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The Role of Carbon Nanofibers in Soil Enhancement: A Path to Sustainable Agriculture

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Abstract: *Carbon nanofibers (CNFs) have shown great potential in multiple applications. These explore the synthesis, properties, and potential uses of CNFs, focusing on their structural characteristics, methods of production, and practical applications. CNFs are distinguished by their high aspect ratios, significant surface areas, and excellent electrical and thermal conductivities. These properties make them suitable for various applications, including reinforcement in composite materials, energy storage, environmental remediation, and biomedical uses. The various studies investigated several synthesis techniques, such as chemical vapor deposition, electrospinning, and carbon arc discharge, each offering specific advantages in terms of control over morphology and scalability. Moreover, the various studies investigated the interaction of CNFs with soil, demonstrating their potential to enhance soil properties by improving nutrient retention and water holding capacity, which can be beneficial in agricultural applications. The present study indicates that CNFs can significantly influence soil conductivity and structure, thereby impacting water and nutrient dynamics. This comprehensive examination of CNFs aims to provide insights into optimizing the application scope, highlighting the role in advancing materials science and environmental sustainability.*

Keywords: Nanomaterials, Carbon nanofibers (CNFs), soil property, soil interaction, nutrient leaching, water retention, soil conductivity, agricultural applications

I. INTRODUCTION

The carbon element is abundant in nature and closely related to human life. Carbon has various types of allotropes (graphite, diamond, carbon nanofibers, carbon nanotubes, graphene, etc.) depending on the molecular bonding mode with hybridized bonding of sp, sp2 and sp3. And it can be used as a single element to form substances with great differences in properties, such as zero-dimensional (0D) carbon dots (CDs) and fullerene, one dimensional (1D) carbon nanofibers (CNFs) and carbon nanotubes (CNTs), as well as two-dimensional (2D) graphene. (Coville, et.al. 2011) For instance, applications of CDs, CNFs, CNTs, and graphene have been explored in the fields of optoelectronics, energy storage, catalysis, bio-imaging, and environmental science due to their exceptional fluorescent, mechanical, thermal, and electrical properties.

What are CNFs?

Carbon nanofibers (CNFs) among various allotropes of carbon are fibrous carbon materials having less than 1μm thickness. It has high aspect ratios, with diameters ranging from tens to hundreds of nanometers and lengths reaching several micrometers. CNFs reveal smooth, porous, hollow, helical, and stacked cup structures, CNFs is smooth, porous, hollow and helical which is composed of graphene layers. A lot of studies have been performed to explore its unique properties and are useful in a variety of applications because of their large surface area, high electrical conductivity, and a large fraction of active sites. It has similar structure and properties to CNTs, but it has easier production, low cost, and improved functions. To produce CNFs, several methods, such as electrospinning, chemical vapor deposition (CVD), and template assisted synthesis, have been widely utilized. The choice of synthesis method depends on factors such as desired CNF properties, production scale, cost considerations, and intended applications. (Feng, et al., 2014)

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Features and applications of CNFs:

- Mechanical Strength: CNFs have extremely high mechanical strength and stiffness, making them ideal for reinforcing composite materials in aerospace, automotive, and structural engineering applications.
- Thermal conductivity: They have high thermal conductivity, making them suitable for use in thermal management applications such as heat sinks and electrical equipment that require effective heat dissipation.
- Chemical Stability: They are chemically stable and corrosion-resistant, making them ideal for use in severe environments and chemical processing applications.
- Biomedical Applications: CNFs are being investigated for a variety of biomedical applications, including drug delivery, tissue engineering scaffolds, and biosensors due to their biocompatibility and unique properties. (Wen, etal., 2015)
- Environmental Applications: They are used in environmental remediation processes such as water purification and air filtration due to their large surface area and adsorption properties. Overall, carbon nanofibers are a type of sophisticated material with several features and applications in industries ranging from aerospace and electronics to healthcare and environmental engineering.

Interaction of CNFs with soils

The interaction of carbon nanofibers (CNFs) with soil can vary depending on factors such as the properties of the CNFs, the type of soil material used, its surface modifications, and the specific application. Incorporating carbon nanofibers (CNFs) into a soil containing mixture of perlite, Irish peat moss, and vermiculite can significantly change how water runs through the soil. (Shweta Vyas, 2021) CNFs have a high surface area, enabling them to absorb and hold nutrients effectively, as a result less nutrient lost during the leaching process. This slow-release mechanism ensures nutrients remain available to plants for longer. The ability of CNFs to retain the water enhances the soil's ability to hold moisture, reducing the frequency and volume of water draining through the soil. This improved water retention, combined with better soil structure, prevents rapid nutrient loss. The improved soil structure and porosity from CNFs result in better water infiltration and distribution, preventing rapid leaching. Less soil compaction ensures better root growth and nutrient uptake, reducing the need for frequent fertilization. In the soil leaching process with increasing quantities of CNFs, the conductivity could potentially increase. Carbon nanofibers are prominent for their high ratio and peculiar structure, which contribute to higher electrical conductivity. When combined with a solid leaching process, they can produce a conductive network within the material, allowing for improved electron transition and consequently improving conductivity. However, the actual increase in conductivity would be determined by a variety of factors, including the material's initial conductivity, nanofiber dispersion and alignment, and overall processing conditions. (Zhou, et al, 2020)

The unique properties of CNFs make them ideal for environmental applications, particularly soil remediation. CNFs can absorb heavy metals and organic pollutants from soil, thereby reducing their mobility and bioavailability. The high surface area and functionalized surface of CNFs enhance their adsorption capacity. (Zhang, D., et al. ,2013)

The introduction of CNFs into soil can influence microbial communities. Studies have shown that while CNFs can support the growth of certain beneficial microbes, they may also inhibit others due to their strong adsorption properties and potential cytotoxicity. This dual effect necessitates careful consideration of CNF concentrations and long-term impacts on soil health. (Ramos, C. L., et al. ,2016)

The fate and transport of CNFs in soil are governed by factors such as particle size, surface charge, and soil composition. CNFs can aggregate or disperse in soil, influencing their mobility and interaction with soil particles. Environmental conditions such as pH, ionic strength, and the presence of natural organic matter also play critical roles. (Petersen, E. J., & Zhang, L., 2011)

Future research should focus on the development of sustainable and safe CNF applications in soil. This includes the optimization of CNF synthesis methods to minimize environmental impact, understanding long-term effects on soil health, and developing guidelines for safe use. (Lee, J. H., et al. ,2019).

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II. MATERIALS & METHODS

I. Materials required:

- Nanofibers
- Soil (from www.amazon.com)

II. Chemicals required: Paraffin oil, 0.1M $AgNO_3$ solution, 0.25M K_2CrO_4 indicator solution, 0.01N H_2SO_4 solution, Phenolphthalein indicator, Methyl orange indicator, 0.01M EDTA solution, Buffer solution (pH 10), 50% w/v NaOH solution, Eriochrome Black T indicator and Hydroxy naphthol blue indicator

III. Instruments required:

- Conductivity Meter (Model EQ660B)
- pH Meter (Model EQ-610)

IV. Techniques used:

- Precipitation titration by Mohr's Method
- Hardness of water
- Complexometric titration
- Alkalinity

V. Experimental Methods:

The experimental method consists of five parts: -

Part I: Preparation of column without carbon nanofibers:

Before starting the experiment, the apparatus used was standardized. The 10g of soil was transferred into standardized column and 50cm3 of distilled water was added into the column. On the upper layer of water 2cm3 of paraffin oil was added and the column was sealed with cotton to prevent evaporation of distilled water, and the column was kept untouched for 24 hours. The time of addition of water in the column was noted down. Figure 02. Column containing 10g of solid and 50cm3 of distilled water.

Part II: Preparation of column with carbon nanofibers:

Before starting the experiment, the CNFs were roasted in oven at 100oC for five minutes to remove excess of moisture and impurities present in it and were cooled. Then 15mg of carbon nanofibers was weighed and the 10g of soil was also weighed. The CNFs and soil were then transferred into a porcelain dish for mixing and after that it was transferred into standardized column. Added 50cm3 of distilled water into it and on the upper layer of water 2cm^3 of paraffin oil was added and then column was sealed with cotton to prevent evaporation of hours and the time of added and then column was sealed with cotton to prevent evaporation of distilled water and the column was kept untouched for 24 hours and the time of addition of water in the column was noted down.

The same procedure was followed for 25mg, 35mg, 45mg, 55mg, 65mg, 75mg, 85mg, 95mg, and 105mg of nanomaterial.

Part III: Collection of Elute from the column

After 24 hours, the elute was filtered into a beaker by using Whatman filter paper number 41. The volume of elute was measured and transferred in a stopper bottle.

Part IV: Dilution of eluted solution: -

10cm^3 of eluted solution were pipetted out from each stopper bottle in 50 cm^3 standard measuring flasks which was then diluted with distilled water up to the mark. After the preparation of standard elute solutions, its conductance, pH, chloride ion concentration, hardness and alkalinity were determined.

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Part V: To determine the properties of standard, elute solutions:

A. Determination of pH: -

The pH meter switched on 10 minutes before starting the experiment and then it was standardized with the help of a supplied connector cable which joins the electrode terminal and pH terminal situated at the back of the instrument. After standardization, the combined glass electrode was dipped into sample solutions to measure its pH.

B. Determination of Conductance: -

The conductivity meter was switched on 10 minutes before starting the experiment and then the range switch was kept at 2 millisimens position and the standard conductance switch is kept on. The digital display reading was calibrated to show 1.000 for standardization. After that the conductivity cell was dipped in the sample solution and the reading was recorded in millisimens.

C. Determination of Chloride ion Concentration by Mohr's method: -

In this method, 10cm^3 of standard elute solution was pipetted into a conical flask and 1cm^3 of 0.25M K_2CrO_4 indicator solution was added which give **faint yellow colored solution**. Then it was titrated with 0.1M $AgNO_3$ solution result in **pinkish brown colored solution** as end point of the titration. The titration process is repeated to get constant burette reading.

Observations: -

Solution in burette: - 0.1M $AgNO_3$ solution

Solution in conical flask: - 10cm^3 of diluted sample solution

Indicator: - K_2CrO_4 solution

End point: - Faint yellow to pinkish brown color

Formula: - Chloride ion concentration(mg/l) = (A-B) x N x 35460/V

A= Volume of $AgNO_3$ for sample titration

B= Volume of $AgNO_3$ for blank titration

N= Normality of $AgNO_3$

V= Volume of water sample taken in cm^3

Calculation for sample A : -

Volume of $AgNO_3$ used for distilled (Blank titration) = 0.5 cm^3

Normality of $AgNO_3$ = 0.134 N

Volume of $AgNO_3$ used for Sample A = 0.7 cm^3

$$\text{Chloride ion concentration} = (0.7 - 0.5) \times 0.134 \times 35460/10$$
$$= 0.2 \times 0.134 \times 35460/10$$
$$= 95.0328 \text{ mg/l}$$

Similarly, concentration of other sample solutions was calculated.

D. Determination of Hardness by Complexometric titration: -

Part -A: Determination of total hardness

10 cm^3 of standard elute solution was pipetted out into a conical flask and 2 cm^3 of buffer solution (pH 10) followed by 3 drops of Eriochrome Black T indicator was added into it. This was then titrated with 0.01M EDTA solution until the color of solution changed from **wine red to sky blue**. The titration process was repeated 3-4 times to achieve C.B.R. This provides the volume of EDTA required for both calcium and magnesium ions.

Observations for total hardness: -

Solution in burette: - 0.01M EDTA solution

Solution in conical flask: - 10cm^3 of diluted sample solution + 2cm^3 of buffer solution

Indicator: - Eriochrome Black T

End point: - Wine red to sky blue color

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Part -B: Determination of concentration of Ca^{2+} ions

10 cm^3 of diluted sample water was pipetted out into a conical flask and 30 drops of 50% NaOH solution were added. The solution was mixed and kept for a few minutes for the complete precipitation of magnesium ions as $Mg(OH)_2$. And in this mixture a pinch of Hydroxy naphthol Blue Indicator were added, resulting in **purplish red colored solution**. Then it was titrated with 0.01M EDTA to give **sky blue** color as end point of titration. The titration process was repeated 3-4 times to achieve C.B.R.

Observations for concentration of Ca^{2+} ions: -

Solution in burette: - 0.01M EDTA solution

Solution in conical flask: - 10cm^3 of diluted sample solution + 30 drops of 50% NaOH solution

Indicator: - Hydroxy naphthol Blue

End point: - Purplish red to sky blue color

Formula:

Total hardness as CaCO3, (mg/l) = V1 x C x 1000 / V, where

V1 = volume of 0.01M EDTA required

C = mg CaCO3 equivalent to 1 cm3 EDTA titrant (1 cm3 0.01 M EDTA ≡ 1.000 mg CaCO3) or C = 1 x Molarity of EDTA / 0.01M

= 1 x 0.012/0.01

= 1.2

V = Volume of water sample in cm3

Calcium hardness as CaCO3 (mg/l) = V2 x C x 1000 / V, where

V2 = volume of 0.01M EDTA

C = mg CaCO3 equivalent to 1 cm^3 EDTA titrant

V = Volume of water sample in cm^3

Magnesium hardness = Total hardness as CaCO3 (mg/l) – Calcium hardness as CaCO3 (mg/l)

The total hardness of all the sample solutions was calculated.

E. Determination of Alkalinity in the Standard Elute Solutions: -

In this method, 10 cm^3 of water sample was pipette out into a conical flask and 3 drops of phenolphthalein indicator were added. The solution remains colorless that indicates alkalinity was absent. In that mixture, 3 drops of methyl orange indicator were added, and the color of the solution became reddish pink which on titration with 0.01N H_2SO_4 remains reddish pink.

Observation: - No change in alkalinity

Alkalinity of CaCO3 =Volume of H_2SO_4 x Normality of H_2SO_4 x 50 x 1000/Volume of water sample (cm^3)

III. RESULT AND ANALYSIS

The experimental study shows the following observation:

Preparing the Column: -

Column numbers	Weight of CNFs	Weight of soil	Volume of D/W added	Time of keeping sample	Elute collected
0	0mg	10g	50cm3	24 Hours	39cm3
1	15mg	10g	50cm3	24 Hours	38cm3
2	25mg	10g	50cm3	24 Hours	37cm3
3	35mg	10g	50cm3	24 Hours	37cm3
4	45mg	10g	50cm3	24 Hours	36cm3
5	55mg	10g	50cm3	24 Hours	35cm3
6	65mg	10g	50cm3	24 Hours	34cm3
7	75mg	10g	50cm3	24 Hours	33cm3
8	85mg	10g	50cm3	24 Hours	32cm3

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9	95mg	10g	50cm3	24 Hours	32cm3
10	105mg	10g	50cm3	24 Hours	31cm3

Table No.- 1: Preparation of Column with CNFs and soil

Burette readings for standard elute solution

Standard Elute solutions	C.B.R. for Cl- ion conc. cm^3	C.B.R. for Hardness	
		Total hardness ($V1cm^3$)	Conc. Of Ca^{2+} ions ($V2\ cm^3$)
Samples A	0.7	0.8	0.5
Samples B	0.8	0.8	0.5
Samples C	0.8	0.8	0.5
Samples D	0.8	0.8	0.5
Samples E	0.9	0.9	0.6
Samples F	0.9	0.9	0.6
Samples G	0.7	0.9	0.6
Samples H	0.7	0.9	0.6
Samples I	0.8	1.0	0.7
Samples J	0.8	1.0	0.7
Samples K	0.8	1.0	0.7

Table No. 2: Burette reading for Chloride ion, total hardness and Ca^{2+} ions

After the completion of the experiments, the following results obtained:

Samples	Cl^- ion conc. (mg/l)	Hardness of std. elute solution (mg/l)			pH	Conductance	Alkalinity
		Total hardness as $CaCO_3$	Ca2+	Mg2+			
A	95.03	96	60	36	7.69	0.73	No change in alkalinity
B	142.55	96	60	36	7.75	0.80	
C	142.55	96	60	36	7.78	0.84	
D	142.55	96	60	36	7.81	0.86	
E	190.10	108	72	36	7.84	0.88	
F	190.10	108	72	36	7.86	0.89	
G	190.065	108	72	36	7.89	0.90	
H	95.0328	108	72	36	7.93	0.91	
I	95.0328	120	84	36	7.96	0.93	
J	142.549	120	84	36	8.01	0.95	
K	142.549	120	84	36	8.08	0.96	

Table No. 3: Results obtained after completion of the experiments

The above experimental study investigated that the interaction of carbon nanofibers (CNFs) in soil enhances water retention capabilities, thereby reducing the frequency and volume of water draining through the soil. As a result, the pH and conductance of elute changes. This indicates that addition of CNFs to soil can significantly impact on various soil properties, particularly focusing on water and nutrient retention which has implications for agricultural and environmental applications.

This improved water retention is critical in preventing rapid nutrient loss, as CNFs can absorb and hold nutrients effectively. This slow-release mechanism ensures that nutrients remain available to plants for a longer duration, reducing the need for frequent fertilization and irrigation.

This also shows promising environmental applications such as water purification due to their high surface area and adsorption capabilities.

IV. CONCLUSION

From the above observation, it is concluded that carbon nanofibers (CNFs) have a significant positive impact on soil properties, particularly in enhancing water retention, reducing nutrient leaching, and improving soil conductivity and structure.

CNFs have a high surface area and peculiar structure, which contribute to higher electrical conductivity when incorporated into soil. The formation of a conductive network within the soil matrix enhances electron transition, potentially improving the soil's overall conductivity. Additionally, the improved soil structure and porosity resulting from CNFs incorporation led to better water infiltration and distribution, preventing rapid leaching and ensuring better root growth and nutrient uptake

The analysis of water samples eluted from CNF-treated soil shows variations in chloride ion concentration, hardness, pH, and alkalinity. These variations suggest that CNFs can influence the chemical environment of the soil, which may be beneficial for plant growth and soil health. Hence, it can be used for agricultural purposes.

Further research is recommended to explore the long-term effects of CNFs on soil ecosystems and their interaction with various soil types and plant species.

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