

Influence of biochar on improving hydrological and nutrient status of two decomposed soils for yield of medicinal plant - *Pinellia ternata*

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Abstract: The root tuber of *Pinellia ternata* has been used as a traditional therapeutic herbal medicine. It is reported to impart beneficial attributes in recovering COVID-19 patients. To meet an increasing demand of *P. ternata*, this study is intended to investigate the effects of biochar on the soil hydrological and agronomic properties of two decomposed soils (i.e., completely decomposed granite (CDG) and lateritic soil) for the growth of *P. ternata*. The plant was grown in instrumented pots with different biochar application rate (0%, 3% and 5%) for a period of three months. Peanut shell biochar inclusion in both soils resulted in reduction of soil hydraulic conductivity and increase in soil water retention capacity. These alterations in hydrological properties were attributed to measured change in total porosity, biochar intra pore and hydrophilic functional groups. The macro-nutrient (i.e., N, P, K, Ca, and Mg) concentration of both soils increased substantially, while the pH and cation exchange capacity levels in the amended soils were altered to facilitate optimum growth of *P. ternata*. The tuber biomass in biochar amended CDG at all amendment rate increases by up to 70%. In case of lateritic soil, the tuber biomass increased by 23% at only 5% biochar application rate. All treatments satisfied the minimum succinic acid concentration required as per pharmacopoeia standard index. The lower tuber biomass exhibits a higher succinic acid concentration regardless of the soil type used to grow *P. ternata*. The biochar improved the yield and quality of *P. ternata* in both soils.

Keywords: Biochar; Nutrient; Soil water retention; Hydraulic conductivity; Covid19.

INTRODUCTION

The indiscriminate use of synthetic drugs and awareness of its associated side effects have paved way for the growing interest of traditional organic medicine in recent times (Sen et al., 2011). In this regard, herbal medicinal plants and plant-based natural drugs have seen a rejuvenation in market value in the past decade (Segun et al., 2018). As per WHO Traditional Medicine Strategy 2014–2023 (WHO, 2013), one of its main goals is to identify and evaluate strategies for upscaling the raw ingredients required for herbal medicines. The Asian traditional medicine industry depends heavily on the supply of raw plants containing pharmacologically active compounds for medicine preparation. The dried root tuber of *Pinellia ternata* (Thunb.) has been used as a traditional medicine since time immemorial. Its medicinal usage has also been reported in the Hong Kong and Korean pharmacopoeia (KIOM, 2017; HKCMMS, 2019). *P. ternata* is extensively distributed throughout South-east Asia, particularly in the eastern and southern provinces of China (Zhang et al., 2013). The dried tuber of this plant (called as “Banxia” in Chinese) is a traditional herbal medicine used for treating coughs, dispelling phlegm and in early pregnancies (Xu et al., 2018). In fact, the plant was recently used as a therapeutic drug for treating COVID-19 patients during its outbreak in China (Luo, 2020; Ren et al., 2020). The plant exhibits strong antibacterial, anti-inflammatory, antioxidant, immunity building, anti-obesity, and even anti-cancerous attributes (Wang et al., 2008). As per recent pharmacological studies, the positive attributes of this plant originate from the numerous active phytochemical ingredients contained in its roots, especially in their tubers (Nagai et al., 2002). Among them, the concentration of active ingredient-succinic acid is used as a marker chemical

for standardization of *P. ternata* root tuber quality (Jie et al., 2015).

P. ternata naturally grows in humid environments along roadsides, forests, and stream banks (Zhang et al., 2013). The market demand has grown in the past years within China and the demand cannot be met by utilizing plants solely from its natural growing areas (Guo et al., 1993). Moreover, incessant cultivation of this medicinal plant from its natural wild resources further leads to a loss of genetic diversity and habitat destruction of other native plants (Canter et al., 2005). It has also been recently reported that *P. ternata* showed a decrease in yield or even die during summer seasons in agricultural fields due to climate change (Juneidi et al., 2020). The plants are shade tolerant up to 50% to 100% (Chen et al., 2017). Thus, it is quite possible that poor hydrological properties (i.e., low soil water retention capacity and high hydraulic conductivity) of certain soils may be a reason for reduced plant survival during summer season, especially considering extreme drought caused by climate change (Garg and Ng, 2015). Therefore, altering the soil hydrological properties by some ideal conditioning material can be beneficial for the perennial cultivation of the herbal plant (Hu and Schmidhalter, 2005). Regular and repeated cultivation can also make the soil nutrient deficient, leading to low yield (Bennett et al., 2012). Indiscriminate overuse of artificial agrochemicals during cultivation processes threatens the quality standards of medicinal plant as well as pollute ground water upon leaching (Liu et al., 2016). Thus, to mitigate the adverse effects of artificial chemicals and improve the hydrological properties of soil, sustainable soil amendment is the need of the hour for bulk production of *P. ternata*.

Biochar has emerged as a sustainable material to boost agricultural crops in the past decade (Das and Sarmah, 2015; Das

et al., 2018). Biochar is a carbonaceous porous material that is produced by heating waste organic biomass in limited to no oxygen environment by a process called “Pyrolysis” (Rahman and Hopke, 2017; Zahedifar, 2020). Biochar has amassed popularity as a mitigation strategy for carbon sequestration in agricultural soils, which can, at the same time, improve soil fertility as well as enhance soil water retention (Darama et al., 2020; Wang et al., 2010). Biochar itself constitute of plant soluble nutrients, exhibits high cation exchange capacity (CEC) for retaining nutrients and provides a favourable media for microbial activity. Biochar conditioning in soil for enhancing growth of traditional medicinal plants have already been showcased for species such as *Salvia miltiorrhiza* and *Moringa oleifera* (Fagbenro et al., 2015; Liu et al., 2016). However, the optimum application percentage for biochar amendment in soil for plant growth is different based on biochar feedstock and plant grown. Based on the above discussion, it is worthwhile to investigate the potential efficacy of biochar in altering soil properties (both hydrological and agronomic) that can improve the quality and quantity of *P. ternata*.

The objective of the current study is to investigate the effects of biochar on the soil hydrological and agronomic properties for the growth of *P. ternata*. Two contrasting soils based on their texture and acidity were selected for carrying out controlled laboratory experiments. *P. ternata* was grown in both soils on instrumented pots with and without biochar application. Biochar application percentage to soils were at 3% and 5% (by dry weight of soil). The hydrological (soil water retention characteristics and hydraulic conductivity) and agronomic properties (macronutrients, CEC, pH, soluble organic matter) were measured for all tested soils. To gauge the growth and quality of the cultivated plants, the harvested tuber biomass and their succinic acid concentration were measured, respectively.

MATERIALS AND METHODS

Soil properties

Two types of soil i.e., completely decomposed granite (CDG) and laterite were chosen for growing the plant species. CDG was obtained from a hill site in New Territories, Hong Kong; and laterite was procured from Bijie City, Guizhou, China. These two soils are selected as they are extensively found in South-east Asia where herbal medicinal plants are traditionally consumed (Chen et al., 2019). Furthermore, they are different in terms of alkalinity and texture. CDG has a pH of 7.4 (basic) whereas laterite has a pH of 5.2 (acidic). As per ASTM- D2487 (ASTM, 2010) classification considering texture and plasticity, the soils are classified as silty sand (SM) and medium plastic inorganic silts (MH) for CDG and laterite, respectively. Based on the results from standard proctor compaction tests, the maximum dry density, and the corresponding optimum moisture content of the soils are (1900 kg m⁻³ for CDG; 1570 kg m⁻³ for laterite) and (12% for CDG; 27.5% for laterite), respectively. The basic index and agronomic properties of the two soils are listed in Table S1.

Biochar properties

Biochar used in this study was produced by pyrolysis of waste peanut shell biomass at a temperature of 500 °C for 30 to 40-minute residence time. Before mixing with individual soils, biochar was sieved through a 425- μ m graded sieve. Based on the measured specific surface area (8.45 m² g⁻¹) the biochar can be categorized as non-activated carbons. Other basic properties of the biochar are provided in Table S2. Fig. S1a shows the surface morphology of individual biochar particle and soil-biochar

mixture (Laterite + 3% Biochar) conducted through Field Emission Scanning Electron Microscopy (FE-SEM). The FE-SEM images for the individual biochar particle reveal high amount of hexagonal intra-pores within the particle ranging from 10–13 μ m diagonally. The soil-biochar mixture also shows this hexagonal intra-pore structure of the biochar wherein fine soil particles could be seen ingrained. Fourier-Transform Infrared (FTIR) spectra of the biochar (Fig. S1b) showed a high peak spectral band at 3618 cm⁻¹ assigned as –OH group (hydrophilic). Spectral peak at 1708 cm⁻¹ could be attributed to the presence of C=O bonds of the non-ionic carboxyl groups (–COOH, –COOCH₃). These are potentially linked to carboxylic acids or their ester groups (Abid et al., 2016; Mohan et al., 2011). Peak at 1395 cm⁻¹ was nominated to aromatic (C=C–C) vibrations (El-Banna et al., 2018).

Test set-up and instrumentation

All soil and soil-biochar mixture used in the test were thoroughly mixed. The soil and soil-biochar mixture were filled in plastic pots of size 200 mm outer diameter and 215 mm depth with drainage holes in the bottom. The soil in each plant pot was compacted at a relative compaction (RC) of 70% for each soil type and mixture. In each pot, the soil was compacted in seven equal layers, wherein the soil was scarified between each layer for better contact. Plant seeds of *P. ternata*, each weighing around 4 g to 7 g were selected and six seeds sowed at a depth of 70 mm in each pot as per the pattern shown in Fig. 1a. Two sensors for measuring soil matric suction (ψ) and volumetric water content (θ) were placed at a depth of 100 mm (accounting for root depth) during compaction process. ψ was measured using small tip tensiometer from Soil-moisture Equipment Corp Pt. Ltd. and θ was measured using SM150t from Delta-T Devices.

Test procedure

The design of the experiment was a completely randomized block of 2 $\times$ 3 factorial; two types of soil and three biochar application concentration were tested. Biochar was thoroughly mixed with each soil at 0% (Control), 3% and 5% (by weight). In total, 18 pots were prepared accounting biochar rate, soil type and replicates. After transplantation, the pots were placed in the temperature-controlled plant room (Fig. 1b) having a day and night temperature of 25 $\pm$ 1 °C and 21 $\pm$ 1 °C, respectively. The relative humidity was maintained at 60 $\pm$ 5%. Day and night were imitated with 12 hours of light and 12 hours of dark conditions. The light was provided by installing fluorescent lamps (T5SA-14D). Pots received irrigation of 200 ml twice a week for the first month. Thereafter, 100 ml irrigation was provided once in three days for the remainder of the growth period. Plants were grown for three months, and no fertilizer was added such that no additional osmotic suction was induced in the soil. The plants were grown for a period of three months after transplantation. Thereafter, the mature *P. ternata* plant (Fig. 1c) was harvested to measure its root characteristics (tuber mass and root length). The influence of biochar on hydrological parameters (i.e., soil water retention curve (SWRC) and hydraulic conductivity (k) were also carried out. The k of the soil was measured using a disk infiltrometer on all 18 pots (Gopal et al., 2019). Negative head applied on the infiltrometer, and volume of water infiltrated was kept at 3 cm and 20 mL, respectively. The infiltration tests were conducted by compacting the soil in a PVC pot (200 mm outer diameter and 215 mm depth) at the same compaction state as done for growing the plants in the instrumented pots. The SWRC was obtained by measuring the ψ and θ from the installed

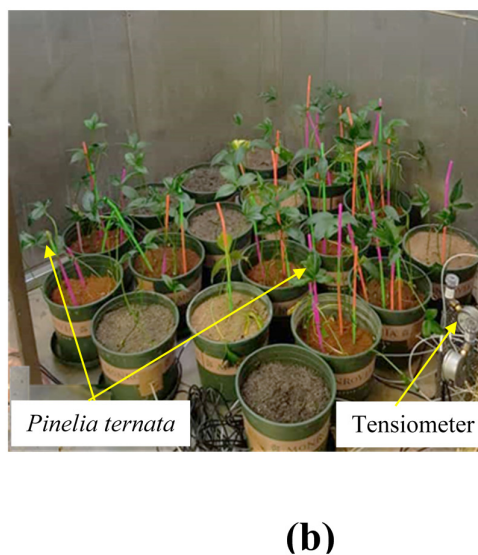
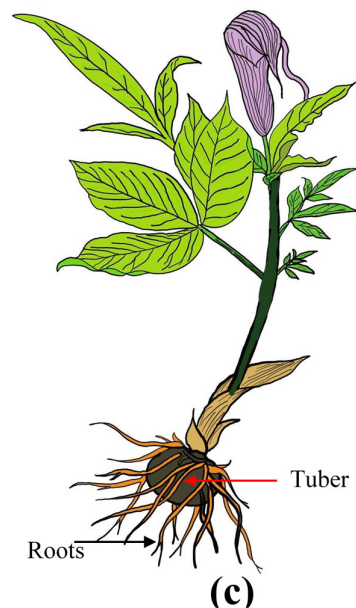
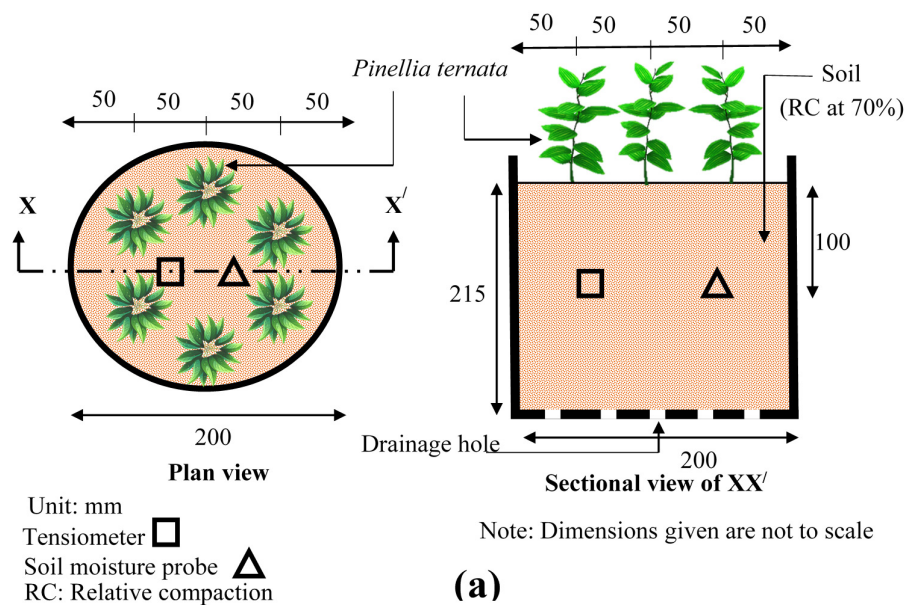


Fig. 1 (a) Schematic diagram of pot experimental set-up: plan view and cross-sectional view; (b) overview of test set-up in temperature and humidity-controlled plant room; (c) Illustrated plate of mature *Pinellia ternata*.

tensiometers and water content sensors. This was done by saturating the pots by giving a ponding head. Saturation was ensured by ponding the soil until free drainage of water was seen at the bottom of the perforated pot and tensiometer reading showed suction value as zero. Thereafter, the soil in the pots were exposed to atmosphere for drying. The ψ and θ were thus periodically measured upon drying to obtain the SWRC.

Mehlich-3 extraction method (Mehlich, 1984) was used to measure soil macronutrient (Ca, Mg, K and P) concentration of the tested soil and soil-biochar mixture. Nitrate and nitrite (NO_3^- , NO_2^-) were measured calorimetrically by automated flow analysis after extracting samples with water (ISO 14256-2, 2005). Total Kjeldahl Nitrogen (TKN) was measured by automated colorimetry after digesting samples in acid (USEPA, 2001). Total nitrogen equals the sum of TKN, NO_3^- and NO_2^- . Weight loss on ignition method (Schulte and Hopking, 1996)

was employed to measure soil organic matter (SOM) content. CEC was determined following the barium chloride (BaCl_2) compulsive exchange method (Gillman and Sumpter, 1986). Succinic acid content was measured by high performance liquid chromatography analysis method according to HKCMMS-2019 (HKCMMS, 2019).

RESULTS

Effects of biochar on soil hydrological properties

Figure 2(a–b) shows the drying path of the SWRC for bare soil and soil-biochar mixture based on measured ψ and θ data points. Data points were fitted using the van Genuchten equation (van Genuchten, 1980) and individual SWRC are presented for all tested soils. The fitting parameters and their designations are given in Table S3. Inclusion of biochar increases the water

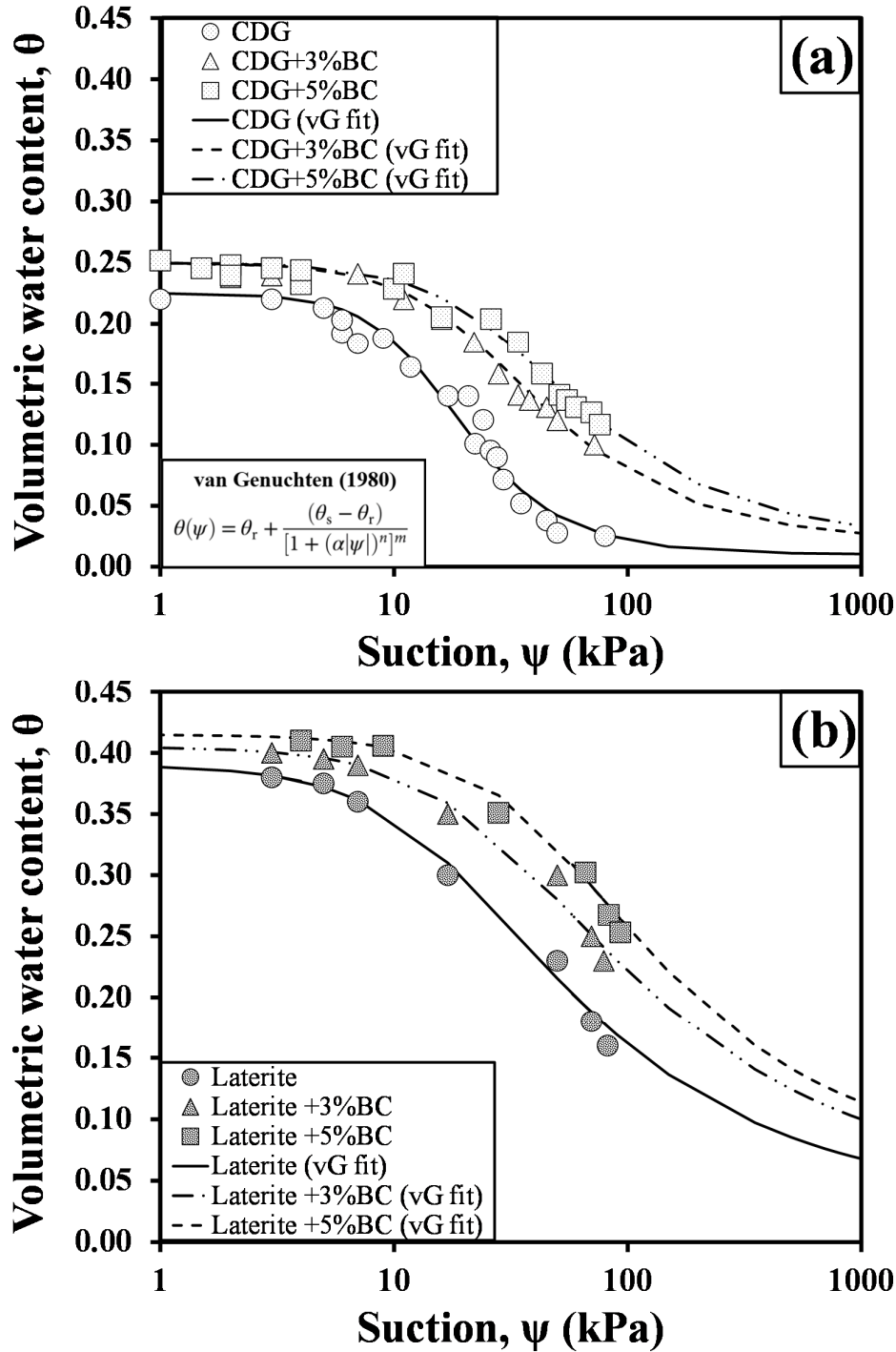


Fig. 2. Soil water retention characteristics for (a) Completely decomposed granite (CDG) and (b) Laterite.

holding capacity of both soils along the measured range of suction. An increase in θ_s by 25% was seen for CDG soil with inclusion of biochar. θ_s increased by (4–7)% with biochar inclusion for lateritic soil. Based on ‘n’ parameter, which is an indicator of the water desaturation rate, it can be inferred that biochar inclusion in CDG significantly lowers the desaturation rate by (24–28)% as compared to lateritic soil (4%). At a particular θ , it can be observed that magnitude of ψ for soil-biochar mixture is higher than bare soil for both CDG and laterite. The results from the SWRC imply that biochar inclusion

significantly improves the water retention characteristics in CDG while it has moderate effects on lateritic soil. Fig. 3 shows the k variation of both CDG and laterite at different biochar percentage. Biochar inclusion decreases the k of CDG gradually with magnitude greater than one order at 5% biochar amendment. The k of bare CDG was 1.9×10^{-5} m/s. Adding 3% and 5% of biochar in CDG decreased the k to 2.5×10^{-6} m/s and 1.6×10^{-6} m/s, respectively. The k also decreased with biochar inclusion in laterite. However, the magnitude was very less as compared to bare laterite (4.1×10^{-6} m/s).

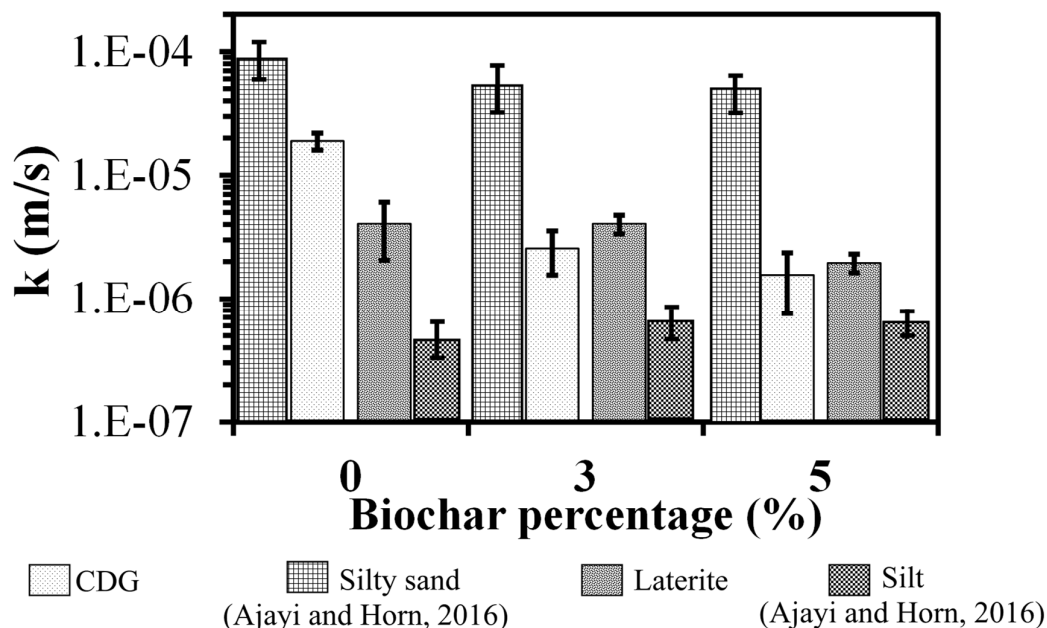


Fig. 3. Measured soil hydraulic conductivity at different biochar application rate.

Effects of biochar on soil agronomic properties and macronutrient concentration

Figure 4 (a–c) presents the pH, CEC and SOM of the soil and soil-biochar mixture collected at the end of the plant growth period. There is a steady increase in pH for both CDG and laterite with inclusion of biochar. At 5% biochar inclusion, there is an increase in pH by more than 1 unit for acidic lateritic soil. In CDG, CEC increased by 128% ($23.8 \pm 4.0 \text{ cmol}_c \text{ kg}^{-1}$) with 5% biochar application compared to control ($11.3 \pm 0.90 \text{ cmol}_c \text{ kg}^{-1}$). For laterite, the CEC did not increase at 3% biochar application while it increased by 24% ($33.2 \pm 2.1 \text{ cmol}_c \text{ kg}^{-1}$) with 5% biochar application ($26.4 \pm 1.8 \text{ cmol}_c \text{ kg}^{-1}$). From Fig. 4c, it is seen that CEC is negatively correlated to SOM for both soils. Compared to CDG, laterite has higher SOM. Hence, it is possible that laterite shows relatively lower change in CEC with biochar application. Biochar inclusion enhances the SOM of both CDG and laterite. 5% biochar inclusion increases SOM of CDG and laterite by 130% and 52%, respectively. Figure 4 (d–h) presents the plant soluble macro-nutrient concentration for soil at different biochar application rate. Five macro-nutrients (N, P, K, Ca, and Mg) were investigated in the current study. In CDG, the inclusion of 5% biochar exponentially increases the concentration of N, P and K by 1808%, 44% and 1000%, respectively. In lateritic soil, the inclusion of 5% biochar also increases the concentration of N and K by 307% and 894%, respectively. However, the soluble P content in lateritic soil did not show any noticeable change with biochar inclusion at both 3% and 5%. The Ca^{2+} and Mg^{2+} concentration increased in 5% biochar amended CDG by 46% and 170%, respectively. For laterite, which inherently have very low Ca^{2+} and Mg^{2+} concentration, 5% biochar inclusion increases the same by 1067% and 512%, respectively. The results on macro-nutrients imply that peanut shell biochar is effective in enhancing the availability of plant soluble nutrients in soil media, especially in basic soils. In acidic soil such as laterite, apart from P, majority of the tested macro-nutrients show an increase in plant soluble nutrients with addition of the biochar.

Effects of biochar on root tuber biomass, root length and tuber succinic acid content

Root tuber biomass obtained at different biochar application rate is presented in Fig. 5a. For CDG, tuber biomass initially increases from 1.6 g to 2.8 g at 3% biochar application rate. Thereafter, this increase tapered down to 2.65 g at 5% biochar application rate. On the contrary, *P. ternata* in lateritic soil exhibited a decrease in tuber biomass by 22% at 3% biochar application rate. At 5% biochar application rate, the tuber biomass increases by 23% in comparison to bare soil. The tuber biomass was relatively lower for laterite as compared to CDG at the same biochar application rate. This can be attributed to deficiency in plant soluble P for laterite as compared to CDG (refer Fig. 4e). The root length density (RLD) showed contrasting trend in growth with biochar inclusion for the two-contrasting soil (Fig. 5b). In case of laterite, RLD increases with biochar inclusion by (48–57)% as compared to bare soil. On the contrary, for CDG there is a drastic decrease in RLD by almost 43% and 94% for 3% and 5% biochar application rate, respectively.

Fig. 6a shows the tuber succinic acid concentration at different biochar application rate for the two tested soils. In laterite, compared to bare soil, tuber succinic acid concentration increased by 167% and decreased by 63% at 3% and 5% biochar application rate, respectively. CDG, biochar inclusion decreases the succinic acid concentration regardless of biochar application rate. Fig. 6b shows the variation of succinic acid concentration with the tuber biomass for the test conditions. For both CDG and laterite, the succinic acid concentration decreases with higher tuber biomass. CDG, which show higher tuber biomass than laterite had relatively lower variation in the concentrations of succinic acid as compared to laterite. This implied that succinic acid concentration in laterite soil is more sensitive to the overall mass of the grown tubers. Based on the measured values, two simple empirical equations for each soil were proposed to estimate the succinic acid concentration from the tuber biomass. This could help cultivators in estimating the quality of the harvested *P. ternata* tuber based on its size and weight.

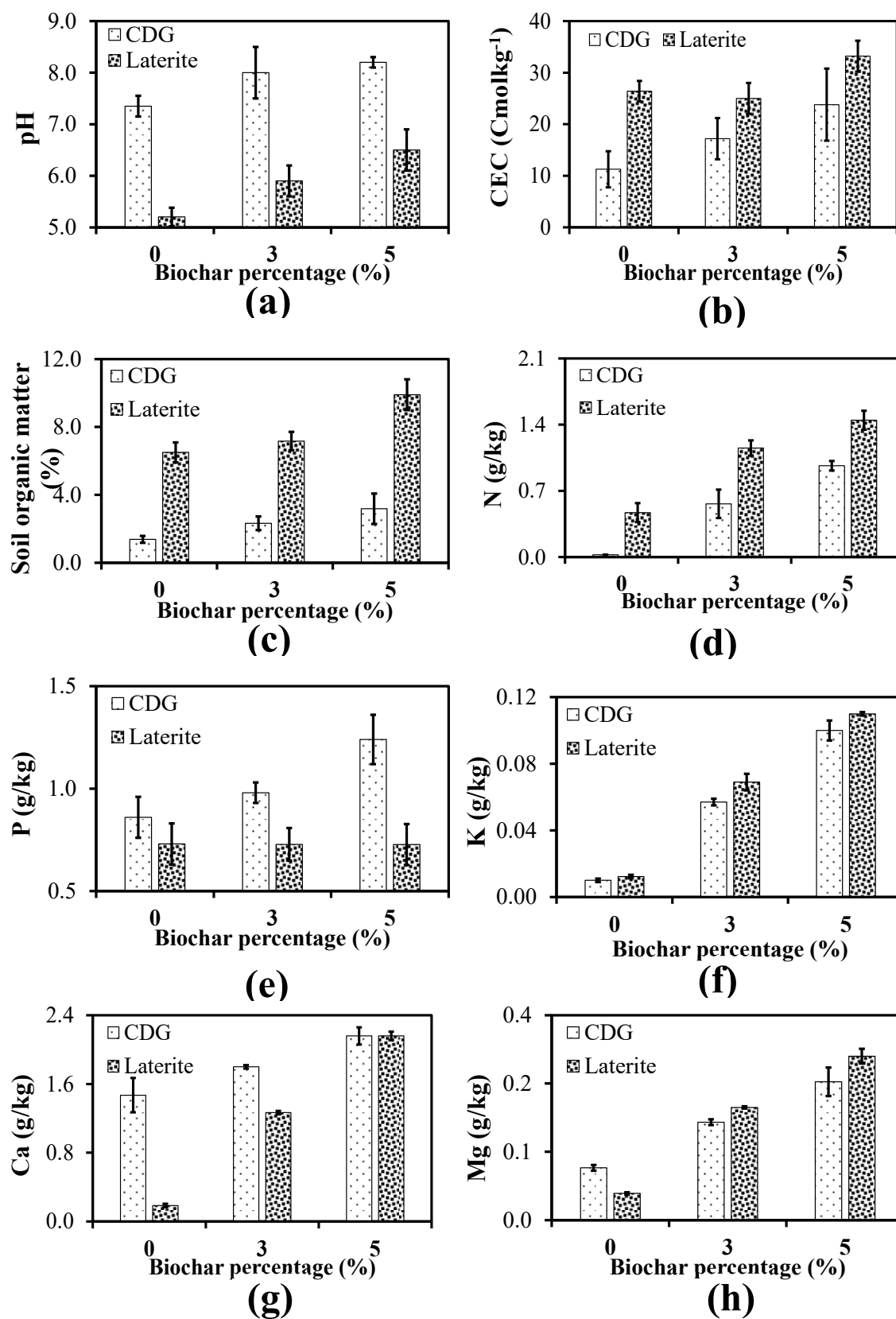


Fig. 4. Measured soil agronomic properties and nutrient concentration at different biochar application rate.

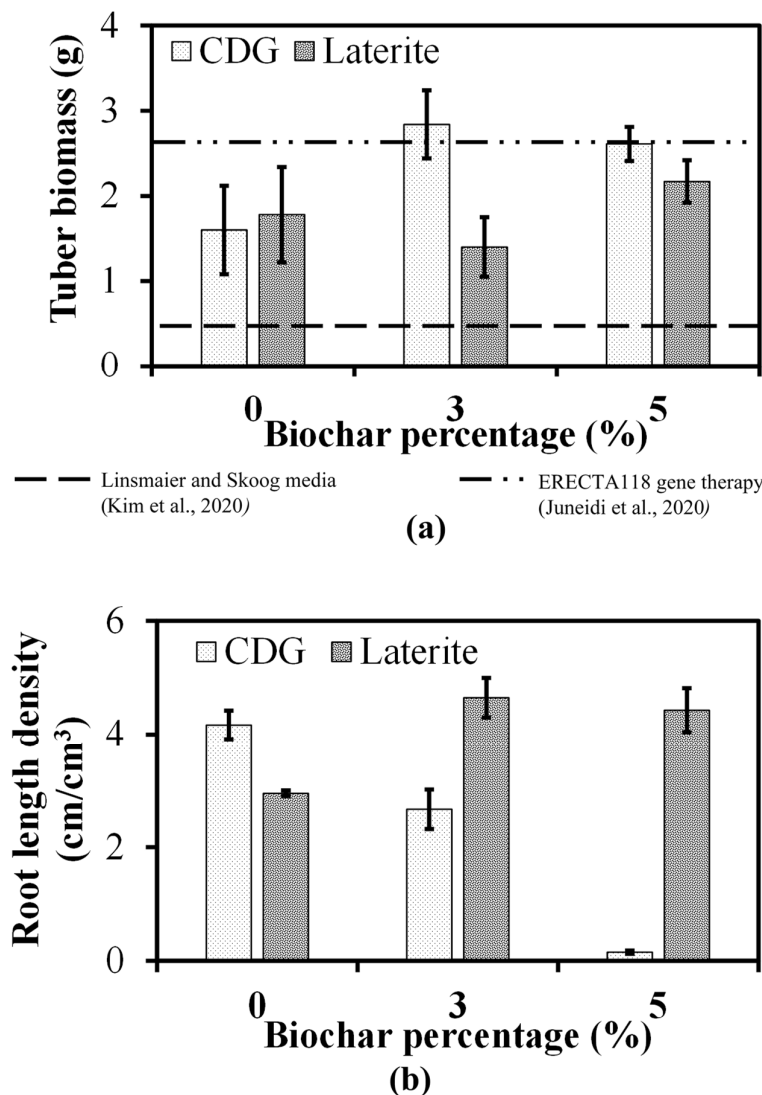


Fig. 5. Effect of biochar application rate on measured (a) tuber biomass and (b) root length density.

DISCUSSION

Effects of biochar on soil hydrological properties

Inclusion of biochar in CDG increased the θ_s by 25%. This range of increase in θ_s for peanut shell biochar amended soil vegetated with *Cynodon dactylon* was also previously reported by Ni et al. (2020). On the other hand, θ_s increased by (4–7)% with biochar inclusion for lateritic soil. Based on ‘n’ parameter, biochar inclusion in CDG significantly lowers the desaturation rate by (24–28)% as compared to lateritic soil (4%). The enhanced water retention ability for CDG as compared to laterite can be discussed based on particle size distribution. CDG has coarser grained particles as compared to laterite (refer Table S1) and thus their pore size would be larger. Biochar inclusion (constituted of particles majorly lower than 0.02 mm) in CDG can decrease the pore size of the CDG-biochar mixture. This decrease in pore size can enhance the water retention ability of the mixture (Ng and Menzies, 2014). Biochar also enhances the retention capacity as they can store water within their intrapore (refer Fig. S1a; Hussain et al., 2020). Moreover, hydrophilic functional groups such as hydroxyl, carboxyl, and amino groups as observed in the FTIR spectra (Fig. S1b) help in retaining water

along the biochar surface during desaturation (Bordoloi et al., 2019). At a particular θ , it can be observed from the SWRC that the magnitude of ψ for soil-biochar mixture is higher than bare soil for both CDG and laterite. This can be attributed to higher formation of air water meniscus due to finer biochar embedded within the soil pores (Hussain et al., 2020). Moreover, fine particles (clay and fine silt particles) may get ingrained within the biochar intra-pores (Fig. S1a) further causing an increase in air-water meniscus (Wong et al., 2018).

In both CDG and laterite, the k decreased after biochar amendment. However, only in CDG, the k decreased with magnitude greater than one order at 5% biochar amendment. A decrease of k by a magnitude greater than one order has practical implication in water drainage in field conditions (Garg et al., 2020). In case of laterite, the decrease in k with biochar inclusion was less pronounced than CDG. Similar decrease in magnitude of k with biochar inclusion has been observed for silty sand and silt in literature (Ajayi and Horn, 2016). This reduced k with biochar inclusion can be discussed based on pore throat size decrease in soil-biochar mixture wherein the amended soil is relatively coarse grained. This reduction was more pronounced for CDG than laterites as it is predominantly coarse grained.

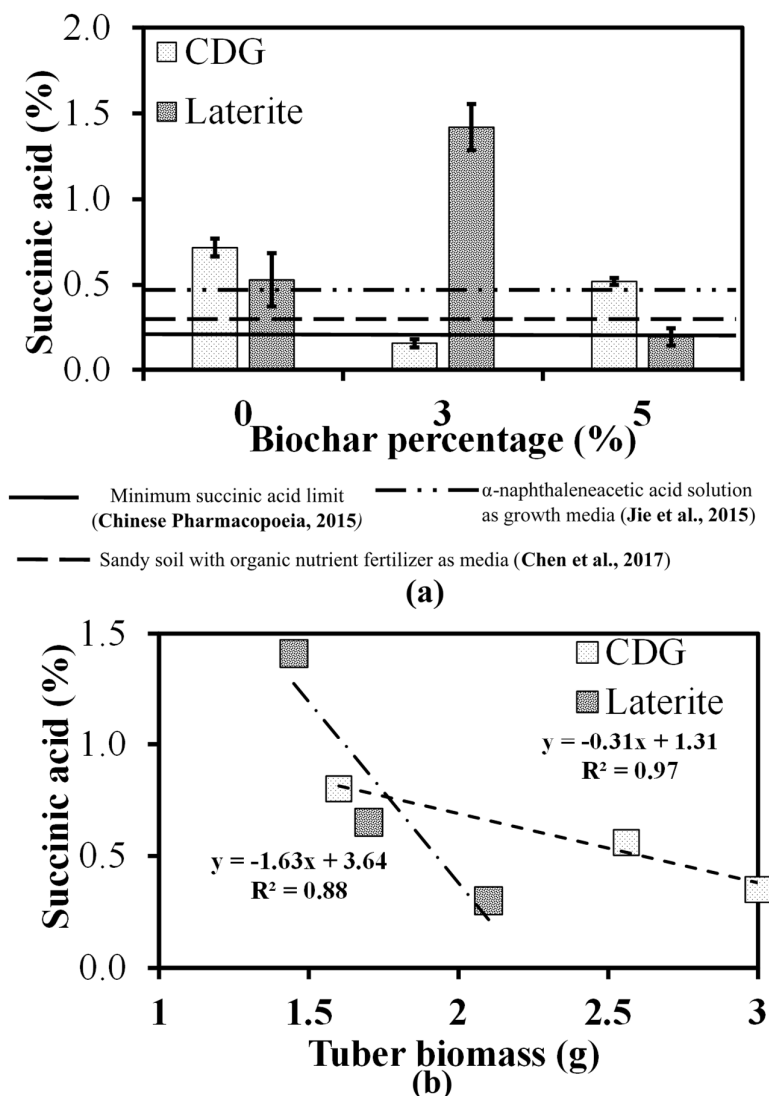


Fig. 6. Measured tuber succinic acid content variation with (a) biochar content and (b) tuber biomass.

For extremely fine-grained clay (flaky clay particles less than 0.002 mm) such as kaolinite, contrasting trend is observed wherein the hydraulic conductivity increases with biochar inclusion (Wong et al., 2018). In their study, 5% biochar inclusion in kaolinite resulted in hydraulic conductivity increasing from 1.5×10^{-9} m/s to 3.3×10^{-9} m/s. Based on mercury intrusion porosimetry results, they show that biochar inclusion shifted the dominant pore diameter of clay (micro and meso pores) to more meso- and macro-pores. In contrast, in the current study, it can be inferred that biochar inclusion can change the macropores of coarse grained CDG into more mesopores, thus reducing the k significantly. The results have implication in plant growth for CDG-biochar mixture as more water would be present in the root zone after irrigation events due to lower drainage, and thus facilitating higher plant available water.

Effects of biochar on soil agronomic properties and macro-nutrient concentration

There is a steady increase in pH for both CDG and laterite with inclusion of biochar. At 5% biochar inclusion, there is an increase in pH by more than 1 unit for acidic lateritic soil as also

reported for other acidic soils in literature (Kloss et al., 2014; Schulz and Glaser, 2012). Changes in soil pH with BC application have been identified as an important factor affecting soluble organic carbon (Li et al., 2007). Favourable pH ranging from 6 to 8 may enhance microbial activities and thus increase soluble organic carbon mineralization (Whitman et al., 2015). This mineralization of soluble organic carbon will thereby promote plant growth with biochar inclusion. Biochar inclusion enhances the SOM of both CDG and laterite. 5% biochar inclusion increases SOM of CDG and laterite by 130% and 52%, respectively. The effects of biochar on SOM can be either direct (soil microbes metabolize BC to produce SOM) or indirect (shift in microbial activity due to change in soil physicochemical properties with BC application) (Whitman et al., 2015). The soluble P content in lateritic soil did not show any noticeable change with biochar inclusion at both 3% and 5%. For acidic soil, Muhammad et al. (2018) reported that P gets adsorbed on Al^{3+} oxides of the lateritic soil and can only be made available for plants through desorption reactions. P may also be clogged in Al^{3+}/Fe^{3+} oxides nanopores within the biochar and as a result, may become unavailable for plants (Shen et al., 2011).

Effects of biochar on root tuber biomass, root length and tuber succinic acid content

For CDG, tuber biomass initially increases from 1.6 g to 2.8 g at 3% biochar application rate. Thereafter, this increase tapered down to 2.65 g at 5% biochar application rate. Liu et al. (2016) also observed similar optimum increase in tuber biomass of the medicinal plant (*Salvia miltiorrhiza*) at 32% v/v (approx. 3.3% w/w) biochar application in loamy soil. There was no clear trend observed on the effects of root tuber biomass upon biochar inclusion for both CDG and lateritic soil. The growth in tuber biomass of *P. ternata* in soil (regardless of biochar application rate) is more than the growth of the same species in a chemical growth media (Kim et al., 2020). Only in case of biochar application in CDG, the tuber growth was more or comparable to genetically modified *P. ternata* reported by Juneidi et al. (2020). The tuber biomass was relatively lower for laterite as compared to CDG at the same biochar application rate. This was attributed to deficiency in plant soluble P for laterite as compared to CDG. Tuber biomass in medicinal plants- *Solatum tuberosum* and *Zantedeschia* spp. were also positively correlated to P addition (Alvarez-Sánchez et al., 1999; Scagel and Schreiner, 2006). In case of laterite, RLD increases with biochar inclusion by (48–57)% as compared to bare soil. On the contrary, for CDG there is a drastic decrease in RLD by almost 43% and 94% for 3% and 5% biochar application rate, respectively. This contrasting trend can be discussed based on the hydrological effects of the soil amended with biochar. Plant available water content decreases for finer soils as compared to coarser soils (Koyro and Huchtermeyer, 2018). Thus, to accommodate plant growth, the roots need to permeate through the finer soil for availing moisture from the mesopores and micropores of the soil. Of course, with biochar addition, the favourable nutrients as well as higher water retention (refer Fig. 2b) help in additional root growth. On the contrary, CDG is coarse grained in nature with minimal clay content. CDG is predominantly constituted with macro and meso pores, which make root water uptake relatively easier. Though it has low water retention capacity and higher hydraulic conductivity (refer Figs. 2a and 3), the regular irrigation regime adopted in the current study might have not put any water stress on the plant. Subsequent inclusion of biochar for CDG also increases the water retention capacity. This means water was readily available throughout the growth period adjacent to the roots. Thus, root growth was stunted with gradual inclusion of biochar in the case of CDG. The results imply that for optimum growth of *P. ternata* in CDG, irrigation amount can be decreased, or the irrigation interval can be increased. In laterite, compared to bare soil, tuber succinic acid concentration increased by 167% and decreased by 63% at 3% and 5% biochar application rate, respectively. In general, tuber succinic acid concentration is dependent on the plant soluble N availability (Xi et al., 2013). This is reflected by the high succinic acid content at 3% biochar application rate for laterite. The relative decrease in succinic acid concentration at 5% is not expected. On the other hand, for CDG, biochar inclusion decreases the succinic acid concentration regardless of biochar application rate. Nevertheless, all treatments satisfied the minimum succinic acid content required as per pharmacopoeia standard index (2.4 mg g⁻¹: 0.24%) (Chinese Pharmacopoeia, 2015). The treatment that showed higher succinic acid content than commonly used nutrient intervention (α -naphthaleneacetic acid solution, organic nutrient fertilizer; (Chen et al., 2017; Jie et al., 2015)) are 3% and 5% biochar application rate for laterite and CDG, respectively.

CONCLUSIONS

From the current study, the following conclusions can be drawn.

- Biochar inclusion significantly improves the water retention characteristics in CDG while it has moderate effects on lateritic soil. The saturated water content improved by up to 25% and 7% upon biochar inclusion for CDG and lateritic soil, respectively. Biochar inclusion significantly lowers the desaturation rate by up to 28% and 4% for CDG and lateritic soil, respectively. The hydraulic conductivity decreased with biochar inclusion for both CDG and lateritic soil. However, the rate of decrease in hydraulic conductivity was more pronounced in CDG (by more than one order) than that of lateritic soil. The changes in hydrological properties were attributed to measured changes in total soil porosity, role of biochar intrapore and detected hydrophilic surface functional groups.
 - The CEC and SOM of both soils increased with biochar inclusion. Biochar inclusion to CDG decreased the pH, while for laterite pH increased. Regardless, pH of biochar amended soil ranged between 6 to 8, which is highly conducive for *P. ternata* growth. The results on macro-nutrients (i.e., N, P, K, Ca, and Mg) of biochar amended soils imply that peanut shell biochar is effective in enhancing the availability of plant soluble nutrients in CDG. Apart from P, majority of the tested macro-nutrients in lateritic soil showed adequate increase in plant soluble nutrients with biochar addition.
 - The tuber biomass increases by up to 70% upon biochar inclusion for CDG soil. For laterite, the tuber biomass increases by 23% at 5% biochar application rate. The succinic acid concentration in the tuber biomass decreases with biochar amendment for CDG soils, while it increases for lateritic soil by almost 167% at 3% biochar application rate. Nevertheless, all treatments satisfied the minimum succinic acid content required as per pharmacopoeia standard index. The lower tuber biomass exhibited higher succinic acid concentration regardless of the soil type.
- The biological, hydrological, and agricultural properties of soil-biochar composite vary with the feedstock type (Aydin et al., 2020). Hence, we can expect response in different magnitude depending on whether it is plant or animal based and on the degree of hemicellulose/lignin concentration. Some potential alternatives to boost yield with biochar include both inhouse modifications (elevated CO₂ and N concentration; Ng et al., 2022; Šimanský et al., 2018) and field soil modification using biopolymers and synthetic nutrients (Aydin et al., 2020; Rattan et al., 2023).

DECLARATION SECTION

Conflict of interest statement. The authors declare that they have no conflict of interest, and there were no human nor animal participants in this research.

Data available statement. The authors declare that all data has been presented in the manuscript and supplementary file. Any additional data can be furnished from corresponding author, on reasonable request.

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L.Touyon: Data acquisition, review of manuscript
S. Bordoloi: Original draft preparation, Data acquisition.

Highlights

- 1) Biochar addition in soil reduces permeability and increases water retention
- 2) Macro-nutrient (N, P, K, Ca, and Mg) concentration of tested soils increased
- 3) All treatments satisfied the minimum succinic acid concentration for tuber quality
- 4) Lower tuber biomass exhibits a higher succinic acid concentration

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SUPPLEMENTARY

Table S1. Index properties of completely decomposed granite and laterite.

	CDG	Laterite
Index property	Value	
Standard compaction tests*		
Maximum dry density: kg m ⁻³	1900	1570
Optimum moisture content: %	12	27.50
Particle-size distribution*		
Gravel content (> 2 mm): %	17	2.2
Sand content (≤ 2 mm): %	48	37
Silt content (≤ 65 μm): %	31	40.5
Clay content (≤ 2 μm): %	4	20.3
Atterberg limits		
Liquid limit	NA	63.25
Plastic limit	NA	34.35
Plasticity index	NA	28.90
Specific gravity	2.62	2.70
Agronomic properties		
pH	7.35±0.01	5.05±0.03
Electrical conductivity (ds cm ⁻¹)	0.1 ± 0.02	0.1 ± 0.01
P (mg kg ⁻¹)	0.9 ± 0.05	0.7 ± 0.04
K (mg kg ⁻¹)	10.3 ± 0.3	12.3 ± 0.06

*ASTM (2010; 2015); NA: Not applicable

Table S2. Production condition, elemental composition, and chemical properties of biochar.

Feedstock source	<i>Arachis hypogaea</i>
Pyrolysis temperature (°C)	500
Elemental analysis	
C (%)	58.27± 0.7
O (%)	35.89± 0.8
H (%)	3.85± 0.4
N (%)	1.91± 0.03
Molar ratios	
H/C	0.066
C/N	30.51
Ash content (%)	48.09± 0.3
CEC (cmol kg⁻¹)	89.27± 0.8
Agronomic properties	
pH	7.5± 0.04
Electrical conductivity (ds cm ⁻¹)	2.28
Specific surface area (m ² g ⁻¹)	44.8
P (mg kg ⁻¹)	3.7
K (mg kg ⁻¹)	1575

Table S3. Summary of fitting coefficients for SWRC.

Parameter	θ_s	θ_r	A	n	m	AEV
Unit	[%]	[%]	[kPa ⁻¹]	[-]	[-]	[kPa]
CDG	22.5	1	0.070	2.50	0.60	14
CDG+3%BC	25.0	2	0.045	1.90	0.47	22
CDG+5%BC	25.0	2	0.035	1.80	0.44	29
Laterite	39.0	3	0.060	1.55	0.35	17
Laterite+3%BC	40.5	4	0.037	1.50	0.33	27
Laterite+5%BC	41.5	6	0.023	1.50	0.37	43

* θ_s is volumetric water content at saturation, θ_r is residual volumetric water content, α is fitting parameter primarily dependent on the air entry value (AEV), n = fitting parameter depending on the rate of desaturation of water from the soil, m = 1-(1/n)

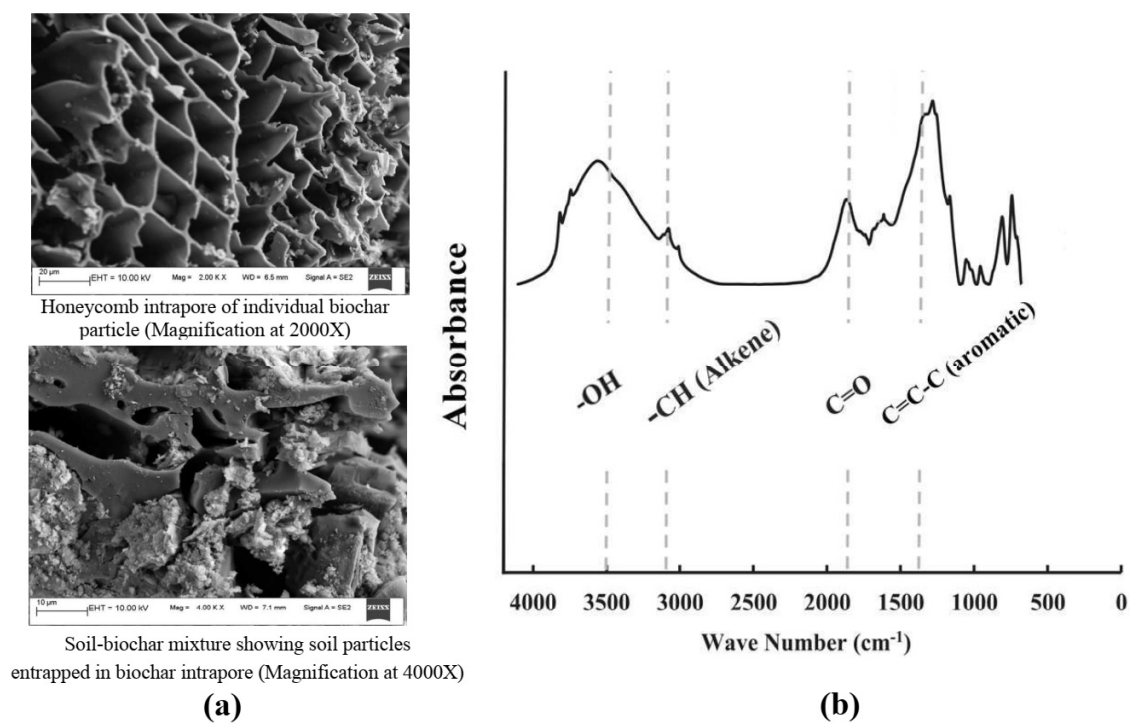


Fig. S1. (a) Surface morphology of biochar particle and soil-biochar mixture; **(b)** Fourier-transform infrared spectra of biochar.