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Improving the Mechanical Properties of Sandy Soil with Nano-Biochar Made from Corn Residues

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ABSTRACT

The use of nanomaterials in soil improvement is a significant development in the field of geotechnical engineering, contributing to increased soil strength, reduced settlement, and improved structural stability. Despite some challenges, ongoing advances in nanotechnology will make this technology more efficient and economical in the future, paving the way for its wider use in infrastructure and sustainable development projects. Ball milling produces nanobiochar, while pyrolysis has more significant applications than biochar. Biochar is a carbonaceous material produced by anaerobic digestion of organic matter in the absence of oxygen (pyrolysis) or partial presence of oxygen (gasification). The case study aims to study some of the physical properties of sandy soil in the **Ramla** area in Al-Alam city, Salah Al-Din Governorate, for the purpose of knowing the properties of this soil and studying the possibility of improving these properties by using nanomaterials, which were biochar manufactured from straw and corn plant residues manufactured by pyrolysis at a temperature of 200-250 degrees Celsius. In closed ovens isolated from oxygen to increase the organic content of nano-charcoal. The results obtained have proven that the addition of biochar significantly enhances the effectiveness of organic soil but has a slight effect on the properties of sandy soil. The addition of charcoal to sandy soil led to a slight increase in the Atterberg limits and a decrease in the relative density and specific density of the soil during the study period of 3 months.

1. Introduction

Soil is a fundamental component of geotechnical engineering, as its mechanical properties affect the stability and performance of engineering structures such as buildings, roads, and bridges. With technological advancements, the use of nanomaterials to improve soil properties has become an innovative option that contributes to enhancing its strength and durability. In this article, we will discuss the role of nanomaterials in soil improvement, the most prominent materials used, and the challenges associated with this technology [1].

Soil improvement aims to enhance its properties to withstand structural loads and reduce the risk of landslides. Key benefits include: increased soil strength: Improved the soil's ability to withstand high loads.

Reduced settlement: Reduced deformations that occur over time under varying loads. Improved soil water resistance: Reduced soil permeability, improving its performance in humid environments. Enhancement of slope stability: Increased soil resistance to landslides. The role of nanomaterials in soil improvement Nanomaterials are very small particles (1-100 nanometers) with unique properties that significantly impact soil performance when added. Their most important effects include: Increasing cohesion and adhesion between soil particles, enhancing its strength. Improving the coefficient of internal friction, increasing soil

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stability. Modifying soil structure to improve load distribution. Reducing soil permeability, making it more resistant to water erosion [2,3].

The most important nanomaterials used in soil improvement [3, 4]

1. Nano-Silica: Effect: Enhances soil strength and stability. Applications: Used to improve sandy and clayey soils in road and building projects.

2. Nano-Titanium Oxide: Effect: Improves soil resistance to dynamic loads such as earthquakes. Applications: Used in seismic and earthquake-prone areas.

3. Nano-Clay: Effect: Enhances the cohesion of clayey soil and reduces its permeability. Applications: Used in dam and water barrier projects.

4. Carbon Nanotubes (CNTs): Effect: Improves soil mechanical properties, such as compressive and tensile strength. Applications: Used in advanced infrastructure projects. Methods of applying nanomaterials in soil improvement

5. Direct mixing

Nanomaterials are mixed directly into the soil using special mixing equipment to ensure homogeneous distribution.

6. Nano injection

Nanomaterials are injected into the soil using carrier fluids, helping to improve properties without the need for excavation or soil replacement.

7. Adding nanomaterials to conventional stabilizers

Nanomaterials are combined with conventional soil conditioners such as lime, cement, and fly ash to enhance their performance [5].

Despite the significant benefits of nanomaterials in soil improvement, there are some challenges to consider: High cost: Nanomaterials are expensive compared to conventional materials.

Requirement of advanced technologies: The application process requires precise instruments and specialized equipment. Environmental and health impacts: Research is still ongoing on the effects of nanomaterials on the environment and human health [5,6,7].

The case study aims to study some of the physical properties of sandy soil in the Ramla area in Al-Alam City, Salah Al-Din Governorate, for the purpose of knowing the properties of this soil and studying the possibility of improving these properties by using nanomaterials, which were biochar manufactured from straw and corn plant residues manufactured by pyrolysis at a temperature of 200-250 degrees Celsius in closed ovens isolated from oxygen to increase the organic content of nano-charcoal.

2. Nanocarbon

Nanocarbon denotes carbon-based compounds with at least one dimension inside the nanometer range (1–100 nanometers). These materials come in many different forms, including graphene, fullerenes (C60), carbon nanotubes (CNTs), carbon quantum dots, and nanostructured biochar. Nanocarbons have distinct mechanical, electrical, chemical, and physical characteristics that set them apart from bulk carbon materials because of their nanoscale size [1,2].

Advantages of High Surface Area Nanocarbon materials are perfect for energy storage, catalysis, and adsorption because of their exceptionally high surface-to-volume ratios.

1-Electrical Conductivity: Some materials, such as carbon nanotubes and graphene, are very good electrical conductors and may be used in batteries, sensors, and electronics.

2-Mechanical Strength: Composite materials that are both strong and lightweight can benefit from the remarkable tensile strength of carbon nanostructures.

3-Thermal Stability: Nanocarbons have outstanding thermal conductivity and can tolerate high temperatures.

4-Environmental Applications: Because of their high reactivity and functional surface groups, nano-biochar and other nanocarbons can be employed for pollutant adsorption, soil remediation, and water purification [2,3,4].

Depending on the required form, nanocarbon can be created via a variety of physical, chemical, and biological techniques:

a-Chemical Vapor Deposition (CVD): This popular process breaks down hydrocarbon gases at high temperatures over metal catalysts to produce graphene and carbon nanotubes.

b-Pyrolysis of Biomass: Nano-biochar, a kind of nanocarbon with active surface functions, may be created by heating organic materials, such as agricultural leftovers (like maize stalks), at regulated temperatures with little oxygen.

c-High-energy techniques called laser ablation and arc discharge are used to vaporize graphite in regulated conditions in order to create fullerenes and carbon nanotubes.

d-Hydrothermal carbonization is a process that uses water at moderate temperatures (180–250 °C) and pressure to treat biomass or organic compounds in order to produce carbon nanodots or nano-biochar.

e-A mechanical technique for reducing carbon compounds to nanoscale particles is ball milling [7,8,9,10].

3. Biochar

Biochar is a coal-like product that does not contain petroleum. It is made by heating biomass, such as grass or woody crop residues, non-reclaimed wood, or animal manure, in a controlled process. Biochar has multiple uses, including water treatment, land reclamation, and carbon sequestration. It can also be used as a soil conditioner for both plant health and carbon storage [1,2].

At least 50% of the carbon in any piece of waste converted into biochar is expected to become stable, locking it up for several hundred years, offsetting its contribution as a greenhouse gas in the form of carbon dioxide.

Biochar is a lightweight, carbon-rich material produced through the process of pyrolysis, which involves heating organic materials such as various agricultural residues, including rice straw, sawdust, sugarcane, and tree leaves, in the absence of oxygen and adding it to the soil to make it richer and more fertile. The first known use of biochar dates back to the Amazonian people who discovered a plot of land that was fertile compared to neighboring lands, where the slow burning of agricultural waste from village communities along the river had accumulated [4,5,6,7].

Biochar production methods involve several steps, beginning with shredding plant waste, such as prunings or crop residues, to increase combustion efficiency. These wastes are then placed in special metal furnaces, sealed tightly, and heated over flames for hours until they reach high temperatures of between 400 and 700 degrees Celsius, without the presence of oxygen. Finally, the cooled biochar is emptied, ground, and packaged for use in soil. Charcoal production decreases with increasing pyrolysis temperature. This suggests that higher temperatures produce less biochar but potentially more concentrated beneficial properties. They also found that properties vary depending on the raw material and temperature [10,11]. Each type of biochar exhibits unique properties depending on the type of waste it is produced from and the processing temperature. These differences affect how the biochar interacts with the soil and impacts plant growth. Biochar can serve as a source of organic carbon and essential nutrients for plant growth, including total nitrogen and potassium content. The use of biochar as a soil conditioner, compared to other commercial fertilizers, can also have implications for reducing the environmental impact of agricultural practices, as shown in fig.1.

4. Location of study

The Ramla site in Al-Alam District, Salah al-Din Governorate, 34°46'55.8"N 43°51'03.9"E, was chosen as the study site because it is characterized by its sandy soil (Fig. 2).

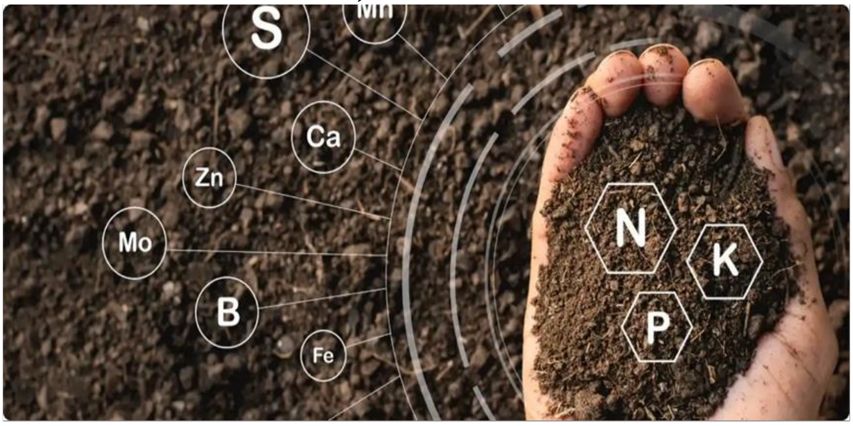

Figure 1. The nutrients in biochar which provides the soil [2]

Figure 2. Ramla site location

The soil in the study area is composed of large grains (fig. 3). It is called light soil because it is easy to weed or till in all weather conditions. Due to the low water content these soils can retain, they dry out quickly. They are considered poor soils because their grains lack ion exchange sites. These types of soils require large amounts of organic matter to improve their condition, fertility level, and water-holding capacity.

Soil is largely composed of mineral particles with specific physical and chemical properties that vary depending on the parent material and the conditions under which the soil was formed. The inorganic part of soil determines its physical properties, such as its texture. This significantly affects its structure, density, and water retention.

This site was chosen because it is a vast area that is not used for agriculture or for civil purposes due to its soft soil. Therefore, in this research, we decided to study the effect of nano-carbon materials on improving the mechanical properties of this soil.

Figure 3. The composition of study location

5. Methodology

5.1. Sampling Procedure

• Collect soil samples from sites. • Use sterilized tools to avoid cross-contamination.

• Take samples from multiple depths (surface and subsurface layers from different depths 0.5-1 m).

• Label samples properly with site and depth details.

5.2. Preparation

• Air-dry soil samples at room temperature.

• Remove debris, such as stones or any material.

• Sieve the soil (through a 2 mm mesh) for uniform particle size.

• Store samples in sealed, clean containers to maintain integrity for testing.

• The tests were conducted in the Soil Laboratory at the College of Engineering, University of Tikrit.

• All samples collected from the site were disturbed samples to ensure proper mixing to accurately represent the actual conditions.

5.3. Soil Tests

A comprehensive laboratory testing program was designed to analyze the physical properties of soils. Disturbed soil samples were utilized to ensure homogeneity and represent field conditions effectively. Sample preparation involved remolding soils based on field unit weight and natural moisture content. The tests conducted included specific gravity (Gs), relative density (Dr%), and Atterberg limits to evaluate key characteristics. These tests provide critical insights into the impact of biochar on soil properties, aiding in environmental and geotechnical assessments.

5.3.1. Specific Gravity (Gs): Is a measure of the ratio of a soil's density to the density of water, indicating the relative density of soil particles. It provides important information for soil classification and engineering analysis. The specific gravity test in this study followed ASTM D854-02.

5.3.2. Relative Density Tests (Dr%): The maximum and minimum dry densities of soil were determined following ASTM standards D4253 (Method 2A) and D4254 (Method B), respectively. These tests provide the extremes of soil compaction behavior under controlled conditions.

The relative density (Dr%) measures how compact a soil sample is relative to its loosest (minimum dry density, γdmin) and densest (maximum dry density, γdmax) states. It is calculated using the formula:

$$Dr\% = \frac{\gamma_{d\text{field}} - \gamma_{d\text{min}}}{\gamma_{d\text{max}} - \gamma_{d\text{min}}} \times 100 \quad (1)$$

Where:

• γdfield: The natural dry unit weight of soil in the field.

• γdmax: The laboratory-determined maximum dry unit weight.

• γdmin: The laboratory-determined minimum dry unit weight.

Relative density helps evaluate the soil's in-situ compaction, with higher values indicating denser conditions and lower values indicating looser conditions. This parameter is crucial for assessing soil stability and compaction potential in engineering applications.

5.3.3. Atterberg Limits: are critical soil properties that describe the behavior of fine-grained soils under varying moisture conditions. These limits help determine the soil's plasticity and are measured using standardized procedures.

In this study, the liquid limit (LL) and plastic limit (PL) were determined following ASTM D4318-00 standards. These tests were conducted on soil particles passing through a No. 40 sieve (0.425 mm opening).

- Liquid Limit (LL): The moisture content at which soil transitions from a plastic to a liquid state.
- Plastic Limit (PL): The moisture content at which soil changes from a semi-solid to a plastic state.

These properties are used to calculate the Plasticity Index (PI = LL - PL), which indicates the soil's workability and deformation characteristics. Soils with low plasticity are less cohesive, while highly plastic soils exhibit greater deformation resistance and water retention. Understanding these limits aids in assessing soil suitability for construction and environmental applications.

6. Treatment of Soil by Using Biochar

The physical and chemical properties of biochar are influenced by the thermochemical conditions during production and the inherent characteristics of the biomass used. Various reactors are designed to produce biochar with specific qualities, but they differ in oxygen usage, heating efficiency, and final temperature. These variations impact both the quantity and quality of the biochar produced.

6.1. Preparation of Biochar

Biochar can be derived from various biomass sources, but corn straw is particularly advantageous due to its high volatile matter, low moisture content making it excellent for decomposition, and minimal nitrogen and sulfur levels. These properties result in reduced production of harmful gases like nitrogen and sulfur oxides during pyrolysis .

For this study, corn straw was collected from City of Alalm farms after the corn harvest period, as shown in Fig. 4. Pyrolysis was conducted at 200–250°C in a sealed container in the absence of oxygen, followed by cooling of the biochar.

Using a relatively low pyrolysis temperature (200–250 °C) for producing biochar from corn residues may seem unconventional, but it can be scientifically justified for specific reasons. To enhance the chemical surface properties and increase the content of active functional groups such as carboxyl and hydroxyl, which play a crucial role in environmental applications like pollutant removal from water. At lower temperatures (200–250 °C), the organic structure does not fully carbonize as it does at higher temperatures, but a significant portion of functional groups remains on the biochar surface. These groups are highly beneficial for Preserving the nanoscale structure of the original biomass, making the resulting biochar more effective in nanotechnological or environmental applications.

Figure 4. Corn Straw

The material was analyzed for moisture content, volatile matter, ash content, and fixed carbon and other characterizations using ASTM D1762-84 standards.

- Moisture content: Low, generally less than 5%, due to the pyrolysis process.
- Volatile matter: Moderate to low, typically around 10–20%, depending on pyrolysis temperature.
- Ash content: Low, often less than 5%, as pine is a relatively clean biomass.
- Fixed organic carbon: High, typically over 70%, indicating good carbonization.

6.2. After the pyrolysis of corn straw in a closed oven isolated from oxygen, the resulting biochar was taken and ground in a mill to obtain nanoparticles. After grinding the coal by the mill, it is screened by a sieve with a hole diameter of 2 mm, as shown in Figure 5. After preparation the nanobiochar will be added to the soil at a ratio of 1:1 as an experimental rate and mixing with soil samples and conducting tests 3 months.

Figure 5. The Nanobiochar

7. Results and discussion

The study aimed to assess the mechanical characteristics of soil. Disturbed and undisturbed samples were analyzed, with the latter reserved for specific tests.

The results demonstrated distinct variations between the soil before and after treatment with nanobiochar, highlighting the influence of nanobiochar on the soil's physical properties [12].

The results show that the sandy soil particles are large and surrounded by large spaces, providing plenty of open space for water to move through. To illustrate, when water runs through sandy soil, it doesn't collect on the surface but rather penetrates deep within. This is a real advantage in humid conditions. However, it can be a problem during dry periods, as water loss is rapid and washes away most of the soil's nutrients. The mechanical and physical properties for sandy soil before adding the nanobiochar are shown in Table 1 below.

Table (1): The mechanical and physical properties for sandy soil

Mechanical and physical properties	Percentage
Gravel	0%
Sand	92.2%
Fine grain	7.8%
Water content ,Wc	5.5%
Specific gravity ,Gs	2.65%
Permeability , k	0.0042%
Classification According to Unified Classification System (UCS)	SP
Relative density	35%
L.L	8.7
P.L	2.9
P.I	5.8

According to preliminary findings, the sand soils undergo a rather fast transition from a liquid to a semi-solid condition. These soils are categorized as non-plastic because they lack plasticity. Sands are often defined as soils with a liquid limit of less than 20%. Adding organic compressibility. In general, when the liquid limit rises, so does the soil's compressibility.

matter to soil raises its plastic limit without appreciably raising its liquid limit. Consequently, the plasticity index is low in soils that contain a lot of organic matter. A soil's liquid limit serves as a gauge for its

Biochar or soil WHC is the capacity to store water for later use by plants. Following a biochar soil amendment, crop yield and soil health are impacted by this crucial characteristic of the soil/biochar or soil-biochar combination. The WHC is impacted by both direct and indirect interactions between soil and biochar particles in soil that has been modified with biochar. The next point goes into further depth about these concerns [12,13,14].

7.1. Specific gravity

The specific gravity of nano-biochar is typically lower than the density of minerals present in the soil. Therefore, its addition leads to a slight decrease in the specific gravity of the soil. This explains the decrease in the specific gravity values of the sandy soil (the study site) when biochar was added to it. The specific gravity was the same before adding the charcoal, 2.65, and then after adding the charcoal during the three months of the study, the density decreased to become 1.95, as shown in table 2 and Fig. 6 below.

Table 2: Specific gravity

Times	Percentage %
0	2.65
1	2.6
2	2.3
3	1.95
4	2.65

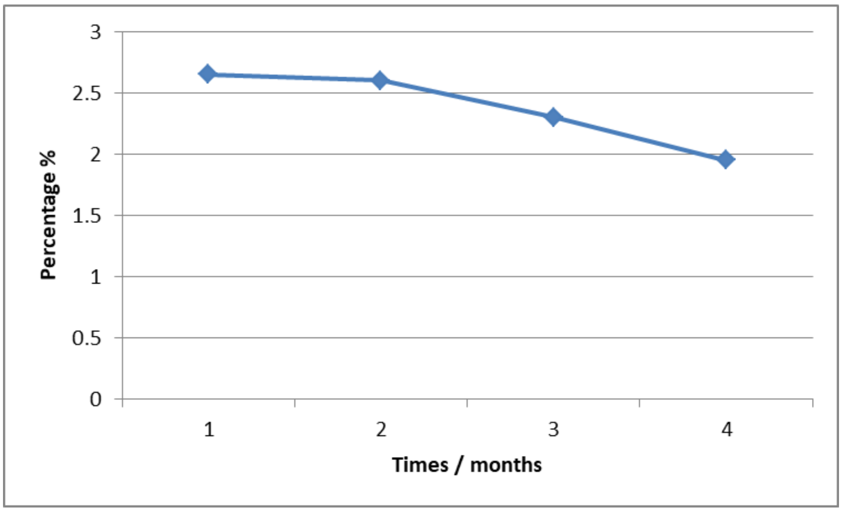

Figure 6. Specific gravity ,Gs

7.2. Relative density

The addition of nano-biochar to sandy soils can positively affect some of the engineering and physical properties of the soil, but it affects it indirectly. Through this study, it was found that the addition of biochar led to a decrease in the relative density of sandy soil. The reason for this is that nano-biochar is very light in weight compared to sand grains, so it reduces the dry weight of the soil per unit volume.

Which is reflected in the decrease in dry density and thus the decrease in relative density. On the other hand, nano biochar has high porosity, which increases the voids within the soil and reduces the relative density. This is what was explained by the results we obtained, as the relative density of the study sample decreased from 35 to 31.8 during the study months as shown in table 3 and Fig. 7 below.

Table 3: Relative density

Times	Percentage %
0	35%
1	33%
2	32.2%
3	31.8%
4	35

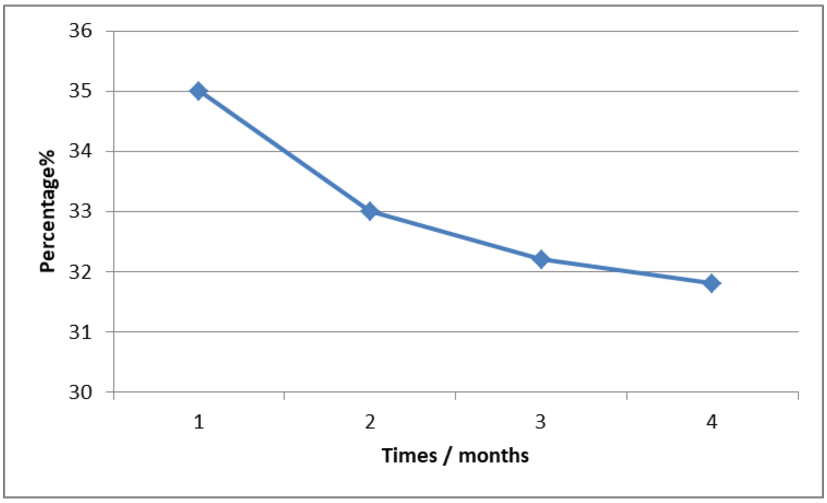

Figure 7. Relative density

7.3. Atterberg Limits

Sandy soils by nature do not have clear Atterberg limits due to the low clay content. When nano-biochar is added, the plasticity and fluidity limits may increase slightly if the biochar contains very fine particles and absorbs water, but the effect is limited compared to clayey soils. This is proven by the results we obtained, as the plasticity and liquidity limits increased slightly during the study period to become 9.3 L.L., 3.8 P.L., and 5.5 P.I. as shown in table 4 and Fig. 8 below .

Table 4: Atterberg Limits

Times	L.L	P.L	P.I
0	8.7	2.9	5.8
1	8.9	3.2	5.7
2	9.1	3.4	5.7
3	9.3	3.8	5.5

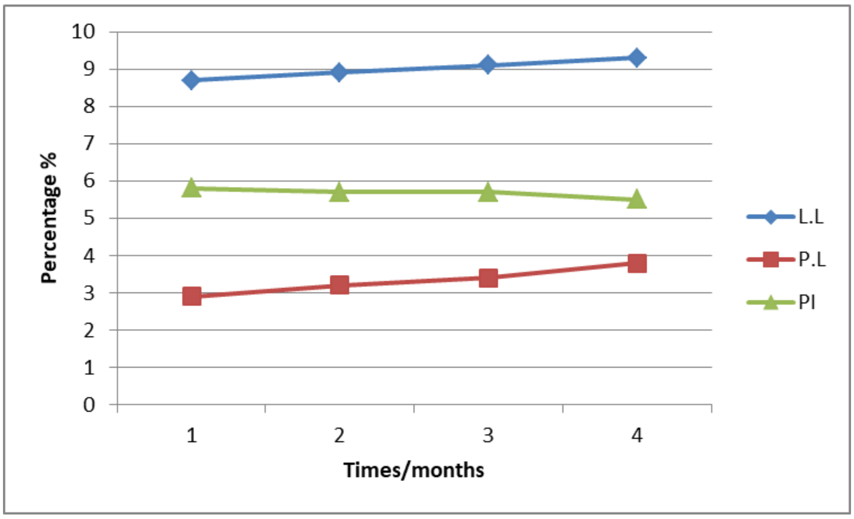

Figure 8. Atterberg Limits

8. Conclusion

The difference between conventional biochar and nano-biochar lies in their composition and structure. It involves synthesizing biochar particles at the nanoscale, which increases surface area, enhances reactivity, and improves nutrient absorption capacity.

Sandy soil was light; soils are typically nutrient-poor and lose water very quickly due to their good drainage qualities. can enhance the soil's ability to retain water and nutrients by adding a generous amount of organic matter to bind the loose sand and turn it into more fertile crumbs [12,13,14].

The result after adding the nanobiochar for 1 month, 2 months, and 3 months, as shown in figures 7 , 8, and 9, indicates that nanobiochar slightly affected the properties of the sandy soil at the study site due to its large pores and low organic content, which confirms either the necessity of adding a larger amount of charcoal to the soil or mixing it in advance with a quantity of colloidal materials to increase its cohesion or extending the study period; perhaps in the long term its properties will change for the better .

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