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Review

Green Chemistry Strategies in the Development of Sustainable Multi-Nutrient Fertilizers for Enhanced Soil and Crop Health

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Abstract

The growing demand for food production has increased the pressure on soil and fertilizer use, often leading to nutrient losses, soil degradation, and environmental pollution. Green chemistry offers practical solutions to these challenges by encouraging cleaner, safer, and more efficient ways of producing and using fertilizers. This review summarizes recent advances in multi-nutrient sustainable fertilizers developed through green chemistry principles, including renewable raw materials, low-toxicity synthesis methods, and environmentally friendly delivery systems. Different approaches, such as controlled-release carriers, nano-enabled formulations, chelated nutrients, and bio-based coatings, are discussed with a focus on how they reduce nutrient losses and improve soil and plant health. The review also highlights the benefits and limitations of these technologies, gaps in current research, and the need for long-term field studies to assess their safety and effectiveness. Overall, green chemistry-guided fertilizer development shows strong potential to support sustainable agriculture by improving nutrient efficiency while reducing environmental impacts.

Keywords: green chemistry; sustainable fertilizer; multi-nutrient fertilizer; soil health; nutrient use efficiency; controlled release; eco-friendly synthesis

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1. Introduction

The accelerating global demand for food, driven by population growth, urbanization, and shifting dietary preferences, continues to pressure agricultural systems [1]. By 2050, food production may need to increase by up to 50% to meet these demands [2]. Fertilizers are essential to replenish soil nutrients and sustain crop yields. However, unregulated and excessive use of conventional fertilizers (N, P, K) has caused significant environmental impacts. Excessive and imbalanced fertilizer application can cause nutrient leaching, water eutrophication, soil acidification, greenhouse gas emissions, and disruption of soil microbial communities. Non-targeted fertilizer use reduces nutrient use efficiency, as significant amounts are lost through leaching, volatilization, runoff, or microbial degradation [3,4]. Further, the undesirable loss of resources causes economic loss to the stakeholder, including farmers [5]. Over time, these impacts erode the sustainability of farming systems and destabilize ecosystems, ultimately harming human health [6].

Farmers and scientists are now prioritizing a shift towards nutrient management methods for both crops and the environment [7], and the promising alternative is multi-nutrient fertilizers [8]. Unlike conventional fertilizers, they provide a balanced supply of

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macronutrients, secondary nutrients, and micronutrients, including sulfur, magnesium, zinc, boron, and iron [9]. Plants need a mix of nutrients to grow well, to survive under stress conditions, and to improve yield [10]. Unlike single-nutrient conventional fertilizers, multi-nutrient fertilizers are designed to improve the nutrient use efficiency of plants, address soil micronutrient deficiencies, and even make crops more nutrient-enriched [11]. However, developing these fertilizers is not easy; it involves complex formulations, higher production costs, and the strict need to fulfill environmental standards [12].

This is where green chemistry steps in as a novel approach to design fertilizers that help crops grow well without harming the environment [13]. The idea is to design fertilizers with eco-friendly or biodegradable coatings, renewable resources, using energy-efficient processes and clean methods to produce them, and designing them in a way that plants get sufficient nutrients slowly over time. The development of fertilizers is guided by principles such as atom economy, reduced toxicity, renewable feedstock utilization, and energy-efficient methods (as shown in Figure 1) to minimize ecological harm [14]. This approach improves fertilizer utilization by crops, as and when required, and a minimum amount is wasted through leaching or volatilization [15].

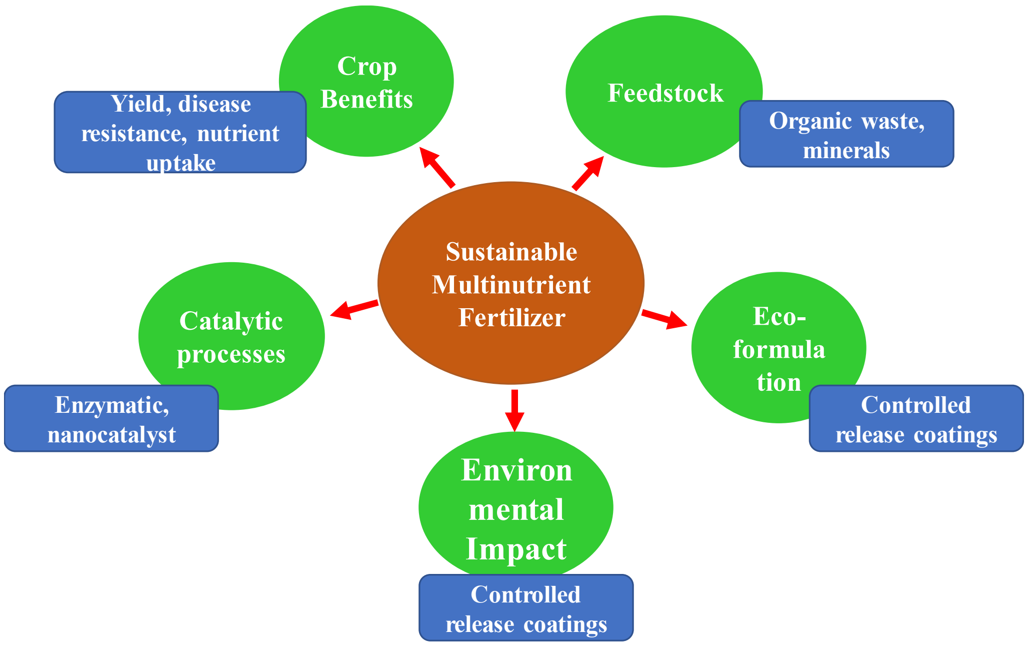

Figure 1. Conceptual framework illustrating the development of sustainable multi-nutrient fertilizers based on green chemistry principles. Different colors represent key components (raw materials, synthesis processes, and delivery systems), while arrows indicate the flow of nutrients and transformation pathways leading to improved soil and crop health.

Combining green chemistry, circular economy, and climate-smart agriculture has sped up the development of eco-friendly multi-nutrient fertilizers [16]. These biodegradable controlled-release fertilizers are made from natural polymers, biochar, and organic waste-based carriers [17]. These materials not only provide nutrients to soil but also improve the soil by making it stronger, improving its structure, boosting microbial activity, and improving water retention [18]. Moreover, fertilizers can also be tailored specifically for certain crops and soil, which saves resources and reduces environmental damage [19].

This review explains how green chemistry is helping to make better multi-nutrient fertilizers. Instead of using conventional raw materials, it uses renewable resources and cleaner methods. With the help of controlled-release fertilizers and nanotechnology, it delivers the plant nutrients more slowly and efficiently, thus boosting soil health, improving nutrient uptake in plants, and enhancing agricultural resilience, while tackling technical and scale-up challenges [20].

Nanofertilizers deliver the plant nutrients more precisely and efficiently, in a controlled manner, and increase their efficiency by upto 30%, thus helping in reducing environmental impact by up to 50%. Nano-biofertilizers, which combine biological agents with nanomaterials, further enhance nutrient delivery and promote plant growth while being safe for the environment [21]. Novel nanoformulations are designed to materials and reduce greenhouse gas emissions. These innovations are essential for their widespread acceptance and for improved crop performance [22].

Nano-biofertilizer can be defined as the intentional coexistence of a nanomaterial and a fertilizer derived from a biological source (wholly organic) that has high efficacy and improved nutrient use efficiency of both materials is included in the definition of nano-biofertilizer. These features serve to increase crop efficiency and nutrient uptake by facilitating the slow release of nutrients over an extended period of crop growth. For example, a nano-biofertilizer using Azospirillum brasilense (strains AbV5 and AbV6) and chitosan nanomaterial was developed by [23]. Application of the developed nano-biofertilizer improved root length (19%) and shoot fresh weight (17%) on the Maize plant. Further, the chlorophyll b content also showed improvement by 71%, as compared to the control. Additionally, the use of nanotechnology prolonged the *A. brasilense* strains' life in the soil by a minimum of 60 days [23]. Utilizing nano-biofertilizer greatly enhances plant development. When nanoparticles are coated with biofertilizers, the biofertilizers work better, and the nanoparticles are released gradually and continuously into the rhizosphere of the plant. They keep the fertilizer dissolved and lessen the likelihood of leaching. Additionally, they improve the quality of crops by increasing the production of secondary metabolites, including enzymatic antioxidants like catalase, superoxide dismutase, and peroxidase, as well as nonenzymatic antioxidants like flavonoids and phenols. These metabolites have several health advantages and extend the shelf life of fruits and vegetables [24]. Nano-biofertilizers assist in bioremediation and replenish vital nutrients in the soil. They upregulate genes involved in the production of antioxidants, osmolytes, and stress-related proteins, minimize the detrimental effects of ROS on plants, and maintain the structural integrity and function of the cell. Additionally, they maintain the activity and increased hormone production of membrane transporters [25]. These approaches activate the plants' antioxidant mechanisms, shielding the organelles and cell membrane from the damaging effects of stress. Additionally, they produce fewer stress hormones (abscisic acid) and more growth hormones, such as cytokinin and indole acetic acid. These modifications boost the plant's ability to withstand stress and raise the likelihood that it will establish a crop in adverse environmental circumstances [25]. Despite these innovations, the adoption of green-chemistry-based multi-nutrient fertilizers remains limited due to field-scale uncertainties, cost, and regulatory constraints.

2. Concept and Principles of Green Chemistry

The relevant literature was collected from scientific databases such as Web of Science, Scopus, and Google Scholar using keywords related to multi-nutrient fertilizers, green chemistry, and sustainable agriculture. AI-based tools (e.g., ChatGPT–GPT5, OpenAI) assisted in organizing the literature and summarizing key findings. Figures and illustrations were created using Canva. All data interpretation, synthesis, and conclusions presented in this review were independently performed and verified by the authors.

Green chemistry is all about designing chemicals in an eco-friendly manner that are safe and sustainable. The main focus is on preventing pollution right from the design stage, instead of focusing on it after it has had its adverse impacts on the environment. This concept is guided by the twelve principles [26] as given in Figure 2. In fertilizer production, these principles encourage maximizing atom economy, which ensures that every input has a functional role, and removal of toxic components that could damage the environment or harm human health [27].

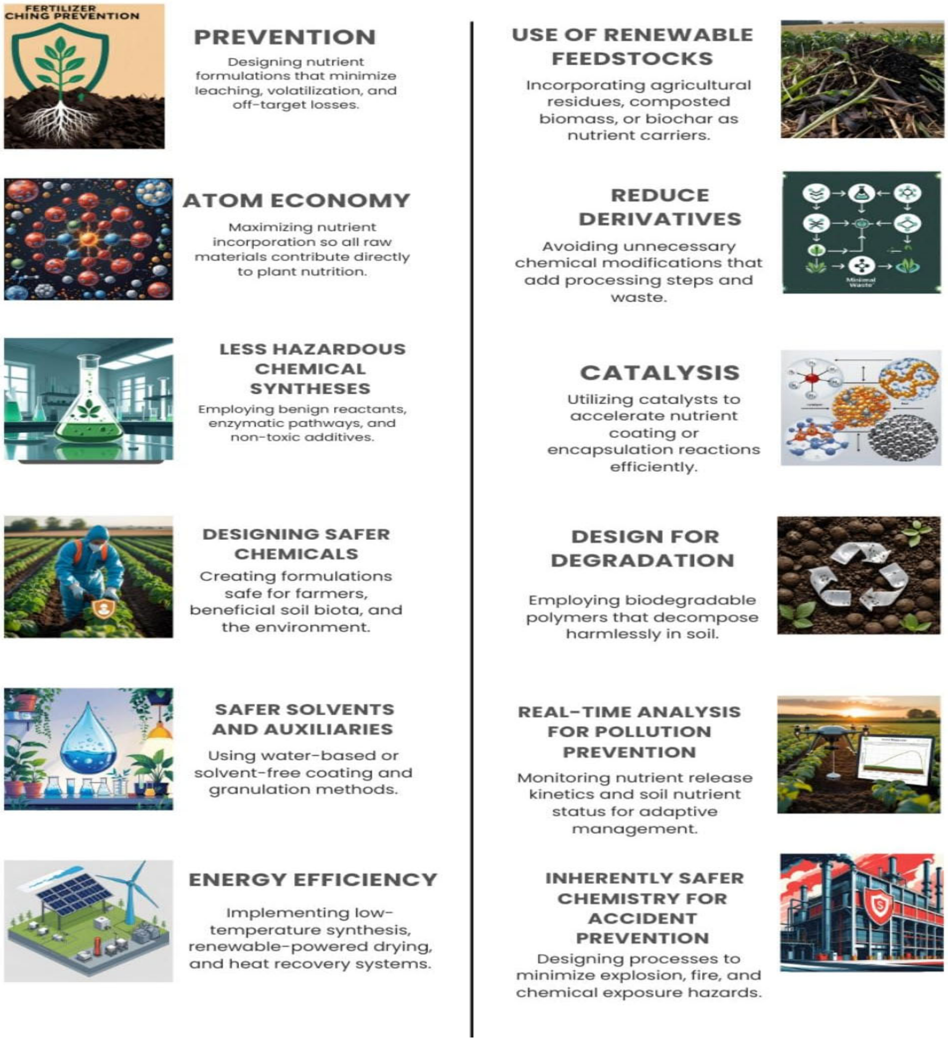

Figure 2. Twelve principles of green chemistry.

The focus is shifting to using renewable resources such as crop residues, compost, or carbon material (such as biochar) as nutrient carriers, reducing the dependence on limited mineral reserves. It also promotes the use of methods that consume less energy and green solvents, instead of energy-intensive processes and harmful solvents. These methods include mechano-chemical synthesis, low-temperature drying, and the use of biological catalysts, which help to cut down emissions during manufacturing [28]. New techniques like biodegradable polymer coatings, controlled-release granules, and nano-enabled carriers ensure that the nutrients are released slowly and gradually over time as and when required by plants. It ensures minimum loss of nutrients through leaching and volatilization, prevents eutrophication, and makes farming systems stronger and more tolerant to stress conditions [29].

By using fewer solvents and using less energy, recent developments in mechanochemistry are consistent with the ideas of green chemistry [30,31]. Mechano-chemical processes are more environmentally friendly because they frequently run in mild environments and produce fewer by-products [32]. Ostwald, who examined chemical reactions from an

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energy perspective, coined the word "mechanochemistry" in 1887 [33]. Heinicke developed a concept in 1984 that is now recognized by the scientific community. According to him, mechanochemistry is a field of chemistry where materials undergo chemical and physical changes when mechanical energy is applied, independent of the state of aggregation [34]. Mechano-chemical processes can be divided into two processes: primary and secondary. The primary mechanisms include a material's reactivity via a rise in surface and internal energies, the expansion of surface area, and the fall in cohesive energy of solids. In activated systems, secondary reactions such as aggregation, adsorption, and crystallization occur naturally while or after grinding is finished. Dry milling (DM) and wet milling (WM) are the two main routes in mechano-chemical applications for extractive metallurgy [35]. While milling and leaching are carried out simultaneously in a single phase in wet milling processes, they are separate operations in dry milling processes. Retch mills, tumbling mills, stirring ball mills, vibratory mills, pin mills, rolling mills, and planetary ball mills are among the tools used to accomplish mechanical activation. Numerous engineering fields, including chemistry, materials science, mineral processing, coal industry, construction, pharmacy, agriculture, and metallurgy, have been using mechanochemistry. For instance, the mechano-chemical reaction to create slow-release potassium fertilizers is by co-grinding KH_2PO_4 with other chemical reagents like γ-Al_2O_3, $Mg(OH)_2$, and $Al_2Si_2O_6(OH)_4$ [36]. The primary feature of these fertilizers is the delay in the availability of nutrients for plant uptake and utilization following application and/or the extension of their availability in the soil. With the use of scalable machinery like twin-screw extruders (TSEs), continuous industrial mills, and vibratory or attrition mills designed for high-throughput operation, recent developments show that the mechano-chemical synthesis can be transferred from laboratory-scale ball mills to industrial production [37]. To guarantee consistent mechanical energy input and reproducibility at scale, equipment adaptation mainly entails optimizing screw configurations, residence periods, torque capacities, and heat management systems [37]. The removal of bulk solvents, quicker reaction times, and streamlined downstream purification processes are examples of cost-reduction strategies that minimize operational expenditure (OPEX) [38]. Additionally, because extruders and continuous mills can be included in established process lines with little retrofit, mechanical and chemical techniques have demonstrated good compatibility with current manufacturing systems, especially in the pharmaceutical and materials sectors. Continuous mechanical extrusion is a promising method for sustainable large-scale synthesis since it can attain kilogram-to-tonne throughput while retaining reaction efficiency, according to reports from both academic and industrial groups [39].

Major issues like climate change and declining soil fertility can be addressed by adopting green chemistry in fertilizer production, as it supports the circular economy, helps farmers cope with climate challenges, and ensures food security for the future.

3. Nutrient Loss Minimization

Fertilizers help to keep soil healthy, increase crop yields, and are essential for ensuring enough food for the growing world population. Historically, the market has focused on single-nutrient formulas that provide nitrogen, phosphorus, or potassium. This was based on the idea that farmers could add other nutrients on their own. While this method has helped intensive farming for many years, research in soil science and plant physiology shows it can upset the balance of nutrients in the soil [40]. This imbalance can lower overall fertilizer efficiency and limit crop yield potential [41,42]. Multi-nutrient formulations using different materials/carriers have been shown in Table 1.

Multi-nutrient fertilizers have become a more complete option by combining macronutrients, secondary nutrients, and essential micronutrients in one formulation. This method not only addresses several nutrient deficiencies at the same time but also improves how plants take up nutrients and supports their overall growth. The advantages go beyond just higher yields; these fertilizers help revive damaged soils, boost crop resistance to stress, and even increase the nutritional value of what we harvest. For example, zinc-enriched multi-nutrient fertilizers have been shown to raise both crop productivity and the zinc concentration in grains, which helps to improve human nutrition and tackle micronutrient malnutrition [43]. In recent years, there has been impressive innovation in how multi-nutrient fertilizers are designed and delivered. Some of the key innovations, like controlled-release fertilizers, ensure that nutrients are delivered to plants as and when required. This helps in minimizing nutrient loss that occurs through leaching and volatilization. Another innovation is using chelated forms of micronutrients, which remain soluble and available to plants even in tough soil conditions. Additionally, nanofertilizers are being used to deliver nutrients precisely and more effectively, ensuring the minimum application [44].

Environmentally safe methods, such as bio-based carriers like biochar, lignin, and natural polysaccharides, are being used to deliver nutrients precisely as they can improve soil water retention, aeration, and microbial activity, making them well-suited for eco-friendly fertilizer solutions. Although multi-nutrient fertilizers have greater potential, their widespread use is still limited because of high production costs, limited awareness among farmers, and the need to adjust formulations to meet the specific nutrient needs of different soils and crops [45]. Still, combining these technologies with principles of green chemistry presents a promising way to make these fertilizers a core part of sustainable farming practices.

Table 1. Innovation in a sustainable fertilizer delivery system.

Type of Delivery System	Description	Agronomic Benefits	Environmental Benefits	References
Controlled-release coatings	Synthetic or bio-based polymer coatings (single or multi-layer) that regulate nutrient diffusion to match crop demand.	Improves nutrient-use efficiency (NUE) and yield stability; reduces frequency of application.	Lowers leaching, volatilization, and runoff; can reduce GHGs associated with fertilizer use.	[46]
Chelated micronutrient complexes	Micronutrients are bound to organic ligands (e.g., EDTA/EDDHA/IDHA or amino-acid chelates) to preserve solubility and plant availability.	Enhances micronutrient uptake (Fe, Zn, Cu, Mn), specifically in calcareous or high-pH soils; improves crop quality/biofortification.	Reduces fixation and precipitation losses; better targeted delivery reduces over-application.	[47]
Nanofertilizers (e.g., ZnO, nano-hydroxyapatite)	Nanoscale carriers/particles that improve solubility, root uptake, and targeted delivery at low doses.	Can increase nutrient uptake, stress tolerance, and biofortification with lower application rates.	Potential to reduce total input and environmental loading (requires nanosafety evaluation).	[48]
Biochar-based carriers	Porous, high-C biochar impregnated/functionalized with macro- and micronutrients for slow release.	Improves nutrient retention, water holding, root growth and microbial habitat; enhances crop response in degraded soils.	Sequesters carbon; reduces nutrient leaching and N losses.	[49]

Table 1. *Cont.*

Type of Delivery System	Description	Agronomic Benefits	Environmental Benefits	References
Lignin/polysaccharide encapsulation	Natural polymers (lignin, starch, chitosan, alginate) are used as biodegradable matrices or coatings for nutrient encapsulation.	Enables controlled nutrient release, improves soil moisture retention and supports soil biota.	Biodegradable; aligns with circular-economy feedstock valorization.	[50]
Multi-layer/staged-release granules	Granules engineered with sequential layers or multi-layer nanofiber carriers to stage release of N, P, K and micronutrients.	Matches nutrient release to crop phenology; reduces "all-at-once" availability and improves nutrient synchrony.	Reduces over-application risk and tailing losses; improves NUE.	[51]

Integrating green chemistry principles in fertilizer development involves changes in the formulation, production, and delivery of nutrients, and it improves efficiency, reduces waste, and supports agricultural productivity, while protecting the environment [52]. By following principles like atom economy, renewable inputs, safer synthesis, and energy efficiency, green chemistry provides a practical way for creating fertilizers that support both healthy crops while also protecting the environment. Some of the green chemistry strategies in fertilizer development are discussed here and shown in Figure 3.

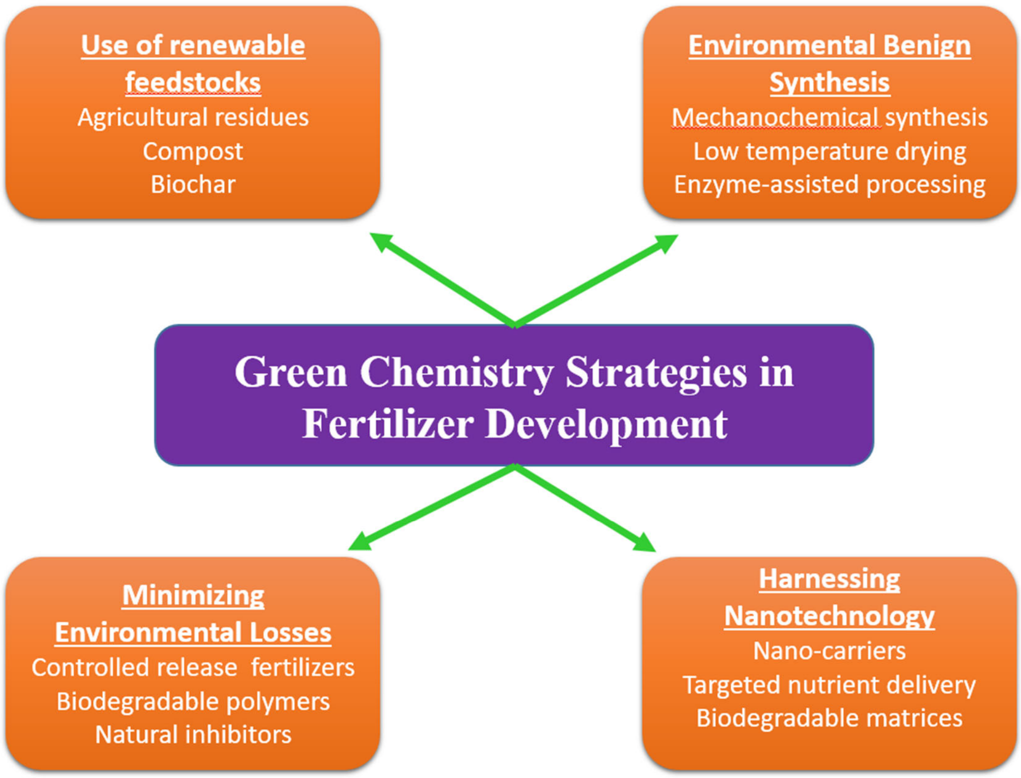

Figure 3. Green chemistry strategies in fertilizer development.

3.1. Use of Renewable Feedstocks

A major change in fertilizer development is moving from limited, non-renewable materials to sustainable, bio-based options. Agricultural residues, compost, algae biomass, and biochar are being increasingly studied as sources of nutrients [53]. These materials

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provide essential macro-, secondary-, and micronutrients. They also improve soil organic matter, enhance structure, and increase water-holding capacity. Turning agricultural and industrial by-products into valuable inputs reduces the waste, lowers production impacts, and supports circular economy practices [54]. For instance, nutrient-rich biochar made from crop residues has shown promise as both a slow-release carrier and a soil conditioner. It reduces nutrient loss while promoting helpful soil microbes.

3.2. Environmentally Benign Synthesis Routes

Green chemistry encourages manufacturing methods that cut down or eliminate harmful intermediates, toxic solvents, and high energy demands. New methods, like solvent-free mechano-chemical synthesis, low-temperature drying, and enzyme-assisted processing, are appearing as cleaner and more efficient options compared to traditional approaches. These techniques lower greenhouse gas emissions and keep sensitive compounds stable, leading to high-quality nutrient products. For instance, enzyme-mediated synthesis allows for the gentle addition of micronutrients without losing their effectiveness. At the same time, mechano-chemical processes produce uniform nutrient blends without the environmental issues tied to solvent use [55].

3.3. Minimizing Environmental Losses

Integration of green chemistry in fertilizers is vital to improve nutrient use efficiency and reduce environmental losses. Controlled-release systems that use biodegradable polymer coatings, natural hydrogels, or layered granules regulate nutrient availability to match crop uptake patterns [56]. The precise nutrient delivery minimizes leaching, volatilization, and runoff. It helps by preventing eutrophication and groundwater contamination. Natural nitrification and urease inhibitors can also increase the amount of nutrient availability. This limits nitrogen losses and lowers greenhouse gas emissions [57].

3.4. Harnessing Nanotechnology

Green chemistry, when combined with nanotechnology, brings more accuracy to fertilizers. Nano-enabled carriers and coatings improve nutrient dissolution, stability, and precise delivery to plants. This helps plants take in essential nutrients more effectively and with lower application rates. Some examples are nano-hydroxyapatite for phosphorus and nano-chelated zinc and iron formulations. When these materials are added to biodegradable compounds and carefully tested for environmental safety, they can significantly improve how efficiently nutrients are used. However, for these technologies to be widely accepted, we need thorough evaluations of their environmental impact, risks of bioaccumulation, and compliance with changing regulatory requirements [58].

4. Impact on Soil and Crop Health

Multi-nutrient fertilizers developed using green chemistry principles can greatly improve both crop productivity and soil health. Unlike conventional fertilizers, these formulations release nutrients slowly, as and when required by plants [59,60]. These fertilizers provide a balanced mix of macronutrients, secondary nutrients, and micronutrients. This balance helps plants carry out photosynthesis better, activate important enzymes, and stay stronger against stress. Field trials show that significant yield increases in cereals, legumes, and horticultural crops occur when micronutrient deficiencies like zinc, iron, or boron, along with macronutrient needs, are addressed. Furthermore, the slow and precise nutrient delivery reduces the application frequency of fertilizers, which saves time, reduces cost, and ensures higher yield and better soil health [61]. The fertilizers also benefit the soil by improving its structure, supporting good microbes, and keeping it healthy for future crops.

The incorporation of bio-based carriers, such as nutrient-enriched biochar and compost-amended granules, contributes to increasing soil organic matter content, augmented cation exchange capacity (CEC), enhanced water retention, improved soil structural integrity and soil microbial population as shown in Table 2. For example, one of the research groups reported that the application of biochar improved the activities of almost all soil enzymatic groups involved in carbon (C), phosphorus (P) and nitrogen (N) acquisition, extracellular soil enzymes, and dehydrogenase (DHA) with mean effect sizes of 4%, 12%, 23% and 22%, respectively [62]. Controlled-release mechanisms mitigate nutrient losses through leaching and volatilization, consequently reducing groundwater contamination risks and diminishing nitrous oxide emissions. Importantly, the utilization of non-toxic and biodegradable materials supports the preservation of soil microbial diversity and activity, which are critical for nutrient cycling and the maintenance of long-term soil fertility [63].

However, the extent and consistency of these benefits are contingent upon site-specific variables, including soil characteristics, climatic conditions, and crop nutrient demands. While investigations across varied agro-ecological environments have demonstrated the agronomic efficacy of these fertilizers, it remains imperative to conduct comprehensive, long-term, system-level research to fully characterize their ecological consequences and to optimize their implementation across diverse agricultural frameworks [64].

Table 2. Case studies of green-chemistry-based fertilizers and their agronomic impacts.

Crop/Study Location	Fertilizer Type and Green Chemistry Feature	Key Soil Health Outcomes	Crop Performance	References
Rice—Eastern India	Slow-release NPK + Zn and B in a biodegradable polymer coating	Soil organic C (+12%), CEC (+8%), and nitrate leaching decreased by 24%	The slow release enhanced nutrient availability over the growth cycle, especially during tillering and panicle initiation. Better grain filling, greater tiller growth, and increased chlorophyll content were all displayed by the plants. As compared to traditional NPK, the final yield increased by 15% due to increased panicle weight and decreased lodging.	[65]
Wheat—North China	Biochar-based multi-nutrient granules enriched with S, Zn, and Fe	Microbial biomass C (+17%), increased water-holding capacity	Early seedling vigor and root biomass were improved by the biochar matrix. Higher photosynthetic efficiency and enhanced protein accumulation in grains were the outcomes of improved micronutrient availability. Grain protein increased by 7% while yield improved by 12%, suggesting both enhanced productivity and better nutritional quality.	[66]

Table 2. *Cont.*

Crop/Study Location	Fertilizer Type and Green Chemistry Feature	Key Soil Health Outcomes	Crop Performance	References
Maize—Kenya	Nano-chelated Zn + controlled-release NPK	Soil enzyme activity (dehydrogenase +25%)	Root growth was reinforced, and leaf area development was enhanced by controlled nutrient administration. Pollen viability and kernel formation were improved by nano-Zn. Both productivity and nutritional biofortification were significantly improved, as seen by the 18% rise in overall grain production and the 21% increase in kernel zinc content.	[67]
Tomato—Spain	Compost-based multi-nutrient with micronutrient fortification	Aggregate stability (+14%) decreased N_2O emissions by 22%	The fertilizer prepared from compost improved floral retention, boosted vegetative growth, and improved nitrogen uptake efficiency. Stronger cell-wall growth in tomatoes resulted in tougher fruits. Fruit size, firmness, and shelf life all significantly improved, and marketable output rose by 13%.	[68]
Soybean—Brazil	Enzyme-assisted synthesis of multi-nutrient fertilizer (Mg, S, Zn)	Soil respiration (+12%), maintained pH stability	Increased availability of Mg and S facilitated nodulation efficiency and photosynthesis. Increased zinc bioavailability aided in the development of the reproductive system and protein synthesis. Improved physiological efficiency and grain quality were shown by a 9% increase in seed output and a 5% rise in oil content.	[69]
Barley	Poultry bone–derived nano-hydroxyapatite (nHAP) as a phosphorus source	Increased P solubility and availability in soil	During the booting stage, nHAP enhanced P absorption and early root growth. Stronger tillers and increased plant vigor were the outcomes of improved nitrogen absorption. Despite the fact that the majority of investigations were conducted in labs or greenhouses, they consistently indicated higher P-use efficiency and better early biomass accumulation.	[70]

Table 2. *Cont.*

Crop/Study Location	Fertilizer Type and Green Chemistry Feature	Key Soil Health Outcomes	Crop Performance	References
Potato—Peru	Amino acid-coated humic acid and NPK	Improved soil moisture retention (+9%) and aggregate stability (+10%)	Coated/biostimulant foliar products increased marketable tuber output, decreased tuber cracking, and enhanced canopy uniformity (reported increases in various trials ranging from ~10–18% depending on formulation).	[71]
Cotton—US (Southeast)	Microbial-based multi-nutrient inoculant (PGPR + slow-release K)	Improved K availability, enhanced microbial diversity index (+18%)	PGPR improved water intake in the late season by increasing root colonization and stress tolerance. Boll retention under heat stress was significantly better than control; fiber length and strength were enhanced (helpful for spinning), and lint production increased by 11%.	[72]
Grapes—Italy	Slow-release K combined with compost tea soil drench	Improved soil structure, enhanced microbial activity (+15%)	Compost tea can boost beneficial microbiome activity, suppress some diseases, enhance vine nutrient cycling and root health. Higher cluster weights (by 9%) and increased Brix (sugar) level when combined with targeted K supply; post-harvest stiffness and shelf life significantly enhanced.	[73]

5. Challenges and Perspectives

Although green-chemistry-based multi-nutrient fertilizers offer compelling agronomic and environmental benefits, their widespread implementation is hindered by a series of interrelated economic, technical and institutional challenges. A primary constraint is the elevated production cost associated with the use of biodegradable carriers, renewable feedstocks, and advanced nutrient delivery systems. While these inputs can improve nutrient efficiency and reduce environmental losses over time, their higher initial price often discourages adoption, particularly in resource-limited farming systems where capital investment capacity is low [74].

Limited awareness and technical familiarity among farmers are major challenges with these innovations. The benefits of controlled-release formulations, nanostructured carriers, and bio-based nutrient sources are not always clear without accessible training programs, local demonstrations, and performance data in specific farming conditions. Moreover, the variety of soils, climate, and cropping patterns requires specifically tailored formulations, instead of one that fits all products. This situation complicates supply chain logistics and increases production complexity. Regulators are becoming stricter with safety rules for nano-enabled and bioengineered fertilizers, which means these products must go through detailed environmental risk checks before they can be sold in the market. The major

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concerns are how they might affect the environment in the long run, whether they could build up in living organisms, and what impact they might have on ecosystems overall [75].

The absence of standardized international guidelines adds to the challenge for manufacturers aiming for expansion to access global markets. On the technological side, the transition from small-scale lab prototypes to large-scale production presents a significant challenge. Techniques like enzyme-assisted synthesis or mechano-chemical processes look promising at the trial stage, but they still need to ensure cost-effectiveness, consistent quality, and compatibility with current manufacturing setups. In the future, combining these fertilizers with smart agriculture tools, such as precise nutrient mapping, variable-rate application systems, and AI-assisted recommendations, could significantly enhance their performance in agriculture and the environment. To make this happen, researchers, industry players, policymakers, and farmer groups will be required to work collectively to bridge the gap between innovation and practical use. Additionally, incorporating these products into circular economy practices, like transforming agricultural waste or industrial by-products into nutrient carriers, can help tackle resource limitations and waste management issues [76].

Overcoming these barriers will require a strategy that combines technology improvements, supportive policies, focused training programs, and financial tools. These tools will ensure that these effective fertilizers are also affordable and suitable for different farming environments [77]. The goal of bio-based fertilizers (BBFs) is to recycle and reuse nutrient-rich by-products in order to lessen the EU's reliance on imported mineral fertilizers. In order to implement the zero-waste program, the first Circular Economy Action Plan was put in place in 2015. It included 54 actions that supported the transition to the circular economy model. Moreover, the EU targets to replace chemical fertilizers by up to 30% using BBFs. It employs a combination of research funding, eco-schemes, CAP conditionality, regulatory targets, and assistance for bio-based fertilizer value chains. The focus of implementation is on low-input agricultural incentives, nutrient loss reduction, and substitution (bio-based goods). The Ministry of Agriculture and Rural Affairs of China implemented the two actions, including "Action Plan for Replacing Chemical Fertilizer with Organic Fertilizer Regarding Fruit, Vegetables and Tea" and the "Action Plan for Zero-Growth in Fertilizer Use by 2020" in 2015 with the aim of reducing fertilizer usage, improving efficiency, and reducing nitrogen loss through the modification of fertilizer application strategy. These findings were based on the goal of green agricultural development [78]. It uses action plans that were provided centrally in addition to provincial implementation, farmer education, reorientation of subsidies, demonstration projects, and more stringent measures (such as encouraging soil testing and formula fertilization). It is a top-down strategy with local execution and oversight.

6. Concluding Remarks and Future Outlook

Despite significant progress, the widespread adoption of sustainable multi-nutrient fertilizers faces numerous interconnected scientific, technical, economic, and policy challenges as shown in Figure 4. A primary technical hurdle is the creation of stable, compatible formulations that can effectively deliver diverse nutrients. Differences in nutrient solubility, reactivity, and interactions with carrier materials complicate development, while micronutrients such as iron, zinc, and boron often become fixed or precipitated in the soil, limiting plant availability [79,80]. The development of biodegradable carriers from materials such as chitosan, cellulose, and starch-based polymers shows promise; however, their degradation rates, mechanical strength, and nutrient compatibility vary significantly with processing methods and soil conditions, requiring further research into their interactions with soil microbes and nutrient cycling [81,82].

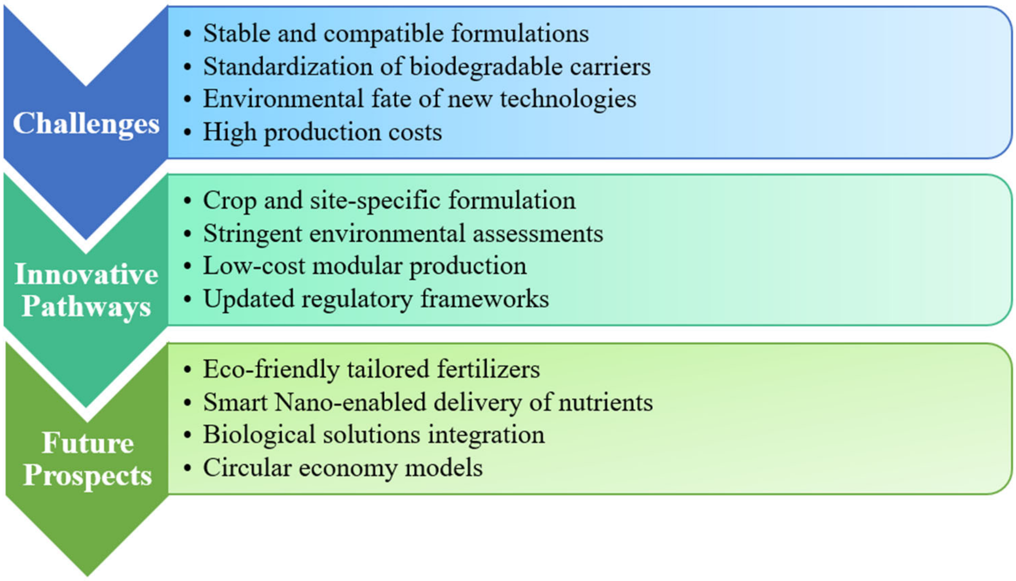

Figure 4. Challenges, innovative pathways, and future prospects in green chemistry adoption.

Novel nano-enabled fertilizers and advanced coating methods demonstrate improved nutrient use efficiency, but concerns regarding their long-term environmental impact, bioaccumulation potential, and effects on non-target species necessitate comprehensive environmental safety assessments before widespread implementation [83,84]. Economically, higher production costs present another significant barrier, as these fertilizers require expensive raw materials, careful synthesis, and advanced blending methods, making them less affordable, particularly for resource-limited, smallholder farming systems. Overcoming cost constraints will require innovative manufacturing approaches, locally sourced renewable materials, and decentralized production models [85].

Regulatory frameworks have failed to keep pace with technological advancements, as most current standards were designed for traditional mineral fertilizers and do not adequately address biodegradable carriers, bio-based additives, or nano-structured formulations. Updating these frameworks through certification schemes, labeling standards, and financial incentives is crucial for ensuring a safe market entry [86]. Future research should focus on developing crop- and site-specific formulations by integrating detailed soil data, plant nutrient modeling, and precision agriculture technologies [87,88]. Combining biological solutions such as biofertilizers, microbial inoculants, and plant growth-promoting rhizobacteria with green-chemistry-based formulations can enhance nutrient cycling, improve plant stress tolerance, and enrich soil biodiversity. Policy measures, including subsidies, carbon credits—particularly for biochar application—and public–private partnerships can reduce initial costs and encourage farmer adoption [89]. The use of biochar offers a viable option for carbon offset programs, providing people and companies with a concrete way to get involved in the fight against climate change. Biochar is in line with sustainable development principles, as it reduces emissions and improves soil health simultaneously, providing a solution that benefits the agricultural and environmental sectors [90].

Scaling up production and use will require strong cooperation among scientists, industry leaders, policymakers, and farmers, linking technological innovation with cost-effectiveness, clear regulations, and farmer-friendly design to transform these fertilizers into powerful tools for building climate-resilient, resource-efficient agricultural systems that strengthen global food security while protecting environmental health [91].

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