

# Nanobiochar: Properties, Preparation, Key features and its Impact on Soil and Crop Ecosystem

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## ABSTRACT

Nano biochar, a carbon-rich material, is increasingly recognized for its pivotal role in sustainable agriculture and environmental management. It is produced through the pyrolysis of biomass under controlled conditions, converting organic matter into a stable form of carbon. This process effectively sequesters carbon and mitigates greenhouse gas emissions while yielding a valuable soil amendment. In agriculture, biochar offers multifaceted benefits. Its porous structure enhances soil fertility and water retention, fostering optimal conditions for plant growth. By serving as a reservoir for nutrients, biochar promotes their slow release, reducing the risk of leaching and nutrient runoff. Moreover, its neutral pH and high organic carbon content contribute to soil health and microbial activity. Some key features of nano biochar are enhancing surface area and porosity, improved soil fertility, nutrient retention and recycling, slow-release fertilizer, enhanced microbial population, carbon sequestration etc. Furthermore, biochar aids in waste management by utilizing agricultural residues as feedstock. However, despite its promising advantages, biochar application requires careful consideration. Variations in feedstock and production methods can influence its efficacy and environmental impact. Moreover, its long-term effects on soil health and crop productivity warrant further research and field trials. It presents a sustainable solution for enhancing agricultural productivity, mitigating climate change, and managing organic waste. However, its optimal utilization necessitates comprehensive understanding, integrated management practices, and ongoing scientific inquiry.

*Keywords: Biomass, organic matter, nano biochar, nutrient, soil fertility, soil health*

## 1. INTRODUCTION

While the precise influence of each factor on climate change is uncertain, it's widely recognized that greenhouse gas emissions stand out as one of the primary drivers. In recent years, the surge in human activities has notably escalated the production and release of these gases into the environment [1- 3]. This is mainly due to population growth, rising urbanization, and the socioeconomic advancement of low- and middle-income countries [4]. Certain agricultural practices can contribute to the generation of waste, posing significant risks to human and animal health, ecosystems, biodiversity, and natural resources [5]. An effective method for capturing and isolating carbon involves extracting greenhouse gases from industrial emissions and securely storing them in tanks. Carbon dioxide emissions from soil also detrimentally impact the global carbon cycle and ecosystems. Soil organic carbon (SOC) represents the largest reservoir of carbon, containing twice as much carbon as the atmosphere. The preservation or release of soil organic carbon significantly influences atmospheric carbon dioxide levels. Biochar's role in mitigating CO<sub>2</sub> emissions is through carbon sequestration, where it stores carbon in a stable form, preventing organic matter-derived CO<sub>2</sub> from escaping into the atmosphere. When biochar is created from biomass via pyrolysis, it transforms easily decomposable biomass into long-lasting carbon, which

33 remains in the environment for extended periods, effectively reducing CO<sub>2</sub> emissions. This  
34 process contributes to achieving carbon neutrality by absorbing atmospheric CO<sub>2</sub> and  
35 storing it in the soil for the long term, thus counteracting greenhouse gas emissions.  
36 Additionally, biochar enhances soil quality, promoting better crop yields, water retention, and  
37 soil pH balance, which further aids in carbon sequestration and mitigating the impacts of  
38 climate change. Biochar, formed by the pyrolysis of biomass feedstocks such as agricultural  
39 and forest residues in an oxygen-limited environment, is a carbon-rich material. This  
40 technology has captured considerable attention due to its ability to mitigate climate change  
41 and enhance soil fertility and health [6]. Initially, biochar production for soil application was  
42 suggested as a means of long-term carbon storage by redirecting carbon from rapidly  
43 cycling biomass to a slower cycling reservoir within the soil. Furthermore, numerous  
44 researchers have noted that biochar can serve as a substitute for adsorbents in eliminating  
45 particular types of pollutants, such as heavy metals, vitamins, minerals, and  
46 pharmaceuticals, from liquid solutions [7]. Moreover, apart from nano biochar's long-term  
47 carbon storage potential, extensive research conducted over the past decade has aimed to  
48 understand its additional effects beyond soil functions. For example, biochar has been found  
49 to potentially reduce greenhouse gas emissions, boost agricultural productivity, and enhance  
50 microbial, fungal, and mycorrhizal growth, as well as soil characteristics [8,9]. Utilizing  
51 biochar has the potential to generate soils that, in their management and efficacy, begin to  
52 resemble the fertile *terra preta*, a form of charcoal historically employed to enhance soil  
53 fertility[10]. Although derived from organic and natural sources, biochar exhibits resistance to  
54 decomposition due to its highly aromatic carbon structure. Consequently, biochar remains a  
55 key component in agricultural practices for its capacity to maximize enhance cation  
56 exchange [11], along with nutrient obtainability [12], with enhanced water holding capacity  
57 [13].

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## 2. AN OVERVIEW OF NANO BIOCHAR

60 Research has demonstrated the extensive advantages of employing nanoparticles in  
61 conjunction with plants for agricultural and food-related purposes [14].  
62 Nano biochar refers to a form of biochar that has been processed or engineered at the  
63 nanoscale, typically with particle sizes ranging from 1 to 100 nanometers. This specialized  
64 form of biochar offers unique properties and enhanced reactivity due to its increased surface  
65 area and altered chemical composition, making it potentially advantageous for various  
66 applications, including agriculture, environmental remediation, and energy production. The  
67 creation of biochar-based nanocomposites, combining the beneficial features of biochar with  
68 various types of nanomaterials, is notably significant. These composite formations often  
69 exhibit remarkable enhancements in specific functional groups, pore characteristics,  
70 increased surface-active sites, and catalytic degradation efficiency, along with rapid  
71 separability[15]. The size of biochar particles falls within the nanometer range, influenced by  
72 the method used to create nano biochar, whether it's adjusting the pyrolysis temperature or  
73 employing exfoliation techniques, as investigated in numerous recent studies [16,17,18].  
74 Nano biochar was produced from pine wood biochar through a process involving a planetary  
75 ball mill. Pre-cooling the biochar at -80°C prior to milling resulted in a particle size reduction  
76 of up to 60 nm and increased the surface area of the nano biochar by 15 times compared to  
77 the original biochar. The resulting nano biochar can be employed for the adsorption of  
78 carbamazepine pesticide from wastewater [19]. Unlike many other nanocomposite materials,  
79 distinct criteria exist for utilizing biochar as the substrate material for nanocomposite  
80 formation. Primarily, the feedstocks for biochar production are abundant and cost-effective,  
81 typically sourced from agricultural biomass and solid waste [10,20]. Micro/nano biochar finds  
82 application in a wide array of fields, serving purposes such as plant growth promotion,  
83 enhancing plant resilience against stress factors, and remediation of pesticide  
84 contamination. Additionally, it can be utilized in soil and water remediation efforts,

85 wastewater treatment, carbon sequestration, and as a component in composite materials for  
86 diverse industrial and environmental applications. Its versatile nature and beneficial  
87 properties make it valuable across multiple sectors, contributing to sustainability and  
88 environmental stewardship initiatives.  
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91 **Fig.1:Pictorial representation of nano enhanced biochar**

92 *(Image credit: Hridesh Harsha Sarma, MSc. Agri, AAU, Jorhat)*

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### 94 **3.STEPS INVOLVED IN THE PRODUCTION OF NANO BIOCHAR**

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96 Nano Biochar production is a complex process that involves several steps. It is a carbon-rich  
97 material produced by heating biomass in an oxygen-limited or oxygen-free environment, a  
98 process known as pyrolysis. Nano biochar is a specific form of biochar that has been  
99 subjected to additional processing to reduce its particle size to the nanoscale range, typically  
100 below 100 nanometres.

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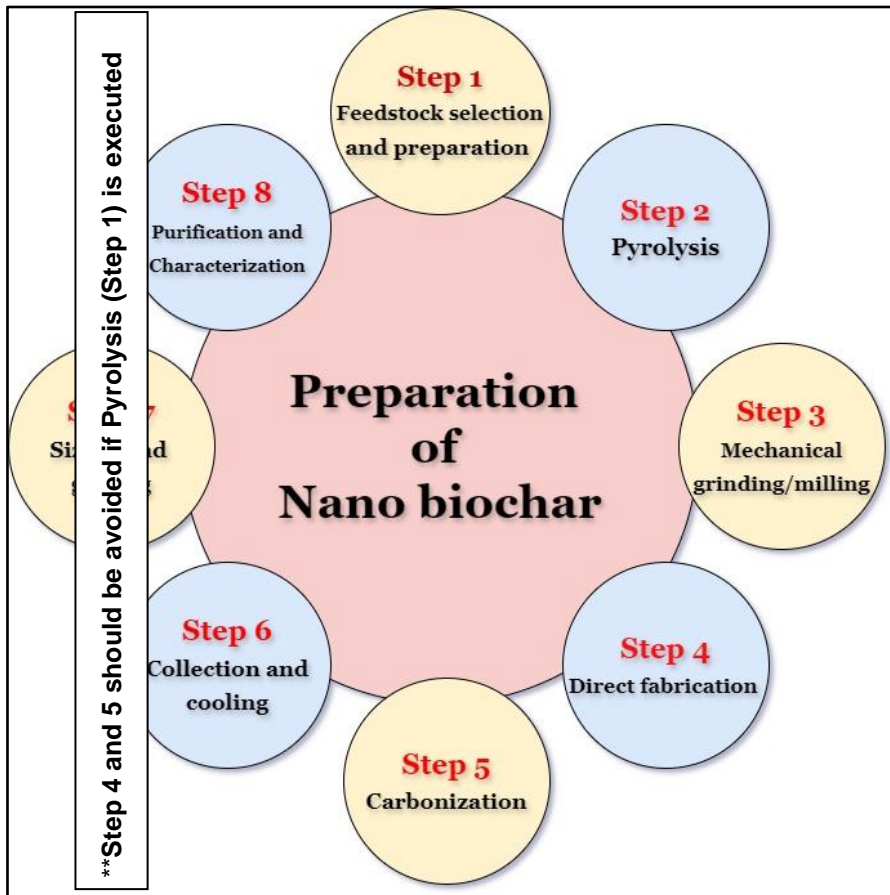
#### 104 **3.1Steps involved in nano biochar production are as follows:**

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- 106 **1. Feedstock selection and preparation:** The first step in nano biochar production  
107 involves selecting the appropriate biomass feedstock and preparing it for the  
108 pyrolysis process. Common feedstocks include agricultural residues like rice husks,  
109 wheat straw, and corn stover, as well as forestry residues such as sawdust and  
110 wood chips. The feedstock is pre-treated by drying, grinding, or chopping to achieve  
111 a uniform particle size and moisture content, which facilitates efficient pyrolysis.
- 112 **2. Pyrolysis:** The prepared feedstock is then subjected to pyrolysis, a thermal  
113 decomposition process that occurs in the absence of oxygen or with limited oxygen

114 supply. The feedstock is heated to temperatures ranging from 300°C to 700°C in a  
115 pyrolysis reactor, which can be either a batch system or a continuous system.  
116 During pyrolysis, the biomass undergoes chemical transformations, releasing  
117 volatile compounds and leaving behind a solid, carbon-rich residue called biochar.  
118 The pyrolysis process also produces bio-oil (a liquid product) and syngas (a  
119 gaseous product), which can be collected and utilized for various  
120 applications. Carbonization can also be done as an alternative approach to  
121 pyrolysis. It involves the thermal decomposition of the biomass in the presence of  
122 limited oxygen, converting it into a carbon-rich solid material

- 123 **3. Mechanical grinding/milling:** The bulk biochar produced from pyrolysis is then  
124 mechanically ground or milled using processes like ball milling to reduce the particle  
125 size and produce nano-biochar. The milling process increases the specific surface  
126 area and reactivity of the nano-biochar compared to the parent biochar. The rate of  
127 temperature increase during milling also affects the structure and porosity of the  
128 resulting nano-biochar. These techniques involve applying mechanical force or  
129 ultrasonic energy to break down the biochar particles into the nanoscale range,  
130 typically below 100 nano meters. The production process may also involve chemical  
131 or thermal treatments to modify the surface properties or introduce specific  
132 functional groups.
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- 134 **4. Direct fabrication through flash heating:** It is also an alternative to pyrolysis. In  
135 addition to mechanical grinding, nano-biochar can also be directly fabricated through  
136 flash heating of the biomass feedstock. This rapid heating process (>1000°C/min)  
137 results in the formation of graphitic nanosheets as the nano-biochar product.
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- 139 **5. Collection and cooling:** After the pyrolysis process, the biochar is collected from  
140 the reactor and allowed to cool down to ambient temperature. Proper cooling is  
141 essential to prevent further oxidation and degradation of the biochar.
- 142 **6. Sizing and grinding:** The cooled nano biochar is then subjected to size reduction  
143 processes, such as grinding or milling, to achieve the desired particle size range.  
144 Depending on the intended application, the biochar may be ground to a smaller size,  
145 ranging from a few microns to a few hundred nano meters.
- 146 **7. Purification and stabilization:** After the size reduction process, the nano biochar  
147 may undergo purification steps to remove any impurities or unwanted byproducts.  
148 Techniques like centrifugation, filtration, or solvent extraction may be employed to  
149 separate and purify the Nano biochar. Stabilization techniques, such as surface  
150 modifications or encapsulation, may be employed to improve the stability and  
151 dispersibility of the Nano Biochar particles in various media.
- 152 **8. Characterization and quality control:** The product is thoroughly characterized to  
153 ensure its desired properties and quality. Characterization techniques may include  
154 particle size analysis, surface area and porosity measurements, elemental analysis,  
155 and spectroscopic techniques (e.g., X-ray diffraction, Fourier-transform infrared  
156 spectroscopy). Quality control measures are implemented to ensure batch-to-batch  
157 consistency and compliance with relevant standards or specifications.  
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162 Fig. 2: Steps involved in nano biochar production

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**\*\*Step 4 or 5: Direct fabrication through flash heating or carbonization is done as an alternative to Pyrolysis**

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*(Image credit: Hridesh Harsha Sarma, MSc. Agri, AAU, Jorhat)*

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#### 4. STRUCTURAL PROPERTIES OF NANO BIOCHAR

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Understanding the physical properties of biochar is essential for comprehending its role in soil and its potential as a means to sequester atmospheric carbon dioxide [21]. Biochar is comprised of carbonaceous material containing polycyclic aromatic hydrocarbons alongside various other functional groups. Some biochars may possess a highly porous structure capable of containing significant quantities of extractable humic and fulvic acids [22] featuring a molecular structure characterized by considerable chemical and microbial stability, biochar exhibits turnover rates influenced by environmental factors over millennia [23]. The varied composition of biochar results in surfaces that can display hydrophilic, hydrophobic, acidic, and basic properties, all of which play roles in their interaction with soil solution substances. The physical and chemical properties of biochar vary depending on factors such as the feedstock material used, the presence of oxygen, and the temperatures reached during pyrolysis[24].

184 Biochar is derived from polycyclic aromatic hydrocarbons, where six carbon atoms form a  
185 ring structure, rendering it resistant to biological and chemical changes. Besides carbon,  
186 biochar contains elements like hydrogen and oxygen, and depending on the source material,  
187 minerals such as nitrogen, phosphorus, and sulfur may also be present. Functional groups  
188 like hydroxyl, ketone, ester, and others contribute to its composition. They often contain  
189 significant amounts of humic acids and fulvic organic acids, and their properties can vary  
190 from hydrophilic to hydrophobic and from acidic to alkaline based on their composition and  
191 level of heterogeneity. These variations allow biochars to interact with both organic and  
192 inorganic materials. During the conversion of plant biomass to nano-biochar, the intrinsic  
193 structure of the plant, including its vascular system, is preserved, leading to a hierarchical  
194 pore structure consisting of macropores, mesopores, and micropores. Micrometer porosity  
195 facilitates air transmission and microbial activity, while also enhancing nutrient storage  
196 capacity in the soil through adsorption and desorption processes. The porosity of biochar,  
197 which dictates its surface area, exhibits a highly variable pore size distribution ranging from  
198 nano- (<0.9 nm), micro- (<2 nm), to macro-pores (>50 nm). The porous structure of biochar  
199 is significant as it can serve as a shelter for beneficial organisms like mycorrhizae and  
200 bacteria. The porosity and surface area of biochar play crucial roles in determining its nutrient  
201 retention capacity through the surface binding of both cations and anions. The specific  
202 surface area of nanobiochar surpasses that of clay particles, with properties such as  
203 elemental composition, porosity percentage, and particle size being influenced by the  
204 thermal decomposition parameters and biomass type. Higher temperatures and longer  
205 exposure durations during biomass treatment result in increased nano-biochar production,  
206 with the maximum specific surface area typically achieved between 650 and 850°C[25].

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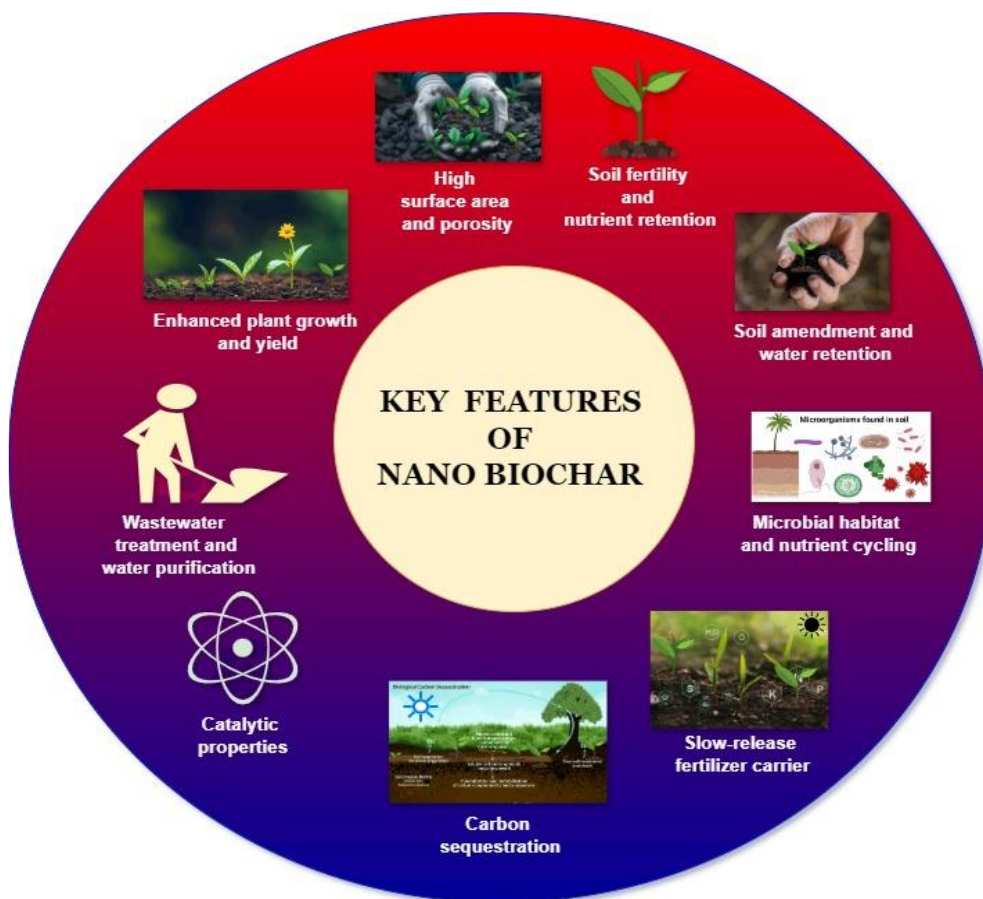
**Fig.3: Incorporation of nano biochar into soil**  
*(Image credit: Hridesh Harsha Sarma, MSc. Agri, AAU, Jorhat)*

### **5.SOME KEY FEATURES OF NANO BIOCHAR ARE AS FOLLOWS:**

Nano-biochar exhibits several unique features that make it a promising material for applications in agriculture and environmental remediation. Some key features of nano-biochar are as follows:

- 1. High surface area and porosity:** Nano biochar's nanoscale size grants it an incredibly high surface area-to-volume ratio and a porous structure. This characteristic is pivotal in environmental applications, particularly in soil and water systems. The increased surface area enhances its adsorption capacity, allowing it to effectively trap and retain nutrients, contaminants, and other compounds. This is crucial for soil remediation and water purification efforts, as nano biochar can immobilize harmful substances, preventing them from causing further harm to the environment.
- 2. Improved soil fertility and nutrient retention:** Nano biochar's porous structure enables it to adsorb essential plant nutrients like nitrogen, phosphorus, and potassium, gradually releasing them into the soil. This process enhances soil fertility by providing a sustained supply of nutrients to plants, thereby promoting healthy growth. Additionally, the retention of nutrients within the nano-biochar helps reduce nutrient leaching, ensuring that valuable resources are utilized efficiently and minimizing environmental pollution.
- 3. Soil amendment and water retention:** The porous nature of nano biochar enhances soil structure, improving aeration and water-holding capacity. This is beneficial for plant growth, as it facilitates root development and nutrient uptake. Moreover, it acts as a reservoir for moisture, reducing water loss through evaporation and enhancing water retention in the soil. This is particularly advantageous in arid regions or during drought periods, where water conservation is critical for sustaining agricultural productivity.
- 4. Contaminant adsorption and immobilization:** Its high affinity for adsorbing and immobilizing contaminants makes it an effective tool for environmental remediation. Whether it's heavy metals, pesticides, or other pollutants, nano biochar can capture and trap these harmful substances, preventing them from spreading further in soil and water systems. By sequestering contaminants, nano biochar helps mitigate the adverse effects of pollution, safeguarding ecosystem health and human well-being.
- 5. Microbial habitat and nutrient cycling:** The porous structure of nano biochar provides an ideal habitat for beneficial soil microorganisms. These microorganisms play a crucial role in nutrient cycling and soil health maintenance. By fostering microbial activity, it promotes the decomposition of organic matter, nutrient mineralization, and symbiotic relationships with plants, ultimately enhancing soil fertility and productivity. Additionally, the presence of microbes can aid in the degradation of organic pollutants, further contributing to environmental remediation efforts.
- 6. Enhanced plant growth and yield:** Nano biochar's multifaceted benefits, including improved soil fertility, water retention, and contaminant immobilization, culminate in enhanced plant growth and crop yields. By creating a favourable environment for plant growth and development, it facilitates optimal nutrient uptake, root proliferation, and stress tolerance. This leads to healthier, more vigorous plants with increased resistance to environmental pressures, ultimately resulting in higher agricultural productivity and food security.

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- 7. Slow-release fertilizer carrier:** Nano biochar's ability to serve as a carrier for slow-release fertilizers offers several advantages in agricultural practices. By encapsulating nutrients within its porous structure, it enables a controlled and sustained release of fertilizers over time. This reduces nutrient losses through leaching or volatilization, ensuring that plants receive a consistent supply of nutrients without the need for frequent applications. Moreover, the gradual release of nutrients enhances nutrient efficiency and minimizes environmental impacts, promoting sustainable farming practices.
  - 8. Wastewater treatment and water purification:** The adsorption properties of nano biochar make it an effective agent for wastewater treatment and water purification. In contaminated water sources, it can adsorb organic and inorganic pollutants, including dyes, heavy metals, and pharmaceuticals, thereby improving water quality. Additionally, it can act as a filter medium or adsorbent in treatment systems, removing contaminants and pathogens from wastewater streams. This contributes to the provision of clean water for various purposes, from agricultural irrigation to drinking water supply, benefiting both human health and the environment.
  - 9. Carbon sequestration:** Nano-biochar plays a crucial role in carbon sequestration, mitigating greenhouse gas emissions and combating climate change. Derived from renewable biomass sources, it contains stable carbon that remains sequestered in the soil for an extended period. By converting biomass into biochar and incorporating it into soil, carbon dioxide is effectively removed from the atmosphere and stored in a stable form. This not only helps mitigate climate change by reducing atmospheric carbon dioxide levels but also enhances soil carbon stocks, improving soil fertility and resilience to environmental stresses.
  - 10. Catalytic properties:** Depending on its composition and surface modifications, nano-biochar can exhibit catalytic properties, making it valuable in various chemical processes. For instance, nano-biochar can act as a catalyst in the degradation of organic pollutants, accelerating their breakdown into less harmful substances. Additionally, it can serve as a catalyst in biofuel production processes, facilitating the conversion of biomass into renewable energy sources like bioethanol or biodiesel. This versatility highlights its potential in promoting sustainable energy production and environmental remediation.
  - 11. Compatibility with other materials:** The compatibility of nano biochar with a wide range of materials allows for the creation of composite materials with enhanced properties for specific applications. By integrating it with polymers, minerals, or nanoparticles, synergistic effects can be achieved, resulting in materials with improved mechanical strength, adsorption capacity, or catalytic activity. These composite materials can be tailored to address specific challenges in agriculture, environmental remediation, or other fields, expanding the potential applications of it and enhancing its effectiveness in diverse contexts.



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313 **Fig.4: Some key features of Nano biochar**  
 314 *(Image credit: Hridesh Harsha Sarma, MSc. Agri, AAU, Jorhat)*  
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**12. Sustainable and renewable source:** Derived from renewable biomass sources such as agricultural residues, forestry waste, or organic byproducts, nano biochar represents a sustainable and environmentally friendly material. Its production contributes to the development of a circular bioeconomy, where biomass is utilized efficiently to create value-added products while minimizing waste and environmental impact. By utilizing renewable resources for its production, reliance on non-renewable materials is reduced, leading to greater resource efficiency and long-term environmental sustainability.

These features of nano-biochar highlight its potential for improving agricultural productivity, enhancing soil health, remediating contaminated environments, and contributing to sustainable practices in various sectors, including agriculture, environmental management, and waste treatment.

**6. IMPACT OF BIOCHAR ON SOIL MICROORGANISMS**

Microbial communities play a vital role in the performance of plant-soil ecosystems, encompassing soil health, fertility, carbon and nutrient cycling, and crop yields[26]. The abiotic processes initiated by biochar, including physical and chemical

335 pathways, can influence the function and diversity of soil microbial communities[27].  
336 Biochar could potentially alter the profile of microbial populations by altering the  
337 physical environment of the soil. Moreover, changes induced by biochar in microbial  
338 growth might also impact soil physical attributes. These physicochemical variances  
339 induced by biochar in soil can significantly impact the prosperity, diversity, and  
340 structure of microbial communities, thereby influencing the dynamics of plant-  
341 microbe interactions in the soil [28]. Changes in pH and oxidation potential resulting  
342 from the presence of biochar in the soil can impact both microbial activity and  
343 population structure [29]. The addition of biochar to the soil has the potential to  
344 affect the adsorption dynamics of rapidly mineralizable carbon and nutrient  
345 fertilizers, leading to alterations in bacterial and fungal community patterns and  
346 behaviors [30]. The positive impact of incorporating biochar on microbial activity and  
347 communities is attributed to its ability to supply readily degradable organic  
348 metabolites and nutrients for microbial growth. Biochar materials with high surface  
349 areas and diverse charges facilitate microbial growth and the sorption of nutrient  
350 ions. The highly porous structure of biochar can create a conducive microhabitat for  
351 soil microbial populations, providing essential organic metabolites and minerals  
352 necessary for microbial development. Biochar amendment has been demonstrated  
353 to increase soil microbial abundance by providing a favorable habitat for  
354 microorganisms, promoting their activity and reproduction. The porous structure of  
355 biochar offers shelter for microorganisms, shielding them from harsh conditions and  
356 reducing inter-species competition, ultimately leading to a rise in their abundance.  
357 Additionally, biochar utilization of labile carbon and improvements in soil properties  
358 such as pH and adhesion contribute to this increase. Moreover, the addition of  
359 biochar alters the relative abundance and composition of soil bacteria and fungi,  
360 influencing the microbial community structure. Specific bacterial genera like  
361 *Sphingomonas*, *Gemmatimonas*, *Nitrospira*, and *Pseudomonas* have been found to  
362 increase in relative abundance with biochar treatments. These changes are  
363 influenced by factors such as soil properties, biochar type, and application duration.  
364 Furthermore, biochar application has been associated with enhanced soil microbial  
365 diversity, as it modifies the soil microenvironment, fostering conditions conducive to  
366 diverse microbial populations. However, the long-term impact of biochar on soil  
367 microbiota is influenced by land management practices, especially in cropland soils  
368 with frequent fertilization and amendments. Successful soil management strategies  
369 involving biochar should consider both biochar properties and existing soil conditions  
370 to achieve desired outcomes. Caroline and Komang's publication effectively  
371 consolidated the latest research findings, introducing molecular-based DNA  
372 techniques to investigate biochar mechanisms for enhancing soil microbial ecology  
373 [31]. Understanding the effects of biochar on variations in microbial populations and  
374 functions can provide a valuable knowledge base for developing biochar-based  
375 systems to improve degraded soils and maintain soil health and plant protection.

## 377 **7.INFLUENCE OF NANO BIOCHAR ON PLANT GROWTH AND** 378 **DEVELOPMENT**

380 Recent studies suggest that biochar is more inclined to effectively enhance plant  
381 growth in acidic soils compared to alkaline soil types [32]. Biochar has been studied  
382 within soil-less fertigation systems, revealing significant benefits in enhancing yields  
383 of peppers and tomatoes [33]. There is widespread recognition of the necessity to  
384 reduce or eliminate the utilization of peat in horticulture, seeking environmentally  
385 friendly and cost-effective sustainable growth mediums. Biochar emerges as a  
386 promising alternative to peat [34]. Saxena *et al.* (2014) found that the application of  
387 biochar alongside water-soluble carbon nanoparticles significantly enhanced wheat

388 growth [17]. Concerning root growth and development, the application of alkaline  
389 biochar rather than acidic biochar can lead to a significant increase in root biomass  
390 [35]. Nano-biochar exhibits remarkable capabilities in nutrient retention and  
391 adsorption due to its elevated specific surface area and porosity. This enables it to  
392 effectively capture and hold essential nutrients like nitrogen, phosphorus, and  
393 potassium, thereby enhancing their availability for plant uptake, consequently  
394 promoting enhanced plant growth and yield. Moreover, nano-biochar acts as an  
395 excellent carrier for beneficial plant growth-promoting bacteria, such as *Bacillus*  
396 *megaterium*, facilitating the solubilization of insoluble phosphorus, which further  
397 boosts plant growth and health. Additionally, the application of nano-biochar leads to  
398 improved soil properties including pH regulation, increased water-holding capacity,  
399 and enhanced cation exchange capacity, fostering a conducive environment for  
400 plant growth and development. In another study, the utilization of bamboo biochar at  
401 concentrations below 10% resulted in nodulation development and enhanced the  
402 growth of soybeans [36]. The specific impacts of biochar supplementation on plant  
403 dry biomass and nutrition predominantly depended on the type of biochar and the  
404 application rate. When soil was amended with coconut husk biochar at a uniform  
405 rate of 30 t ha<sup>-1</sup>, it resulted in a 90% enhancement in maize biomass, with plant  
406 nitrogen and phosphorus concentrations reaching 0.88% and 0.12%, respectively.  
407 Thus, the enhancement in plant biomass and nutrition underscores the effectiveness  
408 of coconut husk biochar as a soil amendment [37].  
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## 410 **8. INFLUENCE OF NANO BIOCHAR ON THE PHYSICAL PROPERTIES** 411 **OF SOIL**

412 The disparity in physical structure between soil and biochar results in alterations in  
413 tensile strength, hydrodynamics, and gas flow within the soil, consequently  
414 impacting soil organisms. These effects are contingent upon the type and  
415 characteristics of the biochar, including its raw material and heat treatment. When  
416 the tensile strength of biochar is lower than that of the soil, such as in clay-rich soil,  
417 adding biochar reduces the soil's tensile strength. For instance, in a study conducted  
418 on Alf sols, the addition of biochar decreased tensile strength from 4.64 to 31 kPa.  
419 Reduced mechanical impedance is critical for facilitating root growth, making roots  
420 less resistant to soil and enabling easier root development [38-39]. Optimal root  
421 growth occurs with around 10% biochar in the growing medium, while further  
422 increases beyond 15% do not significantly enhance root growth. This enhancement  
423 in root growth also promotes mycorrhizal association and increases soil mineral  
424 elements, thus improving seed germination rates. Decreased tensile strength may  
425 enhance the mobility and displacement of invertebrates in the soil, contributing to  
426 increased soil fertility as they feed on organic matter. The reduction in soil bulk  
427 density caused by biochar leads to increased soil porosity, which in turn affects  
428 water retention, root development patterns, and soil organisms. This phenomenon  
429 can be attributed to the lower density of biochar compared to soil minerals. Biochar  
430 contains both macro and micropores, ranging from approximately 1 to over 50 nm in  
431 diameter, which exhibit strong resilience to weathering. Consequently, this  
432 characteristic significantly decreases the bulk density of biochar within the soil.  
433 Research indicates that the density of biochar ranges from 0.09 to 0.5 grams per  
434 cubic centimeter, depending on the raw material used. This density is considerably  
435 lower than that of soil. The macro and micropores of biochar contribute to its  
436 weather resistance and significantly lower bulk density compared to soil minerals.  
437 For instance, adding 60 tons per hectare of biochar to soil reduced bulk density by  
438 approximately 5.8% [2]  
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## **9. INFLUENCE OF NANO BIOCHAR ON CARBON DIOXIDE EMISSIONS FROM SOIL**

At the outset, the introduction of biochar into the soil initially results in increased carbon dioxide emissions. For instance, incorporating 8% biochar into the soil leads to elevated carb within the first 20 days. However, over an extended period, particularly after 120 days, gas emissions notably diminish. In essence, the presence of soil biochar over prolonged durations tends to mitigate carbon dioxide emissions. Overall, the release of carbon dioxide from the soil is contingent upon soil conditions, the microbial population, and the physicochemical attributes of the biochar [40-41]. The addition of biochar to the soil can potentially stimulate and enhance the growth of microorganisms by providing a substrate for their proliferation. The micrometric porosity of biochar enhances soil moisture retention, leading to a reduction in the decomposition of soil organic carbon (SOC). Consequently, biochar indirectly mitigates carbon dioxide emissions by promoting increased soil moisture levels [1].

## **10. ROLE OF BIOCHAR AS PLANT DISEASE CONTROL AGENT**

The efficacy of biochar's plant resistance mechanisms relies on eliciting reactions, involving both systemic acquired resistance (SAR) and induced systemic resistance (ISR) pathways. These pathways collectively contribute to a comprehensive management capability in promoting canopy growth in crops [42]. Combining biochar with compost could potentially enhance pathogen resistance, although it poses some risks. This approach is viable because biochar and compost may have complementary abilities to control various soil-borne pathogens. The disease-suppressing properties of compost are multifaceted. Immature composts, in particular, release volatile compounds such as sulfur, organic acids, and ammonia, which contribute to disease reduction. On the other hand, the suppressive effects of mature compost are primarily biological, often involving microbial antagonism or boosting plant host resistance [43]. In comparison to peat media, biochar typically exhibits positive or straightforward effects on plant growth when applied at concentrations exceeding 25%. However, research on the effects of biochar on plant diseases reveals that while lower concentrations ( $\leq 1\%$ ) of biochar often lead to a reduction in some diseases, higher concentrations ( $> 3\%$ ) are largely ineffective or may even exacerbate plant diseases [44]. The ability of biochar fertilizer to stimulate transcriptional changes, along with its interaction with various plant protection pathways, is likely a key factor in its broad-spectrum effectiveness for reducing diseases [45]. However, our understanding of biochar's ability to confer systemic resistance to plant pathogens remains incomplete, with only a limited number of studies [46]. It is imperative to conduct further research and studies to comprehensively investigate and elucidate this aspect.

## **10. CONCLUSION**

Integration of nano biochar into soil offers a novel approach for long-term atmospheric CO<sub>2</sub> storage, providing a stable carbon sequestration method with minimal risk of carbon return. It enhances soil organic carbon stability, mitigates CO<sub>2</sub> emissions, and improves soil structure, water retention, microbial activity, nutrient availability, soil and plant health while reducing leaching loss. Despite the need for long-term stability investigation, benefits include enhanced water retention in drained soils, landscape rehabilitation, and efficient nutrient absorption by plants. Nano biochar shows promise in saline soil improvement and soil contaminant remediation, contributing to increased plant productivity, reduced pollution, and optimized water

493 and fertilizer usage. Tailored nano biochar development offers further opportunities  
494 for sustainable soil management and climate change mitigation.

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#### 496 **COMPETING INTERESTS**

497 The authors declare that they have no competing interests

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#### 499 **FUTURE PROSPECTS**

500 Future research on nano biochar aims to optimize synthesis methods, understand  
501 interaction mechanisms with pollutants, and enhance performance in soil and crop  
502 ecosystem through functionalization. By characterizing its properties, such as  
503 enhanced surface area and porosity, and investigating its potential in soil  
504 remediation, improved soil fertility, nutrient retention and recycling, slow-release  
505 fertilizer, enhanced microbial population, carbon sequestration and water  
506 purification, we can maximize its environmental benefits. Linking research findings  
507 with real-world applications will drive sustainable solutions for pollution mitigation  
508 and carbon sequestration, contributing to a cleaner environment and promoting the  
509 adoption of nano biochar as a versatile tool in environmental stewardship, thus  
510 fostering a more resilient and productive agricultural ecosystem.

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