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Nanotechnology in Crop Production: Applications, Evidence, Limitations and Future Directions

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This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Review Article

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Abstract

Nanotechnology is increasingly being investigated as a means of improving nutrient delivery, crop establishment, plant growth, stress tolerance and crop protection while reducing losses associated with conventional agricultural inputs. This focused narrative review critically compares four original studies from Elsevier journals and positions their findings within a broader peer-reviewed evidence base. The focal studies evaluated a chitosan-silicon nanofertiliser in maize, a zinc oxide nanofertiliser in maize, chitosan nanoparticles in *Capsicum* species, and calcium-doped zinc oxide nanoparticles in maize and wheat. Across these studies, nanomaterials were applied through seed priming, foliar spraying or soil application and were evaluated using crop growth, photosynthetic pigments, antioxidant responses, yield attributes or pest infestation. Appropriately formulated and dosed materials improved selected outcomes: the chitosan-silicon nanofertiliser increased maize yield per plot by 43.4% at 0.08% and test weight by 45% at 0.04% compared with SiO2, while Ca-doped ZnO significantly improved measured growth parameters in maize and wheat. The review contributes an integrated formulation-route-response-safety framework that distinguishes promising crop responses from the evidence needed for agronomic recommendation. Its conclusions are relevant to crop researchers, input developers, regulators and extension systems, particularly where low nutrient-use efficiency, soil degradation and input costs constrain cereal and vegetable production. However, responses depend on particle composition, concentration, crop species, application route and environment, and the evidence remains dominated by short-duration or limited-location experiments. Multi-

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season field validation, nutrient-equivalent controls, residue and food-safety assessment, soil-microbiome studies, life-cycle analysis, economic feasibility and formulation-specific regulation are therefore required. Nanotechnology should be viewed as a promising component of integrated crop management rather than a universal substitute for conventional agronomic practices.

Keywords: Nanotechnology; crop production; nanofertilisers; nanoparticles; nutrient-use efficiency; seed priming; crop protection; stress tolerance; environmental safety; sustainable agriculture.

1. Introduction

Crop production faces the interconnected challenges of increasing food demand, declining soil quality, inefficient use of fertilisers and pesticides, climate-related stresses and rising production costs. Conventional inputs have contributed substantially to agricultural productivity, but a portion of applied nutrients and crop-protection chemicals may be lost through volatilization, leaching, runoff, fixation, degradation or non-target deposition. Such losses reduce input-use efficiency and may contribute to water pollution, greenhouse-gas emissions, soil degradation and ecological disturbance. Technologies capable of delivering smaller quantities of active ingredients at the required place and time are therefore receiving growing attention.

Recent reviews emphasise that nano-enabled fertilisers, pesticides and delivery systems should be evaluated as complementary tools for improving input efficiency and crop protection rather than as automatic replacements for established agronomic practices (Chhipa, 2017; Kah et al., 2019; Shang et al., 2019).

Recent agriculture-focused reviews also identify nanofertilisers, nanopesticides, nanosensors and nanomaterial-based stress management as recurring application areas, while emphasising the need for careful evaluation of environmental and safety considerations (Revathi et al., 2025; Salama et al., 2021; Suresh Kumar et al., 2025).

Nanotechnology involves the design, characterisation and application of materials with at least one dimension commonly within the nanoscale range. At this scale, materials may exhibit surface reactivity, solubility, catalytic behaviour, optical properties and transport characteristics that differ from those of their bulk counterparts. These properties have enabled the development of nanosized nutrients, nanocarriers, coated or encapsulated fertilisers, nanoemulsions, nanopesticides, seed-priming agents, plant-growth stimulants and nanosensors. In crop production, the intended advantage is not merely a reduction in particle size but the creation of a formulation with measurable agronomic benefits, such as controlled release, improved adhesion, greater dispersibility, enhanced uptake or protection of the active ingredient.

Nanofertilisers may contain nutrients in nanoparticulate form or use nanostructured carriers to transport conventional nutrients. Nutrients can be adsorbed, entrapped, encapsulated or chemically linked to materials such as chitosan, clays, hydroxyapatite, silica or carbon-based structures. Properly designed formulations may slow nutrient release and improve synchronisation between nutrient supply and crop demand (Adisa et al., 2019; Guo et al., 2018). Nevertheless, a nanoformulation does not automatically possess controlled-release behaviour; release kinetics must be experimentally demonstrated for each product.

Evidence from nano-enabled fertiliser research shows that improved nutrient release and availability depend on carrier chemistry, nutrient loading, particle stability and soil-plant interactions, so each formulation requires product-specific verification under relevant crop and soil conditions (Beig et al., 2022; Guo et al., 2018; Mehta et al., 2024).

Nanomaterials may enter plants through seed surfaces, roots or leaves. Uptake and subsequent movement depend on particle size, aggregation, surface charge, coating, dissolution, plant species, tissue anatomy and environmental conditions. Some observed responses may arise from intact nanoparticles, whereas others may result from dissolved ions or signalling responses triggered by low-dose exposure. This distinction is particularly important for metal and metal-oxide nanoparticles because excessive concentrations can disturb cellular redox balance, inhibit growth or accumulate in edible tissues.

Plant uptake and transformation of nanomaterials are influenced by aggregation, dissolution, coating, rhizosphere chemistry and biological barriers, making residue, food-safety and environmental-fate assessment essential before field-scale recommendations are made (Adisa et al., 2019; Nandini et al., 2023; Zhang et al., 2020).

Recent experimental studies have reported beneficial effects of zinc-, silicon- and chitosan-based nanoformulations on germination, chlorophyll formation, antioxidant defence, biomass, yield and tolerance to biotic or abiotic stress. However, comparisons across studies are difficult because treatments differ in concentration, nutrient-equivalent rate, application method, particle characterisation and experimental setting. Many investigations use pot or controlled-environment conditions, and fewer studies assess multi-season field performance, economic returns, residues and effects on soil organisms.

More recent syntheses indicate that particle-size effects, non-target safety, long-term environmental impacts and regulatory clarity remain important considerations when moving nano-enabled agrochemicals from experimental evaluation towards sustainable field use (Liu et al., 2025; Santos et al., 2025).

However, the evidence considered in this review remains distributed across different formulations, crops, delivery routes and response endpoints, and a focused comparison is needed to distinguish promising crop responses from the evidence required for safe and reproducible agronomic recommendation.

Against this background, the objective of this review is to critically evaluate how nanoformulation properties and application routes influence crop establishment, physiological responses, productivity, stress management and crop protection; to compare the strength and limitations of selected experimental evidence; and to identify requirements for safe, reproducible and economically relevant field deployment. The scope covers nano-enabled crop inputs and plant responses in maize, wheat and *Capsicum* represented by four focal Elsevier studies, supported by broader peer-reviewed literature on uptake, nutrient-use efficiency, soil interactions, safety and regulation. It does not attempt a crop-monograph treatment of maize morphology, general cultivation requirements or grain chemical composition, because the evidence base and title encompass multiple crops and the review question concerns nano-enabled interventions.

List 1. Conceptual framework used to interpret nano-enabled crop-production evidence

Framework stage	Evidence considered
1. Nanoformulation	Composition, particle size, coating, stability, dissolution and active-ingredient loading
2. Delivery route	Seed priming, foliar spraying or soil application; dose, crop stage and exposure conditions
3. Soil-plant interaction	Release, aggregation, uptake, transformation, translocation and physiological signalling
4. Crop response	Establishment, pigments, redox balance, nutrient status, pest response, yield and produce quality
5. Evidence appraisal	Comparator adequacy, nutrient-equivalent rate, dose response, replication, location and duration
6. Responsible deployment	Efficacy, residues, food and ecological safety, economics, standards, regulation and farmer usability

Because the review is based on a focused set of studies, the discussion is framed as formulation-specific evidence supported by related peer-reviewed literature rather than as a general claim that all nanomaterials improve crop productivity (Kah et al., 2019; Mehta et al., 2024; Nandini et al., 2023).

2. Methodology

2.1 Review Design and Literature Identification

A focused narrative review was conducted, and the evidence check was updated on 2 September 2026. Searches used publisher webpages and PubMed, supplemented by reference-list cross-checking, with combinations of “nanotechnology”, “nanoparticle”, “nanofertiliser”, “nano-enabled nutrient delivery”, “crop production”, “maize”, “wheat”, “*Capsicum*”, “uptake”, “soil microbiome”, “food safety” and “environmental fate”. English-language peer-reviewed studies and reviews published mainly from 2017 to 2025 were considered, while foundational papers were retained when they defined mechanisms or safety issues. Four original Elsevier articles were designated as focal studies because they offered contrasting formulations, delivery routes and crop-response endpoints; additional peer-reviewed publications were used to test whether their interpretations agreed with the wider literature.

2.2 Selection of Studies

The four focal studies were purposively selected to represent different nanomaterial classes and crop-production functions: a chitosan-silicon nanofertiliser for silicon delivery in maize; chemically synthesised ZnO nanofertiliser applied to maize; chitosan nanoparticles evaluated for *Capsicum* growth, yield and thrips infestation; and Ca-doped ZnO nanoparticles applied to maize and wheat. Inclusion required an experimentally prepared or characterised nanomaterial, an agricultural crop, an identifiable application route, measurable physiological, yield, nutritional or crop-protection outcomes, and sufficient methodological detail for critical comparison. Reviews, sensor-only investigations, non-crop systems and studies without crop-response measurements were excluded from the focal comparison. Because selection was purposive rather than exhaustive, the review is explicitly presented as a focused narrative synthesis rather than a systematic review or meta-analysis.

2.3 Data Extraction and Synthesis

For each focal study, data were extracted on nanomaterial composition, synthesis and characterisation, crop species and genotype where reported, treatment concentration and route, comparator, measured variables, principal findings and acknowledged or inferable limitations. Reported percentages, concentrations and units were retained without conversion when conversion could change the source authors’ intended comparison. Findings were organized through the conceptual sequence shown in List 1 and synthesised qualitatively because crops, treatments, controls, endpoints and experimental designs were heterogeneous. No pooled effect size or meta-analysis was attempted.

2.4 Critical Appraisal

Each study was assessed for its contribution to crop production and for limitations affecting interpretation, including the nature of the comparator, duration and scale of testing, concentration dependence, field validation and evidence on environmental or food safety. A reported improvement relative to an untreated or bulk-material control was treated as formulation-specific evidence and not as proof that all nanomaterials produce the same response.

3. Results and Discussion

3.1 Characteristics of the Selected Studies

The four selected investigations demonstrate that nanotechnology in crop production extends beyond a single product category. Two studies used ZnO-based materials, one used a polymeric chitosan carrier for silicon, and one evaluated chitosan nanoparticles as a biostimulant and crop-protection treatment. Maize was the most frequently studied crop, while wheat and *Capsicum* broadened the evidence to another cereal and a vegetable crop. Application methods included seed priming, foliar spraying and soil treatment, reflecting the multiple entry routes through which nanomaterials can influence crop performance.

All studies connected material properties or nanoformulation with biological responses, but the depth of characterisation and field validation differed. Kumaraswamy et al. (2021) reported detailed physicochemical characterisation and silicon-release behaviour, whereas the other studies focused more strongly on crop responses. These differences highlight a recurring issue in agricultural nanotechnology: agronomic outcomes cannot be interpreted adequately without information on particle size, surface properties, aggregation, dissolution and actual nutrient dose.

The comparative interpretation of Tables 1-3 should therefore be read together because crop response, material characterisation and research limitations collectively determine the strength of evidence for each nanoformulation. Broader syntheses similarly show that efficacy depends on delivery route, dose, nutrient form and soil-plant context, while long-term effects on microbial communities and food safety remain insufficiently resolved (Adisa et al., 2019; Ding et al., 2023; Kekeli et al., 2025; Nandini et al., 2023; Nongbet et al., 2022).

3.2 Chitosan-Silicon Nanofertiliser in Maize

Kumaraswamy et al. (2021) prepared a chitosan-silicon nanofertiliser by encapsulating silicon within a chitosan-tripolyphosphate matrix through ionic gelation. The material was characterised using complementary techniques, including DLS, electron microscopy, spectroscopy and diffraction. This approach was important because it linked particle formation and chemical association with the intended function of slow silicon release.

Seed priming with 0.04-0.12% formulations increased the seedling-vigour index by as much as 3.7-fold compared with SiO2. Foliar application increased total chlorophyll and leaf area and modified antioxidant-enzyme activity and reactive-oxygen balance. Under field conditions, 0.08% CS-Si NF produced 43.4% higher yield per plot, while 0.04% produced 45% higher test weight than SiO2. The different concentrations associated with maximum yield and test weight demonstrate that a single dose may not optimise every crop trait.

Chitosan can protect an encapsulated ingredient, improve adhesion and influence plant defence, whereas silicon can strengthen structural and physiological responses. Their combined effect may therefore arise from delivery characteristics and biological activity of the carrier. However, comparison with SiO2 alone does not completely separate the contribution of chitosan from that of nanoscale silicon delivery. Field studies including bulk chitosan, soluble silicon, nutrient-equivalent conventional treatments and the complete nanoformulation are needed to quantify each component's contribution.

This interpretation is consistent with the broader nanofertiliser literature, which shows that polymeric carriers can improve nutrient retention and delivery, but their agronomic advantage must be demonstrated against both bulk materials and conventional soluble nutrient sources (Beig et al., 2022; Kumaraswamy et al., 2021; Mehta et al., 2024).

3.3 Zinc Oxide Nanofertiliser and Maize Physiology

Azam et al. (2022) evaluated chemically synthesised ZnO nanoparticles in maize hybrid FH-1046 following foliar and soil application. The nanoparticles were characterised using SEM, XRD and FTIR, and foliar treatments included 10, 20, 30 and 40 ppm. The study assessed growth, photosynthetic pigments and antioxidant responses rather than relying on a single biomass endpoint.

The reported foliar-treatment responses included increases of 59.28% in growth, 48.19% in photosynthetic pigments and 52.91% in antioxidant activity. Zinc is required for enzyme function, membrane stability, protein synthesis and regulation of oxidative stress; an adequately dispersed ZnO formulation may increase Zn availability at low application rates. Improvements in pigments and antioxidant activity are consistent with better physiological status, but they do not alone establish higher nutrient-use efficiency unless nutrient uptake and recovery are quantified.

ZnO nanoparticles can dissolve and release Zn ions, and their effects may reflect both nanoparticle-specific interactions and conventional zinc nutrition. Excess Zn can also inhibit growth and disturb redox processes. Therefore, optimum concentrations should be treated as crop- and environment-specific. Comparisons with ZnSO4 or other conventional Zn sources at equivalent Zn rates are necessary to determine whether the nanoformulation offers a genuine efficiency advantage.

For zinc-based nanofertilisers, peer-reviewed studies emphasise that physiological improvements should be linked with Zn uptake, translocation and recovery efficiency before concluding that nano-Zn is superior to conventional zinc fertilisation (Adisa et al., 2019; Azam et al., 2022; Mehta et al., 2024).

3.4 Chitosan Nanoparticles in *Capsicum* Production and Thrips Management

Mawale and Giridhar (2024) evaluated chitosan nanoparticles for their effects on growth, yield and thrips infestation in *Capsicum* species. This study is notable because it integrated crop productivity with a crop-protection endpoint. Chitosan is biodegradable and may act as a carrier, film-forming material, elicitor or biostimulant. At the nanoscale, its surface area and interaction with plant tissues may be enhanced.

Table 1. Experimental approaches used in the selected crop-production studies

Study and journal	Crop and objective	Nanoformulation	Application and measurements
Kumaraswamy et al. (2021), Plant Physiology and Biochemistry	Maize; improve silicon delivery, growth and yield	Silicon encapsulated in a chitosan-tripolyphosphate nanomatrix	Ionic-gelation synthesis; DLS, FTIR, TEM, SEM, XRD, XPS and AAS characterisation; seed priming and foliar treatments; seedling vigour, pigments, redox responses and field yield.
Azam et al. (2022), Biocatalysis and Agricultural Biotechnology	Maize hybrid FH-1046; compare foliar and soil ZnO nano-fertiliser effects	Chemically synthesised ZnO nanoparticles	SEM, XRD and FTIR characterisation; foliar concentrations of 10, 20, 30 and 40 ppm, with soil application also evaluated; growth, pigments and antioxidant system measured.
Mawale and Giridhar (2024), International Journal of Biological Macromolecules	*Capsicum* spp.; evaluate growth, yield and thrips response	Chitosan nanoparticles	Biological evaluation of nano-chitosan treatments; plant growth, yield-related attributes, biochemical responses and thrips infestation assessed.
Patil et al. (2024), Plant Physiology and Biochemistry	Maize and wheat; evaluate growth responses to Ca-doped ZnO	Calcium-doped ZnO nanoparticles	Co-precipitation synthesis and physicochemical characterisation; seed germination, root and shoot length, plant height, root and stem width, number of leaves and leaf size measured.

Table 2. Principal crop responses reported in the selected studies

Study	Main reported response	Quantitative evidence retained from source	Interpretation
Kumaraswamy et al. (2021)	Improved maize vigour, photosynthesis, antioxidant defence and field yield	Up to 3.7-fold higher seedling-vigour index than SiO2; 0.08% CS-Si NF gave 43.4% higher yield/plot; 0.04% gave 45% higher test weight than SiO2.	Encapsulation and slow/protective Si release were associated with better performance than bulk SiO2.
Azam et al. (2022)	Improved maize growth, photosynthetic pigments and antioxidant activity	Across foliar treatments, the study reported increases of 59.28% in growth, 48.19% in photosynthetic pigments and 52.91% in antioxidant activity.	Responses support ZnO nano-fertiliser potential, but depend on dose, route and comparator.
Mawale and Giridhar (2024)	Modified *Capsicum* growth, yield and thrips infestation	Directional improvements were reported; a single universal effect value was not used in this review because responses varied with treatment and *Capsicum* material.	Chitosan nanoparticles may function as both biostimulants and crop-protection modifiers.
Patil et al. (2024)	Enhanced measured growth parameters in maize and wheat	Growth responses were reported across measured traits; a single universal effect percentage was not assigned because responses varied by treatment and crop.	Ca-doped ZnO showed potential as a nanofertiliser for plant growth, with effects dependent on formulation and dose.

Table 3. Critical appraisal and research needs

Study	Strength	Important limitation	Priority for further research
Kumaraswamy et al. (2021)	Links extensive material characterisation and release behaviour with seedling and field responses.	Responses were formulation-, concentration- and comparator-specific.	Multi-season trials at nutrient-equivalent rates, economic analysis and Si fate in soil-plant systems.
Azam et al. (2022)	Directly evaluates foliar and soil application of ZnO nanoparticles in maize.	Percentage summaries do not replace full dose-response and nutrient-equivalent comparison.	Confirm optimum dose across soils and hybrids; quantify Zn recovery, residue and phytotoxicity thresholds.
Mawale and Giridhar (2024)	Connects plant production with a biotic-stress endpoint.	Mechanisms linking chitosan nanoparticles and thrips response require clearer separation from general chitosan effects.	Field pest-pressure trials, non-target arthropod assessment and comparison with bulk chitosan.
Patil et al. (2024)	Evaluates a Ca-doped ZnO formulation in two cereal crops with physicochemical characterisation.	Evidence centred on growth responses; longer-term nutrient fate, residue and soil-biological effects were not established.	Multi-location trials, nutrient uptake and recovery, residue, microbiome and economic studies.

The reported improvements in crop growth and yield, together with modification of thrips infestation, suggest that nano-chitosan may simultaneously influence plant vigour and inducible defence. Possible explanations include improved nutrient assimilation, activation of defence-related pathways, changes in antioxidant metabolism and physical or behavioural effects on insects. Nevertheless, these mechanisms should not be assumed without direct biochemical and entomological evidence.

Crop-protection value must be assessed under natural pest pressure and compared with untreated plants, bulk chitosan and recommended pest-management practices. Effects on predators, parasitoids, pollinators and other non-target organisms also require evaluation. Nano-chitosan may be most useful as one component of integrated pest management rather than as a stand-alone replacement for all crop-protection measures.

This cautious interpretation agrees with previous reviews describing chitosan and other nano-enabled inputs as potential biostimulant or crop-protection tools whose effectiveness depends on formulation, crop species, pest pressure and comparison with standard management practices (Chhipa, 2017; Mawale & Giridhar, 2024; Shang et al., 2019).

3.5 Calcium-doped ZnO Nanoparticles in Maize and Wheat

Patil et al. (2024) examined Ca-doped ZnO nanoparticles in maize and wheat. The study reported significant improvements in measured growth parameters, including seed germination, root and shoot length, plant height, root and stem width, number of leaves and leaf size. It therefore linked the physicochemical characterisation of the Ca-doped ZnO formulation with growth responses in two cereal crops.

Broader ZnO nanoparticle evidence also indicates potential effects on metal uptake and oxidative stress. In wheat, Hussain et al. (2018) reported reductions of 30-77% and 16-78% in grain Cd concentrations following foliar and soil application, respectively, together with reduced electrolyte leakage and increased superoxide dismutase and peroxidase activities.

Such reductions in grain Cd are relevant to food safety, but their interpretation requires consideration of total Zn application, nanoparticle dissolution, soil Cd availability and crop yield. Dilution caused by increased biomass can also influence tissue concentrations. Long-term trials are therefore required to determine whether repeated use changes metal pools in soil or creates residual effects on subsequent crops.

The Patil et al. (2024) study therefore primarily supports the agronomic potential of Ca-doped ZnO for improving measured plant-growth parameters, whereas the broader ZnO literature indicates that metal uptake and exposure pathways may also be modified under specific conditions (Hussain et al., 2018; Nandini et al., 2023; Zhang et al., 2020).

3.6 Mechanisms Supporting Crop Response

Across the selected studies, four interacting mechanisms appear relevant: improved nutrient availability, controlled or protective release, enhanced contact with seed or leaf surfaces, and modulation of plant defence and redox processes. Small particles possess a high specific surface area, but beneficial uptake also depends on colloidal stability and dissolution. Aggregated particles may behave differently from the nominal particle size reported after synthesis.

Root uptake is influenced by rhizosphere chemistry, root exudates, mucilage and apoplastic barriers. Foliar uptake depends on droplet retention, cuticular pathways, stomata and surface damage, whereas seed priming can influence hydration, enzyme activation and early redox signalling. After entry, transport may occur as particles, dissolved ions or transformed complexes. Because different mechanisms can produce similar growth responses, isotope tracing, advanced imaging and mass-balance studies are required to distinguish pathways.

Hormesis is another important consideration. Low nanoparticle concentrations may stimulate antioxidant defences and growth, while higher concentrations can generate excessive reactive oxygen species, damage membranes and suppress development. Thus, the dose-response relationship may be non-linear. Recommendations should specify particle composition, size distribution, coating, concentration, application volume, crop stage and environmental conditions rather than referring generically to a material such as 'nano-zinc'.

Mechanistic studies further indicate that nano-enabled responses may result from intact particles, dissolved ions, transformed species or induced plant signalling, making careful characterisation and pathway tracing necessary for reliable interpretation (Adisa et al., 2019; Kah et al., 2019; Zhang et al., 2020).

3.7 Implications for Nutrient-Use Efficiency and Productivity

Nano-enabled formulations could contribute to nutrient-use efficiency when they reduce premature nutrient loss, improve placement or release nutrients in closer synchrony with crop demand. The slow-release behaviour reported for CS-Si NF illustrates this principle. However, increased growth relative to an untreated control is not sufficient evidence of improved nutrient-use efficiency. A rigorous assessment requires equivalent nutrient rates, measurements of nutrient uptake, partial factor productivity, recovery efficiency and environmental losses.

The field yield response reported by Kumaraswamy et al. (2021) and the growth responses reported by Patil et al. (2024) are encouraging because they extend evaluation beyond material characterisation alone. Still, one-season or limited-location results cannot establish stability across soil types, climates and crop genotypes. Multi-environment testing should examine whether a formulation consistently benefits low-fertility soils, adequately fertilised soils and stress-prone environments.

Economic performance is equally important. A nanoformulation may reduce application rate but remain unattractive if synthesis, characterisation, formulation stability or specialized application increases total cost. Farm-level evaluation should include product cost, labour, yield value, quality premium, compatibility with existing machinery and storage life.

Therefore, claims of improved nutrient-use efficiency should be supported by nutrient-equivalent controls, recovery-efficiency measurements and economic analysis because higher biomass or yield alone does not prove more efficient nutrient delivery (Beig et al., 2022; Guo et al., 2018; Mehta et al., 2024).

3.8 Environmental Safety, Regulation and Adoption

Agricultural nanomaterials may undergo aggregation, dissolution, adsorption, oxidation or biological transformation after application. Their fate is influenced by clay, organic matter, pH, ionic strength, moisture and microbial activity. Some biodegradable carriers such as chitosan may present lower persistence, whereas metal-based materials can contribute ions or transformed residues. Safety assessment must therefore be formulation-specific.

Potential concerns include phytotoxicity at excessive doses, effects on beneficial soil microorganisms and fauna, movement to water bodies, accumulation in edible tissues and occupational exposure during formulation and spraying. Conventional toxicity tests may not fully capture nano-specific behaviour. Studies should characterise both the applied material and its transformed products and should distinguish total elemental concentration from nanoparticulate residues.

Regulatory evaluation requires standardised terminology, particle characterisation, quality control, labelling and data on efficacy, residues and environmental fate. Farmers also need clear dose recommendations and evidence that products provide benefits beyond conventional alternatives. Responsible adoption will depend on transparent communication and locally validated packages integrated with soil testing, balanced fertilization and integrated crop management.

These requirements agree with safety-focused literature recommending formulation-specific assessment of persistence, transformation products, soil biota, edible-tissue residues and occupational exposure before commercial promotion. Recent reviews further stress that interactions with soil microbial communities may be beneficial or disruptive depending on material, concentration and exposure duration (Kalwani et al., 2022; Kekeli et al., 2025; Nandini et al., 2023; Soni et al., 2024; Zhang et al., 2020).

4. Research Gaps and Future Directions

Future studies should use well-characterised materials, transparent controls and agronomically relevant treatment rates. Conventional formulations should be applied at equivalent active-ingredient or nutrient doses. Experiments should report dispersion preparation, application volume, particle-size distribution before and after mixing, and storage stability. These details are essential for reproducibility.

Field research should span multiple seasons and locations and measure yield, produce quality, nutrient recovery, residues, soil health, microbial communities and off-site losses. Crop rotations are particularly important because nanoparticles or transformation products may persist beyond the treated season. Life-cycle assessment should compare energy use and environmental burdens of nanoformulation manufacture with the benefits achieved during crop production.

Biodegradable carriers, green synthesis and stimulus-responsive delivery systems are promising directions, but their advantages must be demonstrated rather than inferred. Integration with precision agriculture could allow nano-inputs to be applied only where and when needed. The strongest future systems will combine material science with agronomy, soil science, plant physiology, toxicology, economics and regulation.

A multidisciplinary research agenda is especially important because agronomic performance, environmental behaviour, farmer adoption and regulation are interdependent components of responsible nano-enabled agriculture (Kah et al., 2019; Mehta et al., 2024; Zhang et al., 2020).

5. Limitations of this Review

This review has four main limitations. First, the four focal studies were purposively selected and do not represent an exhaustive census of agricultural nanotechnology research. Second, heterogeneity in materials, crops, controls and endpoints prevented quantitative synthesis. Third, several conclusions rely on short-duration or limited-location experiments, restricting geographic generalisation. Fourth, publication and positive-result biases may overrepresent beneficial responses. The broader literature was therefore used for contextual triangulation, and all conclusions are framed as formulation-, dose- and environment-specific rather than universal.

6. Conclusion

Nanotechnology offers promising routes for improving crop production through enhanced nutrient delivery, seed priming, physiological stimulation, stress mitigation and crop protection. The four focal studies provide formulation-specific evidence that chitosan-silicon, ZnO, chitosan and Ca-doped ZnO materials can improve selected outcomes in maize, wheat and *Capsicum*. The review's principal contribution is a framework linking material properties and delivery route to soil-plant processes, crop outcomes, evidence quality and responsible deployment. The strongest quantitative observations included a 43.4% increase in maize yield per plot and a 45% increase in test weight with selected chitosan-silicon concentrations, while the Ca-doped ZnO study reported significant improvements in measured growth parameters of maize and wheat. These outcomes should not be generalised to all nanoparticles or regions. Wider adoption requires nutrient-equivalent comparisons, multi-season and multi-location field trials, residue and ecological-safety assessment, robust quality standards and farm-level economic analysis. When supported by responsible design and local agronomic validation, nano-enabled inputs may complement conventional crop-management practices and contribute to more efficient and resilient cereal and vegetable production.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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