
IMPACT OF NANO BIOCHAR AND NANO FERTILIZERS ON SOIL QUALITY AND PLANT PERFORMANCE: A REVIEW**¹Swati, *Dr. Seema Kumari and ²Sohit**¹Research Scholar, Department of Botany, B. M. U, Rohtak 124021, India

*Assistant Professor, Department of Botany, B. M. U, Rohtak 124021, India

²Research Scholar, Faculty of Agricultural Sciences, SGT University, Gurgaon, 122505¹swatisingh22303@gmail.com, *kumareeseema2011@gmail.com and ²sohit1914@gmail.com**ABSTRACT**

The requirement for food will rise in tandem with the population's continued rapid growth. Nutrient imbalances and deterioration of soil quality have resulted from the overuse of chemical-based fertilizers to meet this need. Additionally, excessive use of such fertilizers frequently contaminates water sources, adding to pollution. Therefore, rather than depending just on chemical fertilizers to achieve sustainable agricultural practices, it is crucial to investigate other solutions. In this sense, the potential of nano fertilizers and nano biochar to increase crop outputs and improve fertilizer efficacy while reducing environmental damage has drawn attention. These nano-sized organic and inorganic fertilizers increase crop absorption rates by facilitating the regulated, progressive release of nutrients. Several studies indicate that the use of nano fertilizers and nano biochar has improved the uptake of vital nutrients like zinc and phosphorus in soils deficient in these elements. The program of nano-macronutrients and nano-micronutrient-based nano-biofertilizers, nano-vermicompost, and nano-biochar across a variety of crops to boost growth, enhance yield, improve the nutrient efficacy, and support soil health sustainable development is the main focus of this review, which highlights recent advancements in nano-formulations used as fertilizers. The evaluation also addresses particular issues with sustainable agricultural production and possible additional benefits.

Keywords: Nano Biochar, Nano Fertilizers, Soil Quality, Plant Performance

INTRODUCTION

A major difficulty facing agriculture in the 21st century is ensuring both environmental health and food security for a growing world population. Chemical fertilizers and amendments to the soil have been heavily applied as a result of the growing demand for greater agricultural output. These compounds have caused long-term problems such soil degradation, nutritional imbalances, and environmental pollution, even though they can produce results quickly. Because a significant portion of the nutrients provided are lost through leaching, evaporation, or binding within the soil, traditional fertilizers have a poor nutrient utilization efficiency (NUE) (Subramanian et al., 2015, and Sharma et al., 2021). These inefficiencies have serious ecological effects, such as the overpopulation of aquatic ecosystems, greenhouse gas emissions, and reductions in soil health, in addition to lowering crop yields (Gupta et al., 2022).

The development of novel and sustainable agricultural technology has received more attention in an effort to address these problems. Nanotechnology is one noteworthy area of development that has enormous potential to change modern farming methods. With this approach, materials are manipulated at nanoscale levels (1–100 nm), where they exhibit unique physicochemical characteristics like increased reactivity, a bigger surface area, and better interactions with biological processes (Tarafdar et al., 2014). Because of these characteristics, nanomaterials are very useful for managing soil, delivering nutrients, and improving crop production (Dimkpa and Bindraban, 2017). In this context, nano fertilizers and nano biochar have become significant developments in agricultural inputs. It is generally recognized that biochar, a carbon-rich material generated from pyrolyzing biomass in low-oxygen settings, can improve soil fertility, increase water retention, and trap carbon (Lehmann and Joseph, 2015).

By increasing surface area and availability of the functional groups, Nano Biochar—which is made by mechanically or chemically lowering particle size—overcomes these disadvantages and increases its efficacy as an amendment to soil (Rajput, et al., 2022).

High adsorption capacity, greater porosity, and enhanced interactions with microorganisms and soil particles are just a few of the many advantageous properties of nano biochar. These characteristics enable it to play a crucial part in improving soil structure, immobilizing contaminants, and retaining nutrients. Additionally, by fostering microbial communities and enhancing enzymatic processes—which are essential for nutrient cycling and preserving soil health—Nano Biochar has a good impact on soil biological activity. Nano Fertilizers have been

developed as a contemporary method to maximize nutrient management in agricultural in unison with the breakthroughs in Nano Biochar.

By matching fertilizer supply to plant requirements, this controlled release method lowers losses and increases nutrient uptake efficacy (Dimkpa and Bindraban, 2017). Nano fertilizers can be made using a variety of techniques that improve nutrient delivery and use, including encapsulation, coating, and the use of nanostructured carriers (Mir bakhsh, 2023).

Numerous beneficial impacts on plant growth and development have been associated with the usage of nano fertilizers. Improved photosynthetic performance, better root structure, improved seed germination, and increased tolerance to environmental challenges including salinity and drought are some of these impacts. The ability of nanoparticles to penetrate plant tissues and facilitate efficient nutrient transport within cells is largely responsible for this beneficial effect. However, a number of parameters, such as the size of the particulate matter, their level of concentration, the application technique, and the corresponding environmental conditions, influence the performance of nano fertilizers, highlighting the significance of optimum application techniques.

The potential benefits of integrating nano biochar and nano fertilizer in agricultural operations have been emphasized by recent studies. By acting as a stabilizing agent or carrier for nano fertilizers, nano biochar enhances their soil retention and facilitates the slow release of nutrients. In addition to improving nutrient efficiency, this combination approach also improves the biological and physical properties of the soil, which leads to improved plant development and higher agricultural yields. However, there is still much to learn about the intricate relationships that exist between soil components, plant systems, nano fertilizers, and nano biochar. Concerns exist regarding the ecological and environmental impacts of nano-enhanced agricultural inputs, despite the fact that their benefits are becoming more well recognized. If not controlled, the small size and strong reactivity of nanoparticles may be detrimental to local ecosystems, plant health, and soil microorganisms. Comprehensive research is necessary to address issues such nanoparticle toxicity, bioaccumulation potential, and long-term environmental consequences. Widespread usage of nanomaterials is further hampered by the lack of defined procedures for their synthesis, characterization, and application. The goal of this review is to fully assess how soil properties, plant growth, and agricultural yields are affected by nano biochar or nano fertilizers. Additionally, it looks into their potential to support sustainable agriculture, their synergistic connections, and their effects on the environment.

NANOBIOCHAR

Biochar, a kind of charcoal produced by pyrolyzing biomass in low-oxygen environments, is the source of Nano Biochar (NBC), an advanced carbon-rich nanomaterial. Although conventional biochar is widely recognized for enhancing soil fertility, storing carbon, and controlling trash, new developments have produced nano-scale biochar.

Because of its larger surface area, higher porosity, it as well as more reactive function groups, this type of biochar has better physicochemical qualities.

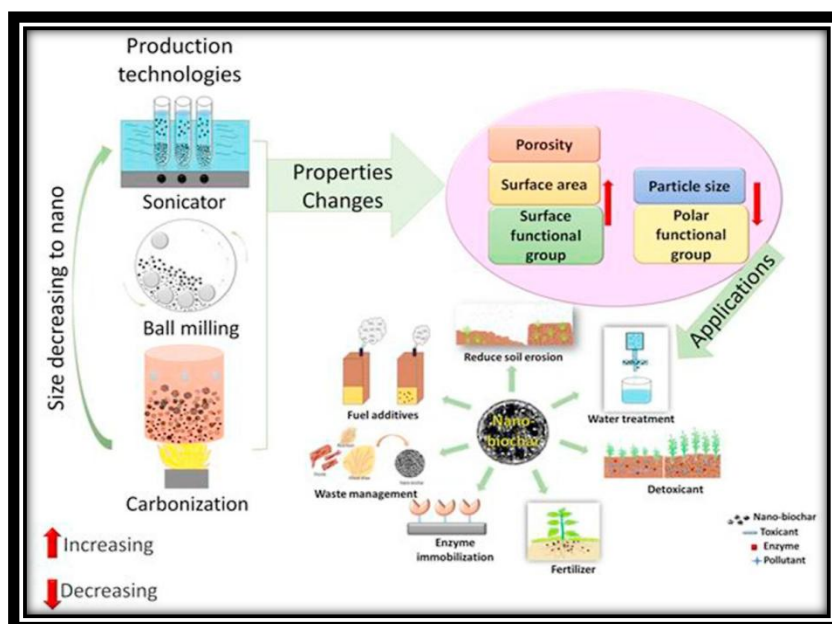


Figure 1: Effects of Nano Biochar

In order to reduce the size of particles to the nanometre range (1–100 nm), biochar is typically further processed using chemical, mechanical, or physical techniques such as ball milling process, ultrasonics, or chemical oxidation to create nano biochar. Biochar's surface charge structure, and sensitivity are altered by the size reduction, which improves its ability to interact with soil, water, or biological processes. Because of its unique qualities, NBC is rapidly emerging as a useful tool for plant sciences applications of nanotechnology, environmental cleaning, and sustainable agriculture. Improving fertility of the soil and health is one of the main uses of nano biochar. Classical biochar has been used for centuries to improve soils, particularly in regions like the Amazon basin, where "terra terra preta" soil have a high carbon content as a result of ancient biochar use.

When compared to higher-scale biochar, nano biochar shows better nutrient delivery and retention due to its larger surface area and smaller particle size. Because of its high capacity for cation exchange (CEC) and porous structure, NBC minimizes nutrient leaching and increases nutrient efficiency by adsorbing and gradually releasing essential nutrients for plants, which include nitrogen, phosphorus, and potassium (K). Additionally, Nano Biochar modifies the physicochemical characteristics of soil, such as pH, carbon organic content, retained water, and microbial activity, to improve the conditions for plant growth. It can raise pH levels and improve nutrient availability in acidic soils by acting as a liming agent. Additionally, by offering appropriate microsites and carbon resources, nano biochar promotes the proliferation and activity of microorganisms, which in turn enhances biological processes crucial for preserving soil health.

One important application of nano biochar is in environmental cleaning. Globally, pollution—especially the poisoning of water and soil with organic materials and heavy metals—has become a serious problem. Nano biochar is an effective adsorbent for a variety of environmental contaminants because of its superior sorption properties and reactive surface. According to research, it can successfully immobilize dangerous heavy metals including chromium, lead, cadmium, and arsenic in soils, reducing their ecological risks and bioavailability. Mechanisms include electrostatic attraction and surface interaction, ion exchange, and precipitated are all implicated in the sorption process of metals by nano biochar. Additionally, the inclusion of functional groups such as carboxyl, hydroxyl, and carbonyl improves its relationship with metal ions, increasing the immobilization's efficacy.

Nano biochar has the ability to adsorb organic pollutants found in waste and agricultural runoff, including pesticides and polycyclic aromatic hydrocarbons, and pharmaceutical residues. It is appropriate for the treatment of water and purification applications due to its high hydrophobic properties and π - π interactions, which allow it to interact with non-polar chemical molecules.

In wastewater treatment systems, nano biochar is being used more and more because of its ability to remove contaminants. It has been demonstrated that adding nano biochar to membrane and filter systems greatly enhances the removal of bacteria, colors, and nutrients from industrial effluent. According to research, nitrogen and phosphorus may be extracted from municipal wastewater more successfully using filters customized with nano charcoal than with conventional adsorbents.

Its antibacterial qualities also help to neutralize dangerous microorganisms in water systems, making the water safer for use in cities and agriculture. Furthermore, to increase its catalytic and antibacterial efficacy and enable its use in sophisticated processes of oxidation and the photocatalytic degradation of contaminants, nano biochar can be improved or mixed with metallic nanoparticles like silver, iron, or zinc oxide. In the field of agriculture, Nano Biochar serves as a medium for the delivery of nano pesticides and fertilizers in addition to improving soil. It is a great carrier for the precise managed application of agrochemicals, enhancing their efficacy and reducing their environmental impact because of its capacity to retain vast quantities and compatibility with biological systems.

For instance, fertilizers like urea can be encapsulated in nano biochar, enabling a slow and continuous release that corresponds with the way crops absorb nutrients. This method saves expenses for farmers, increases fertilizer efficiency, and lessens nitrogen loss through breakdown or leaching. Additionally, nano biochar-based formulations are being created to supply vital micronutrients like iron, copper, and zinc that are frequently deficient in soils but are required for plant metabolism. Nano biochar can enhance sustainable agriculture and boost crop growth by protecting beneficial microorganisms during transportation and facilitating their successful colonization of plant roots when combined with biopesticides or rhizobacteria that promote plant growth. The use of nano biochar is important for carbon as well as capture and climate change mitigation. Because of its high aromatic content and stable carbon architecture, Nano Biochar is extremely resistant to microbial degradation and can stay in soils for hundreds of years. This feature makes it a sustainable carbon store that, when used extensively, can aid in lowering greenhouse gas emissions (Wang et al., 2020).

Additionally, studies show that by increasing nitrogen efficiency and changing the microbial process involved with nitrification and denitrification, Nano Biochar can reduce nitrous oxide (N₂O) emissions from agricultural land. Additionally, it helps lower biogas (CH₄) production in rice fields by changing the redox circumstances and preventing bacteria that produce methane. As a result, using Nano Biochar in agricultural techniques not only increases crop output but also advances broader environmental goals.

Nano Biochar has shown remarkable efficacy in studies pertaining to seed germination and plant growth. It can boost biomass, encourage root growth, and accelerate seed germination when applied as a seed coating or growth enhancer. Because of its nanoscale size, it can interact with seed coats and root surfaces more effectively, retaining moisture and facilitating nutrient absorption in the early phases for development (El-Naggar et al., -2021). Furthermore, phytohormonal signalling pathways, such as auxins, cytokinin, and gibberellins in particular, which are critical for processes like division of cells, elongation, and general plant growth, have been demonstrated to be impacted by nano biochar. This shows that nano biochar has promising applications in precision farming and seed technology.

Additionally, new applications for nano biochar are being investigated in the fields of biosensors and nanocomposite materials. It is an essential component in the development of bio-based sensor for environmental condition monitoring because of its conducive and adsorptive properties. For instance, Nano Biochar can be used to create electrochemical sensors that can find pesticide residues or heavy metals in agricultural environments. Similarly, scientists are looking into using composites based on nano biochar to make biodegradable containers, energy storage devices, and catalysis supports in eco-friendly chemistry. Nano Biochar can be used in industrial and biomedical domains in addition to agriculture and environmental research when combined with polymer and other nanomaterials.

However, the use of nano biochar creates significant concerns about long-term consequences, production scalability, and ecological safety despite its many advantages and potential applications. Although research on its toxic effects and behavior is still in its early stages, there is a chance that Nano Biochar could pass past soil-plant system and reach food chains due to its nanoscale structure. To guarantee that Nano Biochar is financially viable for extensive agricultural application, the expenses related to Nano processing techniques, such as physical milling or chemical transformation, must be improved. For Nano Biochar to be used safely and effectively, standardized production methods, quality control, and regulatory frameworks must be established.

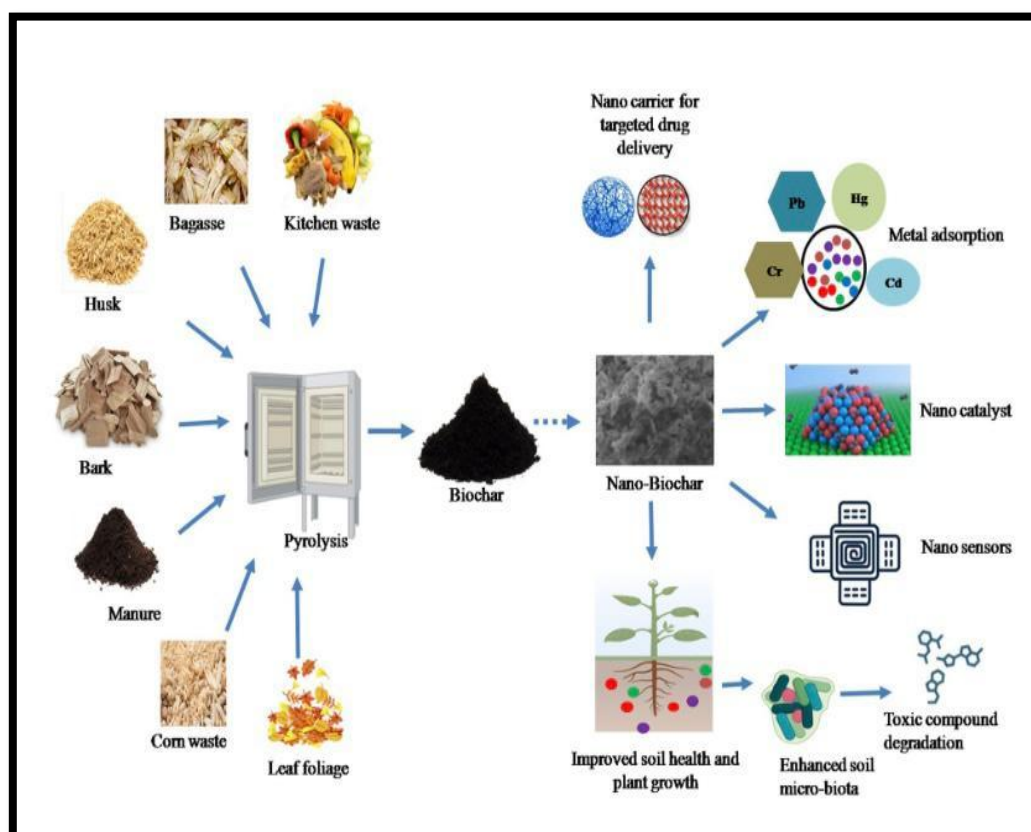


Figure 2. Different Feedstock Material for Fabrication of Nano-BC and Its Wide Applications

Nano Fertilizers:

Given the rising need for food worldwide and environmental concerns, nano fertilizers represent a revolutionary development in agricultural practices. The need for sustainable farming methods has grown as global population growth continues to grow, which has prompted creative use of the nanotechnology in fertilizer manufacturing. These fertilizers are made to improve the effective delivery nutrients to plants and are distinguished by their particle size, ranging from 1 to 100 nanometres (DeRosa et al., 2010). In contrast to conventional fertilizers, which frequently lose nutrients as a result of leaching, volatilization, or insufficient absorption, nano fertilizers offer a more controlled and accurate release of nutrients, encouraging plant growth while minimizing environmental damage.

The primary benefit of nano fertilizer is their small dimensions, which increases their mobility, reactivity, and surface area. This makes it possible for nutrients to be released gradually and continuously. Nano fertilizers can be made using a variety of processes, such as chemical, biological, and physical procedures. They can be divided into three primary categories: (1) directly synthesized nanoscale nutrient fertilizers (like nano- ZnO or nano- Fe₂O₃); (2) nanoscale - ingredients for traditional fertilizers that include nanoparticles to increase their efficacy; and (3) nanoscale-sized carriers that enable controlled nutrient release, in which nanomaterials carry nutrients and release them gradually into the soil or plants (Subramanian et al., 2015).

There are many advantages of using nano fertilizers in agriculture. The increased nutrient usage efficiency (NUE) is one important benefit. Due to different types of loss, a significant amount of nutrients does not reach the roots of plants during traditional fertilization. Because they can release nutrition in a controlled way, nano fertilizers guarantee that the plants receive nutrients at a rate that corresponds with their rates of absorption. For instance, urea that has been nano-encapsulated can release nitrogen ions in accordance with crop requirements, decreasing nitrogen losses and enhancing yields (Tarafdar, et al., 2012). This slow release of nutrients promotes environmental sustainability by reducing greenhouse gas emissions like nitrous oxide and minimizing nutrient leakage into groundwater. Enhancing crops' resilience and stress tolerance is another significant use of nano fertilizers. They can strengthen a plant's resistance to abiotic stresses such salt, drought, and extremely high or low temperatures. According to research, putting nano zinc and nano irons to go away can improve photosynthetic efficiency, antioxidant enzyme activity, and chlorophyll production, allowing plants to flourish under adversity (Rai et al., 2015). Furthermore, nanoparticles like the silicon can fortify cell walls and form protective barriers, increasing plants' resistance to infections and mechanical damage. In light of a changing climate, which is increasing the frequency of extreme weather, these qualities are especially important. Additionally, it has been discovered that nano fertilizers improve microbial activity and soil health. For example, fertilizers based on nano clay can increase soil aeration and water retention.

Although the long-term effects on advantageous soil microorganisms are still being investigated, some nanoparticles have shown antibacterial qualities that may reduce dangerous soil pathogens (Liu & Lal, 2015). Low concentrations of oxides of metal nanoparticles, such ZnO or TiO₂, may increase microbial productivity and enzyme synthesis, which would enhance nutrient availability and cycling in the rhizosphere, according to some research.

Because they enable precise and localized release, nano fertilizers offer a special advantage in the delivery of nutrients. Essential nutrients—both micronutrient and macronutrients, can be encapsulated and produced in specific plant or soil regions using nano-organized carrier like mesoporous, silica, chitosan, or polymer nanoparticles, in response to environmental stimuli like pH, moisture content, or temperature. In addition to increasing crop yields, this methodical approach to farming reduces the amount of fertilizer needed, which can save farmers money and have a smaller negative impact on the environment. For instance, potassium that has been nano-encapsulated has shown improved plant mobility, which improves fruit quality and prolongs its shelf life. Additionally, nano fertilizers have a major role in raising crop quality and output. Applying nano fertilizers has been shown to significantly increase crop production, biomass, and nutrient content in a number of field and experimental investigations. Notably, compared to conventional fertilizers, the application of nano iron and zinc in wheat and rice. has increased grain protein levels, enhanced root growth, and increased overall grain yields. Plant metabolic activities, such as enzyme functioning and hormonal balance, are enhanced by better nutrient absorption and transport, which promotes rapid plant growth. Additionally, nano fertilizers can be integrated into smart agricultural frameworks, where they cooperate with digital technology and sensors to precisely regulate nutrients. In order to ensure that fertilizers are given in the right amounts and at the right times, this clever nano-fertilization technique allows for real-time observation of soil nutrients levels and crop requirements. These techniques increase the productivity and environmental sustainability of farming activities by lowering labor and operating costs in addition to improving crop production.

Nano fertilizers may be applied practically using a variety of techniques, such as fertigation, soil applications, foliar sprays, and seed treatments. Foliar application is very efficient because it avoids soil-related problems that could restrict nutrient accessibility by enabling direct nitrogen uptake through plants stomata and epidermal layers.

For example, it has been demonstrated that foliar application of nano-boron improves fruit setting, pollen viability, and sugar levels of fruit crops. Furthermore, applying nanofertilizers to seeds might enhance germination and the development of seedling particularly in stressful situations. Nevertheless, there are several difficulties and worries associated with using nano fertilizers. The lack of knowledge about the long-term effects of nanoparticles on health of the soil, public safety, and environmental sustainability is a major problem. Certain nanoparticles have the potential to build up in soil or get into the food chain, which could have unforeseen repercussions. Further research is needed on the interactions between nanoparticles and soil organisms, as well as their mobility, durability, and potential toxicity. The regulatory frameworks for the approval and monitoring of nano fertilizers that are still in their infancy in many areas, which may prevent their wider adoption.

Significant obstacles are also presented by the cost of production and sustainability of nano fertilizers. Although effective synthesis has been accomplished in the lab, moving to industrial production while maintaining consistency and safety is still a work in progress. Further challenges that need to be addressed by supportive legislation, educational outreach, and partnerships between the public and commercial sectors include the high initial investment required for the production of nano fertilizers, and the lack of farmer knowledge, particularly in poor countries.

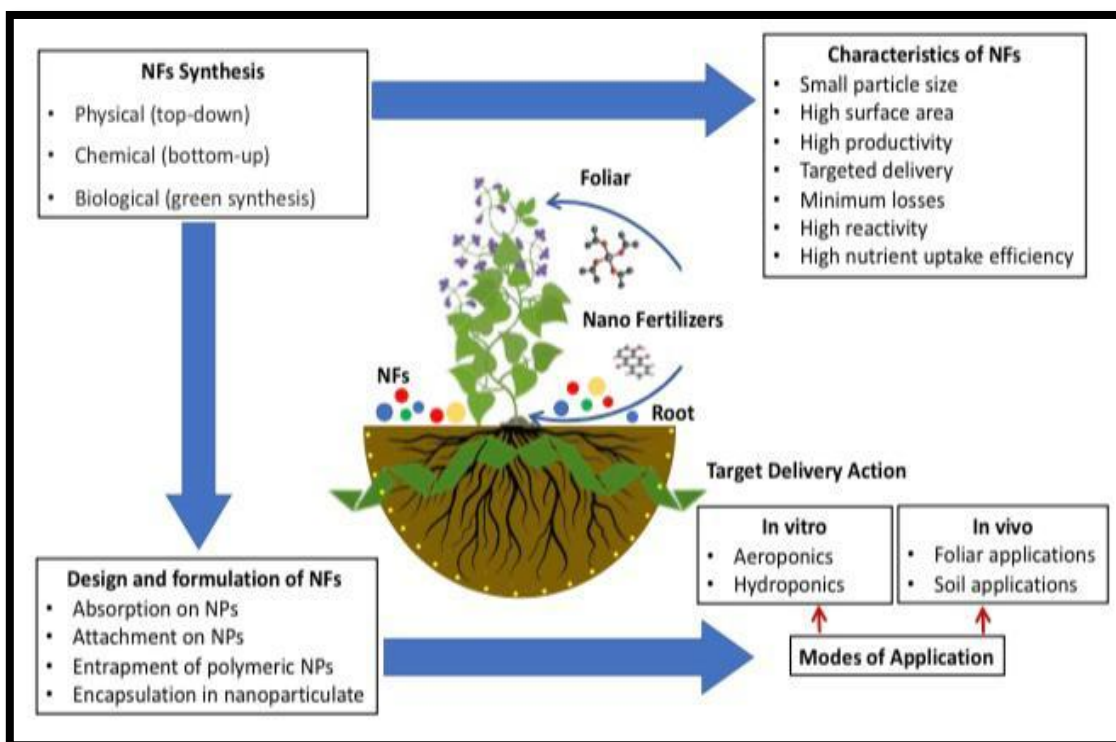


Figure 3. Nano fertilizers and their effects used in Agriculture

Table 1. Categories of Nano Fertilizers:

S. no.	Nano Fertilizers	Benefits	Drawbacks	Sources
1	Zeolite-Based	Better-quality nutrient delivery, custom-made nutrient circulation, and reduced fertilization expenditures	Involve specific synthesis techniques and formulations for ideal results; less effective at managing anionic biopolymers, which necessitate additional biopolymer complexes alongside nutrients.	Manikandan & Subramanian (2016), Benavides-Mendoza et al., (2017)

2	Starch-Based	Sustainable energy foundation, efficient nutrient delivery, and negligible organic waste	Exclusive, labour-intensive, and unreliable in performance	Mishra & Khare (2021), Khan et al. 2021.
3	Polyurethan -Based	Exact nutrient statement, improved soil moisture retention, and decreased degradation	Lacks stability under heat and chemical exposure, can be easily removed, and has a shorter lifespan due to acid-producing monomers within the polymer matrix	Ekanayake et al. (2022), Chen et al. (2005).
4	Nanogel -Based	Highly solvable, recyclable, safe, and enhances water preservation	Issues related to optimizing solubility, biodegradability, non-toxicity, the degradation process, and biodistribution	Luckanagul et al. (2021), Chiriac et al. (2017)
5	Nano Capsule -Based	Decreased risk of nutrient leakage, effective nutrient distribution, & controlled nutrient release	Require complex synthesis methods and are dependent on material limitations	Tiwari et al. (2021), Li, J. (2015).
6	Clay -Based	High external area, reactive nanolayers, and skilful anion announcement	Can inhibit transpiration & leaf growth	Tiwari et al. (2013), Asli & Neumann (2009).
7	Chitosan -Based	Biodegradable, easily adjustable, scalable, and capable of protecting biomolecules from external factors	High hydrophilicity, subpar mechanical properties, low gas perviousness & unsuccessful encapsulation	Zhang et al. 2022, Mujtaba et al. (2021).

Nanotechnology has produced sustainable agriculture solutions for a variety of contemporary issues through nanostructured materials as nano biochar and nano fertilizers. Because of their special qualities and wide range of uses in materials, energy, agriculture, and the environment—particularly in the phytoremediation of different inorganic, organic, and heavy metal-based pollutants—carbon nanomaterials have emerged as potent instruments in recent years. Carbon-based nanomaterials, such as biochar nanocomposites that like nano biochar and nano fertilizers, could be produced through nanotechnology, revolutionizing research in related fields.

In addition to being used as a support material for enzyme immobilization, nano biochar is a nanosized biochar material with improved chemical, physical, and surface attributes, such as improved plant growth and the properties of soil, disease management, biodegradation of contaminants and pesticides, and wastewater treatment.

Table2. Impact of Nano-Biochar and Nano- Fertilizers on Plant Growth

Sr. No.	Scientific Name	Common Name	Impact of Nano Biochar and Nano Fertilizers	Nano Fertilizer	Source
1	Brassica Rapa	Often referred planted as Bird Rape, Turnip Mustard, Field Mustard, or Wild Turnip	it helps increase nutrient availability, improve soil fertility, and improve water retention. It helps plants absorb nutrients and encourages development, which	Ncuo	(Shen et al., 2022).

			could increase cabbage yields and improve plant health.		
2	Solanum Lycopersicum L.,	Commonly Referred to as Tomato	increases nutrient availability, retention of water, and soil fertility. These elements have a favourable effect on tomato plant growth.	Ncu-chitosan	(Mahmoud et al., 2023).
3	Capsicum Annum	Jwala Chili	contributes to increasing soil fertility, water retention, and carbon sequestration in addition to encouraging growth of plants & nutrient uptake.	Nfe	(Khalid et al., 2022).
4	Daucus Carota	Known as Wild Carrot	Enhance nutrient availability, improve soil quality, increase fruit yield, and enhance the flavour of carrots		(Solberg et al., 2023).
5	Triticum Aestivum	Wheat	The potential to improve growth parameters such as leaf and origin length	N Chitosan-NPK	(Al-Tae et al., 2019).
6	Punica Granatum	Pomegranate	Contributes to higher fruit yields		(Khorasani et al., 2016).
7	Oryza Sativa	Rice	Shows improved growth and inhibits cadmium translocation		(Ahmad et al., 2019).
8	Moringa Peregrina	Also Known as the Ben Tree or Wild Drumstick Tree	Experiences significant reductions in growth parameters due to salinity levels	Iron Oxide	(Darwish et al., 2015).
9	Cyamopsis Tetragon Loba	Guar/Cluster Bean	improves growth physiology, increases biomass accumulation, and increases nutrient concentration	Zno	(Raliya and Tarafdar, 2013).
10	Coffea Arabica	Arabian Coffee	increases biomass output and speeds up net photosynthesis	NPK	Lombardini et al., 2019

CONCLUSION

A modified nano fertilizers has been created as a consumer product development and material design innovation. Although their use for agriculture is still in its infancy, these techniques have the capacity to revolutionize farming systems, especially when it comes to manure management issues. By lowering fertilizer prices and eliminating emission hazards, the use of different nano fertilizers could greatly increase crop productivity. Nano fertilizers allow for exact distribution and regulated nutrient release because of their improved solubility, reactivity, and capacity to pierce plant cuticles. Additionally, by lowering heavy metal toxicity and mitigating abiotic stress, they can enhance crop growth, quality, production, and nutrient efficiency. However, worries about the risks connected to using and consuming this technology are mounting, frequently overshadowing its potential advantages and efficacy.

Recent developments in nanotechnology have produced specific nanomaterials and nanoparticles that can act as carriers for macro- and micronutrients and increase crop growth and productivity. There is evidence that the impacts of nanoparticle differ by species of plant and are impacted by size, shape, concentration, and application technique. Crop yields can be greatly increased once the right dosage and individual plant requirements for nano fertilizers that are determined. Given the known nanotoxicological effects of nanomaterials and nanoparticles, environmentally friendly Nano nutrition may have significant benefits for agricultural operations in the future. Green nanomaterials & nanoparticles in general could therefore be an important supply of nutrients for crops, supporting a more environmentally friendly method of Nano nutrition.

REFERENCES

- Aftab, Z. E. H., Aslam, W., Aftab, A., Shah, A. N., Akhter, A., Fakhar, U., ... & Khalid, U. (2022). Incorporation of engineered nanoparticles of biochar and fly ash against bacterial leaf spot of pepper. *Scientific Reports*, 12(1), 8561.
- Al-Juthery, H. W., Al-Fadhly, J. T., Ali, E. A. H. M., & Al-Tae, R. A. H. G. (2019). Role of some nanofertilizers and atonikin maximizing for production of hydroponically-grown barley fodder. *Int. J. Agric. Stat. Sci*, 15, 565-570.
- Asli, S., & Neumann, P. M. (2009). Colloidal suspensions of clay or titanium dioxide nanoparticles can inhibit leaf growth and transpiration via physical effects on root water transport. *Plant, cell & environment*, 32(5), 577-584.
- Aththanayaka, S., Thiripuranathar, G., & Ekanayake, S. (2022). Emerging advances in biomimetic synthesis of nanocomposites and potential applications. *Materials Today Sustainability*, 20, 100206.
- Davarpanah, S., Tehranifar, A., Davarynejad, G., Abadía, J., & Khorasani, R. (2016). Effects of foliar applications of zinc and boron nano-fertilizers on pomegranate (*Punica granatum* cv. Ardestani) fruit yield and quality. *Scientia horticulturae*, 210, 57-64.
- DeRosa, M. C., Monreal, C., Schnitzer, M., Walsh, R., & Sultan, Y. (2010). Nanotechnology in fertilizers. *Nature Nanotechnology*, 5(2), 91.
- Dimkpa, C. O., Bindraban, P. S., Fugice, J., Agyin-Birikorang, S., Singh, U., & Hellums, D. (2017). Composite micronutrient nanoparticles and salts decrease drought stress in soybean. *Agronomy for Sustainable Development*, 37(1), 5.
- El-Naggar, A., Shaheen, S. M., Sarkar, B., Kwon, E. E., Tsang, Y. F., Ok, Y. S., & Rinklebe, J. (2021). Biochar application to low fertility soils: A review on soil productivity improvement and nutrient deficiency correction. *Science of the Total Environment*, 722, 137846.
- El-Ramady, H., Abdalla, N., Sári, D., Ferroudj, A., Muthu, A., Prokisch, J., ... & Solberg, S. Ø. (2023). Nanofarming: Promising Solutions for the Future of the Global Agricultural Industry. *Agronomy*, 13(6), 1600.
- Gupta, A., Sahu, P. K., & Tiwari, R. K. (2022). Nanotechnology in Insect Pest Management. *Molecular Approaches for Sustainable Insect Pest Management*, 377-394.
- Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature nanotechnology*, 13(8), 677-684.
- Khader, A., Ibrahim, M., Alkhatami, F., Elsayy, H., El-Kader, N. A., Shaker, E., ... & Mahmoud, E. (2023). Properties of Nano-Amendments and Their Effect on Some Soil Properties and Root-Knot Nematode and Yield Attributes of Tomato Plant. *Agriculture*, 13(2), 366.
- Khan, H. A., Naqvi, S. R., Mehran, M. T., Khoja, A. H., Niazi, M. B. K., Juchelková, D., & Atabani, A. (2021). A performance evaluation study of nano-biochar as a potential slow-release nano-fertilizer from wheat straw residue for sustainable agriculture. *Chemosphere*, 285, 131382.
- Kumar, A., Saini, H., & Yadav, P. (2020). Nano-biochar: a green nanoparticle for sustainable agriculture. *Environmental Science and Pollution Research*, 27(30), 37399-37415.
- Lehmann, J., & Joseph, S. (2015). Biochar for environmental management: an introduction. In *Biochar for environmental management* (pp. 1-13). Routledge.
- Li, J. (2015). *Protein nanocapsule based protein carriers for industrial and medical applications* (Doctoral dissertation, UCLA).

- Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., ... & Neves, E. G. (2021). Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal*, 70(5), 1719–1730.
- Liu, R., & Lal, R. (2015). Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Science of the Total Environment*, 514, 131-139.
- Liu, Z., Wang, K., Peng, X., & Zhang, L. (2022). Chitosan-based drug delivery systems: Current strategic design and potential application in human hard tissue repair. *European polymer journal*, 166, 110979.
- Manikandan, A., & Subramanian, K. (2016). Evaluation of zeolite based nitrogen nano-fertilizers on maize growth, yield and quality on inceptisols and alfisols. *International Journal of Plant & Soil Science*, 9(4), 1-9.
- Mirbakhsh, M. (2023). Role of nano-fertilizer in plants nutrient use efficiency (NUE)-a mini-review. *arXiv preprint arXiv:2305.14357*.
- Mishra, D., & Khare, P. (2021). Emerging Nano-agrochemicals for Sustainable Agriculture: Benefits, Challenges and Risk Mitigation. *Sustainable Agriculture Reviews 50: Emerging Contaminants in Agriculture*, 235-257.
- Mishra, T., Mohanty, A. K., & Tiwari, S. K. (2013). Recent development in clay based functional coating for corrosion protection. *Key Engineering Materials*, 571, 93-109.
- Morales-Díaz, A. B., Ortega-Ortíz, H., Juárez-Maldonado, A., Cadenas-Pliego, G., González-Morales, S., & Benavides-Mendoza, A. (2017). Application of nanoelements in plant nutrition and its impact in ecosystems. *Advances in Natural Sciences: Nanoscience and Nanotechnology*, 8(1), 013001.
- Naderi, M. R., & Danesh-Shahraki, A. (2013). Nanofertilizers and their roles in sustainable agriculture. *International Journal of Agriculture and Crop Sciences*, 5(19), 2229-2232.
- Neamtu, I., Rusu, A. G., Diaconu, A., Nita, L. E., & Chiriac, A. P. (2017). Basic concepts and recent advances in nanogels as carriers for medical applications. *Drug Delivery*, 24(1), 539-557.
- Parisi, C., Vigani, M., & Rodríguez-Cerezo, E. (2015). Agricultural nanotechnologies: what are the current possibilities? *Nano Today*, 10(2), 124-127.
- Patil, S. S., Balpande, S. S., Mairan, N. R., Sajid, M., & Ghodpage, R. M. (2020). Influence of integrated nutrient management using nano phosphatic fertilizer on nutrient use efficiency and yield of wheat (*Triticum aestivum* L.) in Vertisols. *Int. J. Chem. Stud*, 8(6), 757-762.
- Rahman, M. H., Haque, K. S., & Khan, M. Z. H. (2021). A review on application of controlled released fertilizers influencing the sustainable agricultural production: A Cleaner production process. *Environmental Technology & Innovation*, 23, 101697.
- Rai, M., Ingle, A., Paralikar, P., Gupta, I., Medici, S., & Galdiero, M. (2015). Nanotechnology in agriculture: opportunities, toxicological implications, and occupational risks. *Toxicology Reports*, 2, 295-307.
- Rajput, V. D., Minkina, T., Ahmed, B., Singh, V. K., Mandzhieva, S., Sushkova, S., ... & Wang, B. (2022). Nano-biochar: A novel solution for sustainable agriculture and environmental remediation. *Environmental Research*, 210, 112891.
- Rajput, V. D., Minkina, T., Sushkova, S., Mandzhieva, S., Singh, R. K., Gorovtsov, A., ... & Rajput, S. (2021). The role of nano-biochar in improving the availability and phytoremediation of heavy metals in contaminated soils. *Environmental Geochemistry and Health*, 43(10), 3817–3834.
- Raliya, R., & Tarafdar, J. C. (2013). ZnO nanoparticle biosynthesis and its effect on phosphorous-mobilizing enzyme secretion and gum contents in Clusterbean (*Cyamopsis tetragonoloba* L.). *Agricultural Research*, 2, 48-57.
- Rizwan, M., Ali, S., ur Rehman, M. Z., Malik, S., Adrees, M., Qayyum, M. F., ... & Ahmad, P. (2019). Effect of foliar applications of silicon and titanium dioxide nanoparticles on growth, oxidative stress, and cadmium accumulation by rice (*Oryza sativa*). *Acta physiologiae plantarum*, 41, 1-12.
- Rossi, L., Fedenia, L. N., Sharifan, H., Ma, X., & Lombardini, L. (2019). Effects of foliar application of zinc sulfate and zinc nanoparticles in coffee (*Coffea arabica* L.) plants. *Plant Physiology and Biochemistry*, 135, 160-166.

- Saharan, V., Sharma, G., Yadav, M., Choudhary, M. K., Sharma, S. S., Pal, A., & Saini, M. R. (2016). Synthesis and in vitro antifungal efficacy of Cu-chitosan nanoparticles against pathogenic fungi of tomato. *International Journal of Biological Macromolecules*, 91, 119-127.
- Singh, R., Singh, P., & Singh, A. K. (2022). Controlled-release nanofertilizers: Recent developments and future prospects. *Journal of Controlled Release*, 347, 150-169.
- Soliman, A. S., El-feky, S. A., & Darwish, E. (2015). Alleviation of salt stress on *Moringa peregrina* using foliar application of nanofertilizers. *Journal of Horticulture and Forestry*, 7(2), 36-47.
- Subramanian, K. S., Manikandan, A., Thirunavukkarasu, M., & Rahale, C. S. (2015). Nano-fertilizers for balanced crop nutrition. In K. S. Subramanian (Ed.), *Nanotechnology in soil science and plant nutrition* (pp. 69-80). New India Publishing Agency.
- Sun, Y., Gao, B., Yao, Y., Fang, J., Zhang, M., Zhou, Y., & Chen, H. (2021). Effects of feedstock type, production method, and pyrolysis temperature on biochar and hydrochar properties. *Chemical Engineering Journal*, 366, 608-617.
- Tan, Z., Yuan, H., Chen, Y., & Chen, H. (2022). Impact of nano-biochar on soil properties and microbial activity: A review. *Environmental Research*, 206, 112215.
- Tarafdar, J. C., Raliya, R., & Rathore, I. (2012). Microbial synthesis of phosphorus nanoparticles from Tricalcium phosphate using *Aspergillus tubingensis* TFR-5. *Journal of Bionanoscience*, 6(2), 84-89.
- Wang, J., Xiong, Z., & Kuzyakov, Y. (2020). Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy*, 8(3), 512-523.
- Wen, L. X., Li, Z. Z., Zou, H. K., Liu, A. Q., & Chen, J. F. (2005). Controlled release of avermectin from porous hollow silica nanoparticles. *Pest Management Science: formerly Pesticide Science*, 61(6), 583-590.
- Win, Y. Y., Charoenkanburkang, P., Limprasutr, V., Rodsiri, R., Pan, Y., Buranasudja, V., & Luckanagul, J. A. (2021). In Vivo Biocompatible Self-Assembled Nanogel Based on Hyaluronic Acid for Aqueous Solubility and Stability Enhancement of Asiatic Acid. *Polymers*, 13(23), 4071.
- Yang, R., Shen, J., Zhang, Y., Jiang, L., Sun, X., Wang, Z., ... & Shen, Y. (2022). The Role of Biochar Nanoparticles Performing as Nanocarriers for Fertilizers on the Growth Promotion of Chinese Cabbage (*Brassica rapa* (Pekinensis Group)). *Coatings*, 12(12), 1984.
- Yu, J., Wang, D., Geetha, N., Khawar, K. M., Jogaiah, S., & Mujtaba, M. (2021). Current trends and challenges in the synthesis and applications of chitosan-based nanocomposites for plants: A review. *Carbohydrate Polymers*, 261, 117904.
- Zhang, F. (2025). Nano-biochar in soil ecosystems: Occurrence, transport, and negative environmental risks. *Ecotoxicology and Environmental Safety*, 298, 118312.