [105].

c. Molecular signalling amplification

Nanoparticles modulate ROS (H_2O_2) bursts, Ca^{2+} fluxes, MAPK phosphorylation, and transcriptional activation thus potentiating biostimulant signalling pathways [106].

d. Improved nutrient mobilization and assimilation

Nano-metals, nano-silica, and nano-carbon enhance enzymatic activities (nitrate reductase, phosphatases, siderophore release), supporting PB-driven nutrient uptake [107].

e. Stress-response integration

Combined PB + NM treatments synergistically regulate antioxidant enzymes (SOD, CAT, POD), osmoprotectant accumulation, membrane stability, and ion homeostasis [108].

This conceptual model provides a predictive understanding of how nano–biostimulant interactions operate beyond empirical observations and guides the design of next-generation nano-enabled bioformulations (Fig. 3).

7 Interactive Influence of Nanomaterials and Biostimulants

The synergy between NMs and biostimulants represents a novel and rapidly emerging advancement in sustainable agriculture (Fig. 4). This combined approach introduces unique functional benefits such as enhanced antioxidant regulation, improved nutrient mobilization, and more efficient delivery of bioactive compounds—that are not achievable when either NMs or biostimulants are used alone. Instead of functioning as independent inputs, NMs and biostimulants interact through interconnected biochemical and physiological pathways. These interactions create predictable synergistic effects based on the conceptual framework described above.

In recent years, the combined use of NM and biostimulants has advanced beyond preliminary research and is gaining traction as a viable agricultural strategy. This synergy is mainly attributed to enhanced antioxidant activity and improved metabolic regulation during plant growth and development. The capping strategy-a method that has already been widely used in other fields—demonstrates this progress. As noted by Jíménez-Arias [109], encapsulation technologies, already applied in agriculture, could be adapted for biostimulants using natural polymers and various encapsulation methods. A particularly promising approach involves nanoencapsulating active ingredients within eco-friendly carriers such as cellulose, fly ash, clay-based particles, iron oxide, and hydroxyapatite nanoparticles of different sizes. Often derived from waste materials, these nanocarriers represent a valuable yet underexploited resource. Among them, nanocellulose is especially notable for its high water retention, excellent mechanical strength, and accessibility from sources such as agricultural and forest residues, algae waste, and industrial byproducts [110].

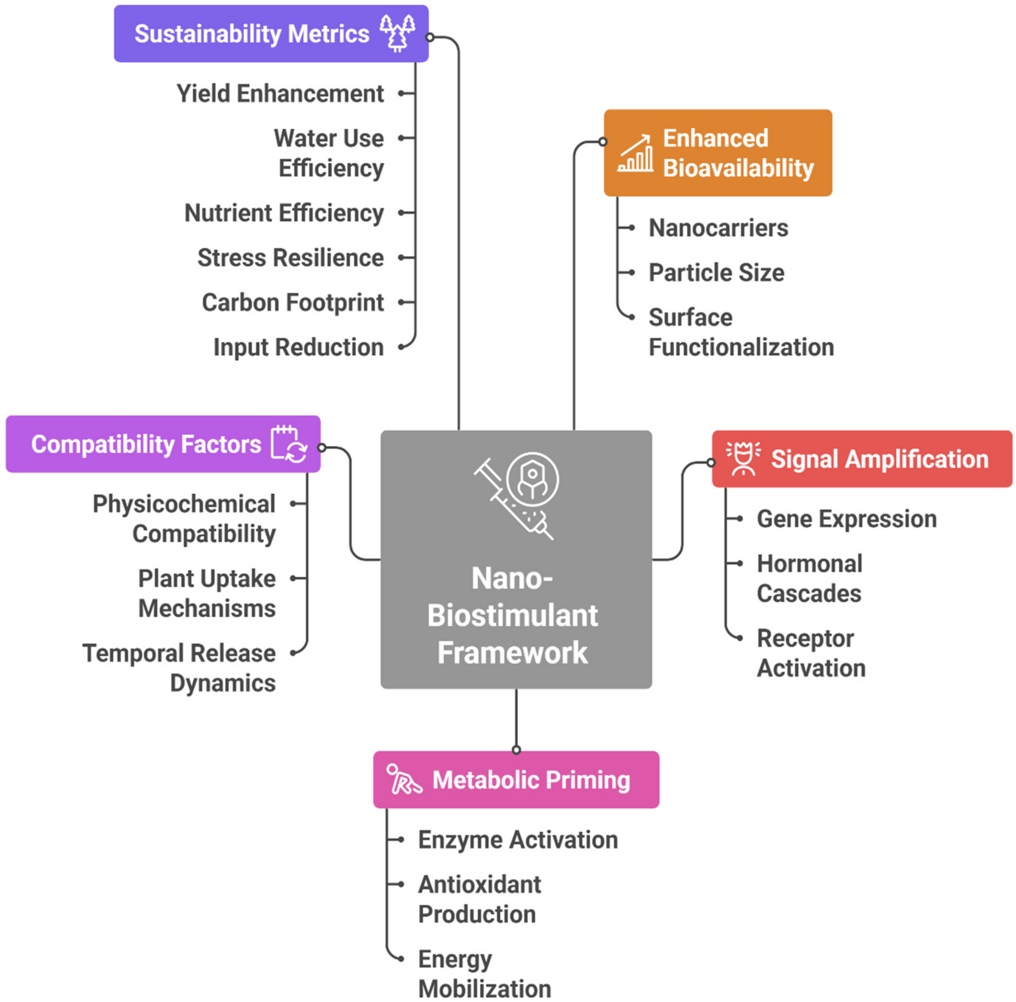

Figure 3: Nano-biostimulant synergies: mechanism and outcomes.

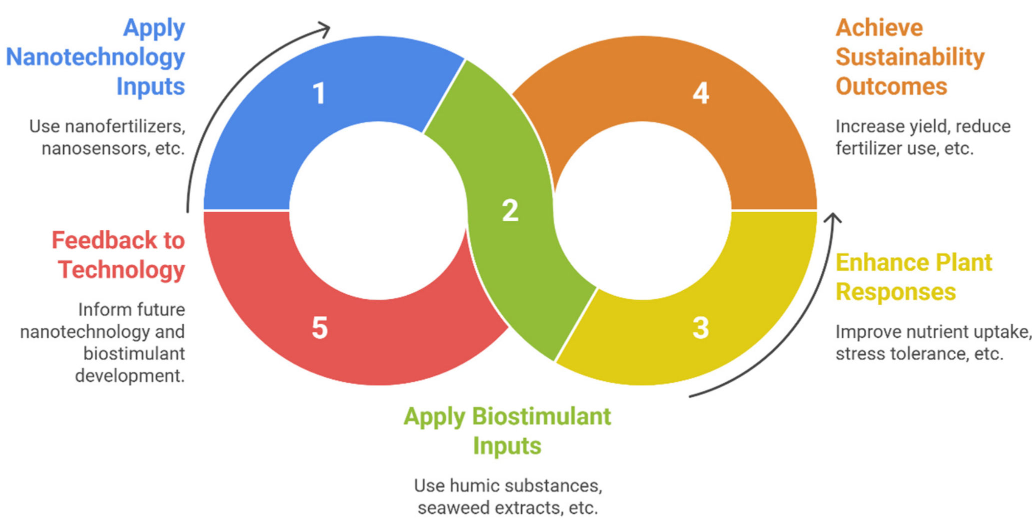

Figure 4: Linkages between nanotechnology, biostimulants, plant responses, and sustainability outcomes.

Al-Ramamneh [111] revealed that although light-harvesting efficiency and photochemical capacity remained largely unaffected except at 60 mg L^{-1} silver NM, silver NM treatments, *Ascophyllum nodosum* and *Spirulina platensis* elevated H_2O_2 levels, total phenolic production related to H_2O_2 bursts, and overall biostimulants improved antioxidant activity and induced variable phenolic accumulation in *Santolina chamaecyparissus*. The effects of NM, a biostimulant, and their combination (zinc oxide NM with biostimulant) on plant cell metabolism were investigated in the cytosol, chloroplasts, and mitochondria of stem, root, and leaf cells [112]. The interaction between NMs and biostimulants produced a more significant positive effect on both morphological and physiological indicators of plant health than the application of either component alone. In particular, the combined use of Folcare biostimulant and zinc oxide NM markedly enhanced the growth of pea crops. This improvement in the quality of pea plant is likely due, at least in part, to the elevated antioxidant activity observed during key stages of development. Al-Saif et al. [113] reported that the combined foliar application of 0.2% yeast extract (YE) + 0.02% potassium nanoparticles (KNPs) resulted in the highest values for yield, bunch weight, fruit weight, flesh weight, soluble solid content, total and reducing sugars, vitamin C, total chlorophyll, and carotene. Similarly, treatments with 0.4% seaweed extract (SWE) + 0.02% K NPs, 0.4% fulvic acid (FA) + 0.02% KNPs, and 6% moringa leaf extract (MLE) also showed significant improvements in these parameters compared with the control and other sprayed treatments. In another study, Matthews et al. [114] observed that red chilies harvested from plants without nano-biostimulant treatment exhibited the highest phenolic content (1.332 ± 0.56 mg L^{-1}) compared with those treated with nano-biostimulants (0.883 ± 0.19 mg L^{-1}). These findings demonstrate the potential of nano-encapsulated microbial and botanical biostimulants to improve the nutritional and postharvest quality of chili fruits. Similarly, Osman et al. [115] found that foliar application of halophyte extract (*Arthrocnemum macrostachyum*) effectively mitigated the adverse effects of salinity stress (75 and 150 mM NaCl) in soybean, improving both growth parameters and photosynthetic pigment content. In onion, the combined application of 1.0 g L^{-1} Nano NPK + 0.5 g L^{-1} algae extract produced the highest yield (25.67 t ha^{-1}), whereas the control treatment resulted in the lowest yield (10.09 t ha^{-1}) [116].

However, more research is required to elucidate the complex interactions between biostimulants, nanosystems, plants, and the environment. Although each approach offers distinct advantages and challenges, factors such as plant response efficiency, loading capacity, sustainability of NM production, and economic feasibility must be carefully considered. Despite the extensive evidence supporting the benefits of NMs in seed germination, nutrient uptake, stress tolerance, and pathogen control, the literature also presents several contradictory findings. Many studies report a clear dose-dependent pattern, where low nanoparticle concentrations stimulate growth while higher concentrations induce oxidative stress, membrane damage, or inhibition of key physiological pathways [117,118]. For instance, metal-based nanoparticles such as ZnO, Fe_2O_3, and AgNPs enhance enzymatic activity at low doses but trigger lipid peroxidation and disruption of root cell architecture at elevated levels. Carbon-based NMs improve photosynthesis in some species but have been shown to impair chloroplast ultrastructure or alter gene expression in others. Additionally, several studies highlight the potential negative impacts on beneficial soil microbes, nutrient cycling, and long-term soil health [119]. These inconsistencies emphasize that nano–bio interactions are highly context-dependent, influenced by particle size, coating, concentration, crop species, growth stage, and exposure duration. Therefore, a balanced evaluation of both beneficial and adverse effects is crucial for developing safe, optimized, and standardized nano-enabled agricultural practices.

8 Limitations and Risks

Multiple studies indicate that NMs toxicity is concentration-dependent, with metal-oxide NPs (ZnO, CuO, TiO_2) causing ROS overproduction, membrane damage, and microbial suppression at higher doses [120]. Soil studies also show 20–40% declines in microbial biomass with AgNP exposure [121]. NMs exhibit size-dependent toxicity, with studies showing that titanium dioxide nanoparticles can induce oxidative stress and inflammatory responses in lung tissue at concentrations as low as 5 mg kg^{-1} body weight, while silver nanoparticles demonstrate antimicrobial efficacy but also cytotoxic effects with IC50 values ranging from 10–100 μg mL^{-1} depending on cell type [122,123]. To address such risks, international frameworks such as EU REACH and FAO guidelines for nanotechnologies in food and agriculture mandate physicochemical characterization, exposure assessment, and environmental fate analysis prior to approval. The EU REACH regulation [124] requires registration and safety assessment of NMs as distinct substances when ≥50% of particles fall within the 1–100 nm size range, while the FAO/WHO Expert Meeting on Nanotechnology in Food and Agriculture [125] has called for case-by-case risk assessments due to insufficient data on long-term exposure effects and bioaccumulation potential. Incorporating these evidence-based regulatory requirements is essential for responsible and transparent agricultural use of NMs.

Nanotechnology and biostimulants offer promising applications in agriculture, but concerns regarding toxicity, environmental persistence, and ecological impacts must be addressed before large-scale adoption [126]. The high reactivity and mobility of engineered NMs raise the risk of their accumulation in soil. Some PB compounds, particularly those derived from chemical synthesis or industrial by-products, can disturb soil biochemical balance when overapplied. Research also shows that certain metal and metal oxide nanoparticles can exhibit phytotoxicity at high concentrations, affecting cellular processes, root growth, and oxidative stress responses [127]. Likewise, excessive or poorly formulated PBs may lead to nutrient imbalances, shifts in microbial diversity, or unintended interactions with agrochemicals. The long-term fate of NMs in soil is still poorly understood. Uncertainties remain regarding their biodegradation, transformation pathways, interactions with soil microbiota, and potential biomagnification through food webs, all of which pose risks to soil health and ecosystem stability [128]. PBs face similar challenges, as variations in raw materials and compositions limit their consistency and predictability under field conditions.

The long-term fate and behaviour of NMs in soil remain poorly understood, yet the limited evidence available provides some direction regarding their transformation and ecological implications. Over multi-year periods, metal-based nanoparticles such as ZnO and CuO typically undergo gradual dissolution, releasing metal ions that subsequently bind with carbonates, phosphates, or organic matter, forming more stable secondary mineral complexes; however, the exact 5–10 year transformation pathways are still not fully mapped due to the scarcity of long-term field studies. These aging processes generally reduce nanoparticle bioavailability and toxicity through aggregation, surface coating, and immobilization, although episodic remobilization may occur in acidic or fluctuating soil conditions. Interactions with soil microbiota remain another significant uncertainty, as nanoparticles can initially inhibit key microbial enzymes and alter community composition, with effects tending to weaken over time as nanoparticles become less reactive. Current evidence also indicates that while nanoparticles can accumulate in plants and soil fauna, true biomagnification across trophic levels appears limited, though not entirely absent. Collectively, these partially answered yet still unresolved questions highlight the need for long-duration field trials and mechanistic studies to adequately assess the ecological risks associated with NMs applications in agriculture [129].

Food safety concerns also arise from the possible movement of nanoparticles or PB residues into edible plant tissues. Their translocation from roots to shootsand eventually into grains, fruits, and vegetables-may expose consumers to these materials, yet toxicological data on chronic dietary exposure remain scarce. Regulatory frameworks for agricultural nanotechnology and biostimulants are still fragmented, with many countries lacking clear guidelines for registration, risk assessment, and post-market monitoring [130]. Environmental sustainability depends on the biodegradability, persistence, and ecotoxicological behaviour of nanocarriers and active compounds [131]. Poor degradation or unintended accumulation of these materials may disrupt soil microflora, soil fauna, and nutrient cycling. Therefore, comprehensive life-cycle assessments, ecotoxicity evaluations, and risk–benefit analyses are essential to ensure that nano-biostimulants support long-term sustainability rather than introduce new environmental risks [132].

From an economic perspective, both nanotechnology and biostimulants face significant barriers to large-scale adoption [133]. The high production costs of engineered NMs and certain bioactive compounds used in PBs remain prohibitive, particularly for smallholder farmers in developing countries who operate with limited capital and narrow profit margins. The synthesis of high-purity, uniform NMs requires sophisticated equipment and quality assurance protocols, while the production of consistent, efficacious biostimulants demands standardized extraction, fermentation, or formulation technologies. Consequently, nano-based agricultural inputs are often more expensive than conventional fertilizers, pesticides, or amendments, with cost–benefit analyses suggesting that farmers would need yield gains of 15–30% or more to justify their use [134]. Infrastructure requirements for safe handling, storage, and application of NMs add further economic burdens, while biostimulant products may require cold-chain logistics or specific storage conditions to maintain bioactivity. The lack of established supply chains, distribution networks, and quality certification mechanisms for nano-agricultural products especially in rural areas creates accessibility challenges and increases transaction costs for end users. Additionally, the absence of standardized testing and efficacy evaluation methods under diverse field conditions makes it difficult for farmers to make informed decisions [135]. Product performance claims for both NMs and PBs often rely on controlled laboratory or greenhouse trials that may not reflect real-world variability in soil types, climatic conditions, or crop species. These scientific uncertainties regarding efficacy, environmental persistence, toxicity, and ecological interactions highlight the urgent need for clear regulatory frameworks, harmonized evaluation protocols, and standardized risk assessment approaches to ensure the safe, economically viable, and sustainable adoption of nano-enabled biostimulants in agriculture.

9 Policy and Regulatory Outlook

The rapid advancement of nano-enabled agricultural inputs, including nano-fertilizers, nano-pesticides, and nano-biostimulants, has outpaced the development of dedicated regulatory frameworks, creating uncertainty for policymakers, industry stakeholders, and farmers. Existing regulatory systems were primarily designed for conventional agrochemicals and often do not adequately address nano-specific characteristics such as particle size distribution, high surface reactivity, altered bioavailability, and potential long-term environmental persistence. Therefore, strengthening regulatory clarity is essential to ensure the safe and responsible adoption of nano-enabled agricultural technologies.

In the United States, the Environmental Protection Agency (US EPA) regulates pesticide products, including nano-enabled pesticides, under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) [136,137]. Under this framework, nano-pesticides are generally evaluated within the existing pesticide registration structure; however, additional data requirements may be imposed where nanoscale properties influence toxicity, environmental fate, exposure pathways, or persistence. The EPA has emphasized case-specific evaluation of nanomaterials, requiring detailed physicochemical characterization, environmental risk assessment, and toxicological evaluation to determine product safety. This adaptive regulatory strategy ensures flexibility but also highlights the need for standardized nano-specific testing protocols.

India has taken significant initial steps toward regulating nano-agricultural products through the "Guidelines for Evaluation of Nano-based Agri-input and Food Products in India" developed by the Department of Biotechnology (DBT) in collaboration with regulatory agencies. In addition, nano-fertilizers such as nano urea have been incorporated under the Fertiliser Control Order (FCO), representing an important milestone in formal regulatory acceptance of nano-enabled inputs. Despite these developments, regulatory gaps remain, particularly regarding standardized definitions of nano-biostimulants, residue monitoring protocols, labelling requirements, environmental risk assessment frameworks, and long-term soil health surveillance [138,139]. The absence of an integrated regulatory pathway covering nano-fertilizers, nano-pesticides, and nano-biostimulants under a unified framework creates uncertainty for product developers and regulatory agencies.

At the international level, harmonization efforts are gradually emerging through organizations such as the Organisation for Economic Co-operation and Development (OECD), which provides guidance documents and standardized test protocols for nanomaterial safety assessment. OECD Test Guidelines and harmonized reporting templates support consistent evaluation of physicochemical properties, environmental fate, and ecotoxicological risks of engineered nanomaterials [140,141]. However, globally accepted regulatory definitions and standardized approval pathways specific to nano-enabled agricultural inputs are still evolving. Differences in regulatory triggers, risk assessment procedures, and data requirements across countries continue to present barriers for commercialization and international trade of nano-agricultural products.

Future regulatory progress should focus on establishing harmonized definitions for nano-enabled agricultural inputs, integrating nano-specific endpoints into environmental risk assessment frameworks, strengthening post-market monitoring systems, and promoting interdisciplinary collaboration among regulatory agencies, researchers, and industry stakeholders. Policy incentives supporting green synthesis approaches, life-cycle risk assessment, and transparent labeling mechanisms can further improve public trust and promote responsible innovation. A coordinated international regulatory strategy will be critical to ensuring that nano-biostimulants and related technologies contribute effectively to sustainable agricultural intensification while maintaining environmental and food safety standards. A comparative summary of regulatory approaches for nano-agricultural products in major jurisdictions is presented in Table 3.

Table 3: Regulatory approaches for nano-agricultural products in major jurisdictions.

Region	Regulatory Framework	Current Regulatory Approach	Strengths	Key Gaps
United States	US EPA under FIFRA (Federal Insecticide, Fungicide, and Rodenticide Act)	Nano-pesticides regulated within existing pesticide framework; nano-specific data required where physicochemical properties differ from conventional formulations	Established registration structure; risk-based evaluation system	Lack of dedicated nano-specific pesticide regulation; case-by-case uncertainty
India	DBT guidelines; Fertiliser Control Order (FCO)	Evaluation guidelines exist for nano-agri inputs; nano urea included under FCO	Early adoption of nano-fertilizer regulation; defined evaluation pathway	Lack of unified framework for nano-biostimulants and nano-pesticides
International (OECD)	OECD test guidelines for nanomaterials	Harmonized test protocols for physicochemical characterization and environmental risk assessment	Promotes global consistency in risk evaluation	No globally harmonized regulatory approval framework

10 Conclusion and Future Perspective

The agricultural sector is increasingly challenged by population pressures, climate change, and a range of geogenic constraints, prompting growing interest in nano-agrotechnology as a promising strategy for enhancing crop productivity and promoting sustainability. Although several studies indicate that nanotechnology-based fertilizers and pesticides can improve input-use efficiency, the associated economic benefits remain variable and are not yet universally supported by comprehensive evidence. Similarly, nano-enabled biosensors provide advanced capabilities for monitoring soil, crop, and microclimatic conditions, yet their practical cost-effectiveness and scalability have not been conclusively established in field settings. To advance responsible deployment, research must extend beyond mechanistic evaluations of plant–nanoparticle interactions to include rigorous techno-economic assessments, long-term environmental impact analyses, and context-specific socio-economic feasibility studies. Broader acceptance of these technologies will depend on coordinated efforts and transparent engagement among governmental agencies, research institutions, non-governmental organizations, consumer groups, and other stakeholders. Furthermore, effective integration of nanotechnology and biostimulants into agricultural systems will require reductions in production costs through innovations in synthesis and formulation, development of evidence-based policy incentives, enhanced extension and farmer-awareness programs, and the establishment of robust, science-driven regulatory frameworks that ensure safety while fostering sustainable technological advancement.

The primary objective of this review was to establish a scientific framework for assessing how NMs and PBs (substances and/or microorganisms) can improve plant resilience to nutrient limitations under different cropping systems. Although numerous studies have demonstrated the positive effects of NMs and PBs on crop growth, yield, quality, and tolerance to chemical soil stress especially nutrient deficiencies these findings are primary related to conventional agriculture. Currently, there is a lack of data on the potential benefits of PBs and nanotechnology in different food production systems. Therefore, more research is needed to elucidate the mechanisms of PBs and NMs in overcoming nutrient-related constraints and to bridge the yield gap between conventional and modern agriculture. This includes identifying optimal doses, application timings, and methods customized to specific crop species and environmental conditions. Unlike previous reviews, this article synthesizes the mechanistic interactions between NMs and PB and proposes an integrative conceptual framework explaining their synergistic behavior. This framework addresses a critical gap in the literature and provides a scientific basis to guide the rational design and optimization of nano-enabled biostimulant formulations.

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References

1. Mikhaylov A, Moiseev N, Aleshin K, Burkhardt T. Global climate change and greenhouse effect. Entrep Sustain Issues. 2020;7(4):2897–913. [CrossRef].
2. Jan A, Pirzadah TB, Malik B. Nanotechnology: An innovative tool to enhance crop production. In: Nanobiotechnology in agriculture. Berlin/Heidelberg, Germany: Springer; 2020. p. 163–70. [CrossRef].
3. Woodhill J, Kishore A, Njuki J, Jones K, Hasnain S. Food systems and rural wellbeing: Challenges and opportunities. Food Secur. 2022;14(5):1099–121. [CrossRef].
4. Said Z, Vigneshwaran P, Shaik S, Rauf A, Ahmad Z. Climate and carbon policy pathways for sustainable food systems. Environ Sustain Indic. 2025;27:100730. [CrossRef].
5. Dorais M, Alsanius BW. Recent advances in organic horticulture technology and management. Sci Hortic. 2016;208:1–2. [CrossRef].
6. Willer H, Lernoud J. The world of organic agriculture—Statistics and emerging trends. Frick, Switzerland: Research Institute of Organic Agriculture; 2016.
7. Dorais M, Alsanius B. Advances and trends in organic fruit and vegetable farming research. In: Horticultural reviews. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2015. p. 185–268. [CrossRef].
8. Seufert V, Ramankutty N, Foley JA. Comparing the yields of organic and conventional agriculture. Nature. 2012;485(7397):229–32. [CrossRef].
9. Clark MS, Horwath WR, Shennan C, Scow KM, Lantni WT, Ferris H. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. Agric Ecosyst Environ. 1999;73(3):257–70. [CrossRef].
10. Tuomisto HL, Hodge ID, Riordan P, MacDonald DW. Does organic farming reduce environmental impacts?—A meta-analysis of European research. J Environ Manag. 2012;112:309–20. [CrossRef].
11. Lester GE, Saftner RA. Organically versus conventionally grown produce: Common production inputs, nutritional quality, and nitrogen delivery between the two systems. J Agric Food Chem. 2011;59(19):10401–6. [CrossRef].
12. De Pascale S, Maggio A, Orsini F, Barbieri G. Cultivar, soil type, nitrogen source and irrigation regime as quality determinants of organically grown tomatoes. Sci Hortic. 2016;199:88–94. [CrossRef].
13. Rouphael Y, De Micco V, Arena C, Raimondi G, Colla G, De Pascale S. Effect of *Ecklonia maxima* seaweed extract on yield, mineral composition, gas exchange, and leaf anatomy of zucchini squash grown under saline conditions. J Appl Phycol. 2017;29(1):459–70. [CrossRef].
14. du Jardin P. Plant biostimulants: Definition, concept, main categories and regulation. Sci Hortic. 2015;196:3–14. [CrossRef].
15. Johnson R, Joel JM, Puthur JT. Biostimulants: The futuristic sustainable approach for alleviating crop productivity and abiotic stress tolerance. J Plant Growth Regul. 2024;43(3):659–74. [CrossRef].
16. Tolisano C, Del Buono D. Biobased: Biostimulants and biogenic nanoparticles enter the scene. Sci Total Environ. 2023;885:163912. [CrossRef].
17. Pirzadah TB, Malik B, Maqbool T, Rehman RU. Development of nano-bioformulations of nutrients for sustainable agriculture. In: Nanobiotechnology in bioformulations. Berlin/Heidelberg, Germany: Springer; 2019. p. 381–94. [CrossRef].
18. Alam MW, Junaid PM, Gulzar Y, Abebe B, Awad M, Quazi SA. Advancing agriculture with functional NM: "pathways to sustainable and smart farming technologies". Discov Nano. 2024;19(1):197. [CrossRef].
19. Chen H, Roco MC, Son J, Jiang S, Larson CA, Gao Q. Global nanotechnology development from 1991 to 2012: Patents, scientific publications, and effect of NSF funding. J Nanopart Res. 2013;15(9):1951. [CrossRef].
20. Naderi MR, Danesh-Shahraki A. Nanofertilizers and their roles in sustainable agriculture. Int J Agric Crop Sci. 2013;19:2229–32.
21. Liu S, Yuan L, Yue X, Zheng Z, Tang Z. Recent advances in nanosensors for organophosphate pesticide detection. Adv Powder Technol. 2008;19(5):419–41. [CrossRef].
22. Nair R, Poulose AC, Nagaoka Y, Yoshida Y, Maekawa T, Kumar DS. Uptake of FITC labeled silica nanoparticles and quantum dots by rice seedlings: Effects on seed germination and their potential as biolabels for plants. J Fluoresc. 2011;21(6):2057–68. [CrossRef].

23. Rana RA, Siddiqui MN, Skalicky M, Brestic M, Hossain A, Kayesh E, et al. Prospects of nanotechnology in improving the productivity and quality of horticultural crops. Horticulturae. 2021;7(10):332. [CrossRef].
24. Di Sario L, Boeri P, Matus JT, Pizzio GA. Plant biostimulants to enhance abiotic stress resilience in crops. Int J Mol Sci. 2025;26(3):1129. [CrossRef].
25. Rouphael Y, Cardarelli M, Bonini P, Colla G. Synergistic action of a microbial-based biostimulant and a plant derived-protein hydrolysate enhances lettuce tolerance to alkalinity and salinity. Front Plant Sci. 2017;8:131. [CrossRef].
26. Rouphael Y, Franken P, Schneider C, Schwarz D, Giovannetti M, Agnolucci M, et al. Arbuscular mycorrhizal fungi act as biostimulants in horticultural crops. Sci Hortic. 2015;196:91–108. [CrossRef].
27. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ. 2021:n71. [CrossRef].
28. Saleh TA. Nanomaterials: Classification, properties, and environmental toxicities. Environ Technol Innov. 2020;20:101067. [CrossRef].
29. Ditta A. Role of nanoclay polymers in agriculture: Applications and perspectives. In: Nanohybrids in Environmental & Biomedical Applications. Boca Raton, FL, USA: CRC Press; 2019. p. 323–34. [CrossRef].
30. Dakal TC, Bhushan R, Dhakar R, Kumar A. Classification and applications of bio-nanomaterials. In: Sharma N, Sharma R, Dakal T, editors. Bio-nanomaterials in environmental remediation: Industrial applications. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2025. p. 47–73. [CrossRef].
31. Saraswat P, Singh S, Prasad M, Misra R, Rajput VD, Ranjan R. Applications of bio-based nanomaterials in environment and agriculture: A review on recent progresses. Hybrid Adv. 2023;4:100097. [CrossRef].
32. Rui M, Ma C, Hao Y, Guo J, Rui Y, Tang X, et al. Iron oxide nanoparticles as a potential iron fertilizer for peanut (*Arachis hypogaea*). Front Plant Sci. 2016;7:815. [CrossRef].
33. Liu C, Zhou H, Zhou J. The applications of nanotechnology in crop production. Molecules. 2021;26(23):7070. [CrossRef].
34. Alidoust D, Isoda A. Effect of γFe_2O_3 nanoparticles on photosynthetic characteristic of soybean (*Glycine max* (L.) Merr.): Foliar spray versus soil amendment. Acta Physiol Plant. 2013;35(12):3365–75. [CrossRef].
35. Razzaq A, Ammara R, Jhanzab HM, Mahmood T, Hafeez A, Hussain S. A novel nanomaterial to enhance growth and yield of wheat. J Nanosci Technol. 2016;2(1):55–8.
36. Kumar V, Guleria P, Kumar V, Yadav SK. Gold nanoparticle exposure induces growth and yield enhancement in *Arabidopsis thaliana*. Sci Total Environ. 2013;461:462–8. [CrossRef].
37. Ngo QB, Dao TH, Nguyen HC, Tran XT, Van Nguyen T, Khuu TD, et al. Effects of nanocrystalline powders (Fe, Co and Cu) on the germination, growth, crop yield and product quality of soybean (Vietnamese species DT-51). Adv Nat Sci Nanosci Nanotechnol. 2014;5(1):015016. [CrossRef].
38. Lakshmi S, Ravichandran V, Anandakumar S, Senthil A, Arul L, Radhamani S, et al. Foliar application of *Ascophyllum nodosum* on improvement of photosynthesis, fruit setting percentage, yield and quality of tomato (*Solanum lycopersicum* L.). J Appl Nat Sci. 2023;15(3):961–71. [CrossRef].
39. Shah V, Belozerova I. Influence of metal nanoparticles on the soil microbial community and germination of lettuce seeds. Water Air Soil Pollut. 2009;197(1):143–8. [CrossRef].
40. Raliya R, Tarafdar JC. ZnO nanoparticle biosynthesis and its effect on phosphorous-mobilizing enzyme secretion and gum contents in clusterbean (*Cyamopsis tetragonoloba* L.). Agric Res. 2013;2(1):48–57. [CrossRef].
41. Joel JM, Johnson R, Puthur JT. Co-application of arbuscular mycorrhizal fungi and engineered nanomaterials: A promising strategy for crop resilience against abiotic stresses. S Afr J Bot. 2023;162:314–23. [CrossRef].
42. Singh H, Sharma A, Bhardwaj SK, Arya SK, Bhardwaj N, Khatri M. Recent advances in the applications of nano-agrochemicals for sustainable agricultural development. Environ Sci Processes Impacts. 2021;23(2):213–39. [CrossRef].
43. Pudhuvai B, Koul B, Das R, Shah MP. Nano-fertilizers (NFs) for resurgence in nutrient use efficiency (NUE): A sustainable agricultural strategy. Curr Pollut Rep. 2024;11(1):1. [CrossRef].
44. Madlala NC, Khanyile N, Masenya A. Examining the correlation between the inorganic nano-fertilizer physical properties and their impact on crop performance and nutrient uptake efficiency. Nanomaterials. 2024;14(15):1263. [CrossRef].

45. Kekeli MA, Wang Q, Rui Y. The role of nano-fertilizers in sustainable agriculture: Boosting crop yields and enhancing quality. Plants. 2025;14(4):554. [CrossRef].
46. Chhipa H. Nanofertilizers and nanopesticides for agriculture. Environ Chem Lett. 2017;15(1):15–22. [CrossRef].
47. Liu R, Lal R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. Sci Total Environ. 2015;514:131–9. [CrossRef].
48. Sharma A, Thakur A, Sharma A, Thakur M, Sharma S, Sharma H, et al. Nano-edible coatings for quality enhancement and shelf-life extension of fruits and vegetables. J Food Sci Technol. 2025;62(3):397–412. [CrossRef].
49. Taban A, Haghighi TM, Mousavi SS, Sadeghi H. Are edible coatings (with or without essential oil/extract) game changers for maintaining the postharvest quality of strawberries? A meta-analysis. Postharvest Biol Technol. 2024;216:113082. [CrossRef].
50. Dasgupta N, Ranjan S, Mundekkad D, Ramalingam C, Shanker R, Kumar A. Nanotechnology in agro-food: From field to plate. Food Res Int. 2015;69:381–400. [CrossRef].
51. Anand U, Chandel AKS, Oleksak P, Mishra A, Krejcar O, Raval IH, et al. Recent advances in the potential applications of luminescence-based, SPR-based, and carbon-based biosensors. Appl Microbiol Biotechnol. 2022;106(8):2827–53. [CrossRef].
52. Kim HS, Kang HS, Chu GJ, Byun HS. Antifungal effectiveness of nanosilver colloid against rose powdery mildew in greenhouses. Solid State Phenom. 2008;135:15–8. [CrossRef].
53. Hashem AH, Saied E, Amin BH, Alotibi FO, Al-Askar AA, Arishi AA, et al. Antifungal activity of biosynthesized silver nanoparticles (AgNPs) against aspergilli causing aspergillosis: Ultrastructure study. J Funct Biomater. 2022;13(4):242. [CrossRef].
54. Kah M, Tufenkji N, White JC. Nano-enabled strategies to enhance crop nutrition and protection. Nat Nanotechnol. 2019;14(6):532–40. [CrossRef].
55. Mohammadi S, Jabbari F, Cidonio G, Babaeipour V. Revolutionizing agriculture: Harnessing nano-innovations for sustainable farming and environmental preservation. Pestic Biochem Physiol. 2024;198:105722. [CrossRef].
56. Klaine SJ, Alvarez PJJ, Batley GE, Fernandes TF, Handy RD, Lyon DY, et al. Nanomaterials in the environment: Behavior, fate, bioavailability, and effects. Environ Toxicol Chem. 2008;27(9):1825–51. [CrossRef].
57. Demirer GS, Zhang H, Matos JL, Goh NS, Cunningham FJ, Sung Y, et al. High aspect ratio nanomaterials enable delivery of functional genetic material without DNA integration in mature plants. Nat Nanotechnol. 2019;14(5):456–64. [CrossRef].
58. Giraldo JP, Wu H, Newkirk GM, Kruss S. Nanobiotechnology approaches for engineering smart plant sensors. Nat Nanotechnol. 2019;14(6):541–53. [CrossRef].
59. Pérez-de-Luque A. Interaction of nanomaterials with plants: What do we need for real applications in agriculture? Front Environ Sci. 2017;5:12. [CrossRef].
60. Kah M, Beulke S, Tiede K, Hofmann T. Nanopesticides: State of knowledge, environmental fate, and exposure modeling. Crit Rev Environ Sci Technol. 2013;43(16):1823–67. [CrossRef].
61. Calvo P, Nelson L, Kloepper JW. Agricultural uses of plant biostimulants. Plant Soil. 2014;383(1):3–41. [CrossRef].
62. Colla G, Rouphael Y, Di Mattia E, El-Nakhel C, Cardarelli M. Co-inoculation of *Glomus intraradices* and *Trichoderma* atroviride acts as a biostimulant to promote growth, yield and nutrient uptake of vegetable crops. J Sci Food Agric. 2015;95(8):1706–15. [CrossRef].
63. Eftekhari M, Alizadeh M, Ebrahimi P. Evaluation of the total phenolics and quercetin content of foliage in mycorrhizal grape (*Vitis vinifera* L.) varieties and effect of postharvest drying on quercetin yield. Ind Crops Prod. 2012;38:160–5. [CrossRef].
64. Taie HA, El-Mergawi R, Radwan S. Isoflavonoids, flavonoids, phenolic acids profiles, and antioxidant activity of soybean seeds as affected by organic and bioorganic fertilization. Am-Euras J Agric Environ Sci. 2008;4:207–13.
65. Karthikeyan B, Joe MM, Jaleel CA, Deiveekasundaram M. Effect of root inoculation with plant growth-promoting rhizobacteria (PGPR) on plant growth, alkaloid content, and nutrient control of *Catharanthus roseus* (L.) G. Don. Nat Croat. 2010;1:205–12.
66. Khalid M, Hassani D, Bilal M, Asad F, Huang D. Influence of bio-fertilizer containing beneficial fungi and rhizospheric bacteria on health promoting compounds and antioxidant activity of *Spinacia oleracea* L. Bot Stud. 2017;58(1):35. [CrossRef].

67. Baslam M, Garmendia I, Goicoechea N. Arbuscular mycorrhizal fungi (AMF) improved growth and nutritional quality of greenhouse-grown lettuce. J Agric Food Chem. 2011;59(10):5504–15. [CrossRef].
68. Matsumiya Y, Kubo M. Soybean peptide: Novel plant growth promoting peptide from soybean. In: Soybean and nutrition. London, UK: InTech; 2011. [CrossRef].
69. Ertani A, Cavani L, Pizzeghello D, Brandellero E, Altissimo A, Ciavatta C, et al. Biostimulant activity of two protein hydrolyzates in the growth and nitrogen metabolism of maize seedlings. J Plant Nutr Soil Sci. 2009;172(2):237–44. [CrossRef].
70. Forde BG, Lea PJ. Glutamate in plants: Metabolism, regulation, and signalling. J Exp Bot. 2007;58(9):2339–58. [CrossRef].
71. Huang PM, Hardie AG. Formation mechanisms of humic substances in the environment. In: Senesi N, Xing B, Huang PM, editors. Biophysico-chemical processes involving natural nonliving organic matter in environmental systems. Hoboken, NJ, USA: John Wiley & Sons, Inc.; 2009. p. 41–109. [CrossRef].
72. Weil RR, Brady NC. The nature and properties of soils. 15th ed. London, UK: Pearson Education; 2017.
73. Chassapis K, Roulia M, Tsirigoti D. Chemistry of metal–humic complexes contained in Megalopolis lignite and potential application in modern organomineral fertilization. Int J Coal Geol. 2009;78(4):288–95. [CrossRef].
74. Sharif M, Khattak RA, Sarir MS. Effect of different levels of lignitic coal derived humic acid on growth of maize plants. Commun Soil Sci Plant Anal. 2002;33(19–20):3567–80. [CrossRef].
75. Lehmann J, Kleber M. The content and nature of organic matter in soil. Berlin/Heidelberg, Germany: Springer; 2015. [CrossRef].
76. Atiyeh RM, Lee S, Edwards CA, Arancon NQ, Metzger JD. The influence of humic acids derived from earthworm-processed organic wastes on plant growth. Bioresour Technol. 2002;84(1):7–14. [CrossRef].
77. Battacharyya D, Babgohari MZ, Rathor P, Prithiviraj B. Seaweed extracts as biostimulants in horticulture. Sci Hortic. 2015;196:39–48. [CrossRef].
78. Pacholczak A, Nowakowska K, Pietkiewicz S. The effects of synthetic auxin and a seaweed-based biostimulator on physiological aspects of rhizogenesis in ninebark stem cuttings. Not Bot Horti Agrobot Cluj-Napoca. 2016;44(1):85–91. [CrossRef].
79. Vernieri P, Borghesi E, Tognoni F, Serra G, Ferrante A, Piagessi A. Use of biostimulants for reducing nutrient solution concentration in floating system. Acta Hortic. 2006;718:477–84. [CrossRef].
80. Hernández-Herrera RM, Santacruz-Ruvalcaba F, Zañudo-Hernández J, Hernández-Carmona G. Activity of seaweed extracts and polysaccharide-enriched extracts from *Ulva lactuca* and *Padina gymnospora* as growth promoters of tomato and mung bean plants. J Appl Phycol. 2016;28(4):2549–60. [CrossRef].
81. Di Mola I, Cozzolino E, Ottaiano L, Giordano M, Rouphael Y, El Nakhel C, et al. Effect of seaweed (*Ecklonia maxima*) extract and legume-derived protein hydrolysate biostimulants on baby leaf lettuce grown on optimal doses of nitrogen under greenhouse conditions. Aust J Crop Sci. 2020;14(9):1456–64. [CrossRef].
82. Ali O, Ramsubhag A, Jayaraman J. Biostimulant properties of seaweed extracts in plants: Implications towards sustainable crop production. Plants. 2021;10(3):531. [CrossRef].
83. Román-Doval R, Torres-Arellanes SP, Tenorio-Barajas AY, Gómez-Sánchez A, Valencia-Lazcano AA. Chitosan: Properties and its application in agriculture in context of molecular weight. Polymers. 2023;15(13):2867. [CrossRef].
84. Katiyar D, Hemantaranjan A, Singh B. Chitosan as a promising natural compound to enhance potential physiological responses in plant: A review. Indian J Plant Physiol. 2015;20(1):1–9. [CrossRef].
85. Rouphael Y, Colla G. Synergistic biostimulatory action: Designing the next generation of plant biostimulants for sustainable agriculture. Front Plant Sci. 2018;9:1655. [CrossRef].
86. Janila P, Nigam SN, Pandey MK, Nagesh P, Varshney RK. Groundnut improvement: Use of genetic and genomic tools. Front Plant Sci. 2013;4:23. [CrossRef].
87. Giordano M, El-Nakhel C, Caruso G, Cozzolino E, De Pascale S, Kyriacou MC, et al. Stand-alone and combinatorial effects of plant-based biostimulants on the production and leaf quality of perennial wall rocket. Plants. 2020;9(7):922. [CrossRef].
88. Scaglia B, Nunes RR, Rezende MOO, Tambone F, Adani F. Investigating organic molecules responsible of auxin-like activity of humic acid fraction extracted from vermicompost. Sci Total Environ. 2016;562:289–95. [CrossRef].

89. Zandonadi DB, Santos MP, Dobbss LB, Olivares FL, Canellas LP, Binzel ML, et al. Nitric oxide mediates humic acids-induced root development and plasma membrane H^+-ATPase activation. Planta. 2010;231(5):1025–36. [CrossRef].
90. Jannin L, Arkoun M, Etienne P, Laîné P, Goux D, Garnica M, et al. *Brassica napus* growth is promoted by *Ascophyllum* nodosum (L.) le jol. seaweed extract: Microarray analysis and physiological characterization of N, C, and S metabolisms. J Plant Growth Regul. 2013;32(1):31–52. [CrossRef].
91. Santaniello A, Giorgi FM, Di Tommaso D, Di Tommaso G, Piaggesi A, Perata P. Genomic approaches to unveil the physiological pathways activated in *Arabidopsis* treated with plant-derived raw extracts. Acta Hortic. 2013;1009:161–74. [CrossRef].
92. Colla G, Rouphael Y, Canaguier R, Svecova E, Cardarelli M. Biostimulant action of a plant-derived protein hydrolysate produced through enzymatic hydrolysis. Front Plant Sci. 2014;5:448. [CrossRef].
93. Tirkey A, Babu PJ, HemaIswarya S, Singh PK. An updated view of nanoparticle interaction with plants: A molecular understanding and beyond. J Plant Growth Regul. 2025;44(6):2665–88. [CrossRef].
94. Sow S, Kumar N, Rana L, Singh H, Kumar V, Kavita, et al. Soil test crop response based integrated nutrient management for enhancing agronomic performance of sugarcane with different planting materials. Not Bot Horti Agrobo. 2024;52(3):13934. [CrossRef].
95. Han H, Lee KD. Physiological responses of soybean inoculation of *Bradyrhizobium japonicum* with PGPR in saline soil conditions. Res J Agric Biol Sci. 2005;1(3):216–21.
96. Rouphael Y, Cardarelli M, Di Mattia E, Tullio M, Rea E, Colla G. Enhancement of alkalinity tolerance in two cucumber genotypes inoculated with an arbuscular mycorrhizal biofertilizer containing *Glomus intraradices*. Biol Fertil Soils. 2010;46(5):499–509. [CrossRef].
97. Sahoo R, Sow S, Ranjan S, Dharminder, Kumar R, Roy DK, et al. Unveiling the potential of plant growth promoting rhizobacteria (PGPR) in phytoremediation of heavy metal. Discov Appl Sci. 2024;6(6):324. [CrossRef].
98. Rana L, Kumar M, Rajput J, Kumar N, Sow S, Kumar S, et al. Nexus between nanotechnology and agricultural production systems: Challenges and future prospects. Discov Appl Sci. 2024;6(11):555. [CrossRef].
99. Kumar N, Sow S, Rana L, Ranjan S, Singh AK. Trash amended with *Trichoderma* effects on cane yield, soil carbon dynamics, and enzymatic activities under plant–ratoon system of sugarcane in calcareous soil. Sugar Tech. 2025;27(1):134–47. [CrossRef].
100. Kumar Sootahar M, Zeng X, Su S, Wang Y, Bai L, Zhang Y, et al. The effect of fulvic acids derived from different materials on changing properties of albic black soil in the northeast plain of China. Molecules. 2019;24(8):1535. [CrossRef].
101. Nardi S, Pizzeghello D, Muscolo A, Vianello A. Physiological effects of humic substances on higher plants. Soil Biol Biochem. 2002;34(11):1527–36. [CrossRef].
102. Nardi S, Schiavon M, Francioso O. Chemical structure and biological activity of humic substances define their role as plant growth promoters. Molecules. 2021;26(8):2256. [CrossRef].
103. Karnwal A, Dohroo A, Malik T. Unveiling the potential of bioinoculants and nanoparticles in sustainable agriculture for enhanced plant growth and food security. BioMed Res Int. 2023;2023:6911851. [CrossRef].
104. Shen M, Liu S, Jiang C, Zhang T, Chen W. Recent advances in stimuli-response mechanisms of nano-enabled controlled-release fertilizers and pesticides. Eco Environ Health. 2023;2(3):161–75. [CrossRef].
105. Magnabosco P, Masi A, Shukla R, Bansal V, Carletti P. Advancing the impact of plant biostimulants to sustainable agriculture through nanotechnologies. Chem Biol Technol Agric. 2023;10(1):117. [CrossRef].
106. Mittler R, Zandalinas SI, Fichman Y, Van Breusegem F. Reactive oxygen species signalling in plant stress responses. Nat Rev Mol Cell Biol. 2022;23(10):663–79. [CrossRef].
107. Khan AR, Salam A, Li G, Iqbal B, Ulhassan Z, Liu Q, et al. Nanoparticles and their crosstalk with stress mitigators: A novel approach towards abiotic stress tolerance in agricultural systems. Crop J. 2024;12(5):1280–98. [CrossRef].
108. Liang X, Zhai Y, Li J, Zhan J, Li F, Wang W. Exogenous biostimulants: Mechanisms and innovations for enhancing seed germination and resilience under abiotic stress. J Adv Res. 2026. [CrossRef].
109. Jíménez-Arias D, Morales-Sierra S, Silva P, Carrêlo H, Gonçalves A, Ganança JFT, et al. Encapsulation with natural polymers to improve the properties of biostimulants in agriculture. Plants. 2023;12(1):55. [CrossRef].
110. Yu S, Sun J, Shi Y, Wang Q, Wu J, Liu J. Nanocellulose from various biomass wastes: Its preparation and potential usages towards the high value-added products. Environ Sci Ecotechnol. 2021;5:100077. [CrossRef].

111. Al-Ramamneh EA, Alsharafa KY, Rababah T, Rahahleh RJ, Al-Rimawi F, Shakya AK, et al. Silver nanoparticles and biostimulants affect chemical constituents, total phenolics, antioxidants, and potential antimicrobial activities of *Santolina chamaecyparissus*. Horticulturae. 2024;10(1):26. [CrossRef].
112. Missaoui T, Boughdiri N, Chemingui H, Al Sobeai SM, Smiri M. Growth and metabolism of pea (*Pisum* sativum) via biostimulants based on greener ZnO nanoparticles. Int J Phytorem. 2024;26(5):764–72. [CrossRef].
113. Al-Saif AM, Sas-Paszt L, Saad RM, Abada HS, Ayoub A, Mosa WFA. Biostimulants and nano-potassium on the yield and fruit quality of date palm. Horticulturae. 2023;9(10):1137. [CrossRef].
114. Matthews S, Ali A, Siddiqui Y. Nano-encapsulated biostimulant enhances growth and postharvest quality of chili peppers (*Capsicum annuum*). Sci Hortic. 2025;340:113920. [CrossRef].
115. Osman MS, Badawy AA, Osman AI, Abdel Hamed Abdel Latef A. Ameliorative impact of an extract of the halophyte *Arthrocnemum macrostachyum* on growth and biochemical parameters of soybean under salinity stress. J Plant Growth Regul. 2021;40(3):1245–56. [CrossRef].
116. Afify RRM. Nano fertilizers with algae extract as biostimulant affecting growth, bulb yield, and quality of onion (*Allium cepa* L.). SABRAO J Breed Genet. 2023;55(6):2128–39. [CrossRef].
117. Nazir MA, Hasan M, Mustafa G, Tariq T, Ahmed MM, Golzari Dehno R, et al. Zinc oxide nano-fertilizer differentially effect on morphological and physiological identity of redox-enzymes and biochemical attributes in wheat (*Triticum aestivum* L.). Sci Rep. 2024;14:13091. [CrossRef].
118. Choudhary RC, Kumaraswamy RV, Kumari S, Sharma SS, Pal A, Raliya R, et al. Zinc encapsulated chitosan nanoparticle to promote maize crop yield. Int J Biol Macromol. 2019;127:126–35. [CrossRef].
119. Arora PK, Tripathi S, Omar RA, Chauhan P, Sinhal VK, Singh A, et al. Next-generation fertilizers: The impact of bionanofertilizers on sustainable agriculture. Microb Cell Fact. 2024;23(1):254. [CrossRef].
120. Zhang N, Xiong G, Liu Z. Toxicity of metal-based nanoparticles: Challenges in the nano era. Front Bioeng Biotechnol. 2022;10:1001572. [CrossRef].
121. Montes de Oca-Vásquez G, Solano-Campos F, Vega-Baudrit JR, López-Mondéjar R, Vera A, Moreno JL, et al. Organic amendments exacerbate the effects of silver nanoparticles on microbial biomass and community composition of a semiarid soil. Sci Total Environ. 2020;744:140919. [CrossRef].
122. AshaRani PV, Low Kah Mun G, Hande MP, Valiyaveettil S. Cytotoxicity and genotoxicity of silver nanoparticles in human cells. ACS Nano. 2009;3(2):279–90. [CrossRef].
123. Sharma V, Shukla RK, Saxena N, Parmar D, Das M, Dhawan A. DNA damaging potential of zinc oxide nanoparticles in human epidermal cells. Toxicol Lett. 2009;185(3):211–8. [CrossRef].
124. European Commission. Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). Off J Eur Union. 2006;L396:1.
125. FAO/WHO. Expert meeting on the application of nanotechnologies in the food and agriculture sectors: Potential food safety implications. Meeting report. Rome, Italy: Food and Agriculture Organization; 2010.
126. Inam A, Javad S, Naseer I, Alam P, Almutairi ZM, Faizan M, et al. Efficacy of chitosan loaded zinc oxide nanoparticles in alleviating the drastic effects of drought from corn crop. Plant Stress. 2024;14:100617. [CrossRef].
127. Rastogi A, Zivcak M, Sytar O, Kalaji HM, He X, Mbarki S, et al. Impact of metal and metal oxide nanoparticles on plant: A critical review. Front Chem. 2017;5:78. [CrossRef].
128. Anuta V, Blidaru A, Dinu-Pîrvu CE, Fierascu RC, Fierascu I, Toma DI, et al. Metal-based nanoparticles with biostimulatory effects: Harnessing nanotechnology for enhanced agricultural sustainability. Materials. 2025;18(13):3142. [CrossRef].
129. Kumari R, Suman K, Karmakar S, Mishra V, Lakra SG, Saurav GK, et al. Regulation and safety measures for nanotechnology-based agri-products. Front Genome Ed. 2023;5:1200987. [CrossRef].
130. Gupta A, Saharan BS. Nanotech innovations in Agriculture: Enhancing plant growth and navigating microbial interactions. Next Bioeng. 2026;2:100012. [CrossRef].
131. Raut K, Sharbidre AA. Risk assessment and registration policies for the safety of nanomaterials in agriculture. In: Nanotechnology in agriculture. Berlin/Heidelberg, Germany: Springer; 2025. p. 325–47. [CrossRef].
132. Grillo R, Fraceto LF, Amorim MJB, Scott-Fordsmand JJ, Schoonjans R, Chaudhry Q. Ecotoxicological and regulatory aspects of environmental sustainability of nanopesticides. J Hazard Mater. 2021;404:124148. [CrossRef].
133. Khoulati A, Ouahhoud S, Taibi M, Ezrari S, Mamri S, Merah O, et al. Harnessing biostimulants for sustainable agriculture: Innovations, challenges, and future prospects. Discov Agric. 2025;3(1):56. [CrossRef].

134. Atanda SA, Shaibu RO, Agunbiade FO. Nanoparticles in agriculture: Balancing food security and environmental sustainability. Discov Agric. 2025;3(1):26. [CrossRef].
135. Mim JJ, Maksudur Rahman SM, Khan F, Paul D, Sikder S, Das HP, et al. Towards smart agriculture through nano-fertilizer—A review. Mater Today Sustain. 2025;30:101100. [CrossRef].
136. Bouhadi M, Javed Q, Jakubus M, Elkouali M, Fougrach H, Ansar A, et al. Nanoparticles for sustainable agriculture: Assessment of benefits and risks. Agronomy. 2025;15(5):1131. [CrossRef].
137. EPA 100/B-07/001. Nanotechnology white paper. Washington, DC, USA: United States Environmental Protection Agency; 2007.
138. Kah M, Hofmann T. Nanopesticide research: Current trends and future priorities. Environ Int. 2014;63:224–35. [CrossRef].
139. Department of Biotechnology. Guidelines for evaluation of nano-based agri-input and food products in India. New Delhi, India: Ministry of Science and Technology, Government of India; 2020.
140. Ministry of Agriculture and Farmers Welfare. Fertiliser (control) order notification for inclusion of nano urea. New Delhi, India: Government of India; 2021 [cited 2026 Jan 1]. Available from: https://www.acfiindia.com/home/central-notice/S.O.884(E)Inexerciseofthepowersconferredbysection3oftheEssentialCommoditiesAct(24-2-21).pdf. (In Hindi).
141. Organisation for Economic Co-operation and Development. Physical-chemical decision framework to inform decisions for risk assessment of manufactured nanomaterials. Paris, France: OECD; 2019. [CrossRef].