Annals of Biology **42** (2) : 199-203, 2026 **http://agribioj.com** **Impact Score : 0.32 (Scopus)**

Effects of Nanofertilizers Application on Physico-chemical Attributes and Carbon Sequestration in Soil

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(Received: January 5, 2026; Accepted: February 3, 2026)

ABSTRACT

Carbon sequestration in soil is a vital process for mitigating climate change and enhancing soil health. It involves the capture and long-term storage of atmospheric carbon dioxide (CO,) in the form of stable organic and inorganic carbon compounds within soil systems. The aim of this research was to find out the role of nanofertilizers in physico-chemical changes and enhancement of soil organic carbon in the crop field. The nanoparticles ZnO, Fe_2O_3 and MnO_2 are green synthesized using pea peel biomass. For the purpose of treating tomato, chilli and brinjal crops, aqueous solutions of nanoparticles were made at concentrations of 10, 20, and 50 ppm. The soil samples were examined for chemical and physical parameters such as soil profile, pH, electric conductivity, moisture holding capacity, bulk density, macro- and micronutrients and soil organic carbon, initially as well as post-harvest of crops. These nanomaterials enhance nutrient use efficiency, promote plant growth and stimulate root exudation, which in turn can increase the input of organic carbon into soils. The application of green Zn, Fe and nanofertilizers may also influence microbial activity and enzyme functions, thereby accelerating the stabilization of organic matter and improving carbon retention.

Key words: Nanofertilizers, zinc, iron, manganese, soil carbon sequestration, root exudation, soil microbiota

INTRODUCTION

Now, smart nanofertilizers are viewed as a highly promising substitute for traditional ones (Dimkpa and Bindraban, 2017; Gilbertson *et al*., 2020). They are sometimes even thought to be superior to them (Periakaruppan *et al*., 2023), *e.g.*, nanofertilizers improve plant vegetative growth and fruit quality by regulating fertiliser delivery according to plant requirements. In contrast to using traditional nano-fertilizers, the effectiveness of nanofertilizers may be attributed to their slower release in uniform quantity and greater space for several plant metabolic processes that boost crop yield, speed up photosynthesis and create more dry matter yield (Abobatta, 2018). Because they are directly delivered to a specific location within the plant tissue, nanofertilizers have prevented environmental harm and the loss of nutrients to soil or groundwater. They are also highly effective at combating infections, particularly those that are soil-borne.

Furthermore, in precision agriculture, nanoparticles increase the products' shelf life (Zuverza-Mena *et al.,* 2017). The toxicity of nanoparticles and nano-based composites is being studied for use in plants and the environment (Hassanisaadi *et al.,* 2022). Furthermore, the behavior of nano-metal oxides such as magnetite, nano-silver and nano-copper still needs more investigation to determine the side effects on living organisms (Iavicoli *et al*., 2017).

Relevant studies have demonstrated that fertilizer can cause serious soil sloughing, which results in an imbalance of soil nutrients, which in turn limits the growth and development of the plant root system and induces leaf nutrient imbalance (Lai *et al.,* 2019). Fertilizers can also cause acidification

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of the soil, which causes a severe nutrient imbalance and is one of the main sources of pollution in the soil, water and air (Zhang *et al.,* 2022). Fertilizer application can directly or indirectly change the physical and chemical properties of soil, thus altering soil productivity. Hence, to apply appropriate nutrient management methods and to support environmental sustainability, it is critical to identify priority regions through systematic assessment and monitoring of soil nutrient status (Getahun *et al.,* 2024).

The enhanced farming practices in agriculture, such as nanotechnology, are used to boost agricultural yield and crop quality. In the era of contemporary agriculture, green nanofertilizers offer a potential technology for increasing soil productivity and lowering the environmental pollution caused by the use of conventional nanofertilizers. Because of their great absorption rates, nanofertilizers are applied in smaller amounts than their conventional counterparts. The nanofertilizers improve efficacy by targeting particular locations in plant tissues. The nanofertilizers speed up photosynthesis by acting as light traps and creating dry matter, which improves plant development and yield. Therefore, this study design to test the soil samples for chemical and physical parameters such as soil profile, pH, electric conductivity, moisture holding capacity, bulk density, macro- and micronutrients and soil organic carbon, initially as well as post-harvest of crops; to assessed the efficiency of green nanofertilizers, in plant growth, and stimulation root exudation, which in turn can increase the input of organic carbon into soils.

MATERIALS AND METHODS

The soil samples were taken from the field soil from the surface layer down (at a depth of 0-30 cm) to conduct a laboratory examination to know before planting and after harvesting, the field soil's physical and chemical characteristics (Arora *et al.,* 2018). The amount of accessible nutrients (N, P, K, Fe, Mn and Zn, mg/kg) in the soil was measured during the harvest stage. The gathered soil samples were examined for chemical and physical parameters such as soil profile, pH, electric conductivity, moisture holding capacity, bulk density and soil fertility parameters as per the procedure documented by Indian Standards. Determination of available micronutrients in the samples will be analyzed by UV-visible spectrophotometer and 1 g of soil will be digested and added with 50 ml of water. Heavy metals were analyzed by atomic absorption spectrophotometer (AAS).

RESULTS AND DISCUSSION

Before transplanting, the amount of available physical, chemical properties, macro- and micronutrients and soil parameters like bulk density in g/cm^{-3} (0.8±0.07), moisture content in g (1.63±0.04), water holding capacity (5±0.007) and organic carbon (0.59±0.02) were evaluated. The chemical properties of soil were pH (8.12±0.10), electrical conductivity in dS/m (0.26±0.05), nitrogen in kg/h (86.2±0.63), phosphorus in kg/h (56.43±0.53) and potassium in kg/h (80.13±0.67) were analyzed. The available micro-nutrient contents in soil were zinc in mg/kg (1.11±0.05), iron in mg/kg (5.43±0.05), manganese in mg/kg (4.99±0.03) and copper in mg/kg (0.40±0.07) before transplanting of vegetable crops (Table 1).

Table 1. Physico-chemical analysis of the soil before cultivation

S. No.	Parameters	Concentration
Physical properties		
1.	Soil texture	Sandy loam
2.	Bulk density (g/cm^{-3})	0.8±0.07
3.	Moisture content (g)	1.63±0.04
4.	Water holding capacity (%)	5±0.007
5.	Organic carbon (%)	0.59±0.02
Chemical properties		
1.	pH	8.12±0.10
2.	Electrical conductivity (dS/m)	0.26±0.05
3.	Nitrogen (kg/h)	86.2±0.63
4.	Phosphorous (kg/h)	56.43±0.53
5.	Potassium (kg/h)	80.13±0.67
Micronutrients		
1.	Zn (mg/kg)	1.11±0.05
2.	Fe (mg/kg)	5.43±0.05
3.	Mn (mg/kg)	4.99±0.03
4.	Cu (mg/kg)	0.40±0.07

The heavy metals were present in the soil before transplantation–Al in ppb (5467.53±6.34), As in ppb (7.76±0.04), Cd in ppb (9.43±0.04), Cr in ppb (23.65±0.03), Ni in ppb (321.65±0.72) and Pb in ppb (175.643±0.05) concentration in the soil (Table 2).

After harvesting, the amounts of available physical, chemical properties and macro- and micronutrients in the soil were found higher

Table 2. Heavy metals in soil sample

Heavy metals	Concentration in soil sample
Al ppb	5467.53±6.34
As ppb	7.76±0.04
Cd ppb	9.43±0.04
Cr ppb	23.65±0.03
Ni ppb	321.65±0.72
Pb ppb	175.643±0.05

than before sowing. The parameters of like bulk density in g/cm^{-3} (1.3±0.07), moisture content in g (1.72±0.01), water holding capacity (6±0.007), and organic carbon (0.63±0.108) were reported. The chemical properties of soil: pH (7.80±0.004), electrical conductivity dS/m (1.03±0.004), nitrogen kg/h (219.52±0.70), phosphorus kg/h (71.68±0.68) and potassium kg/h (88.59±0.65) analyzed. The available micro-nutrient contents in soil: Zn mg/kg (1.74±0.01), Fe mg/kg (26.12±0.67), Mn mg/kg (14.33±0.22) and Copper mg/kg (0.67±0.06) were reported after harvesting of vegetable crops. The effect of nanofertilizer on soil parameters listed above in soil after harvest of vegetable crops (Table 3).

Table 3. Physical and chemical properties of the soil of the experimental field after cultivation

S. No.	Parameters	Concentration
Physical properties		
1.	Soil texture	Sandy loam
2.	Bulk density (g/cm^{-3})	1.3±0.07
3.	Moisture content (g)	1.72±0.01
4.	Water holding capacity (%)	6±0.007
5.	Organic carbon (%)	0.63±0.108
Chemical properties		
1.	pH	7.80±0.004
2.	Electric conductivity (dS/m)	1.03±0.004
3.	Nitrogen (kg/h)	219.52±0.70
4.	Phosphorous (kg/h)	71.68±0.68
5.	Potassium (kg/h)	88.59±0.65
Micronutrients		
1.	Zn (mg/kg)	1.74±0.01
2.	Fe (mg/kg)	26.12±0.67
3.	Mn (mg/kg)	14.33±0.22
4.	Cu (mg/kg)	0.67±0.06

The physicochemical analysis of the soil was conducted before and after the field trials to determine any changes in soil health and nutrient composition (Tables 1-3). Before transplanting, the amount of available physical, chemical properties, macro- and micronutrients and soil parameters like bulk density in g/cm^{-3} (0.8±0.07), moisture content in g (1.63±0.04), water holding capacity (5±0.007), organic carbon (0.59±0.02), pH (8.12±0.10), and electrical conductivity in dS/m (0.26±0.05) were evaluated. After harvesting, the amount of available physical and chemical properties and macro- and micronutrients in the soil were found higher than before sowing.

The physiochemical assessment of soil samples in agricultural ecosystems is highly beneficial to maintaining or enhancing soil quality and efficiently controlling soil fertility and plant nutrition (Periakaruppan *et al.,* 2023). The interdependent characteristics of physical, chemical and biological qualities make up soil quality, which affect many processes in the soil that make it suitable for agricultural practice and other purpose (Adamu, 2019). In vegetable crop production evaluation of the physico-chemical characteristics of soil is crucial because elements like pH, organic matter, nitrogen and phosphorus have an impact on the growth and development of plants (Yakasai and Rabiu, 2024). Chemical fertilization has been demonstrated to have a major impact on the physical and chemical characteristics of soil (Atakora *et al.*, 2025), as well as to encourage microbial exudation from the roots, as well as affect soil fast-acting nutrients that can be directly absorbed and utilized by the plant, which ultimately affects the yield (Brunetto *et al.,* 2018; Dikir, 2023).

Soil pH refers to the acidity or alkalinity of the soil. It measures how much of the soil's free hydrogen ions (H^+) are present (Bello, 2024). It is an important parameter in assessing soil samples. If the pH is less than 6 then it is said to be acidic soil, while a pH of 6 to 8.5 is considered normal, soil that is higher than 8.5 is considered alkaline (Adamu, 2019). In this study the pH was 8.12±0.10 before transplanting of plantlets found acidic, which was reduced up to 7.80±0.004. The acidity in the soil may be attributed to overuse of urea as reported by Lai *et al.* (2019). According to Tang *et al.* (2023), soil microorganisms can convert urea quickly into $NH4^+$. This process releases H^+ into the soil, which speeds up the acidification of the soil. The acidity may also be caused by the composition of parent soil material, leaching, high organic matter decay, or cultivation of high-yield crops (Sharma *et al.,* 2025). Soil organic matter increases soil organic carbon promotes soil health and fertility and is the foundation of soil fertility. In the present study, the organic carbon

0.59±0.02 was reported, its value ranged from 0.44-1.86 (Yakasai and Rabiu 2024). According to Periakaruppan *et al.* (2023), the normal value of O.M is 0.52 to 0.72. From the above results, we can conclude that brinjal, chilli and tomato crop soils have moderate to average physico-chemical attributes for vegetative and reproductive growth of plants. The cropping system, crop rotation and organic manuring were found suitable to maintain the physico-chemical characteristics of soil (Zhang *et al.,* 2022; Kostrzewska *et al.,* 2022).

CONCLUSION

Overall, nanofertilizers represent a promising, next-generation tool for improving soil fertility, optimizing nutrient delivery, and contributing to soil carbon sequestration which could support sustainable agriculture while helping mitigate climate change. Additionally, improved plant productivity associated with balanced micronutrient supply contributes to greater biomass input and soil organic carbon accumulation. The nanofertilizer solution not only contributes to climate mitigation but also improves soil fertility, water retention and biodiversity. However, the long-term effects of nanofertilizers on soil carbon dynamics remain underexplored. Understanding the interactions between nanomaterials, soil microbiota, and carbon pools is essential to optimize their use for enhancing soil carbon sequestration while ensuring environmental safety. Without such care, there is a risk of unintended negative effects on soil microbial life, nutrient cycling, and environmental health.

ACKNOWLEDGEMENTS

The authors are also thankful to the Department of Bio-sciences and Technology, M. M. D. U., Mullana, Ambala, Haryana.

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