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Review Article

Emerging Trends in Smart Fertilizer Technologies: Towards Climate-Resilient and Sustainable Agriculture

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Abstract

Agricultural systems currently occupy nearly 40–50% of the Earth's terrestrial surface and are central to global food security, yet they face increasing pressure due to rapid population growth and environmental degradation. However, increasing population pressure and the need for higher food production have intensified the demand for efficient nutrient management strategies. Conventional fertilizers, although widely used, suffer from low nutrient use efficiency due to substantial losses through leaching, volatilization, runoff, and fixation, leading to environmental degradation and economic inefficiencies. These losses contribute to groundwater contamination, eutrophication, greenhouse gas emissions, and deterioration of soil health. In response to these challenges, smart fertilizers have emerged as an innovative approach to enhance nutrient use efficiency and promote sustainable agriculture. These include nano fertilizers and slow or controlled release fertilizers, which are designed to synchronize nutrient availability with plant demand. Nano fertilizers, owing to their small particle size, high surface area, and enhanced reactivity, facilitate improved nutrient absorption and targeted delivery while minimizing environmental losses. Similarly, slow and controlled release fertilizers regulate nutrient release through coating materials and matrix systems, ensuring a steady nutrient supply over time and reducing the frequency of fertilizer application. The adoption of these advanced fertilizer technologies offers multiple agronomic, environmental, and economic benefits, including improved crop productivity, reduced nutrient losses, enhanced soil fertility, and lower environmental risks. Furthermore, they play a crucial role in achieving sustainable intensification of agriculture by optimizing resource use and minimizing ecological footprints. Overall, smart fertilizers represent a promising solution for addressing the limitations of conventional fertilization practices and advancing sustainable agricultural systems. Continued research and technological development are essential to improve their efficiency, scalability, and field-level applicability under diverse agro-ecological conditions.

1. Introduction

The global population is projected to increase steadily, reaching approximately 9.5 billion by the year 2050, which will significantly intensify the demand for food, feed, and fiber production [1]. This rapid population growth, coupled with changing dietary preferences and urbanization, has placed unprecedented pressure on agricultural systems to enhance productivity. It is estimated that global food production must increase by nearly 70% to meet future demand, as projected by the Food and Agriculture Organization (FAO) [2]. However, achieving

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this target using conventional agricultural practices remains a major challenge due to declining resource use efficiency and increasing environmental concerns.

One of the critical limitations of modern agriculture is the inefficient utilization of applied fertilizers. A substantial proportion of essential nutrients is lost from the soil-plant system through various physical, chemical, and biological processes. Nitrogen, for instance, experiences losses ranging from 40–70% due to ammonia volatilization, mineralization, emission of nitrogen oxides, leaching, denitrification, and soil erosion. Similarly, phosphorus losses can reach 80–90% due to fixation processes involving iron and aluminum oxides as well as surface runoff, while potassium losses through leaching and runoff are estimated to be between 50–70% [3]. These significant nutrient losses not only reduce fertilizer use efficiency but also lead to considerable economic losses for farmers.

Beyond economic implications, inefficient fertilizer use has serious environmental consequences. Nitrate leaching from nitrogen fertilizers contaminates groundwater resources, posing risks to human health by degrading drinking water quality. Additionally, nitrogen volatilization contributes to atmospheric pollution through the release of harmful gases, which can lead to respiratory problems and broader ecological impacts. Excessive phosphorus accumulation in aquatic ecosystems accelerates eutrophication, resulting in algal blooms, oxygen depletion, foul odors, and fish mortality. Furthermore, prolonged and excessive fertilizer application can degrade soil health through acidification, accumulation of heavy metals, and persistence of organic pollutants.

In response to these challenges, there is a growing emphasis on the development of advanced nutrient management strategies. Among these, smart fertilizers have emerged as a promising innovation designed to enhance nutrient use efficiency by synchronizing nutrient release with plant demand. These fertilizers aim to minimize nutrient losses, improve crop productivity, and reduce environmental impacts, thereby contributing to sustainable agricultural intensification.

2. Smart Fertilizers

2.1. Nano fertilizers

Nano fertilizers represent an advanced class of smart fertilizers engineered to enhance nutrient delivery efficiency through nanotechnology-based formulations. These fertilizers are developed either by modifying conventional fertilizers, incorporating bulk fertilizer materials into nanoscale carriers, or synthesizing nanoparticles capable of delivering nutrients in a controlled manner. Such formulations enable regulated and targeted nutrient release, thereby improving soil fertility, crop productivity, and overall agricultural output quality [4].

The defining characteristic of nano fertilizers lies in their nanoscale size, which significantly enhances their surface area-to-volume ratio and reactivity. This facilitates improved interaction with plant systems and allows nutrients to be released in a controlled and synchronized manner with crop demand. As a result, nano fertilizers contribute to enhanced nutrient use efficiency by reducing nutrient losses through leaching, volatilization, and fixation processes, while simultaneously minimizing environmental risks [5]. Furthermore, their increased solubility and reactivity improve nutrient bioavailability, thereby promoting efficient uptake and utilization by plants [6].

2.2. Mode of Action and Chemistry of Nano Fertilizers

The excessive application of conventional mineral fertilizers has been widely associated with soil degradation and groundwater contamination due to nutrient leaching and gaseous emissions, which ultimately threaten agricultural sustainability [7]. In contrast, nano fertilizers offer an environmentally sustainable alternative by improving nutrient delivery efficiency while reducing pollution and enhancing soil microbial activity [8].

Nanotechnology provides a versatile platform for improving fertilizer performance by enabling site-specific nutrient delivery, reducing toxicity, and enhancing nutrient use efficiency. Nano fertilizers function through mechanisms such as controlled nutrient release, targeted delivery, and increased interaction with plant surfaces. These properties are attributed to their high solubility, mobility, and surface reactivity, which collectively contribute to improved agronomic performance [9–11].

At the physiological level, nano fertilizers interact with plant systems through multiple pathways. Their small size allows them to penetrate plant tissues efficiently, either through root uptake or foliar absorption. Additionally, their physicochemical properties facilitate adsorption onto plant surfaces and subsequent transport within plant systems, ensuring effective nutrient utilization. Eco-friendly nano fertilizers serve as a sustainable alternative to conventional mineral fertilizers by enhancing soil fertility, improving crop yield, reducing environmental pollution, and stimulating microbial activity, as illustrated in Figure 1 [8].

2.3. Maximization of Nano Fertilizer Efficiency

The efficiency of conventional fertilizers remains relatively low, with nutrient use efficiencies estimated at 20–50% for nitrogen, 10–25% for phosphorus, and 30–40% for potassium, indicating significant scope for improvement in fertilizer management strategies [12]. Nano fertilizers address these inefficiencies by enhancing nutrient accessibility and uptake through improved physicochemical interactions with soil and plant systems. Their application has been shown to increase nutrient absorption efficiency and improve the effectiveness of applied fertilizers [13].

The enhanced efficiency of nano fertilizers can be attributed to several key mechanisms:

i. **Increased reactivity:** Due to their reduced particle size and higher surface area, nano materials exhibit greater reactivity compared to conventional fertilizers, resulting in more efficient nutrient interactions within the soil–plant system.
ii. **Improved nutrient penetration and uptake:** The nanoscale dimensions of these fertilizers enhance their ability to penetrate plant tissues. Increased surface area and particle density improve contact with plant roots and leaves, facilitating nutrient absorption [14]. The entry of nanoparticles into plant cells is influenced by cell wall pore size, typically ranging between 5–20 nm, which allows smaller nanoparticles to pass through more efficiently [15]. Additionally, nanoparticles can traverse cell walls and reach cell membranes due to their small size and aggregation properties [16].

iii. **Enhanced cellular uptake mechanisms:** Nano fertilizers can induce structural and functional modifications in plant cell walls, including enlargement of pore size and formation of new transport pathways, thereby improving nutrient uptake efficiency [17]. Furthermore, nanoparticle uptake may occur through multiple biological processes such as carrier protein-mediated transport, aquaporin channels, endocytosis, and ion channels, enabling efficient internalization and translocation within plant systems.

Overall, nano fertilizers represent a transformative approach in nutrient management by integrating nanotechnology with agricultural practices. Their ability to enhance nutrient use efficiency, reduce environmental losses, and improve crop performance positions them as a key component of sustainable agricultural systems.

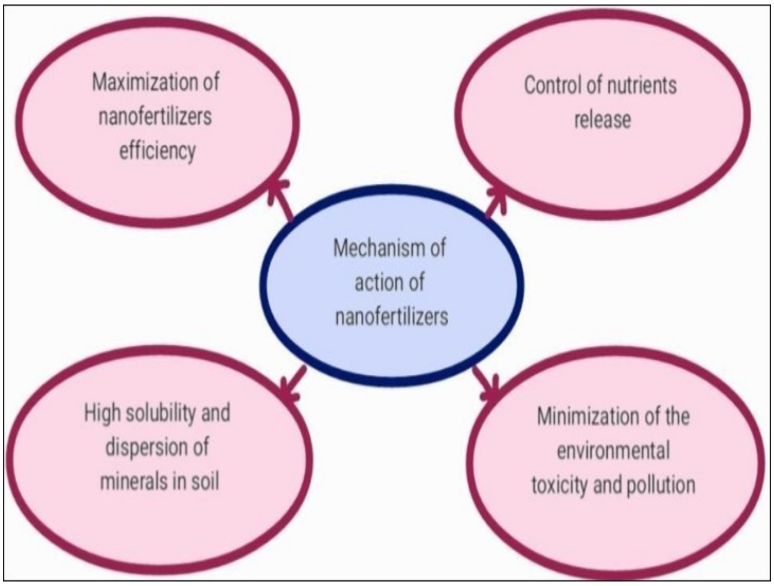

Figure 1: Mechanism of action of Nano fertilizers

2.4. Control of Nutrient Release

The efficiency of conventional fertilizers is inherently limited, as only a fraction of the applied nutrients is effectively utilized by crops, while the remaining portion is lost through various pathways such as volatilization, runoff, leaching, hydrolysis, and microbial degradation in the soil [18]. Quantitatively, nutrient losses are substantial, with approximately 40–70% of nitrogen, 80–90% of phosphorus, and 50–90% of potassium fertilizers failing to reach the target plant system [19]. This inefficiency often compels farmers to apply higher doses of fertilizers to compensate for losses, which in turn disrupts nutrient balance, increases production costs, and exacerbates environmental pollution.

Nano fertilizers have emerged as an effective strategy to overcome these limitations by enabling controlled and sustained nutrient release. Slowly released nano fertilizers are designed to provide a regulated supply of nutrients over the crop growth period, thereby improving synchronization between nutrient availability and plant demand. This controlled release mechanism enhances nutrient uptake efficiency and minimizes losses, allowing plants to utilize a greater proportion of applied nutrients [20].

At the physicochemical level, nano fertilizers exhibit strong binding affinity between nutrients and nanomaterial carriers due to their high surface energy and surface tension. When fertilizers are coated or encapsulated within nanomaterials, the release of nutrients is significantly regulated, preventing rapid dissolution and loss. Such coatings improve fertilizer efficiency by controlling the rate of nutrient discharge into the soil system [21].

Nitrogen fertilizers, despite being essential for crop growth, are highly soluble and prone to rapid losses, leading to environmental and agronomic challenges. Advances in nanotechnology have enabled the development of controlled-release nitrogen formulations, such as nanoporous zeolite-based systems, which significantly enhance nitrogen uptake efficiency [22]. Similarly, urea-modified hydroxyapatite nanoparticles have demonstrated prolonged nitrogen release patterns, extending nutrient availability up to 60 days compared to approximately 30 days in conventional fertilizers [23].

In controlled-release nano fertilizer systems, soluble nutrients are encapsulated within nanomaterials, protecting them from premature exposure to environmental factors. Nutrient release primarily occurs through diffusion mechanisms, ensuring gradual and sustained availability in the soil [20]. Studies have also shown that nano fertilizers can delay nitrogen release by up to 50 days compared to conventional mineral fertilizers, further enhancing nutrient retention and utilization [24]. Additionally, nano-membrane coatings are increasingly employed to regulate nutrient diffusion rates, thereby improving fertilizer performance [25]. Nanocomposite fertilizers containing essential macronutrients such as nitrogen, phosphorus, and potassium are particularly effective in improving nutrient uptake and overall crop productivity.

The excessive and indiscriminate use of fertilizers and pesticides has led to severe ecological imbalances, including nutrient accumulation, disruption of soil microbial communities, increased pest resistance, and degradation of natural ecosystems [26]. In contrast, nano fertilizers reduce nutrient losses and minimize dependency on conventional fertilizers, thereby mitigating soil and environmental contamination. Encapsulated nano fertilizers, including nano-clays and zeolite-based systems, enhance nutrient use efficiency while promoting soil health and reducing agro-ecological degradation [27].

2.5. High Mineral Solubility and Dispersion in Soil

An important advantage of nano fertilizers is their ability to improve the solubility and dispersion of mineral nutrients in soil systems. Nano-sized micronutrients enhance the dissolution of otherwise insoluble nutrient forms, thereby reducing nutrient fixation and improving bioavailability. This increased availability facilitates greater nutrient uptake efficiency by plants [28]. For instance, nano-sized rock phosphate improves phosphorus availability by minimizing its fixation with iron, aluminum, and calcium compounds in the soil. Similarly, zinc oxide nanoparticles exhibit higher dissolution rates compared to their bulk counterparts, making them more effective as micronutrient fertilizers.

Overall, nano-enabled controlled release systems provide a significant advancement in nutrient management by enhancing nutrient retention, improving synchronization with crop demand, and reducing environmental losses, thereby contributing to sustainable agricultural production systems.

2.6. Slow Release and Controlled Release Fertilizers

Slow release fertilizers (SRFs) and controlled release fertilizers (CRFs) are advanced nutrient delivery systems developed to improve nutrient use efficiency by regulating the rate, timing, and availability of nutrients to plants. Slow release fertilizers are characterized by their ability to release nutrients gradually through chemical or biological processes, whereas controlled release fertilizers are specifically engineered to deliver nutrients at a predetermined and consistent rate under defined environmental conditions. This distinction is primarily based on the mechanism governing nutrient release, with SRFs relying on natural decomposition processes and CRFs utilizing physical or chemical barriers for regulated release [1].

The adoption of these fertilizers has gained importance due to their ability to minimize nutrient losses, enhance synchronization between nutrient availability and plant demand, and reduce environmental pollution associated with conventional fertilizers.

2.7. Classification of Slow and Controlled Release Fertilizers

Slow and controlled release fertilizers can be broadly classified into three major categories based on their composition and release mechanisms [1, 29]:

i. **Organic substances:** This category includes low-solubility, naturally derived organic nitrogen compounds that release nutrients through microbial decomposition. These can be further divided into chemically synthesized compounds such as urea acetaldehyde, cyclo-diurea, and isobutylidene diurea (IBDU), and biologically decomposable materials such as urea-formaldehyde (UF) and crotonylidene diurea (CDU). Organic amendments such as manure, compost, crop residues, slurry, sewage sludge, and organic-mineral fertilizers (e.g., horn meal, bone meal, leather meal, and rapeseed meal) also fall under this category, contributing to sustained nutrient release and improved soil health.

ii. **Inorganic compounds with low solubility:** These fertilizers include compounds such as metal ammonium phosphates (e.g., $MgNH_4PO_4$ and partially acidulated phosphate rocks (PAPR), which exhibit reduced solubility and release nutrients slowly into the soil solution. Their limited solubility minimizes nutrient fixation and leaching losses, thereby improving nutrient retention in the soil.

iii. **Water-soluble fertilizers with physical barriers:** This category represents the most advanced form of controlled release fertilizers, where soluble nutrients are encapsulated within coatings or matrices that regulate nutrient diffusion. These barriers may include sulphur coatings, polymer coatings (resin-based or thermoplastic), or combinations of both. Matrix-based systems may also utilize hydrophobic materials such as polyolefins and rubber, as well as gel-forming polymers (hydrogels), to control nutrient dissolution and release rates. Such systems ensure a sustained and predictable nutrient supply aligned with crop requirements. The different categories of slow and controlled release fertilizers, along with their mechanisms, materials, and functional advantages, are presented in Table 1.

Table 1: Mechanisms, materials, and functional advantages of slow and controlled release fertilizers

Category	Fertilizer Type	Key Materials / Technology	Mechanism of Nutrient Release	Functional Advantage	References
Organic-based SRFs	Urea-formaldehyde, IBDU, CDU	Organic N compounds, condensation products	Microbial decomposition and chemical breakdown	Gradual nutrient availability, improved soil health	Azeem et al., [1] Xie et al., [29]
Inorganic low-solubility SRFs	Metal ammonium phosphates, PAPR	Low-solubility mineral compounds	Slow dissolution in soil solution	Reduced nutrient fixation and leaching	Xie et al., [29]
Polymer-coated CRFs	Polymer-coated urea/NPK	Resin, thermoplastic polymers, polyolefins	Diffusion through semi-permeable membrane	Controlled and predictable nutrient release	Azeem et al., [1] Rop et al., [3]
Sulfur-coated fertilizers	Sulfur-coated urea (SCU)	Sulfur + wax coatings	Physical barrier degradation and diffusion	Cost-effective controlled release	Azeem et al., [1]
Nanocomposite fertilizers	Nano-encapsulated NPK	Nanomaterials, hydrogels, nano-clays	Diffusion and nano-mediated controlled release	Enhanced nutrient use efficiency and reduced losses	Huiyuan et al., [20]
Hydrogel-based systems	Matrix-based fertilizers	Superabsorbent polymers, hydrogels	Swelling-controlled diffusion	Moisture retention and sustained nutrient supply	Xie et al., [29]

3. History and Scientometric Investigation of Slow and Controlled Release Fertilizers

The concept of slow release fertilizers dates back to the early 20th century; however, systematic scientific understanding and technological development began in the 1960s with the work of Oertli and Lunt, who elucidated the principles governing controlled nutrient release through encapsulation technologies [30, 31].

The first commercial slow release fertilizer was introduced in the United States in 1955 and was based on urea-formaldehyde (UF) condensation products. Subsequent advancements in the 1960s led to the development of polymer-enhanced formulations such as urea-formaldehyde polymers (URP), which improved nutrient release characteristics. Sulfur-coated urea (SCU), developed during the same period, became one of the earliest widely used coated fertilizers. However, limitations in its performance led to the development of polymer-coated sulfur-coated urea (PSCU) in 1969, which offered improved nutrient release control.

Further innovations included the commercialization of polymer-coated NPK fertilizers under the trade name "Osmocote" in California in 1967, followed by sulfur-coated NPK fertilizers in Japan in 1975. A major breakthrough occurred in 1976 with the development of "Nutricote" by the Chisso-Asahi Fertilizer Company, which utilized polyolefin-coated NPK granules to achieve precise nutrient release. This was followed by the introduction of polyurethane-coated fertilizers such as "Plantacote" in 1982 and "Polyon" in 1988, which employed advanced membrane coating technologies to enhance release efficiency.

The development of biopolymer-based coatings marked another significant advancement, with starch-based coatings introduced by [32], followed by chitosan and alginate-based coatings [33] and lignin-based formulations. These innovations contributed to the development of environmentally friendly and biodegradable fertilizer coatings. From a global perspective, the demand for slow and controlled release fertilizers has increased significantly, reaching over 1.5 million metric tonnes in 2018, with a projected annual growth rate of approximately 6%. China represents the largest consumer, accounting for nearly 46% of global usage, followed by the United States, Western Europe, and Japan.

Scientometric analysis further highlights the growing research interest in this field. Since 2000, a substantial number of publications have focused on controlled release fertilizers, slow release fertilizers, and polymer-coated fertilizers. Among these, controlled release fertilizers account for the largest proportion of research output, followed closely by slow release fertilizers, indicating a strong and expanding global research focus on improving fertilizer efficiency and sustainability. The steady increase in publications over time reflects the rising importance of these technologies in addressing challenges related to nutrient management and environmental sustainability.

4. Advantages of Slow Release Fertilizers and Controlled Release Fertilizers

Slow release fertilizers (SRFs) and controlled release fertilizers (CRFs) represent a significant advancement in nutrient management technologies, offering improved efficiency and sustainability compared to conventional fertilizers. Although both categories are often grouped together, they differ fundamentally in their mechanisms of nutrient release. The release characteristics of these fertilizers are largely governed by coating properties such as thickness, composition, porosity, and solubility, as well as environmental factors including soil temperature, moisture, pH, texture, and microbial activity.

Controlled release fertilizers are typically characterized by the presence of inorganic or organic coatings, particularly polymer-based encapsulation systems, which regulate nutrient diffusion through semi-permeable membranes. In contrast, slow release fertilizers, such as compost, animal manures, and plant-based residues, depend primarily on microbial decomposition processes for nutrient release, making their release patterns less predictable and more dependent on environmental conditions. The mechanism of nutrient release and global adoption trends of these fertilizers are illustrated in Figure 2, which highlights the widespread utilization and increasing demand for slow and controlled release fertilizers.

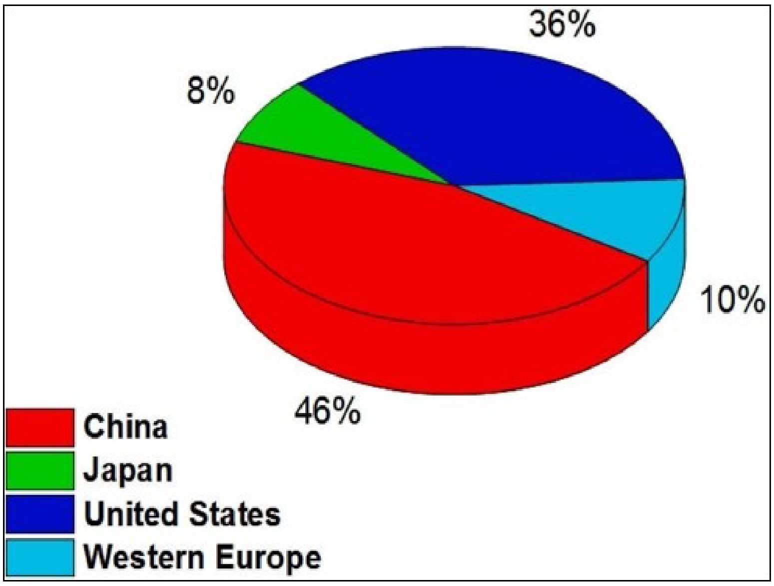

Figure 2: Mechanism of action of Nano fertilizers

In addition to conventional formulations, several chemically synthesized slow release compounds such as crotonylidene diurea (CDU), isobutylidene diurea (IBDU), and urea formaldehyde (UF) have been developed to improve nutrient availability and reduce losses [34]. Controlled release fertilizers, due to their engineered coatings, provide a more consistent and regulated nutrient supply over time. This controlled release mechanism significantly reduces nutrient losses and minimizes environmental risks associated with conventional fertilization practices [35].

4.1. Agronomic Effects

From an agronomic perspective, CRFs and SRFs contribute to improved crop growth and productivity by ensuring a sustained and synchronized supply of nutrients in accordance with plant demand. This synchronization enhances nutrient uptake efficiency and reduces the likelihood of nutrient deficiencies during critical growth stages. Additionally, the gradual release of nutrients prevents the accumulation of high concentrations of soluble salts in the soil, thereby minimizing osmotic stress and reducing the risk of root and leaf injury commonly associated with conventional fertilizers. These fertilizers also contribute to improved seed germination, enhanced root development, and better soil structure due to reduced nutrient fluctuations. Furthermore, the steady nutrient availability can lower the incidence of certain diseases by maintaining optimal plant health and reducing physiological stress.

4.2. Environmental Benefits

One of the most significant advantages of SRFs and CRFs is their ability to reduce environmental pollution. By minimizing nutrient losses through leaching, volatilization, and runoff, these fertilizers help prevent groundwater contamination, eutrophication of water bodies, and greenhouse gas emissions. Their use also reduces the accumulation of excess nutrients in soil systems, thereby maintaining ecological balance and promoting sustainable agricultural practices [35].

4.3. Economic Impacts

From an economic standpoint, controlled release fertilizers offer considerable cost-saving potential. Due to their higher nutrient use efficiency, the recommended application rates of conventional fertilizers can be reduced by approximately 20–30% without compromising crop yield [36]. Additionally, the need for multiple fertilizer applications is minimized, as a single application of CRFs can supply nutrients throughout the cropping season. This reduction in application frequency translates into savings in labor, energy, and operational costs, making these fertilizers economically viable in the long term. Furthermore, improved nutrient efficiency and reduced losses contribute to better return on investment for farmers by enhancing productivity while lowering input costs [36].

Overall, slow and controlled release fertilizers provide a balanced approach to nutrient management by integrating agronomic efficiency, environmental sustainability, and economic feasibility, thereby playing a crucial role in modern sustainable agriculture.

5. Conclusion

Achieving global food security while ensuring environmental sustainability remains a major challenge for modern agriculture. With increasing population pressure and the need for higher productivity, it is essential to adopt nutrient management strategies that enhance efficiency while minimizing environmental impacts. Conventional fertilization practices, although effective in improving yields, are often associated with substantial nutrient losses, leading to reduced efficiency, increased production costs, and environmental degradation such as soil deterioration, water contamination, and greenhouse gas emissions. In this context, smart fertilizers have emerged as a promising solution to address the limitations of traditional fertilizers. Nano fertilizers, owing to their unique physicochemical properties such as high surface area, enhanced reactivity, and targeted delivery, improve nutrient availability and uptake efficiency while reducing losses. Similarly, slow and controlled release fertilizers provide a sustained and regulated supply of nutrients, ensuring better synchronization between nutrient availability and plant demand. This not only enhances crop productivity but also reduces the frequency of fertilizer application and associated input costs. The adoption of these advanced fertilizer technologies contributes significantly to improving soil health, enhancing nutrient use efficiency, and reducing environmental pollution. Furthermore, they support sustainable agricultural intensification by optimizing resource utilization and minimizing ecological footprints. However, large-scale adoption of smart fertilizers requires further research to optimize formulations, assess long-term field performance, and improve economic feasibility under diverse agro-climatic conditions. Greater emphasis is also needed on developing cost-effective, environmentally safe, and farmer-friendly technologies. Overall, smart fertilizers represent a transformative approach in nutrient management, offering a balanced pathway toward increased agricultural productivity and environmental sustainability. Their integration into modern farming systems will play a crucial role in achieving long-term sustainability goals and ensuring food security for future generations.

Article Information

Disclaimer (Artificial Intelligence): The author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.), and text-to-image generators have been used during writing or editing of manuscripts.

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