Journal of Advances in Biology & Biotechnology

Volume 27, Issue 10, Page 813-819, 2024; Article no.JABB.122846
ISSN: 2394-1081

Nano Management Techniques for Soil Reclamation

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jabb/2024/v27i101504

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here:
https://www.sdiarticle5.com/review-history/122846

Minireview Article

Received: 13/07/2024
Accepted: 15/09/2024
Published: 05/10/2024

ABSTRACT

The application of nano-scale management strategies for soil remediation presents a promising avenue for tackling soil salinity issues and bolstering agricultural sustainability. Nano-sized materials like gypsum, biochar, sulphur, and zinc offer novel solutions by capitalizing on their distinct properties to alleviate soil stressors and bolster soil vitality. These nano materials demonstrate heightened reactivity, mobility, and efficacy compared to traditional alternatives, facilitating precise delivery and enduring effects on soil characteristics and crop performance. Through targeted ion displacement, soil structure enhancement, and improved nutrient accessibility, nano management approaches play a pivotal role in rehabilitating saline and sodic soils, thereby fostering agricultural resilience in adverse environmental conditions. Moreover, the integration of nano technologies in farming practices holds considerable promise for advancing precision agriculture, optimizing resource utilization, and mitigating ecological concerns associated with conventional farming methods. As research in this domain advances, ongoing exploration and

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***Cite as:** Prabha, V.Vijay, M. Jayanthi, and A.Venkateshwar. 2024. "Nano Management Techniques for Soil Reclamation". Journal of Advances in Biology & Biotechnology 27 (10):813-19. https://doi.org/10.9734/jabb/2024/v27i101504.*

refinement of nano management techniques are imperative to ensure their effectiveness, safety, and long-term sustainability, thereby contributing to the establishment of robust and productive agricultural systems.

Keywords: Nano-scale management; soil reclamation; soil stressors; efficacy; sustainability.

1. INTRODUCTION

Nanotechnology is one of the most exciting new technologies of the twenty-first century. It is the capacity to apply the theory of nanoscience to practical situations by monitoring, quantifying, assembling, regulating, and producing matter at the nanoscale scale (Bayda *et al*. 2020). Nanotechnology, with its focus on the unique properties exhibited by materials at the nanoscale, holds immense promise for transforming various sectors, including food production, healthcare, environmental protection, safety measures, water management, energy generation, and beyond. This groundbreaking field offers unprecedented opportunities to enhance processes and address challenges across diverse industries (Baruah *et al*., 2008). Nanotechnology applications in agriculture are gradually transforming the theoretical possibilities into the practical applications. Novel tools are being designed which can operate at nanometric levels to boost research in molecular and cellular biology. Nanotechnology possesses the potential to augment agricultural productivity through genetic improvement of plants and animals (Kuzma *et al*l., 2006; Scott *et al*., 2007) along with cellular level delivery of genes and drug molecules to specific sites in plants and animals (Maysinger *et al*., 2007). The potential of nanotechnology is rapidly expanding as researchers identify suitable techniques and sensors tailored for precision agriculture, effective management of natural resources, early detection of pathogens, and contaminants in food products, as well as efficient delivery systems for agrochemicals like fertilizers and pesticides. Moreover, nanotechnology offers avenues for improved integration of systems in food processing, packaging, and other critical areas, thereby enhancing monitoring of agricultural and food system security. As innovations in nanotechnology continue to flourish within the agricultural sector, it is foreseeable that this field could emerge as a primary economic driver, benefiting both consumers and farmers without adverse effects on the ecosystem. One emerging area of interest lies in the utilization of nanoporous zeolites in farming practices. This interest stems from growing public concerns regarding the potential negative impacts of chemical fertilizers on the agro-ecosystem. By exploring alternatives such as nanoporous zeolites, which offer unique properties conducive to efficient nutrient delivery and soil enhancement, researchers aim to mitigate environmental risks associated with conventional agricultural practices while maintaining productivity and sustainability in food production. (Moraru *et al*., 2003; Chau *et al*., 2007; Subramanian and Rahale,2009).Soil salinity, characterized by the accumulation of soluble salts, profoundly affects plant growth in two primary ways. Firstly, it directly hampers plant development by impeding water absorption and limiting nutrient accessibility. Secondly, it indirectly undermines soil quality by deteriorating its physical properties (Kumar *et al*., 2023). The adverse effects of salinity include impacts on the movement of water from the soil into the roots and through the plant tissues, thereby inducing osmotic stress (Abobatta, 2020). Furthermore, it influences the absorption of macro- and micronutrients, with certain ions competing for transport into the root cells (Das *et al*., 2022). Excessive concentrations of sodium (Na^+) and chloride (Cl^-), usually resulting from salinity, can trigger toxicity symptoms such as leaf burn and dry leaf tissue (Hammami *et al*., 2022; H. Liu *et al*l., 2023). To combat these excess ions, plants use energy-intensive mechanisms, which negatively affect growth (Stavi *et al*l., 2021). Nano management of soil salinity can be achieved through various techniques which mainly aims in enhancing the plant and root growth, tolerance to salinity stress and improvements in soil structure and quality. Mitigating soil salinity can also be accomplished by the use of nano management techniques, such as nano gypsum, nano sulfur, nano halophytes, salt-tolerant genotypes, nano fertilizers, and biological nano fertilizers, as well as nano amendments like biochar, compost, and chitosan.

2. NANOTECHNOLOGY APPLICATIONS IN AGRICULTURE

Nanotechnology stands poised to transform the agricultural and food industry by introducing innovative tools for addressing a myriad of challenges. From molecular-level disease treatment to swift disease detection and improving plants' nutrient absorption abilities, nanotechnology offers promising solutions. Smart sensors and delivery systems, enabled by nanotech, are set to empower the agricultural sector in combating crop pathogens effectively. Moreover, the advent of nanostructured catalysts holds the potential to enhance the efficiency of pesticides and herbicides, thereby reducing the required doses. Beyond its direct applications, nanotechnology is anticipated to have indirect environmental benefits. By promoting the adoption of alternative and renewable energy sources and deploying filters and catalysts to mitigate pollution, nanotechnology can play a pivotal role in safeguarding our environment and addressing existing pollutants. In developing nations, the potential of nanotechnology is particularly significant. Enhancing agricultural productivity ranks as a critical application area, second only to energy conversion and storage in importance for achieving millennium development goals. Additionally, water treatment emerges as another vital focus area, highlighting the diverse ways nanotechnology can contribute to sustainable development worldwide (Buentello *et al*., 2005).

3. ROLE AND EFFECT OF NANO GYPSUM

Gypsum ($CaSO_4 \cdot 2H_2O$) is a naturally occurring mineral containing Ca (29.2%) and S (18.6%) (Reddy and Reddy, 2010) . Benefit of gypsum in agriculture include reclamation of alkaline soil, source of nutrient for calcium and sulfur and compensates the negative effects of subsoil acidity (Dick *et al*., 2006) . Gypsum reduces the pH of alkaline soils by forming calcium carbonate, which decreases the concentration of soluble carbonates (Patle and Sharma, 2022)

Application of gypsum in calcium deficient soil is known to improve root growth, thus reducing water stress (Farina and Channon, 1988). Calcium is regarded as a secondary macronutrient that is vital to plants. It is essential to several physiological functions as well as to the growth and development of plants [1,2]. Further more, its an essential component for signalling pathways, enzymatic activity, the structural integrity of cell walls and membranes, and general plant health (Thor, 2019) . Gypsum is known to increase yield and enhance quality of peanut and concentration of calcium in peanut seeds as it acts as a source of calcium (Summer and Lorrimore, 2006). Sulfur benefits the plant by better nitrogen utilization in plant, synthesis of amino acids viz. cystine, cysteine and methionine, synthesis of protein and fat etc (Faiyad *et al*. 2020) . Hence, gypsum application seems to be promising in improving yield and quality of crops. It also helps to reduce the risks of Calcium and Sulfur deficiency in soil.

Nano-sized gypsum represents a cutting-edge approach in nano management strategies for addressing soil salinity issues. This innovative application involves the use of gypsum particles at the nano scale to mitigate soil salinity and enhance soil fertility and crop productivity. By leveraging the unique properties of nano-sized gypsum, such as its increased surface area and reactivity, farmers and researchers can more effectively combat soil salinity while minimizing environmental impacts. Nano gypsum works by effectively displacing sodium ions in the soil, thereby reducing soil salinity levels and improving soil structure. This, in turn, enhances water infiltration, root development, and nutrient uptake by plants. Additionally, nano-sized gypsum particles have been shown to improve soil aggregation, leading to better soil aeration and drainage. Furthermore, the use of nano-sized gypsum in agriculture offers several advantages over traditional gypsum application methods (El-Henawy *et al*. 2024) . Nano gypsum can be applied in lower quantities compared to conventional gypsum, making it a cost-effective solution for farmers. Moreover, its nano-scale properties ensure better distribution and penetration into the soil, maximizing its effectiveness in mitigating soil salinity [3-5]. Overall, nano gypsum represents a promising avenue in nano management strategies for sustainable agriculture, offering innovative solutions to the pressing challenge of soil salinity while promoting soil health and crop productivity. As research in this field continues to advance, nano-sized gypsum holds the potential to revolutionize soil salinity management practices and contribute to the development of more resilient and productive agricultural systems [6,7]. Nano-particles have less diameter than cell’s pore diameter, so it can easily cross the barrier and make entry into the plant cell (Navarro *et al*., 2008). Nano-sized gypsum possess high specific surface area, high surface energy, reactivity, mobility and solubility (Verma, 2015). Nano-sized gypsum holds significant effects for enhancing the emergence, growth, and yield of wheat crops [8-10]. The application of parthenium-based nano-sized gypsum has the potential to effectively replace up to 25% of the RDF without compromising crop yield. The highest biological yield (9.85 t/ha) was recorded with 100% RDF which was at par with 75% RDF plus nano-sized gypsum and significantly higher over the other treatments. Within plant-based nano-sized gypsum formulations maximum biological yield was recorded with parthenium based nano-sized gypsum and minimum with daincha based nano-sized gypsum however, all the plant-based formulations were higher than control. (Anupama Rawat *et al*l.,2020). Sulphuric acid, gypsum applications in combination with deep tillage improved physical and chemical properties of saline-sodic soils, and consequently enhanced growth and yield of wheat, confirming the importance of deep tillage in reclaiming saline-sodic soils compared with reduced tillage [11]. Incorporating nano-sized gypsum as a seed treatment alongside the full recommended dose of fertilizers shows promise in boosting the seed yield of Indian mustard, this innovative approach offers potential benefits for enhancing crop productivity while maintaining optimal nutrient levels (Sumit Chaudhary *et al*., 2021). The application of gypsum with nanoparticles improves some chemical and physical properties of soil and the yield and water productivity in salt affected conditions (Megahed M. Amer *et al*., 2023).

4. ROLE AND EFFECT OF NANO BIOCHAR

Biochar is a carbonaceous byproduct of lignocellulosic biomass produced by several thermochemical processes. Biochar can be converted into "nano-biochar" by reducing its size to the nano-meter level. Nano-biochar exhibits exceptional physicochemical behaviour when compared to macro-biochar, including increased stability, a distinct nanostructure, increased catalytic capacity, a greater specific surface area, increased porosity, better surface functionality, and surface active sites (Bhandari *et al*. 2023).

Nano-biochar plays a pivotal role in agriculture by significantly improving soil health, enhancing crop productivity, and fostering environmental sustainability. Acting as a potent soil amendment, it bolsters soil structure and fertility, boosts organic matter content, and fosters stable soil aggregates, thereby curbing erosion and elevating overall soil quality. Its capacity to retain and release nutrients like nitrogen, phosphorus, and potassium optimizes fertilizer use efficiency, curbing nutrient runoff and environmental pollution. Moreover, its prowess in water management enhances soil water holding capacity, ameliorating drought resistance and augmenting water use efficiency, particularly in degraded soils. Additionally, nano-biochar contributes to carbon sequestration, mitigating climate change impacts by locking carbon in soil for extended periods. By fostering beneficial microbial activity, it facilitates nutrient cycling, suppresses diseases, and fosters plant growth, ultimately enhancing crop productivity and quality. Furthermore, nano-biochar's aptitude for environmental remediation, including heavy metal immobilization and organic pollutant adsorption, underscores its potential in soil remediation and pollution mitigation. While offering a sustainable and eco-friendly approach to agriculture, ongoing research is essential to optimize application methods and gauge long-term effects on soil and ecosystem health. Yang *et al*l [12] studied the impact of applying nano-biochar at different rates on soil and crop growth in maize fields. Results showed that placing nano-biochar near the roots slightly increased soil density but significantly enhanced soil structure by increasing large soil aggregates. This helped retain water in the soil, reducing evaporation and nutrient leaching. Maize plants in nano-biochar-treated soil exhibited better growth, with taller plants, thicker stems, and larger leaf area. Additionally, higher nano-biochar levels led to increased grain weight and higher yields, with a 5.7% increase at the highest application rate. Despite these benefits, implementing nano-biochar application on a large scale may be complex.

5. ROLE AND EFFECT OF NANO SULFUR

Sulfur is classified as the fourth important nutrient, following nitrogen (N), phosphorus (P), and potassium (K). It is crucial for plant growth since it aids in the synthesis of peptides, including cysteine, glutathione, secondary metabolites, vitamins (B, biotine, and thiamine), and chlorophyll in the cell (AL-Shammery, 2024) . Sulfur application to soil has several key effects, including lowering soil pH, improving soil water relations, and boosting nutrient availability. Applying sulfur fertilizer to salt-affected soils can reduce the uptake of toxic elements (Na + and Cl-) and promote K/Na selectivity. Calcium ions can also reduce the negative effects of sodium ions on plants [13].

Nano sulfur plays a pivotal role in modern agriculture, offering diverse applications and significant benefits. As a vital nutrient source, nano-sulfur contributes to fundamental metabolic processes in plants, fostering overall plant health and vigor. Its utility extends to fertilizer enhancement, where it boosts the efficiency of conventional fertilizers by enhancing nutrient availability and uptake, thus minimizing losses and maximizing agricultural productivity. Additionally, nano-sulfur's potent antifungal properties make it a valuable tool for disease management, effectively combating various fungal pathogens and reducing reliance on synthetic fungicides. Moreover, its role in pest control, soil amendment, and environmental sustainability further underscores its importance in promoting sustainable farming practices. While nano-sulphur holds immense promise for enhancing crop health and productivity, ongoing research is crucial to optimize its formulations, application methods, and long-term impacts on soil and ecosystem health. The application of nano-sulphur (Nano-S) has consistently shown significant increases across all examined traits compared to control plots in agricultural studies. Typically, controlled application (CA) is followed by soil incorporation (SC), while other Nano-S applications yield the highest averages. Among these, surface application (SA) often demonstrates the highest trait values, particularly concerning grain yield and protein ratio properties. This pattern suggests that Nano-S application, particularly through surface application methods, holds substantial promise for enhancing both grain yield and quality in bread wheat cultivation. Therefore, to achieve significant improvements in bread wheat production, incorporating Nano-S, especially through surface application techniques, could be a viable strategy [14]. The use of nano sulfur emerges as a cost-effective and easily accessible solution to address soil fertility issues. By applying nano sulfur at appropriate rates, significant improvements in maize yield have been observed, primarily attributed to enhanced concentrations of both macro and micronutrients, including nitrogen, phosphorus, potassium, iron, manganese, and zinc, reaching sufficient levels in the soil. This positive outcome stems from the acidifying nature of nano sulfur, leading to a decrease in soil pH, which in turn facilitates nutrient availability. Moreover, nano sulfur contributes to enhancing soil physical properties by promoting soil aggregation and permeability through reactions with soil microorganisms and calcium carbonate, forming calcium sulphate. Compared to mineral sulfur, nano sulfur demonstrates superior effectiveness, owing to its unique properties such as high surface-to-volume ratio and controlled-release kinetics, ensuring targeted delivery and sustained impact [13].

6. ROLE AND EFFECT OF NANO ZINC

Zinc is an essential micronutrient for plants, and zinc deficiency is widespread in many crops. Zinc is essential for enzyme activity, such as dehydrogenases, aldolases, isomerases, transphosphorylation, RNA and DNA polymerases. It also plays a role in tryptophan synthesis, cell division, membrane structure maintenance, photosynthesis, and protein synthesis regulation (Pandao *et al*. 2021).

Nano zinc offers a multifaceted approach to enhancing agricultural practices. Its role spans from improving nutrient delivery and fertilizer efficiency to aiding in pest and disease management and enhancing stress tolerance in plants. Additionally, nano zinc can serve as a soil amendment, bolstering soil quality and fertility while enabling precision agriculture through innovative sensor and delivery systems. Furthermore, its environmental sustainability potential lies in reducing pollution associated with conventional zinc fertilizers by minimizing leaching and runoff. The application of nano-Zinc Oxide (ZnO) has been found to have positive effects on both the physical and chemical properties of soil as well as on the growth of faba bean plants, especially when cultivated under saline-sodic conditions. The research indicates that incorporating nano-ZnO along with sulfur and compost into the soil, coupled with foliar application, can effectively mitigate soil salinity and improve soil sodicity. This integrated approach not only enhances soil health but also leads to increased yields and improved quality of faba bean plants Essentially, nano-ZnO acts as a beneficial amendment that helps to alleviate soil stressors, thereby fostering better plant growth and productivity in challenging environmental conditions [15].

7. CONCLUSION

The utilization of nano management techniques for soil reclamation represents a promising avenue for addressing soil salinity and enhancing agricultural productivity sustainably. Nano-sized amendments such as gypsum, biochar, sulfur, and zinc offer innovative solutions that leverage their unique properties to mitigate soil stressors and promote soil health. These nano materials exhibit enhanced reactivity, mobility, and efficiency compared to their conventional counterparts, enabling targeted delivery and sustained impact on soil properties and plant growth. By effectively displacing harmful ions, improving soil structure, and enhancing nutrient availability, nano management techniques contribute to reclaiming saline and sodic soils, thereby fostering crop resilience and productivity in challenging environmental conditions. Furthermore, the integration of nano technologies in agricultural practices holds significant potential for advancing precision agriculture, optimizing resource use, and mitigating environmental risks associated with conventional farming methods. As research in this field progresses, it is essential to continue exploring and refining nano management techniques to ensure their efficacy, safety, and sustainability, ultimately contributing to the development of resilient and productive agricultural systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

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 this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://www.sdiarticle5.com/review-history/122846