

Characterization of pine needle and pine needle biochar: a potential soil amendment for sustainable forest waste management

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ABSTRACT

Pine needles are the residue of pine (*Pinus roxburghii*), a problematic forest waste and is highly flammable which is the one of major causes of forest fire in the North Western hills of India. High lignin and resin content with low moisture is the reason behind it being one. To find an appropriate management of this residue the pine needle was characterised and further converted to biochar (500 °C), a carbon-rich solid material produced through a process called pyrolysis by heating biomass, in the absence of oxygen. This process breaks down the organic matter into volatile gases, leaving behind a residue known as biochar. Pine needles are suitable for generating biochar due to their high carbon content, low moisture content, high lignin content, abundance and availability. The pine needles aromatic compounds contribute to biochar stability and potential applications. Physical, Physico-chemical, and spectral characterisation of biochar was performed to analyse its further applicability and the biochar, was found suitable as soil amendment and as a mean of enhancing soil organic carbon.

Keywords: Pine needle residue, pine needle biochar, characterisation, soil amendments

INTRODUCTION

Pine needles, which are the result of the regular shedding of leaves from the fast-growing Chir pine (*Pinus roxburghii*) in the North Western Himalaya region (encompassing India, Nepal, and Bhutan), cover a vast forest area of approximately 7.62 million hectares (Mha). Every year a large amount of flora and fauna get affected due to fire in the pine forest. The reserve pine forest in Uttarakhand includes an area of about 0.343 Mha. In Uttarakhand alone, about 2.058 million metric tonnes (MMT) of needle wastes are available annually and in the Indian Himalayas region, it accounts for about 15.9 MMT per annum. Studies conducted in the hills of Uttarakhand, India, have revealed that pine needle productivity is estimated to be 6.3 tons per hectare per year (Singh *et al.*, 2016, Singh *et al.*, 2021). However, the natural decomposition process of pine needles is slow (Kainulainen *et al.*, 2002), leading to their accumulation on the forest floor. This thick layer of dry needles poses two significant issues: it acts as a fire hazard and inhibits the growth of grass, which is a food source for cattle (Dwivedi *et al.*, 2016). The occurrence of large-scale forest fires, often caused by the presence of this

dense layer of pine needles, contributes to severe air pollution and has devastating environmental consequences (Tzamtzis *et al.*, 2006). Consequently, it is crucial to find alternative uses for pine needles to mitigate the risk of forest fires. The kinetic studies suggest that pine needles can be a good source for conversion to bio-oil and biochar through pyrolysis. In light of the fire hazard posed by pine needles and their abundant availability in India, especially in hilly regions of Uttarakhand, the objective of this research was to study the properties pine needle biochar for its use as soil amendments/conditioner.

MATERIAL AND METHODS

Characterization of Pine needle residue

Pine needle were first air-dried and then dried in an oven at 60±5°C for 72 h and 6 h respectively. Proximate analysis was carried out to determine the volatile matter, fixed carbon and ash content of the pine needle (Table 1). According to the standardized test method for moisture analysis, 1 g of the sample was retained in a hot-air-oven at 105°C for 1 h. Next, the oven-dried sample was weighed. Moisture

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content was estimated as percent change in fresh biomass weight to oven dry weight.

Volatile matter determines the percentage of the gaseous products which is released under the specific conditions of the test in the analysis of the sample free from moisture content. As per the standard test method for volatile matter analysis, the oven-dried sample enclosed in a crucible with a lid was placed in a muffle furnace, and maintained at $950^{\circ} \pm 20^{\circ}\text{C}$ for 7 min. Therefore, the crucible was first cooled in the surrounding air and then in a desiccator, and percent weight loss was calculated (ASTM D3175-07) which is volatile matter (Sirrajudin *et al.*, 2016).

According to the standardized test method for ash content analysis, the remaining sample residue after volatile matter test, was heated in the muffle furnace at $700^{\circ} \pm 50^{\circ}\text{C}$ for 4 h (ASTM D3174-02). The ash content in each sample of the block was estimated as percent change in mass of over the volatile matter free biochar (Sirrajudin *et al.*, 2016). The fixed carbon is a calculated value, it is the resultant of the summation of the percentage moisture, ash and volatile matter subtracted from 100. All percentage will be on the same moisture reference base. The fixed carbon was determined using the standard formula

$$\text{FC (\%)} = 100 - \{\text{MC (\%)} + \text{VM (\%)} + \text{AC (\%)}\}$$

where FC is the fixed carbon, MC the moisture content, VM the volatile matter and AC is the ash content (Sirrajudin *et al.*, 2016). To determine the amount of extractives in biomass (pine needle), solvent extraction (60 ml acetone for 1 g of dried biomass sample) was used, and the temperature was held at 90°C for 2 h. After that, the sample was dried at 105°C until a constant weight was obtained. The weight difference before and after the extraction is the amount of the extractives (Blasi *et al.*, 1999).

To determine the amount of hemicellulose, 10 ml 0.5 mol/l of sodium hydroxide solution was added to 1 g of extractive-free dried biomass, and the temperature was held at 80°C for 3.5 h. After that, the sample was washed using de-ionised water until pH value of the solution approach 7, then it was dried to a constant weight. The difference between the sample weight before and after this treatment is hemicellulose content (Blasi *et al.*, 1999).

To determine the amount of lignin, 30 ml of 98 wt.% sulfuric acid was added for each extractive-free dried biomass. After the sample was held at ambient temperature for 24 h, it was boiled at 100°C for 1 h. The mixture was filtered, and then the residue was washed until the sulphate ion in the filtrate was undetectable (via titration of a 10% barium chloride solution); it was then dried to a constant weight. The weight of the residue was recorded as the lignin content (Blasi *et al.*, 1999). The content of cellulose was calculated by difference, assuming that extractives, hemicellulose, lignin, and cellulose are the only components of the entire biomass. (Blasi *et al.*, 1999; Li *et al.*, 2004).

Preparation of biochar

Dried pine needle was cut into small pieces (10–20 mm) for the preparation of biochar in an electrically operated temperature-controlled biochar maker (Labex Instruments Pvt. Ltd., India) at 500°C under a constant flow of N_2 (1.5 mL sec^{-1}). The pyrolysis temperature was increased at the rate of $2^{\circ}\text{C min}^{-1}$ from room temperature (25°C) to 500°C , kept at this temperature for 2 h and then cooled down to room temperature overnight (Purakayastha *et al.*, 2015). An outlet tube was connected to a series of five steel traps immersed in the water tank, two empty glass jars and an exhaust pump for removing the liquid and syn gases produced during pyrolysis. The biochar sample was weighed, and the charring yield (% biochar) was calculated using Eq. 1:

$$\text{Yield of biochar (\%)} = \frac{\text{Mass of biochar}}{\text{Mass of feedstock}} \times 100 \text{ (Eq. 1)}$$

Biochar samples were grinded and sieved to obtain size fractions between 0.5 – 2 mm, and stored airtight for further analysis. Conversion of pine needle via pyrolysis route has 33.6% conversion efficiency.

Characterization of biochar

Physical properties

Biochar samples were characterized for physical properties such as BD (Veihmeyer and Hendrickson, 1948), particle density (PD) (Hernandez-Mena *et al.*, 2014), maximum water holding capacity (MWHC) (Keen and Raczowski, 1921).

The Brunauer-Emmett-Teller (BET) surface area and pore volume along with porosity of pine needle biochar was determined by the surface analyser (Quanta-chrome Instruments version 5.21, Autosorb iQ Station 1). For each run, 0.1298 g of sample was used and the samples were degassed at 300 °C for 3 hours under nitrogen.

Ultimate and proximate analysis

In the instance of proximate analysis, ash and volatile matter content were measured following the procedure described by Mukherjee *et al.* (2011). About 1.5 mg of biochar samples were placed in a drying oven for 24 h at 70°C and allowed to cool in desiccators before weighing. After combustion in a ceramic crucible with a loose ceramic cap at 850-900°C for 6 minutes, volatile matter (VM) content was measured by means of weight loss. The ash content was determined by means of weight loss after ignition at 750°C for 6 hours with no ceramic cup. The weighing of sample was done after cooling in desiccators for 1 hr. By the subtraction method using equation below, Fixed carbon (FC) was also determined: $FC (\%) = 100 - \{MC (\%) + VM (\%) + AC (\%)\}$

TC, TN, TH, TS and TO contents in biochar were determined by the CHNSO analyzer (Thermo-Finnigan) using dry combustion method (Nelson and Sommers, 1982) at Deptt. of CIL, Panjab University Chandigarh. The above biochar parameters were analyzed in three replicated samples and average values were reported.

Physico-chemical properties

The pH of biochar in water (pH_w), and 1N KCl solution (pH_{KCl}), and electrical conductivity (EC) in water, were determined at 1:10 (w/v) ratio after nonstop shaking for an hour (Lee *et al.*, 2013). The cation exchange capacity (CEC) of the biochars was measured following the procedure by Yuan *et al.* (2011) with slight alteration. As an alternative to washing 0.2 g of biochar with water to remove the basic cations as stated by Yuan *et al.* (2011); 5.0 g of biochar was intensively leached with double distilled water to remove salts and ash. Then the moist biochars were oven dried for 3 days at 70°C, cooled in a

desiccator, and kept in airtight sample storage bottle. These salts and ash free biochars (0.2 g) were again leached with 20 mL of 1 N sodium acetate (pH 7) five times. To remove the excessive Na⁺, biochars were washed with 20 mL of ethanol five times. Thereafter, the Na⁺ on the exchangeable sites of biochars was displaced by 20 mL of 1 M ammonium acetate (pH 7) five times, and the CEC of the biochars was calculated from the amount of Na⁺ displaced by NH₄⁺. Sodium was measured using a flame photometer (Flame photometer Systronics 128).

Total elemental analysis of biochar

Total elemental composition of biochars done by using modified dry ash method (Enders and Lehmann, 2012) of digestion. 200 mg of each biochar was placed in porcelain discs; transferred to muffle furnace and heated from ambient to 500°C temperature at the rate of 5°C min⁻¹. After reaching at 500°C, it was kept for 8 hours, then, cooled to ambient temperature at ~ 5°C min⁻¹. Subsequently, the samples were relocated into digestion block, 5 mL HNO₃ was added in it, heated at 120°C to oxidise carbon and evaporate HNO₃ thus the sample volume is reduced to ~2 mL. The above step was repeated till all the carbon is oxidized. Subsequently, 4 mL of H₂O₂ and 1 mL HNO₃ were added and the sample was heated at 80°C and hold for 1 h. Samples were again heated at 120°C to oxidise carbon and evaporate H₂O₂-HNO₃ mixture without physical losses due to aggressive boiling. Subsequently, samples were reduced to volume over the next several hours to ~2 mL. after cooling to the ambient temperature, the final volume of the digested sample was made up to 100 mL with Milli Q water. Further elemental analysis was done by ICP-MS (Agilent ICP-MS 7900 with UHMI).

Spectral analysis of biochar

Scanning Electron Microscopy (SEM) (Chia *et al.*, 2012) and Energy-Dispersive X-Ray Spectroscopy (EDX) (Purakayastha *et al.*, 2015) of biochar samples were done for morphological, physical, spectral, and chemical characterization of biochar. After 1-2 mm coating the samples by alloy of palladium and gold with the beam energy of 20 kV (Downie *et al.*, 2011) Scanning Electron Microscopy was performed with Field Emission

Scanning Electron Microscope [FEI Quanta 200 F SEM (FEI Company (Netherlands)]. The details about the resolution and operating voltage are stated in each specific image. Energy dispersive X-Ray (EDX) were also conducted to analyse elemental composition (Surface element as C, O, Si, Mg, Ca, S, K, Fe, Mn, Cu, Zn etc.) of biochar surface in qualitative basis. For EDS, biochar samples were also mounted on Al stubs and coated with gold/palladium; with beam energy of 20kV as in SEM. The X-ray diffractograms of biochar samples were collected using Ni filter Cu-K α radiation at scanning speed of 1.5°2 θ min⁻¹ in a Phillip diffractometer-1710, while operating at 40 kV and 20 Ma. The phase peak was identified by comparing the observed XRD pattern to the published literature.

RESULTS AND DISCUSSION

Properties of pine needle biomass

Table 1 depicts the properties of pine needle biomass. It has very low ash (2.1%) and high volatile contents (66.7%) that makes it a suitable material for thermo- conversion as Biochar. Being a ligno-cellulosic biomass, the major constituents of pine needles is lignin (39.42%) and cellulose (21.92%). The elemental analysis of pine needles indicates carbon and nitrogen content as 43.47% and 1.13%, respectively, that are in line with another agricultural biomass. The carbon, nitrogen content and C/N ratio of PNB is 43.47%, 1.13% and 36.21, respectively. These compounds provide biochar strong absorptive behaviour towards organic compounds and heavy metals (Chen *et al.*, 2019) and many distinctive physicochemical properties (Keiluweit *et al.*, 2010; Sohi *et al.*, 2010). As biochar prepared from pine needles has been used in the adsorptive removal of heavy metals from an aqueous solution (Jeon *et al.*, 2020) According to research (Labanya *et al.*, 2022, Cheung *et al.*, 2001; Font *et al.*, 2009), hemicellulose, one of the major components of plants, undergoes degradation within the temperature range of 220°C to 315°C. On the other hand, cellulose degradation takes place between 315°C and 400°C, resulting in the release of a significant amount of volatile matter as a result of the breaking of C-O and C-H bonds. The volatile content of biochar in this study is 27% and in line

with high amount of hemicellulose of pine needle residue (Table 1 & 2) Lignin, being the most resistant component, experiences the majority of its thermal degradation at temperatures exceeding 607°C. This high temperature requirement is attributed to the presence of multiple ether linkages as well as hydroxyl and methoxy groups within lignin's structure (Cheah *et al.*, 2014; Kotake *et al.*, 2013).

Table 1: Pine needle residue characterization

Parameter	Content
Water content (wt %)	9.1±0.2
Analysis on dry basis	
Volatile matter (wt %)	66.7±66.86
Ash content (wt %)	2.1±2.07
Fixed carbon (wt %)	26.01±25.97
Compositional analysis	
Cellulose (wt %)	21.92±0.3
Hemicellulose (wt %)	27.62±0.98
Lignin (wt %)	39.42±0.51
Extractives (wt %) (Acetone)	22.1±0.21
Extractives (wt %) (Hot water)	12.57±0.25
Total Elemental analysis (wt %)	
Carbon (%)	43.47±0.76
Nitrogen (%)	1.13±0.06
C/N	36.21±0.52

Data represented as Mean of triplicate sample followed by standard deviation

Physical properties of pine needle biochar

The bulk density (BD) of the biochar was 0.30 Mg m⁻³ and PD is 1.45 Mg m⁻³ and it was higher than the BD as biochar is highly porous material (Antal and Gronli, 2003) (Table 2). The maximum water holding capacity (MWHC) is 353%. This attribute is advantageous for soil amendment as it helps retain moisture in the soil, reducing water stress on plants and improving drought resilience. At higher temperature (>500°C) the hydrophilic functional group did start formation, cause water repellancy and thus high-water holding capacity (Keiluweit *et al.*, 2010). The specific surface area, pore volume and size were: 181 m²g⁻¹, 0.01ml g⁻¹, and 1.87 nm respectively. This low bulk density and high pore volume provide allows for better aeration and water movement within the soil, promoting favourable soil conditions for plant growth. The high carbon content and porosity of biochar can improve soil structure and aggregation by mean of affecting the microbial diversity and their function. This can improve

water infiltration, reduced erosion, and increased nutrient retention in the soil.

Table 2: Physico-chemical properties of biochar

Physical Properties	
Yield (%)	32.69±1.28
MWHC (%)	353±2.5
BD (Mg m ⁻³)	0.30±0.02
PD (Mg m ⁻³)	1.45±0.06
Surface Area (m ² g ⁻¹)	181±0.07
Pore Volume (ml g ⁻¹)	0.01±0.00
Pore Diameter Dv(d) (nm)	1.87±0.08
Physicochemical parameters	
pH _w (Soil: Solution ::1:10)	9.53±0.02
pH _{KCL} (Soil :Solution::1:10)	9.1±0.02
EC (dS m ⁻¹)	0.70±0.01
CEC [c mol (P ⁺) kg ⁻¹]	40.45±1.85
Proximate analysis	
Moisture (%)	0.06±0.00
Volatile Matter (%)	27.90±0.22
Ash (%)	6.62±0.48
FC (%)	73.77±4.10
Ultimate analysis	
C (%)	76.92±4.28
H (%)	3.02±0.15
N (%)	0.9±0.05
S (%)	0.02±0.00
O (%)	22.41±1.25

Data represented as Mean of triplicate sample followed by standard deviation

Proximate and ultimate analysis and total elemental analysis of Biochar

The volatile matter, ash and fixed carbon were 27.90%, 6.62% and 73.77% respectively. volatile matter content of biochar is important as it contributes to nutrient release, stimulates soil microbial activity (Nain *et al.*, 2022), aids in carbon sequestration, enhances soil structure, and adds to the organic matter content of the soil. These factors collectively make biochar an effective soil amendment for improving soil health, promoting sustainable agriculture, and mitigating climate change. It also has 76.92%, 3.02%, 0.9%, 0.02% and 22.4% of total C, H, N, S, and O, respectively. The C/N ratio is 84 and is high related to the optimum C/N ratio for the mineralisation of organic material in soil (20-30:1). The analysis provides information about the concentrations of various elements, including sodium, magnesium, aluminium, potassium, calcium, titanium, vanadium, manganese, iron, nickel, copper, zinc, boron, and molybdenum

(Table 3). The nutrient content in biochar is mainly governed by the type of feedstock and also by pyrolysis temperature (Gaskin *et al.*, 2009). As pine needle biochar contains essential micronutrients and cations that enhance its role as a nutrient supplier in the soil. These nutrient-rich properties of biochar can improve soil fertility and nutrient availability for plants.

Table 3: Total elemental analysis of biochar

Element (ppm)	Concentration
Sodium (Na)	1014 ± 56.4
Magnesium (Mg)	404 ± 22.5
Aluminium (Al)	156± 8.73
Potassium (K)	545 ± 30.4
Calcium (Ca)	1896 ± 105
Titanium (Ti)	11.1 ± 0.61
Vanadium (V)	0.31 ± 0.02
Manganese (Mn)	36.6 ± 2.03
Iron (Fe)	388 ± 21.6
Nickel (Ni)	3.10 ± 0.17
Copper (Cu)	4.75 ± 0.26
Zinc (Zn)	41.3 ± 2.30
Boron (B)	8.37 ± 0.47
Molybdenum (Mo)	1.14 ± 0.06

Data represented as Mean of triplicate sample followed by standard deviation

Physico chemical properties of biochar

The pH_w of the biochar in water suspension (1: 10 :: w/v) was 9.53 (Table 2). This higher pH of biochar was ascribed to the factors which include organic functional groups and inorganic minerals forms due to charring residues at higher temperature (Yuan *et al.*, 2011). Salts of alkali and alkaline earth elements include (i) readily soluble salts, (ii) carbonates (iii) sparingly soluble metal oxides and hydroxides and (iv) silicates (specifically when feedstocks are having soil particles) (Wang *et al.*, 2014) includes SiO₂, CaCO₃, KCl and CaSO₄ as well as nitrates, oxides, and hydroxides (Amonette and Joseph, 2009). Presences of these minerals in pine biochar in present study were also proven by the X- ray diffractogram. Carbonates were the major alkaline component among the inorganic fractions responsible for the alkaline pH_w of biochars as during the process of carbonisation (Bera *et al.*, 2017). The pH of biochar in neutral salt solution *i.e.*, in 1N KCl (1: 10 :: w/v, pH_{KCl}) was of 9.01. Overall, the pH_w of biochar in water suspension was higher than that in 1N KCl suspension (Table 2).

The reduction in pH of biochar suspended in salt (1 N KCl) solution indicates the presence of negative charged surfaces on biochar. The K⁺ of the salt displaces the H⁺ adsorbed on the negative sites of the biochar to bring it into solution, thus, decreasing the solution pH (Bera *et al.*, 2017; Mukherjee *et al.*, 2011). This also explained the Cation exchange properties exhibited by the biochar at alkaline pH range. The electrical conductivity of the biochar in water suspension (1:10 :: w/v) 0.7 dS m⁻¹ and the cation exchange capacity (CEC) was 40.4 cmol (p⁺) kg⁻¹ (Table 2). In addition to the aliphatic moieties, volatile matter present in the

biochar matrix also contributes to the CEC of biochar, as the volatile matter content has been reported to decrease with the increase in pyrolysis temperature resulting in a decrease in CEC of biochar (Labanya *et al.*, 2022). High CEC allows the biochar to adsorb and retain essential nutrients, making them more available to plants over time. As the biochar exhibits alkaline pH values (pH_w of 9.53 in water suspension) due to the presence of organic functional groups and inorganic minerals formed during the pyrolysis process. This higher pH can help neutralize acidic soils and create a more suitable pH range for plant growth.

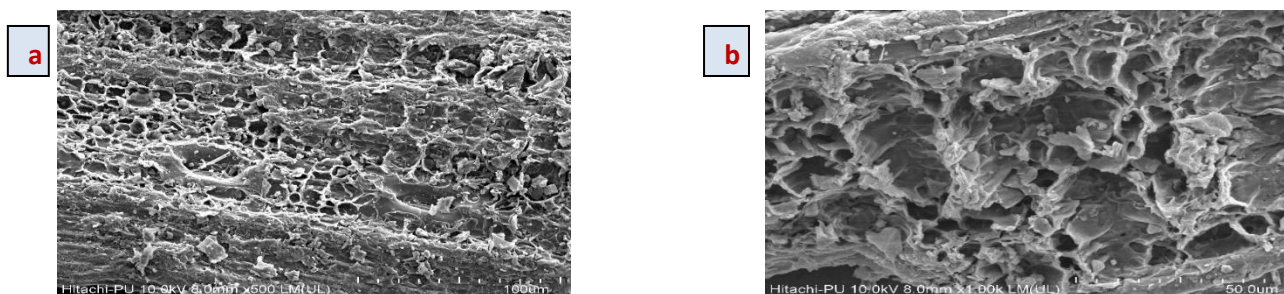


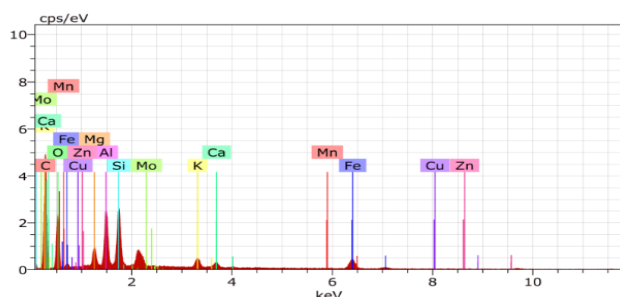
Plate 1: SEM image of PNB (a) 500 & (b) 1000 times magnified

Spectral Characterisation

Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) of Biochar

The SEM images (Plate. 1) of pine needle biochar showed many pores on their surface which indicates the adsorption ability of

biochar (Amin *et al.*, 2018) The SEM images of the biochar samples represented the presence of ash and agglomerates of various minerals. Purakayastha *et al.* (2015) reported similar agglomerates containing calcium in rice straw and pearl-millet biochar. Morphologically PNB particles were flaky.



Element	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (3 Sigma) [wt.%]
Carbon	K-series	29.47	46.93	62.51	11.61
Oxygen	K-series	15.70	25.00	25.00	6.67
Iron	K-series	6.86	10.93	3.13	0.78
Silicon	K-series	3.94	6.28	3.57	0.58
Aluminium	K-series	3.45	5.50	3.26	0.57
Potassium	K-series	1.18	1.87	0.77	0.21
Magnesium	K-series	1.10	1.75	1.15	0.27
Calcium	K-series	0.76	1.22	0.49	0.17
Copper	K-series	0.05	0.09	0.02	0.12
Zinc	K-series	0.04	0.06	0.02	0.12
Molybdenum	L-series	0.10	0.15	0.03	0.10
Manganese	K-series	0.14	0.22	0.06	0.12
Total:		62.79	100.00	100.00	

Figure 1: EDX image of PNB

EDX images revealed an uneven surface studded with overlapping sheets, cracks, and crevices. The surface features were formed from the rapid removal of volatile components, breakdown of cellulose, and extensive, non-uniform growth of graphene sheets during the cooling stage of the pyrolysis step (Jeon *et al.*, 2020). Various elements, such as Na, Mg, Al, Si, Cl, K, Ca, Mn, and Fe were found in the biochar (Fig.1).

X-ray Diffractography of pine needle biochar

The X-ray diffraction pattern of the pine needle biochar is illustrated in Figure 2. A narrow, sharp peak at 2θ values of around 16° was observed due to the presence of crystalline cellulose (Yang *et al.*, 2007). The absence/less number of distinct peaks suggested the amorphous nature of the biochar sample (Tongpoothorn *et al.*, 2011). Broader peak ranging from approximately 22 to 24° was observed, indicating the development of atomic order within the carbonized sample and partial degradation of cellulosic material (Keiluweit *et al.*, 2010) which generally formed at high temperature ($\sim 500^\circ\text{C}$). The presence of a broad

peak around 22 to 24° in the biochar produced at higher temperatures suggested the formation of a crystalline structure with improved layer alignment (Yang and Lua, 2003). Similar outcomes have been reported for the carbonization of *Jatropha curcas* and nut shell (Tongpoothorn *et al.*, 2011). The peak appeared at 26.84° (3.32 \AA), 26.79° (3.32 \AA), and 26.75° (3.33 \AA) correspond to quartz (crystalline SiO_2) (Cui *et al.*, 2011; Wornat *et al.*, 1995). Calcite (CaCO_3) was confirmed at 29.52° (3.01 \AA and 3.02 \AA). A sharp peak at $2\theta = 28.15^\circ$ (3.15 \AA), represent presence of Sylvite KCl (Bera *et al.*, 2017). Similarly, the peak at 30.49 shows the presence of Dolomite ($\text{CaCO}_3 \cdot \text{MgCO}_3$), (Singh *et al.*, 2017).

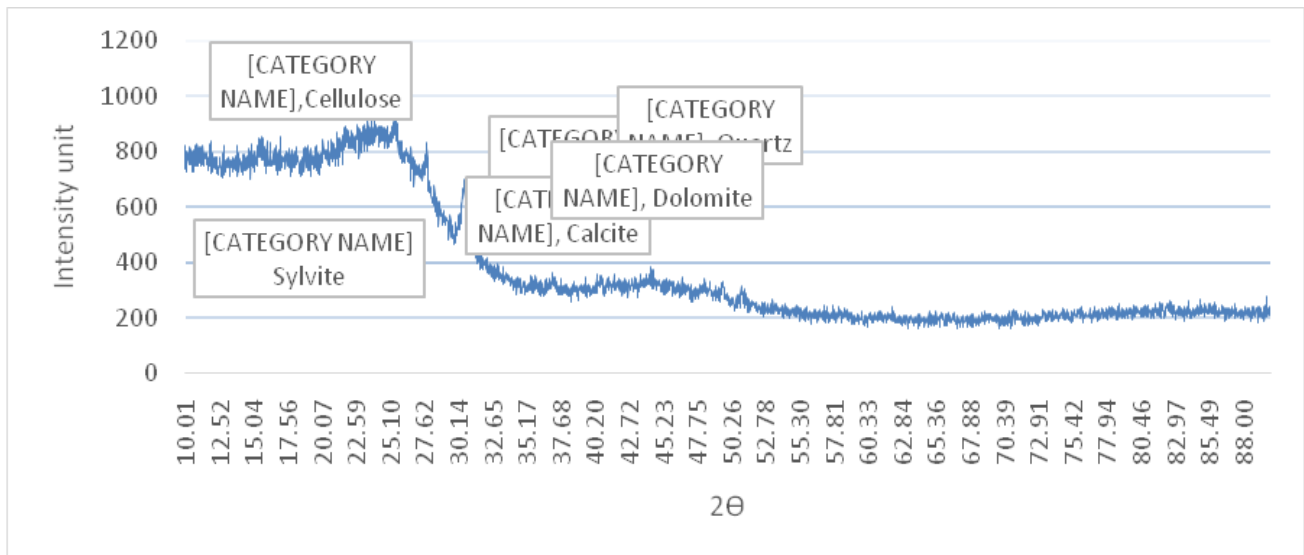


Figure 2. X- ray diffractogram of PNB

CONCLUSIONS

The biochar derived from pine needles is a promising soil amendment due to its various beneficial properties. The high porosity of biochar, as indicated by its low bulk density and high pore volume, allows it to effectively retain water, making it useful in improving soil water retention and reducing water stress on plants. The high specific surface area of the biochar also provides a large surface area for nutrient adsorption and retention, which can improve soil fertility. Furthermore, the presence of micronutrient cations and anions in the biochar, along with its high cation exchange capacity and alkaline pH, make it an excellent nutrient supplier for plant growth. The alkaline pH can

also help to neutralize acidic soils, which can be beneficial for crops that prefer a more neutral pH. In addition, the biochar's high fixed carbon content can help to sequester carbon in the soil, reducing atmospheric carbon dioxide levels and mitigating climate change. Overall, the use of pine needle biochar as a soil amendment can contribute to improving soil health, increasing crop yields, and reducing greenhouse gas emissions.

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