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NEXT GENERATION NUTRIENT MANAGEMENT: A REVIEW OF NANO SCALE SMART FORMULATIONS IN AGRICULTURE

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ABSTRACT

In the modern agricultural era, the indiscriminate and heavy application of conventional synthetic chemical fertilizers, pesticides and herbicides has introduced serious ecological hazards, including soil degradation, water eutrophication, heavy metal accumulation and low nutrient use efficiency (Abdel *et al.*, 2019). Nanotechnology presents a revolutionary framework to counter these multi-dimensional crises through the development of nano scale smart formulations (Banotra *et al.*, 2017). Nano fertilizers, typically ranging from 1 to 100 nm, possess exceptional physicochemical properties such as an enhanced surface-to-volume ratio, high surface tension, higher target reactivity and precise on-demand controlled nutrient delivery pathways (Adhikari *et al.*, 2010). This comprehensive review synthesizes foundational nanotechnology principles alongside state of the art field scale research data covering nano formulations of macro (N, P, K) and micro (Zn, Cu, B, Mo) nutrients across major agronomic and horticultural crop systems, including chickpea, potato, tomato, soybean, chilli, okra and cucumber (Meena *et al.*, 2024, Al-juthery & Al-Shami, 2019, Mishra *et al.*, 2020). The compiled evidence consistently demonstrates that replacing or supplementing 25 percent to 50 percent of the recommended traditional chemical inputs with foliar nano sprays or fertigation significantly enhances morpho-physiological traits, yields, post-harvest quality and economic net returns while fundamentally mitigating chemical loading into sub-surface soil and groundwater environments (Naderi & Danesh Shahraki, 2013).
***Keywords* :** Nano scale, Smart formulations and Agriculture

Introduction

Nanotechnology and Agriculture

The nomenclature "Nanotechnology" traces its root to the Greek word "Nanos", translating directly to "dwarf" (Banotra *et al.*, 2017). Initially coined by Norio Taniguchi in 1947, modern nanotechnology manipulates and engineer's structures operating at a scale of 100 nanometres (nm) or less. In modern crop production architecture, nanotechnology introduces specialized diagnostic tools and high-efficiency inputs: nano bio-sensors for real-time site-specific tracking of moisture profiles and nutritional deficits**,** nano-herbicides and target-oriented pesticide carriers (e.g., polymer-coated systems for compounds like Paraquat) that control aggressive weed floras and pest complexes and nano fertilizers engineered for precision nutrient management (Ghormade *et al.*, 2011). This dynamic framework provides a viable pathway to unlock vertical crop productivity, stabilize fragile agricultural value chains, support long-term food security and ensure strict ecological sustainability (Jyothi & Hebsur, 2017).

Nano-Particles Properties

The unprecedented efficacy of nanoparticles relative to macro-scale bulky materials is driven by foundational quantum and structural characteristics (Tarafdar *et al.*, 2012):

- **High Surface-to-Volume Ratio:** A significantly higher proportion of atoms reside on the outer structural boundaries of nanoparticles compared to their interior mass, creating high outer charge densities and heightened surface chemical reactivities (Adhikari *et al.,* 2010).

- **Quantum Mechanical Transition:** Below critical dimensional thresholds, particles transition from classical bulk behaviors into clear quantum mechanical regimes, altering light absorption, magnetism and fluorescence profiles (Banotra *et al.,* 2017).
- **Enhanced Thermal and Structural Strength:** Large surface-to-volume interfaces maximize structural atomic interactions when nanoparticles are intermixed with matrix materials, generating elevated heat resistance and lowered melting thresholds.
- **Geometric Catalytic Superiority:** Nanoparticles display variable catalytic efficiencies based on crystalline orientation, where tetrahedral matrix networks exhibit superior performance over cubic and spherical geometries due to intense chemical reactivity concentrated along sharp spatial edges (Ghormade *et al.,* 2011).
- **Zeta Potential Stability:** Most engineered nanoparticles (except specialized materials like hydroxyl apatite) maintain distinctive electro-kinetic values between +30 and -30 mV, governing their dispersion and targeted aggregation profiles (Adhikari *et al.,* 2010).

Nano Fertilizers

Nano fertilizers represent strategically modified, high-efficiency nutrients synthesized via advanced chemical, physical, mechanical, or biological pathways using nanotechnology (Kottegoda *et al.,* 2011). By packing traditional bulk fertilizer substrates or specialized organic matrix extracts into molecular formulations, these materials dramatically optimize crop nutrient absorption dynamics. Capping, thin-film polymer binding, or lipid encapsulation inside nano-capsules allows for highly synchronized, slow, or on-demand release profiles corresponding with distinct crop vegetative and reproductive growth phases (Jyothi & Hebsur, 2017).

For example, transforming raw rock phosphate into a nano formulation prevents immediate soil fixation, bypassing chemical precipitation with native iron and calcium ions to keep phosphorus continuously bioavailable. Similarly, iron-chelated nano fertilizers supply highly stable, gradual releases of bivalent iron across wide pH ranges (pH 7.0 to 11.0) without requiring traditional ethylene compounds. This continuous supply is essential for sustained chlorophyll synthesis, cellular respiration, and electron transport assemblies (Banotra *et al.,* 2017).

Conventional Fertilizer Versus Nano fertilizer

Limitations of Traditional Application

Traditional nutrient delivery relies heavily on soil broadcasting, band placement, or heavy liquid drenching. Under these regimes, only a small fraction of the applied active minerals successfully reaches target plant destination tissue. Extensive commercial fields lose roughly 40 to 70 percent of total applied Nitrogen, 80 to 90 percent of Phosphorus and 50 to 90 percent of Potassium via deep leaching, surface runoff, wind drift, chemical volatilization, hydrolysis, and rapid microbial immobilization (Brady & Weil, 1999).

These persistent losses force growers into repeated, heavy fertilizer applications. This practice damages soil micro-flora, restricts native nitrogen-fixation mechanisms, drives heavy metal accumulation, and triggers widespread surface water eutrophication (Abdel *et al.,* 2019).

Conceptual Mechanisms of Nano Formulations

Nano fertilizers offer substantial advantages over commercial bulk configurations (Naderi & Danesh Shahraki, 2013):

Conventional Bulk Granule -> High Losses (Leaching/Volatilization) -> Low Absorption

Engineered Nano Fertilizer -> Surface Tension Capping -> Stomatal/Cuticular Entry -> High Nutrient Use Efficiency

Because of their small particle sizes and high surface tension properties, surface-coated nano materials adhere to foliar and root surfaces far more tightly than conventional fertilizers. Encapsulated inside thin, protective polymer films, the active nutrient cores are isolated from immediate soil fixation and environmental degradation (Naderi & Danesh Shahraki, 2013). Once applied, these nanoparticles pass into the inner plant systems through cuticular micro-pores (less than 5 nm) or stomatal openings and hydathodes before entering the deep cellular networks via plasmodesmata channels (50 to 60 nm). This target-oriented transportation path ensures rapid tissue absorption, high mobility, minimal environmental toxicity, and optimized metabolic conversion (Taiz & Zeiger, 2010).

Key Advantages over Commercial Bulk Fertilizers

- **Dramatically Heightened Input Efficiency:** Maximizes partial factor productivity and minimizes chemical quantities required per unit area (Adhikari *et al.,* 2010).

- **Controlled, On-Demand Delivery Dynamics:** Eliminates localized nutrient spikes, matching release patterns with active plant physiological requirements up to 60 days (Kottegoda *et al.*, 2011).
- **Upgraded Crop Protection and Vitality:** Triggers systemic acquired resistance (SAR) path mechanisms, thickens structural stalks to limit lodging, and induces deep, robust rooting profiles (Banotra *et al.*, 2017).
- **Enhanced Nutritional and Organoleptic Profile:** Maximizes protein synthesis, carbohydrate accumulation, essential antioxidant yields, and post-harvest shelf stability (Merghany *et al.*, 2019).

Nano fertilizer Formulations and Smart Delivery Systems

The structural configuration of any high-efficiency nano fertilizer must balance structural stability, localized solubility, precise release timing, and negligible eco-toxicological risks. Loading active nutrient matrices onto carrier nanoparticles is achieved through five primary chemical and physical strategies (Banotra *et al.*, 2017):

1. Direct physical absorption onto porous nanoparticle surfaces.
2. Ligand-mediated chemical conjugation or attachment.
3. Encapsulation within polymeric nano-particulate shell structures.
4. Entrapment within advanced internal polymeric nanoparticle matrices.
5. Direct synthesis of standalone nanoparticles composed entirely of the target nutrient material.

For instance, synthesizing urea-modified hydroxyapatite (HA) nanoparticles provides a highly effective template for gradual nitrogen release. The immense surface area of HA binds high densities of urea molecules. This strong structural interaction controls structural dissolution, sustaining slow nitrogen delivery for up to 60 days, whereas conventional commercial alternatives deplete their active contents within 30 days (Kottegoda *et al.*, 2011). Similarly, mesoporous silica nanoparticles (average diameter 150 nm) can load approximately 15.5 percent net urea inside their engineered micro-pores, providing excellent slow-release profiles in both soil and aquatic systems (Banotra *et al.*, 2017).

Methods of Delivery to Plant Systems

Nutrient delivery pathways can be broken down into Aeroponics (suspended root misting), Hydroponics (closed liquid circuits), Soil Application (drip fertigation/slow-release), and Foliar Application (direct stomatal penetration).

- **Aeroponics:** In aeroponic culture networks, plant root architectures are suspended directly in sealed internal chambers and continuously misted with specialized nano-nutrient solutions. While this configuration enables precise management of the gas-exchange profiles surrounding the rhizosphere, it demands high, continuous inputs to maintain rapid vegetative development, which limits its broad scale implementation (Banotra *et al.*, 2017).
- **Hydroponics:** Commonly designated as closed "solution culture," hydroponic frameworks immerse active root structures directly inside soil-free, circulating liquid nutrient media. Operating these networks requires strict, automated control over net liquid volumes, absolute oxygen demands, and active pH shifts. A key operational vulnerability includes rapid pathogen transmission through the shared water loop, which can cause sudden crop wilting (Banotra *et al.*, 2017).
- **Soil Application:** Soil application remains the most widely deployed strategy for baseline organic and chemical nutrition. Operational success depends heavily on structural soil textures, localized salinity profiles, background pH values, and native chemical exchange capacities. Because typical agricultural fields possess net negative exchange charges, mobile anions like nitrate move freely through the soil solution and remain highly vulnerable to heavy downward leaching. Conversely, phosphate anions bind tightly to iron (Fe2+/Fe3+) and aluminum (Al3+) oxides via hydroxyl group exchange, causing rapid structural fixation that limits seasonal root acquisition (Brady & Weil, 1999). Drip fertigation addresses these issues by delivering liquid nano fertilizers directly into the active root zone, minimizing chemical fixation risks and structural element losses (Al-juthery & Al-Shami, 2019).
- **Foliar Application:** Foliar application sprays liquid nano-nutrient complexes directly onto active crop leaf surfaces. This strategy circumvents traditional root acquisition barriers, soil fixation traps, and moisture deficits. Because nutrient uptake occurs directly through open stomatal pathways and epidermal cell walls, foliar spraying provides rapid metabolic assimilation during

critical vegetative and reproductive transitions (Taiz & Zeiger, 2010). To optimize uptake, spraying protocols must target early morning or late evening windows when stomatal conductivity peaks.

Nanoparticle Interfacial Transport and Internalization

Nanoparticles enter plant systems by passing through lateral root cell junctions or external leaf stomatal pores. Once inside the foliar layer, their movement is governed by the structural pore limits of the plant cell walls (typically 5 to 50 nm). Particles smaller than 5 nm move efficiently through cuticular pathways, while larger variants (up to 50 nm) travel along stomatal routes to reach the primary conducting bundles (Taiz & Zeiger, 2010).

After crossing these outer barriers, nanoparticles bind to specialized internal transport complexes, moving through aquaporins, endocytosis pathways, or membrane ion channels to create new structural entry openings. They travel through cortical tissue and the pericycle to enter the primary xylem lines, distributing globally via vascular translocation (Taiz & Zeiger, 2010). At the cellular level, internalized nanoparticles interact through physical and chemical pathways, regulating reactive oxygen species balances, modifying membrane ion channel potentials, and binding with cellular sulfhydryl and carboxyl protein groups to optimize core metabolic processes (Prasad *et al.*, 2012).

Nano fertilizers and Plant Growth Dynamics

Seed Germination and Seedling Development

Nano fertilizers easily penetrate outer seed coat structures, accelerating internal moisture absorption and increasing overall nutrient availability for developing embryonic axes. This early metabolic stimulation significantly enhances structural seed vigor, speed of emergence, shoot elongation, and primary root growth (Prasad *et al.,* 2012). However, strict adherence to optimal dosage thresholds is essential; exceeding crop-specific concentration limits can reverse these benefits and inhibit initial seedling development (Prasad *et al.,* 2012).

Interaction with Water Stress

Under conditions of severe soil water deficit, traditional root nutrient uptake drops sharply due to reduced transpiration currents, impaired cell membrane permeability, and limited mineral diffusion through dry soil matrices. Water stress also alters the physical layout and penetration angles of root systems, reducing their overall absorbing surface area (Mosanna & Behrozyar, 2015). Foliar nano fertilizer applications bypass these soil moisture dependencies by delivering essential minerals directly to the leaves. This targeted delivery helps maintain internal organic acid and sugar levels, protects chloroplast ultrastructures, and preserves overall photosynthetic efficiency under drought conditions (Mosanna & Behrozyar, 2015).

Crop-Wise Responses to Nano Fertilizers

Chickpea (*Cicer arietinum* L.)

Field trials on chickpea crops under arid conditions demonstrate the high efficacy of combined macro and micro nano formulations. Foliar application of 100 percent recommended NPK combined with Nano Urea (3 ml per liter) and Nano Zinc (2 ml per liter) at flowering and pod development stages significantly improves plant height, lateral spread, and branch density (Meena *et al.,* 2024). This combination delivers essential nitrogen to active meristematic zones and provides zinc to support chlorophyll synthesis, auxin production, and tryptophan pathways. This optimized application strategy delivers substantial grain yields (1902 kg per hectare), matching or exceeding traditional bulk fertilizer regimes while dramatically lowering total chemical applications (Meena *et al.,* 2024).

Potato (*Solanum tuberosum* L.)

Potatoes have high structural demand for consistent macro and micronutrient availability throughout their growth cycle. Integrating drip irrigation fertigation with foliar nano sprays provides an optimized delivery strategy. Using nano-nitrogen fertigation (40 liters per hectare of 25 percent N) combined with foliar nano-boron (9 percent B at 1 kg per hectare) and nano-molybdenum (5 percent Mo at 500 grams per hectare) applied in progressive intervals significantly increases total chlorophyll index and vegetative dry mass (Al-juthery & Al-Maamouri, 2019). The small particle sizes and slow-release characteristics prevent traditional leaching and volatilization losses. This balanced nutrient access increases soft tuber production to 37.53 Megagrams per hectare, starch yields to 4.152 Megagrams per hectare, and total protein to 481.3 kg per hectare. Additionally, it improves structural Water Use Efficiency to 20.62 kg per cubic meter (Al-juthery & Al-Maamouri, 2020).

Tomato (*Solanum lycopersicum* L.)

Tomato cultivation responds favorably to integrated nutrient management combining traditional basal inputs with foliar nano sprays. Applying a 100 percent Recommended Dose of Nitrogen split as a 50 percent basal urea dose combined with two foliar sprays of Nano Urea at 30 and 45 days after transplanting optimizes fruit firmness (1.47 Newtons) and color metrics (L* = 37.54, a* = 39.79) (Yashaswini *et al.,* 2025). Furthermore, using a multi-tier strategy combining a 50 percent inorganic soil NPK base with sequential foliar sprays of Nano Nitrogen, Nano Zinc, and Nano Copper significantly increases plant height (122.45 cm), branch count (12.4), and total harvest yield (425.24 quintals per hectare), delivering a benefit-cost ratio of 4.01 (Mishra *et al.,* 2020). Conversely, reducing macro inputs with a single nano spray triggers localized nutrient stress, leading to early first flowering (18.40 days) and accelerated fruit harvest (64.20 days) (Vineela *et al.,* 2025).

Soybean (*Glycine max* L.)

Field evaluations of soybean varieties grown on vertisol profiles show that integrated nano-fertilizer schedules perform exceptionally well. Combining seed priming with Nano DAP alongside a 75 percent conventional basal application and two foliar sprays of 25 percent Nano Urea and Nano DAP produces plant heights, branch counts, leaf area indices, and total dry matter accumulations that are statistically on par with 100 percent conventional mineral fertilizer inputs, reducing total chemical requirements (Daware *et al.,* 2024).

Capsicum and Chilli (*Capsicum annuum* L.)

Field trials with bell pepper varieties demonstrate that applying 100 percent structural PK alongside 100 percent Nano Nitrogen, Nano Zinc, and Nano Copper foliar sprays maximizes dry matter production, fruit set percentages (80.4 percent), single fruit weights (159.8 grams), and total estimated yields (21.2 tonnes per hectare) (Nandhinidevi & Sam Ruban, 2022). This combination also increases vitamin C content to 159.8 mg per 100g. Reducing the solid nitrogen base by 50 percent and supplementing with nano sprays maintains high crop productivity (20.8 tonnes per hectare). For long-pod chilli varieties, applying a foliar nano-complex improves plant height (73.77 cm), lateral canopy spread (63.11 cm), and total leaf area (41.07 square centimeters) (Rather *et al.,* 2022). This targeted delivery strategy improves mineral utilization and limits nutrient losses (Srilekha *et al.,* 2025).

Okra (*Abelmoschus esculentus* L.)

In tropical island ecosystems characterized by high annual precipitation (e.g., 3100 mm), standard granular urea applications face severe leaching. Field experiments show that applying 66 percent of the recommended nitrogen base through the soil combined with two foliar sprays of 0.4 percent Nano Urea matches the growth attributes of a 100 percent conventional fertilizer regime. This strategy boosts total okra yields to 13.82 tonnes per hectare. Economically, this nano spray intervention generates high net returns (541,876 Rupees per hectare) and an additional monetary benefit of 65,561 Rupees, reducing total mineral nitrogen fertilizer requirements without causing negative shifts in the native rhizosphere environment (Subramani *et al.,* 2023).

Cucumber (*Cucumis sativus* L.)

Greenhouse and field trials with cucumber crops demonstrate that liquid nano NPK formulations significantly outperform traditional bulk mineral inputs. Applying liquid nano NPK at an optimal concentration of 6 ml per plant optimizes plant height and total chlorophyll content. This balanced nutrient supply increases total yield per plant up to 53.42 percent compared to standard mineral controls. Post-harvest evaluations show that fruits cultivated under this regime exhibit superior storage quality over a 21-day period at 5 degrees Celsius, minimizing decay percentages and extending commercial shelf life (Merghany *et al.,* 2019).

Synthesis of Field-Scale Crop Responses

To illustrate the systemic impacts of nanotechnology across diverse crop architectures, the following table consolidates structural treatments, key morpho-physiological expressions, and performance outcomes:

Table 1 : Consolidates Structural Treatments, Key Morpho-Physiological Expressions, and Performance Outcomes

Crop System	Optimal Nano Fertilizer Treatment Structure	Measured Morpho-Physiological & Quality Expressions	Core Agronomic & Economic Performance Outcomes
Chickpea *(Meena et al., 2024)*	100% NPK + Nano Urea + Nano Zn at flowering & pod stages.	Heightened meristematic division; expanded leaf photosynthetic area.	Yields peak at 1902 kg/ha; statistically superior over chemical drenching.
Tomato *(Mishra et al., 2020)*	50% N + 100% PK + 50% Zn base + Nano N, Zn, Cu foliar sprays.	Optimal fruit firmness; high lycopene; enhanced taste acceptance.	Harvest reaches 425.24 q/ha; high economic net returns (4.01 B:C).

Soybean *(Daware et al., 2024)*	Seed priming with Nano DAP + 75% basal NPK + 25% Nano Urea/DAP spray.	Increased root biomass accumulation; enhanced leaf area retention.	Growth matches 100% conventional inputs; reduced bulk chemicals.
Capsicum *(Nandhinidevi & Sam Ruban, 2022)*	100% PK base + 100% Nano N, Nano Zn, Nano Cu foliar sprays.	37.6% increase in fruit length; high vitamin C (159.8 mg/100g).	Yields of 21.2 tonnes/ha; replaces 50% of granular urea inputs.
Cucumber *(Merghany et al., 2019)*	Liquid Nano NPK (6 ml per plant applied in staged intervals).	Higher nitrogen-potassium in leaf tissue; preserved chlorophyll.	53.42% yield increase; minimizes decay over 21 days of cold storage.

Conclusion

- **Optimized Structural Development:** Foliar and fertigation applications of engineered nano fertilizers (such as Nano Urea, Nano DAP and nano-micronutrient complexes) significantly enhance crop growth parameters, including plant height, branching density, leaf area indices and root system architecture across diverse crop families (Jyothi & Hebsur, 2017).
- **Excellent Input Efficiency:** Nano fertilizers deliver high nutrient utilization efficiency, with recovery rates reaching up to 97 percent in optimized field trials. This performance allows for a 25 percent to 50 percent reduction in traditional bulk chemical applications, preventing common losses from leaching, volatilization, and soil fixation (Naderi & Danesh Shahraki, 2013).
- **Enhanced Post-Harvest Quality:** Staged nano applications improve key quality metrics, including fruit firmness, color values, starches, total protein profiles, and essential vitamins, while extending commercial storage stability and shelf life (Merghany *et al.*, 2019).
- **Rhizosphere Protection:** Bypassing traditional heavy soil applications with targeted foliar nano sprays or precision drip drenching prevents heavy mineral accumulation in the soil, protects native micro-flora, prevents groundwater contamination, and supports long-term sustainable agriculture (Banotra *et al.*, 2017).

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