

Review Article

Nano Fertilizer in Modern Agriculture: A Sustainable Approach for Enhanced Crop Productivity and Soil Health in Ethiopia: Review

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Abstract

Ethiopian agriculture is challenged by low soil fertility, erratic rainfall, and limited nutrient use efficiency of conventional fertilizers. A more innovative fertilization strategy is needed to enhance productivity while remaining environmentally sustainable. This article reviews recent advancements in nano fertilizers (NFs) and highlights their potential benefits for Ethiopian smallholder and commercial farming systems. Nano fertilizers can significantly contribute to sustainable farming in both field and greenhouse environments by improving nutrient use efficiency (NUE), particularly for staple crops like teff, maize, wheat, sorghum, and pulses. Unlike conventional synthetic fertilizers, which typically release nutrients rapidly within 4–10 days, NFs can provide a slow and steady nutrient supply over 40–50 days, either alone or in combination with organic amendments or inorganic inputs. In addition to enhancing nutrient availability, NFs strengthen crop tolerance to drought, heat, and soil stressors common across Ethiopian agro ecologies. Their precise nutrient delivery minimizes environmental losses, enhances crop growth, and reduces the ecological footprint of agricultural inputs. Engineered nanomaterials (ENMs) present opportunities to replace or reduce conventional fertilizers and pesticides, thereby decreasing soil and water contamination. Controlled release or slow-release nano nitrogen fertilizers, in particular, have shown promising results in improving yields while reducing agro-environmental constraints in Ethiopian contexts. Nano fertilizers - whether applied to the soil or foliage - represent one of the most promising engineered materials for future Ethiopian agriculture. This article highlights the potential of nano-enabled fertilizers (n NFs) as an innovative approach to improving NUE and reducing nutrient losses, thereby supporting sustainable agricultural intensification. It examines synthesis, mode of action, and various types of nano fertilizers, including those formulated with nanoparticles of essential macro- and micronutrients (such as N, P, K, Fe, and Mn). In these formulations, nutrients are either individually bonded or combined with nano-dimensional carriers to ensure regulated and efficient delivery to the plant rhizosphere.

Keywords

Nano Fertilizers (NFs), Slow-release Nano Nitrogen Fertilizers, Nutrient Use Efficiency (NUE), Nutrient Losses, Sustainable Agriculture, Ethiopia

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1. Introduction

Climate change, increasing temperatures, urbanization, and rapid population growth present serious threats to Ethiopian food security and agricultural sustainability [6]. Average temperatures in Ethiopia have risen significantly over the past century, impacting crop phenology, water availability, and soil processes. Water scarcity, uncertain weather patterns, and recurring drought events are driving production instability in both highland and lowland cropping systems. These challenges force farmers to rely heavily on external inputs such as irrigation and fertilizers to maintain yields, often leading to environmental degradation.

With Ethiopia's population projected to continue growing rapidly, the focus must shift toward enhancing productivity, input efficiency, and natural resource conservation to ensure food security [12]. Currently, dependence on chemical fertilizers contributes moderately to yield increases but suffers from low nutrient use efficiencies: approximately 30–40% for nitrogen (N), 15–20% for phosphorus (P), 50–55% for potassium (K), and 2–5% for essential micronutrients under Ethiopian smallholder conditions [1, 2]. Overuse and unregulated application of inorganic fertilizers negatively impact soil physical properties (structure, porosity), disrupt nutrient cycling, reduce microbial diversity, and alter crop and food web interactions over time [14].

Degraded soils and limited arable land necessitate improvement in fertilizer efficiency, which can be achieved through adoption of nano fertilizers tailored to Ethiopian soils [20]. Concerns have emerged regarding the long-term environmental impact of nanoparticles, including their accumulation in ecosystems and implications for flora and fauna. Potential health risks for both consumers and farm workers, especially due to nanoparticle uptake and bioaccumulation, also warrant in-depth research [3, 8].

Nano fertilizers - defined as fertilizer formulations with particle sizes less than 1–100 nanometers - deliver nutrients as small, highly reactive particles. They have become prominent as tools for enhancing productivity and tackling the growing food demand in Ethiopia's smallholder and commercial agricultural systems [9, 11]. Their nano scale increases effective surface area, leading to improved nutrient uptake, higher output with reduced input levels, and greater resilience to stressors [7, 10]. Considering the likelihood of increased regulation and potential pest adaptations, policymakers face the complex task of establishing regulatory frameworks that support innovation while safeguarding health and ecosystems [18].

According to crop nutrient requirements, nano fertilizers can be classified into macro nano, micro nano, and nano particulate fertilizers [4]. The common qualities of nano fertilizers include (a) increasing crop health through improved nutrient provision, (b) serving as sustainable and profitable alternatives, (c) delivering high output per unit application, and (d) reducing contamination of soil and water [20]. Nano fertilizers should be effective, environmentally sustainable, and capable of addressing diverse agricultural challenges in Ethiopia.

2. Classification of Nano Fertilizers

Nano fertilizers can be grouped into different types based on nutrient content, mechanism of delivery, or consistency of release. Important classes include nanocomposites, nano-coated fertilizers, and nanoscale nutrient particles (macro and micronutrient based). Another categorization relies on function, such as controlled release, targeted delivery, or plant growth stimulating fertilizers.

To understand their function, efficiency, and applications, nano fertilizers can be categorized into three groups: nutrient based, action based, and consistency-based NFs.

2.1. Nutrient Based NFs

Nutrient-based NFs are advanced agricultural inputs that use nanomaterials to deliver key plant nutrients more efficiently with reduced environmental impact compared to conventional fertilizers [11, 18].

In Ethiopian soils, nutrient losses via leaching and fixation are common, especially for phosphorus, which is often tightly bound in clay soils. Nanotechnology-based phosphorus fertilizers offer improved solubility and reduce fixation, enhancing P uptake by teff and wheat [12]. Nano diammonium phosphate (Nano DAP) trials in Ethiopian wheat fields showed significant yield increases and improved N and P uptake even at reduced application rates [10].

Inorganic NFs - consisting of metals, non-metals, or metalloid nanoparticles - act as carriers and sometimes as direct nutrient sources, enhancing NUE. For example, nitrogen-based NFs can provide slow and prolonged N release, reducing losses via leaching and gaseous emissions - a major concern in humid Ethiopian highland soils [3].

2.2. Action Based NFs

Action-based NFs (ABNFs) represent an advance in precision nutrient management, supplying nutrients in alignment with crop developmental stages. This enables efficient nutrient absorption, enhanced physiological performance, and improved tolerance to stresses such as drought and high temperature - conditions frequent in eastern and southern Ethiopia [16, 19].

For instance, urea coated with nanoparticles of iron, sulfur, copper, zinc, and magnesium has shown improved nutrient retention compared to conventional urea, particularly under water stress conditions typical of the Ethiopian lowlands [20]. Carbon nanotubes (CNTs) and chitosan-based NFs further enhance nutrient transport, root growth, and water use efficiency, contributing to improved biomass and yield in maize and sorghum cropping systems [5].

2.3. Consistency Based NFs

Consistency-based NFs focus on delivering nutrients grad-

usually over time according to plant demand. These formulations maintain consistent nutrient availability, enhance NUE, and reduce major environmental losses found in conventional fertilizers [6, 14].

Surface-coated NFs use polymers and biopolymers (e.g., chitosan, lignin, alginate) to encapsulate nutrients, facilitating slow release that matches Ethiopian crop growth rhythms [5, 8]. Nanocarrier-based fertilizers incorporate clay composites, mesoporous silica nanoparticles, and nanocellulose, providing large surface areas for nutrient retention and sustained release - highly relevant in sandy, leached soils of the Rift Valley [13].

Together, consistency-based NFs offer a promising innovation for precision agriculture, boosting efficient nutrient utilization, improving soil structure, and enhancing long-term sustainability of Ethiopian soils [2].

3. Mechanism of Nutrient Delivery and Plant Uptake (Root and Foliar Pathways)

Nutrient uptake mechanisms involve complex interactions among soil, roots, and aerial plant structures. Efficiency of these mechanisms affects productivity, biomass, and stress tolerance [2].

Root absorption in Ethiopian soils is mediated by mass flow, diffusion, and root interception, influenced by soil moisture, pH, and texture. Membrane-bound transport proteins facilitate selective ion absorption, allowing entry of essential nutrients into the plant system [6].

Foliar application offers an alternative nutrient delivery route. Leaf cuticles, composed of cutin polymers and wax layers, can hinder penetration. However, nanoscale particles enhance adhesion, droplet retention, and penetration through stomata and cuticular pores [17]. Surfactants and humectants further improve nutrient uptake during foliar feeding, especially under high humidity conditions common in Ethiopian highland cropping seasons.

Novel nano-biosensors developed for early detection of plant stressors enable targeted interventions, improving precision nutrient delivery and overall plant performance [15]. Nanomaterials also support synchronization of nutrient supply with crop demand, reducing losses such as volatilization and leaching [18].

4. Contribution of NFs to Climate Smart Agriculture

4.1. Enhancing Nutrient Use Efficiency and Reducing Input Waste

Optimized fertilizer use is core to climate-smart agriculture (CSA). NFs improve NUE via controlled and continuous nutrient supply. Nano-scale particles bind more effectively to

soil particles, reducing losses and sustaining nutrient flow to the rhizosphere [7, 14].

In trials across diverse Ethiopian soils, nitrogen-based NFs demonstrated improved N uptake and reduced N₂O emissions compared with conventional urea [3, 10].

4.2. Encouraging Productivity Under Abiotic Stress

Abiotic stresses such as drought, high temperature, and soil salinity significantly affect crop productivity in Ethiopia. NFs help strengthen physiological processes, including chlorophyll maintenance, osmotic balance, and antioxidant activity, enabling crops to withstand stress [6, 11].

For example, nano silicon applications improved root morphology and water use efficiency in sorghum under dryland conditions [20].

4.3. Greenhouse Gas Emissions Reduction

Conventional nitrogen fertilizers contribute to nitrous oxide emissions through nitrification and denitrification processes. Controlled availability of nitrogen via NFs moderates these processes, reducing emission intensity and overall carbon footprint of agricultural systems [7].

4.4. Soil Health Restoration and Nutrient Retention

Sustainable soil management aims to restore fertility and stabilize nutrient cycles. NFs with encapsulation technologies supply nutrients efficiently and slowly, preventing toxicity and excessive buildup [5, 18]. Nano iron and nano silicon fertilizers have been shown to enhance soil enzymatic activity and microbial diversity, encouraging nutrient cycling and carbon sequestration [8].

4.5. Environmental and Safety Implications

Although NFs enhance nutrient delivery, their long-term interactions with soil ecosystems remain a concern. Nano zinc oxide and nano titanium oxide, for instance, may disrupt microbial communities and enzyme activities if not carefully formulated [2]. Monitoring soil microbiota and nanoparticle movement toward water bodies is essential for sustainable use.

Due to their small size, nanoparticles can be absorbed by roots and translocated within plant tissues. Concerns about transfer of nanoparticles into edible parts of crops underline the need for comprehensive food safety evaluations [6].

Ethiopia currently lacks specific regulatory frameworks for nano agricultural inputs, posing challenges for risk assessment. Robust policies are required to manage exposure, promote biodegradable and less toxic formulations, and align with international safety standards [11].

Life cycle assessment (LCA) provides a systematic approach to evaluate environmental burdens associated with nano fertilizer production, use, and disposal [21]. Application of LCA is critical to ensure that gains in NUE and productivity do not come at the cost of unrecognized environmental trade-offs.

5. Future Prospects

Nano fertilizers integrated with precision farming tools - such as GIS, sensors, IoT, and variable rate technology - can tailor nutrient applications to specific Ethiopian landscapes, reducing waste and enhancing site-specific management [15, 16].

Nano biofertilizers that combine plant growth-promoting microbes with nanocarriers offer opportunities for regenerative soil health management [20]. These formulations can enhance nitrogen fixation, phosphorus solubilization, and hormone synthesis, promoting productivity in organic and low-input farming systems.

Successful adoption of NF technologies in Ethiopia depends on policy support, farmer education, and cost-sharing mechanisms. High initial costs, limited research infrastructure, and technological barriers require public-private partnerships, extension services, and subsidy programs to facilitate uptake [6, 12].

6. Conclusion

Nano fertilizers offer a sustainable alternative to traditional fertilizers by encouraging controlled nutrient supply, enhancing soil vitality, and minimizing environmental footprints. Their integration with precision agriculture and climate-adaptive strategies positions them as key inputs for future Ethiopian agricultural systems. However, toxicity concerns, microbiota disturbance, and lack of regulatory frameworks remain limitations that must be addressed. By improving nutrient use efficiency, reducing emissions, and enhancing crop resilience, Nano fertilizers can significantly improve crop productivity in Ethiopia. Collaborative research, policy frameworks, and life cycle-based risk assessments are essential to ensure safe and effective application of nanotechnology in Ethiopian agriculture [11, 18].

Abbreviations

CSA	Climate Smart Agriculture
NF	Nano Fertilizers
NUE	Nutrient Use Efficiency

Author Contributions

Tesfaye Ketema Defar: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review &

editing

Ketema Negesse Tola: Conceptualization, Data curation, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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