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# Nano Urea's Role in Agricultural Innovation: A Comprehensive Review of Efficacy and Environmental Impact

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**ABSTRACT**

Nano urea's potential to revolutionize agriculture by enhancing nutrient management and promoting sustainability has garnered increasing attention. This comprehensive review examines the role of nano urea in agricultural innovation, encompassing its impact on yield, nutrient efficiency, soil health, and environmental sustainability. Through an analysis of case studies and field trials, it highlights improved crop yield, quality, and reduced pollution as major outcomes. Challenges, including nanoparticles' behavior and safety considerations, are discussed alongside potential benefits. Future research areas are identified, including tailored formulations, environmental impact assessment, and regulatory frameworks. Overall, nano urea offers a promising solution to address critical agricultural challenges and drive innovation, but further studies and collaborative efforts are essential to ensure its safe and responsible integration into global farming systems.

**Keywords: nano urea, agricultural innovation, nutrient management, sustainability, crop yield, environmental impact, soil health, case studies, field trials, challenges, future research.**

## 1. Introduction to Nano Urea and Agricultural Innovation

In recent years, the realm of agriculture has witnessed a remarkable convergence of science and technology, giving rise to novel solutions aimed at addressing the growing challenges of food security, resource conservation, and environmental sustainability. One such innovation that has garnered significant attention is the utilization of nano urea in modern agricultural practices. Nano urea, a nanotechnology-enabled formulation of urea, presents a promising avenue to enhance nutrient delivery, improve crop yield, and mitigate the environmental impacts associated with conventional urea application.

Nano urea, characterized by its reduced particle size and enhanced solubility, offers a revolutionary approach to nutrient management in agriculture. The conventional use of urea, a widely utilized nitrogen fertilizer, has often resulted in nutrient losses due to volatilization and leaching, contributing to soil and water pollution. Nano urea, through its controlled nutrient release mechanisms, aims to enhance nutrient use efficiency, thereby minimizing environmental degradation.

Agricultural innovation, encompassing advancements in farming practices, technology adoption, and sustainable resource management, is imperative to ensure global food security and meet the demands of a rapidly growing population. The integration of nano urea into these innovations presents a transformative opportunity for farmers to optimize nutrient utilization, increase crop productivity, and reduce the ecological footprint of agriculture.The significance of this interdisciplinary approach lies not only in its potential to reshape the agricultural landscape but also in its alignment with broader sustainability goals. As the world grapples with the challenge of producing more food with fewer resources, nano urea stands at the crossroads of scientific innovation and agricultural necessity.

This review article delves into the multifaceted realm of nano urea's role in agricultural innovation. It critically examines the efficacy of nano urea in nutrient management, its impact on crop yield and quality, and its implications for soil health and the environment. Through a comprehensive analysis of existing literature and research findings, this review seeks to provide a holistic understanding of the potential benefits and challenges associated with the adoption of nano urea in modern agriculture.By shedding light on the promise of nano urea and its contributions to agricultural innovation, this review aims to contribute to the ongoing dialogue surrounding sustainable farming practices, technological advancements, and the pursuit of a more resilient and productive global food system.

### *1.Nano Urea Formulations and Delivery Mechanisms*

Nano urea, as a cutting-edge innovation in agriculture, offers not only enhanced nutrient utilization but also diverse formulations and delivery mechanisms that set it apart from traditional urea fertilizers. This section provides a comprehensive discussion of the various formulations and delivery methods of nano urea, highlighting their potential to revolutionize nutrient management practices.

#### *1.1. Formulations of Nano Urea*

Nano urea formulations exhibit variations in terms of particle size, coating materials, and nutrient encapsulation techniques. These formulations aim to optimize nutrient release, control solubility, and prolong the availability of nitrogen for plant uptake. Encapsulation of urea nanoparticles in polymer coatings or matrices is one prominent approach, enabling gradual nutrient release in response to environmental factors and crop demand.

#### *1.2. Nano Urea Delivery Methods*

Nano urea can be delivered through multiple channels, including foliar application, fertigation, and soil incorporation. Foliar application involves spraying nano urea directly onto plant leaves, facilitating rapid nutrient absorption. Fertigation, the integration of nano urea into irrigation systems, allows for precise nutrient delivery to the root zone. Soil incorporation entails mixing nano urea with the soil during planting or cultivation, enabling gradual nutrient release over time.

#### *1.3. Comparison with Conventional Urea*

When compared to conventional urea, nano urea exhibits distinct advantages in nutrient release and efficiency. Conventional urea often suffers from rapid volatilization and leaching, leading to significant nitrogen losses and reduced plant uptake. In contrast, nano urea's controlled release mechanisms, such as polymer coatings or encapsulation, mitigate these losses by providing nutrients to plants in a more targeted manner.

Numerous studies have demonstrated the superior nutrient use efficiency of nano urea compared to conventional urea. Research findings indicate that nano urea formulations lead to higher nitrogen retention in the soil and improved nutrient uptake by plants, resulting in increased crop yields and reduced environmental impact. This increased efficiency not only addresses concerns related to resource wastage but also aligns with the sustainable intensification of agriculture.

## 2. Enhanced Nutrient Use Efficiency

The utilization of nano urea in agriculture has demonstrated a remarkable potential to enhance nutrient use efficiency, thereby revolutionizing the way crops acquire and utilize essential nutrients. This section delves into the mechanisms through which nano urea improves nutrient uptake and utilization by crops, as well as the key factors contributing to its increased nutrient use efficiency.

#### *2.1. Mechanisms of Improved Nutrient Uptake*

Nano urea's reduced particle size and enhanced solubility play a crucial role in facilitating nutrient uptake by plant roots. The smaller particle size of nano urea enables a larger surface area for interaction with soil and root surfaces, enhancing the contact and absorption of nutrients. Furthermore, nano urea's ability to release nutrients gradually aligns with crop nutrient demands, minimizing nutrient wastage and maximizing plant uptake.

#### *2.2. Enhanced Nutrient Utilization*

Nano urea's controlled release mechanisms lead to a sustained availability of nutrients in the root zone, preventing the excessive and rapid release of nitrogen often associated with conventional urea. This controlled release aligns with the metabolic needs of plants, reducing nutrient losses through leaching and volatilization. As a result, plants supplied with nano urea can more efficiently assimilate and utilize nutrients, contributing to improved growth, development, and yield.

#### *2.3. Factors Contributing to Increased Nutrient Use Efficiency*

Several factors contribute to the increased nutrient use efficiency associated with nano urea:

2.3.1. Reduced Leaching and Volatilization: Nano urea's controlled release minimizes the risk of nutrient leaching into groundwater and volatilization into the atmosphere.

2.3.2. Enhanced Root Accessibility: Nano-sized particles enhance root contact and nutrient uptake due to their increased surface area.

2.3.3. Targeted Nutrient Delivery: Nano urea's gradual release aligns with crop nutrient demands, reducing wastage and ensuring nutrients are available when needed.

2.3.4. Improved Soil Retention: Nano urea's interaction with soil particles can enhance nutrient retention in the root zone, reducing nutrient runoff.

2.3.5. Stress Mitigation: Nano urea's gradual nutrient release can help plants better withstand environmental stresses, leading to improved overall nutrient utilization.

## 3. Impact on Crop Yield and Quality

Nano urea's application in agriculture has shown promising results in terms of enhancing both crop yield and quality. This section reviews studies that demonstrate the positive effects of nano urea on crop productivity and discusses examples of various crops and regions where nano urea has exhibited significant benefits.

### *3.1. Enhanced Crop Yield:*

Numerous studies have highlighted the positive impact of nano urea on crop yields. Nano urea's controlled nutrient release, improved nutrient uptake, and reduced nutrient losses contribute to higher crop productivity. For example, research on rice cultivation has shown substantial yield increases due to the efficient utilization of nano urea compared to conventional urea.

### *3.2. Improved Crop Quality:*

In addition to increased yields, nano urea has been associated with improved crop quality attributes. Fruits and vegetables grown with nano urea often exhibit enhanced nutritional content, increased uniformity, and improved post-harvest shelf life. These qualities can lead to improved market value and consumer satisfaction.

**Examples of Crop-Specific Benefits:**

1. Rice (*Oryza sativa*): Studies have reported significant yield improvements in rice fields treated with nano urea. Enhanced grain quality, increased tiller numbers, and improved nutrient utilization efficiency have been observed, contributing to higher overall rice yields.

2. Wheat (*Triticum aestivum)*: Nano urea application has been linked to improved wheat grain yields and quality characteristics. Studies suggest that nano urea's gradual release of nutrients aligns well with wheat's nutrient demand throughout its growth stages.

3. Maize (*Zea mays*):Research on maize crops has shown that nano urea application leads to increased plant height, ear length, and grain yield. The controlled nutrient release mechanism of nano urea contributes to sustained nutrient availability during critical growth phases.

4. Tomato (*Solanum lycopersicum*):Nano urea-treated tomato plants have demonstrated higher fruit yield, improved fruit quality (size, color, and nutritional content), and extended shelf life compared to conventional urea-treated plants.

### *3.3. Regional Benefits:*

The benefits of nano urea are not limited to specific crops but extend to various regions and agroecosystems. From Asian rice paddies to North American cornfields and European vegetable gardens, nano urea has exhibited positive impacts on crop productivity and quality across diverse geographical locations.Overall, the application of nano urea in agriculture offers a promising avenue to achieve sustainable increases in crop yield and quality, contributing to food security and improved livelihoods for farmers worldwide.

## 4. Environmental Implications and Reduced Pollution

Nano urea's unique properties offer the potential to mitigate environmental pollution and reduce nitrogen losses, presenting a promising avenue for sustainable agriculture. This section assesses how nano urea minimizes environmental pollution and provides a comparison of the environmental impacts between nano urea and conventional urea.

### *4.1. Reduced Nitrogen Losses:*

One of the significant environmental benefits of nano urea is its ability to reduce nitrogen losses. Conventional urea application often leads to nitrogen volatilization and leaching, contributing to air and water pollution, respectively. Nano urea's controlled release mechanisms, such as encapsulation or polymer coatings, help minimize these losses by providing nutrients to plants in a manner aligned with their uptake rates, reducing the risk of nutrient runoff and gaseous emissions.

### *4.2. Minimized Environmental Pollution:*

Studies have shown that the utilization of nano urea can lead to a substantial reduction in environmental pollution compared to conventional urea. This reduction stems from the following factors:

**Reduced Volatilization:** Nano urea's gradual release limits the volatilization of ammonia, a common byproduct of conventional urea that contributes to air pollution and acid rain formation.

**Diminished Leaching:** Nano urea's controlled nutrient release minimizes the risk of nutrient leaching into groundwater, thereby reducing the contamination of water bodies with nitrates.

### *4.3. Comparison of Environmental Impacts:*

When comparing the environmental impacts of nano urea and conventional urea, nano urea tends to demonstrate a more favorable profile due to its reduced nutrient losses and targeted nutrient delivery. While conventional urea contributes to eutrophication, groundwater pollution, and greenhouse gas emissions, nano urea's properties result in fewer adverse effects. Additionally, nano urea's potential to enhance nutrient use efficiency translates to fewer inputs being applied, further reducing the overall environmental footprint of agriculture.

By minimizing nitrogen losses and pollution risks, nano urea plays a pivotal role in advancing environmentally sustainable agricultural practices and supporting the broader goal of responsible resource management.

## 5. Soil Health and Microbial Communities

Nano urea's application in agriculture has prompted interest in its impact on soil health and its interaction with soil microorganisms. This section examines how nano urea influences soil health and its potential effects on soil structure, microbial diversity, and nutrient cycling.

### *5.1. Soil Structure and Aggregation:*

Studies suggest that nano urea may contribute positively to soil structure and aggregation. The controlled release of nutrients from nano urea may lead to improved root growth and exudation, which in turn can promote the development of soil aggregates. Enhanced soil aggregation benefits water infiltration, root penetration, and overall soil structure, facilitating better nutrient and water availability to plants.

### *5.2. Microbial Diversity and Activity:*

Nano urea's interaction with soil microorganisms is a subject of interest in modern agricultural research. It is suggested that nano urea's gradual nutrient release may provide a more sustained nutrient supply to soil microbes, promoting microbial growth and activity. This can have cascading effects on nutrient cycling, organic matter decomposition, and overall soil ecosystem health.

### *5.3 Nutrient Cycling and Availability:*

Nano urea's potential to release nutrients gradually aligns with microbial nutrient mineralization and plant uptake patterns. This synchronized nutrient release could enhance nutrient cycling efficiency, with microorganisms breaking down organic matter and releasing nutrients for plant uptake. As a result, the use of nano urea may contribute to a more balanced nutrient supply, reducing the risk of nutrient imbalances and losses.

## 6. Challenges and Potential Risks

While nano urea holds promise for transforming agriculture, there are notable challenges and potential risks associated with its application. This section discusses these challenges, including the behavior of nanoparticles in the environment, long-term effects, and regulatory considerations.

### *6.1. Nanoparticles' Behavior in the Environment:*

The behavior of nanoparticles in the environment is complex and can vary based on factors such as soil type, climate, and crop type. Concerns arise regarding the potential for nanoparticles to accumulate in soil, water bodies, or plant tissues. Understanding the fate, transport, and potential for bioaccumulation of nano urea particles is crucial to assess their long-term environmental impacts.

### *6.2. Long-Term Effects on Ecosystems:*

Long-term effects of nano urea on soil ecosystems, including soil health, microbial diversity, and soil structure, need further investigation. While short-term benefits are evident, potential shifts in microbial communities or unintended alterations in nutrient cycling could have unforeseen consequences over extended periods.

### *6.3. Regulatory and Safety Considerations:*

The use of nanotechnology in agriculture brings regulatory challenges related to safety, labeling, and approval processes. Regulatory agencies must establish guidelines for assessing the safety of nano urea for human health, wildlife, and the environment. Adequate risk assessments are necessary to ensure that nano urea does not pose undue harm.

### *6.4. Human Health and Worker Safety:*

As with any new technology, the safety of workers handling nano urea is a concern. Inhalation or skin exposure to nanoparticles during application could have health implications. It's crucial to establish best practices, safety protocols, and protective measures to minimize potential risks to workers.

### *6.5. Consumer Perception:*

Public perception of nanotechnology in agriculture can influence acceptance and adoption. Clear communication regarding the benefits, safety measures, and regulatory oversight of nano urea is necessary to foster trust among consumers and stakeholders.

Balancing the potential benefits of nano urea with these challenges requires interdisciplinary research, regulatory frameworks, and proactive risk assessment strategies. Addressing these concerns will ensure that nano urea contributes positively to sustainable agriculture without compromising environmental and human safety.

## 7. Economic and Practical Considerations

The adoption of nano urea in agriculture carries economic and practical implications that warrant thorough analysis. This section delves into the economic viability of integrating nano urea into different agricultural systems and provides a comparison of costs, benefits, and potential returns on investment.

### *7.1. Economic Viability Across Agricultural Systems:*

The economic viability of using nano urea can vary based on factors such as crop type, farming practices, and local conditions. In some cases, the initial cost of nano urea may be higher than conventional urea. However, its potential to improve nutrient use efficiency, increase yield, and reduce the need for frequent applications could lead to long-term economic benefits.

### *7.2. Costs and Benefits Comparison:*

When comparing costs, the initial investment in nano urea might be higher due to its innovative technology and production processes. However, the benefits it offers in terms of reduced nutrient losses, improved crop yield, and enhanced nutrient utilization efficiency could offset these higher upfront costs.

### *7.3. Potential Returns on Investment:*

The calculation of returns on investment (ROI) for adopting nano urea depends on multiple factors, including crop yield increase, market prices, and input costs. Studies have shown that the ROI from using nano urea can be substantial due to improved yield and quality. The extent of the ROI largely depends on the specific crop and management practices.

### 7.4.Consideration of Farm Size and Scale:

The economic considerations also depend on the scale of farming operations. Larger farms might benefit more from the efficiency gains of nano urea due to economies of scale. However, small-scale and subsistence farmers may need to carefully evaluate whether the increased yield and quality justify the initial investment.

### 7.5.Long-Term Sustainability:

While economic considerations are vital, long-term sustainability and environmental benefits also play a crucial role. The reduction in nutrient losses, improved soil health, and reduced environmental impact associated with nano urea can contribute to the overall viability of adopting this technology.

## 8. Case Studies and Field Trials

Real-world case studies and field trials provide valuable insights into the practical applications and actual impact of nano urea on various crops. This section reviews selected case studies and field trials, offering a glimpse into the benefits, challenges, and farmer experiences associated with using nano urea.

**Case Study 1: Rice Yield Enhancement**

In a field trial conducted in India, nano urea was applied to rice fields alongside conventional urea. The study observed a significant increase in rice yield with nano urea application, attributed to improved nutrient availability and uptake. Farmers reported higher profits due to increased yields, which encouraged wider adoption of nano urea in the region.

**Case Study 2: Maize Nutrient Efficiency**

Field trials conducted in North America focused on maize cultivation with nano urea. The trials demonstrated reduced nitrogen losses and improved nutrient efficiency compared to conventional urea. This led to enhanced crop growth and yield. Farmers noted that despite the initial higher cost of nano urea, the improved nutrient utilization and yield gains made it a viable investment.

**Case Study 3: Vegetable Quality Enhancement**

In a case study involving tomato cultivation, nano urea application resulted in improved fruit quality, including enhanced color, taste, and nutritional content. The controlled release of nutrients contributed to prolonged nutrient availability, resulting in desirable attributes for consumers. Farmers found that the improved quality positively impacted market prices and consumer demand.

### *8.1. Farmer Experiences and Lessons Learned:*

The adoption of nano urea in these case studies and field trials demonstrated several common themes:

**Yield Improvement:**Across various crops, nano urea consistently led to increased yield, contributing to improved farm income and livelihoods.

**Quality Enhancement:** Farmers often reported improvements in crop quality, resulting in higher market value and consumer satisfaction.

**Nutrient Efficiency:** Nano urea's controlled release mechanisms reduced nutrient losses and enhanced nutrient utilization, ultimately improving resource efficiency.

**Initial Investment:** While nano urea may have a higher upfront cost, the potential returns on investment, improved yield, and reduced environmental impact were noted by farmers.

**Sustainability**: Farmer experiences highlighted the potential for long-term sustainability through reduced environmental pollution and improved soil health.

These case studies and field trials collectively emphasize the practical relevance of nano urea in addressing agricultural challenges and enhancing productivity. While challenges such as cost and regulatory considerations persist, the positive outcomes reported by farmers provide valuable insights into the technology's potential to contribute to sustainable and economically viable farming practices.

## 9. Future Directions and Research Needs

The field of nano urea in agriculture is continually evolving, and ongoing research holds the key to unlocking its full potential. This section explores emerging research areas, potential innovations, and identifies gaps in current knowledge that warrant future investigation.

### *9.1. Tailored Formulations for Specific Crops:*

Research could focus on developing nano urea formulations customized for specific crop types and their nutrient requirements. Understanding how different crops respond to various nano urea formulations could lead to optimized nutrient delivery and enhanced crop productivity.

### *9.2. Environmental Fate and Impact Assessment:*

In-depth studies are needed to comprehensively assess the environmental fate of nano urea, including its potential to accumulate in soils, water bodies, and plants. Evaluating the long-term impact on soil health, microbial communities, and nutrient cycling will provide valuable insights into the sustainability of nano urea application.

### *9.3. Synergistic Approaches with Other Technologies:*

Exploring how nano urea can synergize with other technologies, such as precision agriculture, biostimulants, and soil amendments, could lead to holistic solutions for optimizing nutrient management and crop production.

### *9.4. Multi-Year Studies for Long-Term Effects:*

Long-term studies spanning multiple growing seasons can provide a comprehensive understanding of nano urea's impact on soil health, yield stability, and potential cumulative effects on ecosystems.

***9.5. Safety and Health Considerations:***

In-depth research into the potential health impacts on workers handling nano urea and consumers consuming crops treated with nano urea is essential. Investigating inhalation risks, skin contact, and potential uptake of nanoparticles by plants is crucial for ensuring safety.

***9.6. Farmer Adoption and Socioeconomic Impact:***

Studying the socioeconomic impact of adopting nano urea across different farming systems, regions, and scales can shed light on its potential role in enhancing farmer livelihoods and addressing food security challenges.

***9.7. Regulatory Framework Development:***

Research should contribute to the development of robust regulatory frameworks that ensure the safe and responsible use of nano urea in agriculture, balancing innovation with environmental and human safety.

***9.8. Public Perception and Education:***

Understanding public perceptions of nano urea and disseminating accurate information through education and outreach efforts will play a pivotal role in shaping its acceptance and adoption.

***9.9. Closing Knowledge Gaps for Sustainable Agriculture:***

Future research in these directions will contribute to closing existing knowledge gaps and ensuring that the integration of nano urea into agricultural systems is grounded in scientific evidence. A collaborative effort among researchers, policymakers, farmers, and stakeholders will be essential to harness the potential of nano urea for a sustainable and resilient global food system.

## Conclusion

In conclusion, the review of nano urea's role in driving agricultural innovation has revealed a promising and transformative technology with significant potential to revolutionize nutrient management practices and contribute to sustainable agricultural systems. Nano urea's unique properties, such as controlled nutrient release and improved nutrient uptake, have been shown to enhance crop yield and quality across various crops and regions. It offers a pathway to address challenges related to nutrient losses, environmental pollution, and resource efficiency. Numerous case studies and field trials have demonstrated the tangible benefits of using nano urea, including increased yields, improved crop quality, and reduced environmental impact. Farmers' experiences underscore the economic viability of adopting this technology, despite initial higher costs, due to improved returns on investment and long-term sustainability.

However, challenges and knowledge gaps remain. The behavior of nano urea in the environment, potential long-term effects on ecosystems, safety considerations, and regulatory frameworks require ongoing research and careful assessment. Future research should focus on tailoring nano urea formulations, understanding its interactions with soil microorganisms, and evaluating its impact on soil health and long-term sustainability.The potential long-term significance of nano urea lies in its ability to contribute to a more efficient and environmentally responsible agricultural sector. By reducing nutrient losses, enhancing nutrient use efficiency, and promoting responsible nutrient management, nano urea can play a pivotal role in ensuring food security while minimizing the environmental footprint of agriculture. Its adoption, when accompanied by proper regulatory oversight and continued research, offers a pathway towards a sustainable and resilient future for global agriculture.

**References**:

1. Smith, A. M., & Walker, A. J. (2019). Nanotechnology in agriculture: Prospects and constraints. Frontiers in Plant Science, 10, 4.
2. El-Ramady, H., Abdalla, N., Alshaal, T., El-Ghamry, A., Shalaby, T., Singh, M., & Kalaji, H. M. (2020). Nanotechnology for sustainable agriculture: Recent developments, challenges, and prospects. Frontiers in Plant Science, 11, 581599.
3. Gupta, P., Yadav, S., & Verma, R. (2021). Nanotechnology in agriculture: A boon for sustainable plant nutrition. In Nanotechnology for Sustainable Agriculture (pp. 151-178). Springer.
4. Prasad, R., Pandey, S., & Singh, V. K. (2020). Nanotechnology and its application in agriculture: A review. Plant Archives, 20(1), 250-256.
5. Nair, R., & Shabala, S. (2017). Nano-scale drug delivery and targeting to overcome physiological barriers. Molecules, 22(10), 1719.
6. Ghosh, A., Choudhury, R. R., & Ghosh, S. B. (2019). Nanotechnology in agriculture: A review. International Journal of Pure and Applied Bioscience, 7(3), 331-342.

7. El-Mashad, H. M., & Mohamed, H. I. (2019). Impact of nano-fertilizers on growth, productivity, and biochemical responses of Solanum lycopersicum. Biocatalysis and Agricultural Biotechnology, 22, 101366.
8. Sharma, S., & Kaur, H. (2021). Nano-fertilizers and their smart delivery system: A breakthrough in enhancing nutrient use efficiency in plants. In Nanotechnology for Sustainable Agriculture (pp. 243-258). Springer.
9. Rizwan, M., Ali, S., Adrees, M., Rizvi, H., Rehman, M. Z., Hannan, F., ... & Tsang, D. C. (2020). Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: A comprehensive review. Ecotoxicology and Environmental Safety, 197, 110600.
10. Khan, M. I. R., Fatma, M., Per, T. S., Anjum, N. A., & Khan, N. A. (2015). Salicylic acid-induced abiotic stress tolerance and underlying mechanisms in plants. Frontiers in Plant Science, 6, 462.
11. Ismail, I. M., & Bagyaraj, D. J. (2018). Nanotechnology in agriculture: A way to sustainable crop production. In Advances in Soil Microbiology: Recent Trends and Future Prospects (pp. 145-158). Springer.
12. Hussain, S., Khattak, A. M., & Farooq, M. (2018). Impact of nanotechnology on plant growth and development: A review. In Nanotechnology for Agriculture: Crop Production & Protection (pp. 1-18). Springer.
13. Kalathur, R. C., Jaiswal, A. K., & Sharma, V. K. (2021). Nano-urea for enhanced crop yield: A review. Frontiers in Environmental Science, 8, 633370.
14. Khan, N. A., & Samiullah, T. R. (2020). Nanotechnology in agriculture: Current status, challenges, and future perspectives. Frontiers in Plant Science, 11, 565099.
15. Kumar, V., & Sharma, S. (2019). Nano-urea modulates nitrogen metabolism, seedling growth and yield attributes in rice. Ecotoxicology and Environmental Safety, 172, 35-45.
16. Mahmoudi, H., SeyedSharifi, R., Gharanjik, B. M., & Asghari, F. (2021). Impact of nitrogen fertilizers on fruit yield, fruit quality and plant nitrogen-use efficiency of tomato (Solanum lycopersicum L.). Scientia Horticulturae, 285, 110171.
17. Chhipa, H., & Bajpai, A. (2019). Nanofertilizers and their roles in sustainable agriculture. In Nanotechnology for Agriculture: Crop Production & Protection (pp. 19-34). Springer.
18. Singh, J., & Kumar, A. (2020). Effects of nanotechnology in agriculture and food sector: A comprehensive review. Food and Bioprocess Technology, 13(1), 15-40.
19. Mousavi, S. R., & Rezaei, M. (2020). Impact of nano-fertilizers on agricultural ecosystems: A review. Journal of Cleaner Production, 259, 120897.
20. Sarwar, M., Bibi, S., Sher, M., Ata-Ul-Karim, S. T., Nawaz, A., Faridullah, & Ullah, R. (2018). Impact of granular urea coated with different polymers on ammonia volatilization and nitrogen use efficiency in wheat. Journal of Plant Nutrition, 41(13), 1695-1705.
21. 2. Tripathi, P., Singh, P., & Mishra, A. (2020). Impact of nanofertilizers on soil microbiota: A critical insight into their fate, transport, and ecological responses. Ecotoxicology and Environmental Safety, 207, 111274.
22. Swaminathan, M. S. (2011). Sustainable agriculture: Towards an evergreen revolution.Proceedings of the Indian National Science Academy, 77(2), 73-84.
23. Taheri, M., & Abdollahzadeh, G. (2019). Agricultural sustainability indicators: A review. Agronomy for Sustainable Development, 39(4), 32.
24. 2. Ge, Y., Schimel, J. P., Holden, P. A., & Jenkins, M. W. (2018). Regulation of microbial communities and nitrogen cycling in soil by a nanoparticle, a silver ion, and a silver–thiosulfate complex. Environmental Science & Technology, 52(13), 7317-7327.
25. Jeyarajan, R., Rajendran, P., Mahimairaja, S., & Veerappapillai, A. (2021). A review on the impacts of nanomaterials on plant growth, water quality, and microbial community. Journal of Environmental Chemical Engineering, 9(5), 106206.