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ORIGINAL ARTICLE

Biochars produced from coconut palm biomass residues can aid regenerative agriculture by improving soil properties and plant yield in humid tropics

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Abstract

Lignin-rich recalcitrant biomass residues of coconut palms viz. (i) mature coconut husk, (ii) tender (immature or green) coconut husk (iii) coconut leaf petiole and (iv) coir-pith were successfully pyrolysed using a simple charring kiln into carbon-rich, black, light weight and porous biochars. High alkalinity and good ash content made them fit for remediating acid soils. High potassium content in these biochars could help reduce the use of inorganic K. Thermogravimetric analysis showed the mass loss phases of husk and coconut leaf petiole biochars to be similar. However, all four biochars gave smooth curves indicating thermal stability of the product. Positive seed germination and earthworm avoidance tests proved their potential as soil amendment. Soil incubation studies with coconut biochars in graded doses, alone or in combination with coconut leaf vermicompost, increased the pH, organic carbon and potassium contents, and promoted plant-beneficial microbiota and enzyme activities. Pot studies with tender coconut husk biochar and coconut leaf vermicompost enhanced the dry weight of cowpea plants accompanied with increased arbuscular mycorrhizal sporulation and root colonization, and root nodule dry weight. A field trial resulted in higher chilli yields with tender coconut husk biochar + coconut leaf vermicompost addition. The results from our studies highlight the potential of pyrolysis as an innovative technology for quick recycling of highly recalcitrant coconut palm biomass residues to biochars as a local source of soil amendment to aid regenerative agriculture in humid tropics.

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Graphic abstract

Keywords Coconut husks · Biochar · Plant-beneficial microbiota · Earthworm avoidance · Mycorrhizae

1 Introduction

Biochar is a solid, carbon-rich, value-added product obtained by heating biomass residues from agriculture, forestry, animals, etc. at temperatures ranging between 300 and 1000 °C under limited or nil oxygen environments. The heating of the biomass under oxygen-limited conditions is called pyrolysis that yields liquids (bio-oils), gas (syngas) and solids (biochar) (Verheijen et al. 2010). Based on the chemical properties (cellulose, hemicellulose and lignin contents) of the biomass and pyrolysis parameters (temperature, residence time of feed stocks and oxygen conditions in the kilns/retorts), the final output can be used for bioenergy creation or as soil amendment to improve agriculture production (Tan et al. 2017) or to remediate environmental pollutants (Yaashikaa et al. 2019). Thus, pyrolysis offers an avenue for quick recycling of organic biomass residues to biochars that could otherwise become a source of environmental pollution. Usually, slow pyrolysis, i.e., heating between 300 and 500 °C with long residence time yields biochar suitable for agricultural purposes (Lee et al. 2013). Fast pyrolysis at temperatures above 500 °C generates more of bio-oils and syngas that can be used for energy generation. There are several pyrolysis systems ranging from in situ soil pyrolizer to simple, low-cost kilns for on-farm biochar production from crop residues; or retorts to modern electronic-controlled reactors available for biochar production (Zhou et al. 2018). Biochars are mainly known for their ability to sequester carbon in soils for a long duration, reduce greenhouse gas emission and enhance crop production capacities of the soils in a regenerative manner as they are recycled products of perennial crops (Toensmeier 2016).

1.1 Biochar application in agriculture

Biochar production and use as soil amendment is an age-old tradition practised in India and elsewhere in Asia and other countries. In addition to the char supplementation via slash and burn method practiced by nomadic farmers in the north-eastern states of India (Jha et al. 2010), the traditional method of biochar production involved heaping agriculture residues into a conical mound and patting it with wet clayey soil layer to form an envelope which prevented atmospheric oxygen entering the mound. Small openings were made in the bottom of the mound to provide space for lighting fire to residues. Once the fire was lit, the agricultural biomass residues would smoulder under low-oxygen conditions and get converted to biochars, which were applied to crops for potash supplement and insect pest prevention. This traditional method was slowly abandoned as it produced thick, black smoke that polluted the atmosphere and was a time-consuming process. Availability of inorganic fertilizers also added to its discontinuation. However, now again based on the traditional methods, an improved and cost-effective in situ procedure for the production of biochars from agro-wastes is being suggested for agricultural uses (Zhou et al. 2018).

Research interests in the use of biochar in agriculture got freshly renewed since the discovery of Terra Preta, an area in Amazon River Basin in Brazil, which was reported to have soils containing more than 70% charcoal and a very high organic matter content compared to the surrounding soils making it highly productive for agriculture (Lehmann et al. 2003). This Terra Preta was created thousands of years ago by the Amazonians who heated the organic matter resulting in the addition of carbon-rich biochars to the soils. The slash and burn cultivation followed by many in the hilly tracts of India was also similar to Terra Preta.

Present research in biochars is indicating that their addition to soil enhance the carbon residence in the soil for long periods owing to their highly stable form resulting from the thermal modification which makes them resistant to biodegradation (Paustian et al. 2016). In addition, they also are able to modify the soil physico-chemical and biological properties positively as they possess large surface area and millions of small-sized pores (micropores) on the surface. Being mostly alkaline (pH above 8), biochars are highly suitable for acid soils. Their addition has also been reported to reduce bulk density, improve water holding capacity and moisture contents of soil, which, however, is influenced by the rates of biochar application (Blanco-Canqui 2017). They also alter the hydraulic conductivity, for example, water movement in sandy soils slowed down by 92% and speeded up by 300% in clay-rich soils upon addition of biochars. Improvement in potash nutrition and organic matter content in soil is another vital contribution. On the microbiological aspects, biochars have shown to improve the biological nitrogen fixation by more than 50%, increase the mycorrhizal abundance by 40%, restrict soil pathogen attack on plants by inhibiting their signal molecules, etc. The ability to stimulate the microbial population occurs as biochars are able to allow stable availability of the limited moisture and carbon sources present in soil to the microbes (Al-Wabel et al. 2018). However, all such effects are governed by the biochar types, their rates of application, and soil and weather parameters. The positive effects of the biochars on soil properties make them an attractive input for regenerative agriculture.

1.2 Potential for coconut palm biomass residues to be recycled as biochars

Plantation crops such as coconut palms live for at least 60–70 years and generate voluminous amounts of biomass residues during their life time. In India, more than 1.9 million ha area is under coconut palm cultivation mainly spread in southern states, that generates about 12 million MT of biomass residues annually. Leaf fronds, inflorescence portion, mature nut husk and shell are the common wastes of the coconut palms that can be used as feedstocks for biochar production. In addition, coir-pith, which is a waste produced from coir industries is also available in tonnes. In recent times, the consumption of tender coconut water has started yielding large volumes of coconut husks as wastes that are beginning to become an environmental and health issue. Coconut wood is also obtained when diseased, insect-damaged or senescent palms are uprooted. Such uprooting, en masse, is also common in the east coast of India where cyclones are prevalent. All these biomass residues from coconut palm have a good potential to be recycled as soil amendment to aid agriculture and environment. However, the high-lignin and complex phenolic contents make them very recalcitrant to natural decomposition resulting in huge accumulation of the residues in rural and urban areas causing environmental pollution; and source of human health hazard by becoming breeding sites for disease-causing mosquitoes and flies. Technologies for converting coconut leaves to vermicompost and coir-pith to compost have been developed but they are time consuming. We hypothesize that pyrolysis can be an excellent and innovative alternative for quick recycling of coconut biomass residues to biochars that would possess high pH, organic carbon and potassium and be highly suitable for re-invigorating depleted and acidic humid topical soils prevalent in the west coast of India. The following objectives were planned to prove this hypothesis: (1) developing a simple protocol for conversion of coconut biomass residues such as (i) mature coconut husk, (ii) tender coconut husk (iii) coconut leaf petiole and (iv) coir-pith to biochar via pyrolysis (2) assess their non-toxicity as agricultural input and (3) assess their impact on soil nutrient,

microbial properties including arbuscular mycorrhizae and plant yield when applied alone or in combination with coconut leaf vermicompost.

2 Materials and methods

2.1 Coconut biomass residue collection

The following coconut biomass wastes: (a) mature coconut husks, (b) tender (immature or green) coconut husk with shell, (c) coconut leaf petiole and (d) coir pith were collected for the study. The feedstock (b) was obtained from the tender coconut water sales counter run at the Institute premises and roadside vendors, (a) and (c) from the ICAR-CPCRI Farm Office and Agro-Processing Centre, respectively, and (d) from Local Co-operative Coir Production Unit, Manya, Kasaragod, India. A simple drum-type charring kiln developed by ICAR-Central Institute for Agricultural Engineering (ICAR-CIAE), Bhopal, India was used for the production of biochar in batches by slow pyrolysis. The drum was slightly modified at CPCRI's Technology Unit by making a circular hole in the centre of both sides of the head plate, and the hole covered with a moveable circular metal sheet for improving the efficiency of the pyrolysis.

2.2 Biochar production

The process involved sun drying of the coconut biomass residues until the moisture contents of the feedstocks reduced considerably. Among the different substrates tried, the coconut leaf petiole was chopped into 10–15 cm pieces before pyrolysis, whereas, all others were used as such. The dried feedstock was then layered into the kiln and heated at fluctuating temperatures of 350–450 °C range for 2–6 h for producing the biochars. The colour of the smoke was used as a visual indicator for the process of carbonization. No harvesting of the volatiles released during the process was adopted. Once the material was carbonized (turned black colour) through partial combustion, water was sprinkled over the hot biochar and allowed to cool. The cooled biochars were then crushed to coarse particles by beating with a wooden mallet and stored. Portions of biochars that had uncarbonized knots, evident during crushing, were discarded. The particle size of the biochars ranged between 1.5 and 3.0 mm with coir-pith biochar having more percentage of smaller and uniform-sized particles. A minimum of three batches were run for each type of substrate tried in this study.

2.3 Analysis of the biochar properties

The moisture content of the different biochars was estimated by drying 100 g substrate in dry air oven at 60 °C for extended period until there was no additional weight loss. The difference in the initial and final weight was used to arrive at the moisture content. Sub samples from the completely carbonized powdered bulk were taken for further analysis after it was properly mixed by cone and quartering technique. They were finely powdered in mill and the pH and EC of the biochars were recorded by preparing 1:10 solid: solution ratio and shaking on a reciprocating shaker for one hour. After this, samples were allowed to stand for 30 min and then pH was measured using pH/EC meter (Lee et al. 2013). The ash content was estimated by heating biochar samples in muffle furnace (Slattery et al. 1991) and organic carbon content as described by Walkley and Black (1934). The CEC of biochars was estimated by modified ammonium acetate compulsory displacement method (Gaskin et al. 2008). Bulk density of the biochar was estimated as per the procedure outlined by Ahmedna et al. (1997). Total nitrogen was estimated by wet digestion with concentrated sulfuric acid (Jackson 1973). The total P and K in biochars were determined after the acid digestion of the biochars. Phosphorus (P) concentration was measured on a UV–visible spectrophotometer (UV-1601, Shimadzu, Tokyo, Japan) after developing yellow colour by vanadate-molybdate method (Chapman and Pratt 1961). The potassium (K) concentration was measured in a flame photometer (model CL-378, Elico Ltd., India). The microflora of the freshly produced and stored biochar was assessed by plating the biochar in different media selective for bacteria, fungi and actinomycetes. For this 10 g of powdered biochar was added in 90 mL of sterile distilled water and shaken vigorously for 5 min followed by spread as well as pour plating 0.1 and 1 mL suspension, respectively, on agar medium and incubated at 28 ± 2 °C for 2–7 days. In addition, thermogravimetric analysis (Mettler Toledo-TGA/SDTA instrument) for the four different biochars was carried out to assess the degree of charring and thermal stability by recording the mass loss of the sample under higher heating temperatures. Biochar samples for the TGA were accurately weighed in the 70 µL alumina crucibles using the TGA/SDTA microbalance. They were then heated from room temperature (28 °C) to 800 °C at a heating rate of 10 °C/min for 80 min under a nitrogen flush and the changes in their weights were recorded.

2.4 Ecotoxicological assays

Important biological tests to evaluate the toxicity viz. seed germination percentage and earthworm avoidance tests prescribed by the International Biochar Initiative (IBI) were carried out to assess the use of coconut biomass-based biochars for their suitability in crop production. For the seed germination test, ten uniform size cowpea seeds were sown in petriplates filled with biochar admixed soils (0.1–8%

concentration of different biochars) and the seed germination percentages were recorded. Each treatment was replicated thrice. To test earthworm avoidance, plastic basins were half-filled with biochar (0.1–1.0%) admixed soil and rest with plain soil. Ten adult coconut leaf degrading earthworms, *Eudrilus* sp., were introduced into the centre of the basin at the juncture area of biochar-admixed and plain soil. After a few hours, the number of earthworms present in each section of soils determined the earthworm avoidance to biochar. Again 15 days later, a second observation of earthworm habitat choice was recorded. Wetting of the soils was carried out periodically during the experiment period.

2.5 Biochar-soil incubation experiment

To evaluate the impact of the addition of coconut residues-based biochars on the soil nutrient, microbiological and enzyme properties, a 90 days-incubation experiment in pots was carried out. The soil selected for the incubation study was obtained from the Southern Block of CPCRI farm. The soil was a sandy loam type having 4.6 pH, 0.28% organic carbon, 0.06% N, 32 ppm available phosphorus, 17.7 ppm available potassium, which is typical of the nutritionally-poor humid tropical soils of Kerala. Five kg soil per pot was used for the study. Tender coconut husk and coir-pith biochars were added in graded doses (2, 4 and 8 t/ha), alone or in combination with coconut leaf vermicompost (applied @ 4 t/ha) to the soil. A treatment with an application of recommended dose of fertilizer for vegetables (as per Kerala Agricultural University package of practice: 75:40:25 kg N_2, P_2O_5, K_2O/ha) and another with no addition of any biochar or vermicompost or chemical fertilizer (control) were also maintained. Each treatment was replicated four times. The pots were kept at 40% moisture holding capacity throughout the period of the study. Soil sub-samples were collected one week after the set up of the study and at the end of 90 days incubation period for analyzing the pH, %OC, NPK, general and function-specific microbial communities, and soil dehydrogenase activity following the standard soil science and microbiological methods (Khadeejath Rajeela et al. 2017).

2.6 Pot trials to evaluate biochar effect on arbuscular mycorrhizae (AM) fungi

A pot experiment was carried out to evaluate the effect of tender coconut husk biochar on spore count and root association of mycorrhizae in cowpea plants. The sandy-loam soil used in soil-incubation experiment was used for this study too. AM spore count was assessed by wet sieving and decanting techniques of Gerdemann and Nicholson (1963). A portion of hairy roots of the cowpea from each treatment were thoroughly washed and fixed in FAA (Formalin: Acetic acid: Amyl alcohol = 90:5:5) to assess mycorrhizal colonization following staining with Trypan blue by Phillips and Hayman method (1970). The pH of the soil was 5.07 and it had approximately 12 mycorrhizal spores/10 g soil. The experiment was conducted in plastic pots of 10 × 8 cm dimensions. Each pot could accommodate 300 g soil. Treatments included the addition of biochars alone at two doses (2 and 4 t/ha) and along with coconut leaf vermicompost (4 t/ha). Three control treatments viz. soil + vermicompost, soil + recommended dose of fertilizer for cowpea (urea-1.1 g, Rajphos-1.25 g, muriate of potash-0.5 g/kg soil) and unamended soil were also kept. Ten replications were maintained for each treatment. Five cowpea seeds were dibbled into each pot. After 10 days, two best seedlings were retained in each pot. Mycorrhizae spore analysis was carried out before sowing of the seeds and at 50 days when the cowpea seedlings were harvested for estimating the plant growth parameters. Root association % of mycorrhizae was also studied in the harvested cowpea roots. pH, soil moisture content, total seedling dry weight and nodule dry weights were also recorded at the end of the experiment.

2.7 Field study

A small-scale field study was carried out to determine the impact of the application of coconut leaf vermicompost and tender coconut husk biochar + coconut leaf vermicompost on yield of chilli. In an area of 20 m^2, three sub-plots of equal dimensions (4.5 × 1.2 m^2 with at least 0.25 m space between each treatment) were transplanted with healthy chilli seedlings (var. Vellayani Athulya released by Kerala Agricultural University, Vellayani, Kerala). Before transplanting the seedlings, coconut leaf vermicompost @ 4 t/ha was mixed with topsoil in one sub-plot and coconut leaf vermicompost + tender coconut husk biochar (4 t + 2 t/ha) in the other. One sub-plot was grown with chilli without any soil amendments. Until the harvest of the chilli fruits, only irrigation was provided and no other agronomic interventions were done. The chilli fruits were harvested regularly once the plants entered yielding stage and finally summed up for total yield.

2.8 Statistical analysis

The data were analyzed using analysis of variance (ANOVA) and the sample means ($n = 3$) were compared using Duncan's Multiple Range Test (DMRT) at the level of significance set for P value < 0.05. In the pot trials to study the effect of biochar on mycorrhizae, co-variance analysis was carried out where the pre-treatment values were factored in with the post-treatment values for generating the statistical results.

3 Results and discussion

3.1 Biochar yield from coconut biomass and physico-chemical properties

Biochar production trials with simple charring kiln obtained from ICAR-CIAE, Bhopal resulted in improper and unequal pyrolysis of the coconut biomass residues. The feedstock in the sides of the drum failed to convert to biochar because of uneven firing of the substrates. To overcome this, a circular hole was opened on the central portion of the head plates and fixed with a movable circular metal lid. In the initial stages of the pyrolysis, the circular opening was regulated to allow proper flaming of the feedstock in the sides of the kiln. Later, the circular lid was completely closed and the pyrolysis was continued in the normal method. The moisture contents of sun-dried coconut biomass ranged between 10 and 12.4% with the order coir pith > tender coconut husk > mature coconut husk > coconut leaf petiole. The biochars produced from all the coconut residues were porous, deep black in colour and light in weight. The percentage of biochar produced ranged between 35 and 50% concomitant to the input amount on weight-by-weight basis with coconut leaf petiole producing the maximum and coir-pith the least biochar. Biochar yield was found to be higher when coconut husks (THB-Tender coconut husk biochar; MHB-mature coconut husk biochar) and coir-pith (CPB-coir-pith biochar) were used as feedstocks. In a study conducted earlier by Sukartono et al. (2011) with coconut shell, about 65% biochar turnover was obtained when the substrate was pyrolized at 190–280 °C for 8 h. The temperature and retaining period in the charring kiln also played a major role in the biochar output (Brewer et al. 2014).

The physico-chemical properties of the different coconut biomass residue biochars are furnished in Table 1. The bulk density of coconut leaf petiole biochar (CLPB) was highest and coir-pith biochar lowest but the values were not statistically significant. This result reflected the density of the original substrates used; coconut petiole having higher density than others. The ash contents of biochar obtained from husks (> 22%), tender and mature, were highest followed by that of coir-pith. Elsewhere, a lower ash content of about 16% was reported in biochar produced from coconut husks (Vasujini et al. 2014). These variations in our studies might be due to the different pyrolysis conditions as well as the variations in the inorganic compounds present in their biomass. Alkaline pH, ranging between 7.9 and 9.7, of the different coconut waste biochars was a common factor observed in our studies. This observation is well supported by earlier reports of high pH of biochars produced from coconut shells and coconut husk (Sukartono et al. 2011; Shenbagavalli and Mahimairaja 2012; Vasujini et al. 2014). Biochars with high pH are ideal

Table 1 Physico-chemical properties of biochars produced from different coconut biomass residues

Types of biochars	Bulk density (g/cc)	Ash content (%)	pH	EC (µS/cm)	CEC (m.e/100)	Moisture content (%)	Org. C (%)	Total N (%)	Total P (%)	Total K (%)
THB	0.3	22.3^{a}	9.3^{a}	281	28^{b}	9.0^{b}	23^{a}	0.9	0.4^{a}	3.6
MHB	0.3	24.8^{a}	9.7^{a}	254	31^{b}	16.0^{a}	19^{b}	1.0	0.4^{a}	2.8
CLPB	0.4	10.3^{b}	9.2^{a}	226	23^{b}	14.0^{a}	10^{c}	0.6	0.5^{a}	2.8
CPB	0.2	21.1^{a}	7.9^{b}	315	46^{a}	10.0^{b}	15^{b}	0.7	0.2^{b}	3.1
CD at $P=0.05\%$	NS	8.78	0.88	NS	10.78	2.7	3.78	NS	0.18	NS

The results are average of three replicates. Means followed by the same letter are not significantly different at $P=0.05$ using analysis of variance and mean separation (LSD)
THB-Tender coconut husk biochar, *MHB* mature coconut husk biochar, *CLPB* coconut leaf petiole biochar, *CPB* coir pith biochar

for reducing the aluminium toxicity of acidic soils, commonly prevailing in coastal and peninsular India because of heavy rainfall and high humidity, because of their liming values (Domingues et al. 2017). Biochars, because of their hygroscopic nature, had higher moisture status in them compared to the moisture status of the dried biomass residues used as feedstocks. The nitrogen and phosphorus contents in different coconut waste biochars were low but the potassium content was high ranging between 2.8 and 3.6% with tendernut husk biochar having the highest. Higher potassium contents make these biochars an important alternative to reduce the consumption of chemical potassium sources as plant nutrients. As the properties of the feedstock influenced the biochar properties, coconut husks which are known to contain low N and P, and a high K (close to 25% K) (Bonneau et al. 2010) could be one of the reasons for the high potassium levels in these biochars and lesser of N and P. High potassium content in coir dust had been reported earlier (Abad et al. 2002). Pyrolysis temperatures below 500 °C had been reported to accumulate large quantities of available K (Yu et al. 2005). Overall, it was reported that with increase in pyrolysis temperatures, the surface area, ash content, pH, CEC and the basic functional groups got enriched in biochars produced from coconut fibre and coconut shells (Lan et al. 2016). In our studies, the organic carbon contents were below 25% with tender coconut husk biochar possessing the highest of 23% and coconut leaf petiole biochar with least at 10%. Coconut husks have been reported to contain carbon contents of 75%. This gets reduced by > 69% in biochars produced in our studies owing to improper oxygen regulation in the kiln used for their production and, therefore, coming under Class III biochar category in terms of carbon content. A more robust pyrolysis unit which would effectively reduce the carbon oxidation could possibly help in producing Class I biochars with above 70% carbon in them.

Analysis of coconut biomass biochar within 72 h after its production showed no presence of any microflora, whereas after one month storage one or two morphotypes of bacteria were recorded. The colony morphology and other characters indicated it to be *Bacillus* type bacteria (Fig. 1). The ability of *Bacillus* species to become resident in biochar could be associated with its endospore-forming capabilities that enabled to survive in pyrolyzed inert material.

The thermogram of the different biochars is furnished in Fig. 2a–d. A three-stage weight loss was noticed in THB, MHB and CLPB whereas it was two stages for CPB. In all the four samples, a quick mass loss was seen within 100 °C range indicating the loss of surface moisture. Coir-pith biochar showed the steepest mass loss. The second phase weight loss in case of THB was from 100 to 380 °C, for MHB between 100 and 450 °C, and CLPB 50–450 °C. This weight loss is attributed to hemicellulose and cellulose content in the biochar. The third phase of weight loss for three biochars except CPB was from 450 to 800 °C and was attributed to lignin content. The overall curve of the weight loss was quite smooth in the second and third phase indicating highly thermostable biochars. The results specified typical pyrolysis of lignocellulosic biomass with four stages of decomposition; first being dehydration, then hemi-cellulose followed by cellulose and lignin. Results from TG analysis of biochars produced from slow pyrolysis of oil palm kernel shells, empty fruit bunch and palm oil sludge were also reported to give similar mass loss curves (Lee et al. 2017). The phase in which lignin decomposition took place was the longest phase from 450 to 800 °C owing to the tight chemical bonding in its aromatic carbon structure. The temperature ranges observed in our studies matched with those already reported and could be used for determining the lignin content in the biochar. The thermal stability of coconut biomass residue biochars and their highly aromatic character makes it an ideal material for C sequestration in the soil as has been reported with oil palm wastes (Usman et al. 2015) and other wood and sugarcane-based biochars (Domingues et al. 2017).

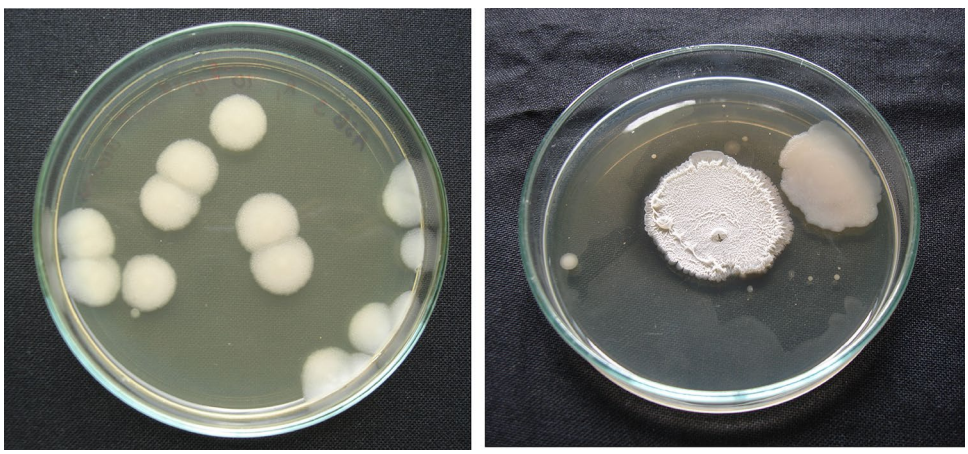


Fig. 1 *Bacillus* spp. in tender coconut husk biochar (from biochar stored for 30 days)

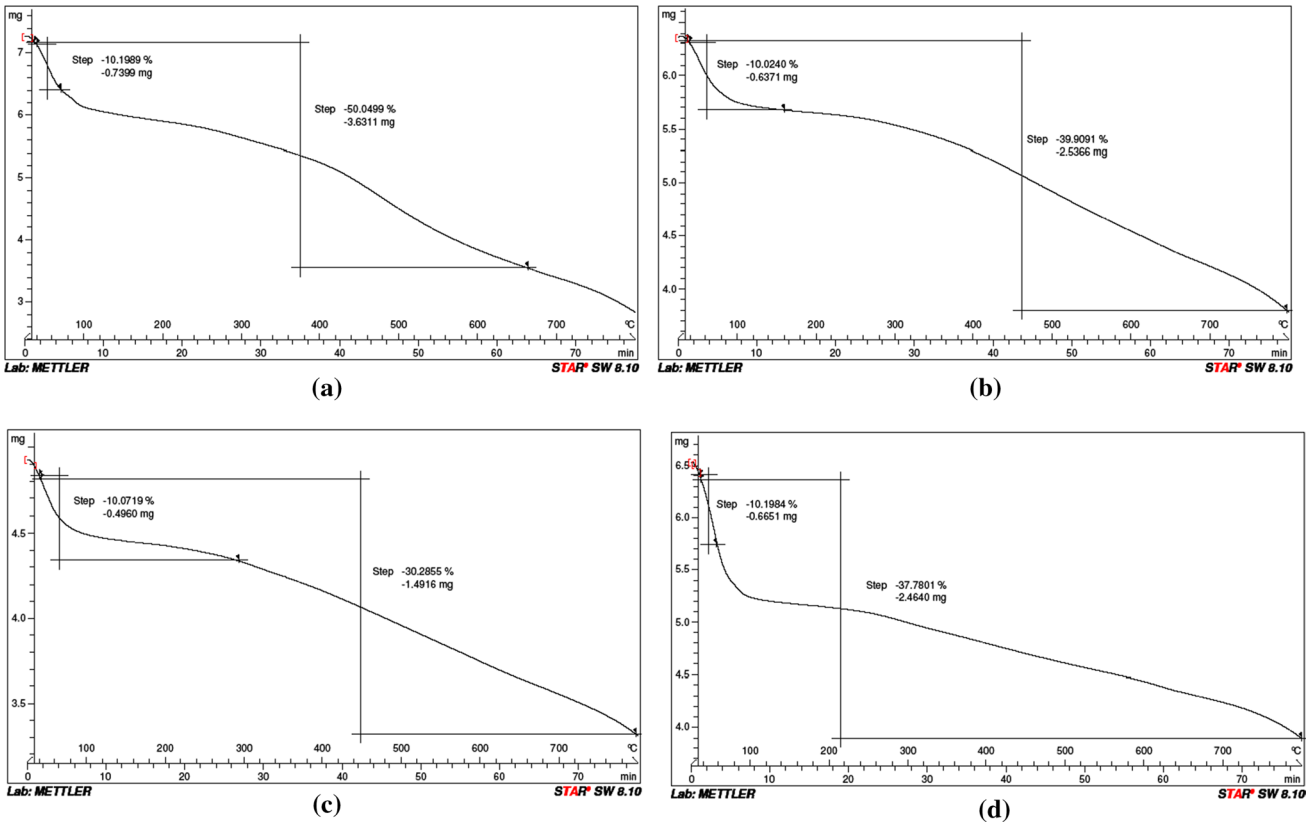
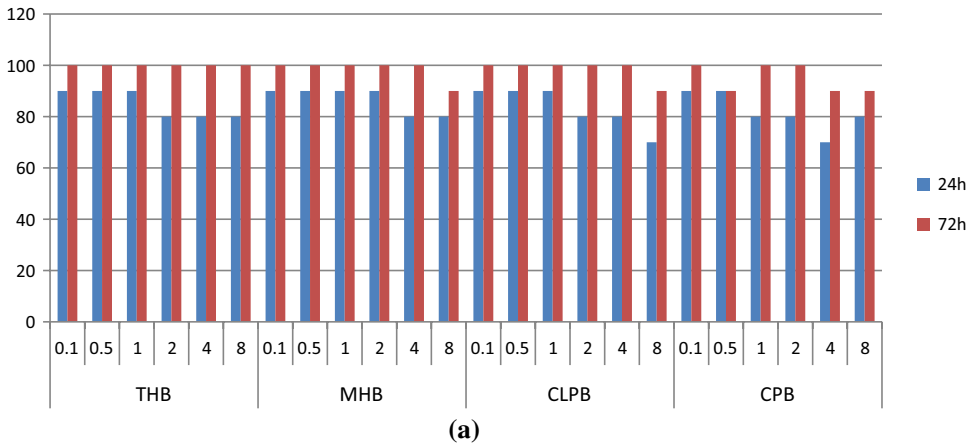


Fig. 2 Thermogravimetric analysis of tender coconut husk biochar (**a**), mature coconut husk biochar (**b**), coconut leaf petiole biochar (**c**) and coir-pith biochar (**d**)

3.2 Ecotoxicological assay

Cent percent germination was recorded within 72 h of sowing of the cowpea seeds in biochar-admixed soils, which was on par with control treatment having no-biochar soil (Fig. 3a, b). Our results were similar to those of Hoover (2018) who reported that coconut shell biochar had neutral to positive effect on the germination and growth of *Coreopsis grandiflora*, *Leucanthemum superbum* and *Eschscholzia californica* seeds. In an earlier experiment, coconut husk biochar mixed in dry sand was able to induce good germination in lettuce seeds when added @ 0.5% concentration and improved the seedling properties of maize at 1% concentration; however, an inhibition in lettuce germination was observed when added at 1% concentration (Vasujini et al. 2014). Ecotoxicological test of different biochars on germination of wheat, mung bean and clover seeds had indicated that germination rate and seedling growth parameters were influenced by the dosage biochars and the type of seeds. One of the reasons given for the difference in germination rates was the pyrolysis temperature and residence time during production of biochars. A pyrolysis at 300 °C had the likelihood of increased bioavailability of heavy metals that reduced germination percentage compared to biochars produced at 500 °C (Benavente et al. 2018).

In the earthworm avoidance test conducted by us, the number of earthworms found in different coconut biomass biochar admixed soils was equal or slightly lower than the numbers found in no-biochar soil (Fig. 4). In none of the tests, complete avoidance by earthworms was recorded (data not included). Our results corroborate the application of spruce chip biochar on earthworm *Apporectodea caliginosa* avoidance when added @ 16 g/kg soil in vitro and in field studies. No significant effect on earthworm density and biomass was detected in the study and it was concluded that spruce chip biochar had no toxic effect on earthworm (Tammeorg et al. 2014). As earthworms were sensitive to soil moisture content and pH, any significant changes to these two soil properties upon addition of biochars had an appropriate effect on earthworms too. Thus the positive results of seed germination and earthworm avoidance tests confirmed that the coconut biomass biochars produced by our protocol were not toxic to plants and soil macro-fauna in the dosages tested.



(a)

(b)

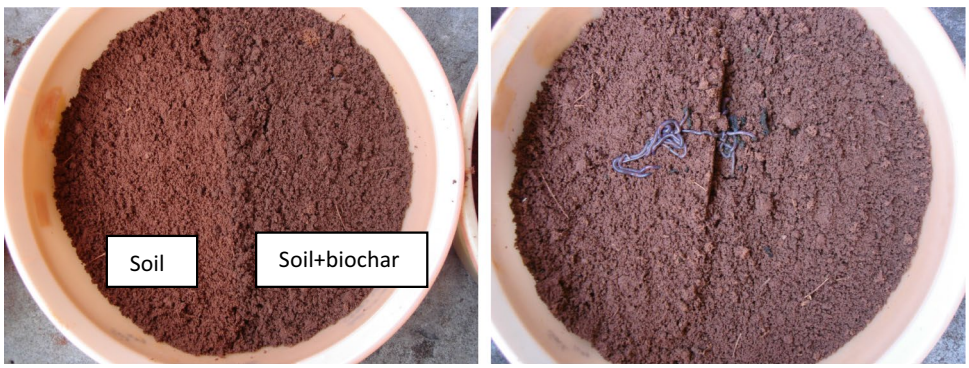


Fig. 3 Results of cowpea seed germination experiment using different types of coconut biochars. *THB* tender coconut husk biochar, *MHB* mature coconut husk biochar, *CLPB* coconut leaf petiole biochar, *CPB* coirpith biochars (**a**), Cowpea seed germination in soil mixed with coconut leaf petiole biochar at different doses. Similarly all biochars at different rates were tested for seed germination (**b**)

Fig. 4 Earthworm avoidance test performed by adding biochar to one half of the soil in the basin and other half containing only soil. *Eudrilus* sp. earthworms (10 numbers) were released at the centre and allowed to migrate to either sides. After a period (4 h and 15 days), the number of earthworms in each half were counted. The test was performed with all four types of coconut biomass residue biochars at 0.1, 0.2, 0.5 and 1% concentrations

3.3 Biochar-soil incubation experiment

Two biochars, THB and CPB, were taken up based on their widely varying organic carbon and pH values for the biochar-soil incubation study. The impact of mixing of THB and CPB alone and with coconut leaf vermicompost on the chemical parameters of soil is given in Table 2. With an increase in dosage of biochars, a significant increase ($P \leq 0.05$) in organic carbon, N, P, K and pH values were recorded in the soil compared to the recommended dose of fertilizers and control soils at the end of the experiment. The combination of tender coconut husk biochar with coconut leaf vermicompost @ 8 and 4 t/ha, respectively, resulted in a significant increase in the chemical parameters of the soil compared to the application of biochars alone. The increasing trend, compared to the fertilizer and control soil treatments, was observed until the end of the 90-days trial. However, compared to initial (0 day) reading, the final reading (90 days) showed a decrease in the concentrations of

Table 2 Effect of tender coconut husk and coir-pith biochars on soil chemical properties in a 90-days incubation study

Treatments	Org. C (%)		Total N (%)		Avl. P (ppm)		Avl. K (ppm)		pH	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
THB-2	0.43^{e}	0.43^{e}	0.046^{def}	0.040^{c}	39.4^{fg}	33.0^{fg}	107^{f}	105^{f}	4.60^{ef}	4.37^{ef}
THB-4	0.55^{c}	0.51^{cd}	0.050^{cde}	0.050^{ab}	48.3^{d}	38.5^{d}	188^{bc}	166^{e}	4.68^{d}	4.54^{d}
THB-8	0.61^{b}	0.61^{b}	0.053^{cd}	0.050^{ab}	69.6^{a}	65.4^{a}	347^{a}	246^{b}	5.04^{b}	4.80^{bc}
THB2 + 4VC	0.55^{c}	0.54^{c}	0.050^{cde}	0.046^{abc}	41.6^{fg}	37.6^{d}	117^{ef}	111^{f}	4.57^{ef}	4.45^{de}
THB4 + 4VC	0.61^{b}	0.61^{b}	0.050^{cde}	0.050^{ab}	51.7^{c}	41.0^{c}	202^{b}	183^{d}	4.61^{de}	4.84^{b}
THB8 + 4VC	0.66^{a}	0.65^{a}	0.060^{b}	0.053^{a}	61.6^{b}	57.9^{b}	333^{a}	279^{a}	5.13^{a}	5.16^{a}
CPB-2	0.40^{f}	0.38^{f}	0.0433^{ef}	0.040^{c}	29.3^{jk}	29.6^{i}	39^{h}	32^{i}	4.46^{g}	4.16^{h}
CPB-4	0.42^{ef}	0.40^{ef}	0.046^{def}	0.043^{bc}	34.7^{h}	30.2^{i}	42^{h}	38^{i}	4.56^{ef}	4.32^{f}
CPB-8	0.50^{d}	0.48^{d}	0.046^{def}	0.046^{abc}	42.3^{ef}	32.2^{gh}	128^{e}	68^{h}	4.57^{ef}	4.45^{de}
CPB2 + 4VC	0.50^{d}	0.49^{d}	0.050^{cde}	0.043^{bc}	31.1^{ij}	26.6^{j}	62^{g}	28^{i}	4.36^{h}	4.28^{fg}
CPB4 + 4VC	0.54^{c}	0.51^{cd}	0.056^{bc}	0.053^{a}	39.1^{g}	34.8^{ef}	115^{ef}	62^{h}	4.52^{fg}	4.46^{de}
CPB8 + 4VC	0.62^{b}	0.62^{ab}	0.060^{b}	0.053^{a}	44.8^{e}	42.3^{c}	176^{cd}	89^{g}	4.59^{ef}	4.73^{c}
VC-4	0.50^{d}	0.49^{d}	0.040^{f}	0.043^{bc}	32.2^{hi}	30.9^{hi}	52^{gh}	35^{i}	4.31^{hi}	4.20^{gh}
RFD	0.49^{d}	0.49^{d}	0.070^{a}	0.050^{ab}	42.3^{ef}	35.0^{e}	167^{d}	197^{c}	4.90^{c}	4.20^{gh}
CONTROL	0.40^{f}	0.39^{f}	0.040^{f}	0.040^{c}	26.7^{k}	26.4^{j}	39.9^{h}	34.1^{i}	4.25^{i}	4.11^{h}
CD ($P \leq 0.05\%$)	0.05	0.07	0.01	0.01	4.7	3.1	25.79	20.12	0.12	0.17

The results are an average of three soil sub-samples. Means followed by the same letter are not significantly different at $P = 0.05$ using analysis of variance and mean separation (LSD)

THB tender coconut husk biochar, *CPB* coir pith biochar, *VC* coconut leaf vermicompost, *RFD* recommended fertilizer dose. The biochars were added @ viz. 2, 4 and 8 t/ha and coconut leaf vermicompost at constant 4 t/ha

N, P and K in all the treatments. As the soil used in this incubation study was of degraded quality and the coconut biomass biochars had higher pH values, high organic carbon and potassium contents, the addition of the later, therefore, had significant positive impact on the humid tropical soil in terms of crop production capacities. Alleviation of acidity, due to liming effect of biochar (produced from cacao shell, oil palm shell and rice husk) with high pH values, in humid tropical acid soils had been reported to be one of the most important modes of action for improvement of soil fertility (Martinsen et al. 2015; Jeffery et al. 2017; Yao et al. 2019).

Application of organic amendments to soil improve the soil organic matter (SOM) content that increases the soil aeration, retention of water and nutrients and, therefore, enhances the soil quality. Coconut biochars and vermicompost used in our study have more than 15% organic carbon which naturally would have increased the SOM of the soil when added in different doses. Similar higher SOM values were reported by Sukartono et al. (2011) when coconut shell biochar was added with manure to soil. Increased potassium availability in soil is another common effect of biochar reported by many others (Wang et al. 2018).

Coconut husk (Bonneau et al. 2010) and coir dust (Abad et al. 2002) have already been reported to contain very high potassium and, therefore, their biochar addition had resulted in high potassium availability in the degraded soils. Similarly, biochars produced from biomass residues of plantation crops such as palm oil wastes (Lee et al. 2017) were reported to possess high potassium content which helped in improving the potassium availability to many crops. Overall, a significant increase in soil organic carbon and fertility status of soil, when applied with coconut biomass biochar along with coconut leaf vermicompost, indicated their ability to recompense the loss of organic matter and aid in improving the physical, chemical and biological properties of the soils.

The response of general (Table 3) and plant-beneficial microflora (Table 4) in soils, with increase in dosage of the coconut biomass biochars, showed a significant increase ($P \leq 0.05$) in their populations. Barring the bacterial numbers, all other microbiota showed an increasing trend as the incubation progressed. Again, the combination of tender coconut husk biochar at highest dose with coconut leaf vermicompost resulted in the highest increases in microbial counts. Between the two types of biochars, tender coconut husk biochar was observed to improve the microbial properties more than the coir-pith biochar. This was because of the higher pH, organic matter, as well as the nutrients present in the former. Increase in microbial abundance upon addition of biochar had been reported in several instances (Lehmann et al. 2011; Abujabhah et al. 2016). The increase was greater when biochar was mixed with composts (Abujabhah et al. 2016). These positive changes in microbiota population and structure in soils upon addition of biochars and composts could be due to to many possible factors (Lehmann et al.

Table 3 Effect of tender coconut husk and coir-pith biochars on general microbial communities in a 90-days incubation study

Treatments	Bacteria ($n\times10^5$)		Fungi ($n\times10^4$)		Actinomycetes ($n\times10^4$)	
	Initial	Final	Initial	Final	Initial	Final
THB-2	23.6^{hi}	21.5^{fg}	38.7^{e}	33.8^{ef}	42.1^{ef}	61.9^{fgh}
THB-4	32.2^{fg}	25.0^{efg}	35.0^{ef}	47.8^{c}	45.6^{de}	62.9^{fg}
THB-8	57.7^{ab}	26.4^{def}	48.3^{d}	49.2^{c}	63.7^{b}	68.4^{ef}
THB2 + 4VC	49.0^{cd}	25.4^{efg}	56.1^{bc}	70.4^{b}	43.8^{de}	72.2^{def}
THB4 + 4VC	46.3^{d}	27.8^{cde}	61.0^{b}	80.4^{a}	66.9^{b}	85.0^{abc}
THB8 + 4VC	62.7^{a}	41.0^{a}	82.7^{a}	88.7^{a}	79.3^{a}	92.8^{a}
CPB-2	22.1^{ij}	15.4^{i}	27.9^{fg}	38.5^{cde}	50.1^{cd}	52.1^{hi}
CPB-4	26.6^{ghi}	30.5^{bcd}	37.8^{e}	47.7^{c}	54.9^{c}	52.1^{hi}
CPB-8	33.5^{ef}	32.5^{bc}	33.0^{ef}	45.1^{cd}	42.7^{ef}	52.7^{ghi}
CPB2 + 4VC	29.8^{fgh}	21.4^{fg}	50.8^{cd}	62.6^{b}	31.7^{gh}	81.9^{bcd}
CPB4 + 4VC	39.2^{e}	33.7^{b}	37.8^{e}	39.2^{cde}	41.3^{ef}	72.0^{def}
CPB8 + 4VC	54.4^{cb}	44.7^{a}	47.1^{d}	49.4^{c}	47.7^{de}	88.9^{ab}
VC-4	26.8^{ghi}	20.4^{gh}	30.7^{ef}	60.2^{b}	36.4^{fg}	77.4^{cde}
RFD	14.5^{k}	16.1^{hi}	31.8^{ef}	35.3^{def}	26.3^{h}	48.7^{i}
CONTROL	17.0^{ijk}	12.3^{i}	22.7^{g}	25.7^{f}	30.7^{gh}	18.0^{j}
CD ($P\leq0.05\%$)	10.79	7.99	13.19	17.10	10.69	17.18

The results are an average of three soil sub-sample and three plates/sub-samples given as $n\times10^{x}\times$cfu/g dry weight soil. Means followed by the same letter are not significantly different at $P=0.05$ using analysis of variance and mean separation (LSD)

THB tender coconut husk biochar, *CPB* coir pith biochar, *VC* coconut leaf vermicompost, *RFD* recommended fertilizer dose. The biochars were added @ 2, 4 and 8 t/ha and coconut leaf vermicompost at constant 4 t/ha

Table 4 Effect of tender coconut husk and coir-pith biochars on plant-beneficial microbial communities in a 90-days incubation study

Treatments	Free living nitrogen-fixers ($n\times10^2$)		Phosphate solubilizers ($n\times10^4$)		Fluorescent pseudomonads ($n\times10^2$)	
	Initial	Final	Initial	Final	Initial	Final
THB-2	7.3^{ef}	1.7^{hi}	8.1^{cd}	4.3^{e}	1.3^{ef}	3.6^{de}
THB-4	5.0^{fg}	2.1^{h}	6.3^{d}	5.0^{de}	2.6^{cde}	4.4^{cd}
THB-8	6.9^{ef}	4.0^{fg}	7.9^{cd}	7.4^{c}	3.9^{c}	3.2^{de}
THB2 + 4VC	6.8^{ef}	12.6^{b}	7.5^{d}	6.5^{cd}	5.4^{b}	2.3^{e}
THB4 + 4VC	13.3^{a}	11.2^{b}	7.7^{d}	9.7^{b}	2.4^{cde}	6.4^{bc}
THB8 + 4VC	12.9^{ab}	16.4^{a}	12.2^{a}	15.5^{a}	3.2^{cd}	9.0^{a}
CPB-2	11.7^{abc}	2.3^{gh}	7.9^{cd}	5.0^{de}	1.4^{ef}	2.6^{de}
CPB-4	10.4^{bcd}	2.9^{gh}	7.9^{cd}	4.8^{de}	3.2^{cd}	4.5^{cd}
CPB-8	9.3^{cde}	5.2^{ef}	6.3^{d}	5.1^{de}	3.6^{c}	6.3^{bc}
CPB2 + 4VC	10.4^{bcd}	7.3^{cd}	10.3^{b}	10.3^{b}	5.3^{b}	7.5^{ab}
CPB4 + 4VC	10.4^{bcd}	7.3^{ef}	6.5^{d}	7.9^{c}	3.9^{c}	2.9^{de}
CPB8 + 4VC	14.4^{a}	8.1^{c}	9.6^{bc}	11.0^{b}	6.9^{a}	6.3^{bc}
VC-4	8.4^{de}	4.2^{fg}	4.4^{e}	8.0^{c}	1.9^{de}	3.5^{de}
RFD	2.6^{gh}	0.0^{i}	0.0^{f}	1.3^{f}	0.0^{f}	2.1^{e}
CONTROL	2.1^{h}	0.0^{i}	0.0^{f}	0.0^{f}	0.0^{f}	0.0^{f}
CD ($P\leq0.05\%$)	4.45	2.99	2.89	2.92	2.4	3.12

The results are an average of three soil sub-samples and three plates/sub-sample given as $n\times10^{x}\times$cfu/g dry weight soil. Means followed by the same letter are not significantly different at $P=0.05$ using analysis of variance and mean separation (LSD)

THB tender coconut husk biochar, *CPB* coir pith biochar, *VC* coconut leaf vermicompost, *RFD* recommended fertilizer dose. The biochars were added @ 2, 4 and 8 t/ha and coconut leaf vermicompost at constant 4 t/ha

2011; Zhu et al. 2017) such as (i) improved pH of the soils that could have resulted in better mineralization activity and, therefore, an altered microbial community structure, (ii) physiochemical characters of biochar and the compost added to soil and (iii) increased nutrient and water retention in the pores of biochar offering a suitable niche for soil microflora.

An interactive influence of biochar + vermicomposts and the microflora could be the reasons for this combination offering a better nutrient status to the soils. The coconut leaf vermicompost contained very high populations of plant-beneficial microbiota such as phosphate and silicate solubilizers (Gopal et al. 2009) which impacted the soil microbial structure significantly in the first 100 days of its application (Gopal et al. 2012). Upon the addition of such microbiota via the vermicompost along with the biochar, a positive impact on the fertility of the soils in terms of improved nutrient availability has been well documented (Maienza et al. 2017). Deb et al. (2015) also reported that in phosphorus-deficient soils, the addition of biochars significantly improved the population of phosphate solubilizing bacteria and, therefore, the availability of phosphates to plants. Microbiome studies from three different European sites (UK, France and Italy) after application of same biochar indicated a shift towards copiotrophic ecology and increased mobility of ammonium and phosphates and, therefore, an increased availability of these two nutrients to crops (Jenkins et al. 2016). Biochar application not only increased the potassium availability in soils directly, but also enhanced the growth of potassium solubilizing bacteria which could then solubilize K-containing minerals in soils with high K contents (Wang et al. 2018).

The dehyrogenase enzyme activity in the soils is considered as a good indicator of soil quality and microbial activity (Paz-Ferreiro et al. 2012). This enzyme is an important intracellular component of oxidative phosphorylation physiology in microorganisms linking it to their respiratory process and giving a direct measurement of soil microbial biomass and activity. This enzyme also indicates the C mineralization status of soil. It was observed in our studies that application of both coconut biomass biochars significantly increased ($P \leq 0.05$) the dehydrogenase activity at all doses compared to soils that was applied with inorganic fertilizer and control soil with no addition (Fig. 5). The combination of tender coconut husk biochar with coconut leaf vermicompost in soil exhibited the highest dehydrogenase activity. One of the possible reasons for higher dehydrogenase activity could be the pH neutralization of acid soils by coconut biomass biochars alone or mixed with vermicompost, which increased the activity of soil microbiota, as was earlier reported in holm oak biochars applied to two contrasting Mediterranean soils (Teutscherova et al. 2018). Yao et al. (2019) also reported improved soil microbial and enzyme parameters when they applied *Solanum tuberosum* biochars to acidic soils thus supporting our results.

3.4 Pot trials to evaluate biochar effect on arbuscular mycorrhizae (AM) fungi

The pH, moisture content, spore count, root mycorrhizal colonization along with total plant and nodule dry weights, recorded on 50th day of the experiment (co-variant analysis

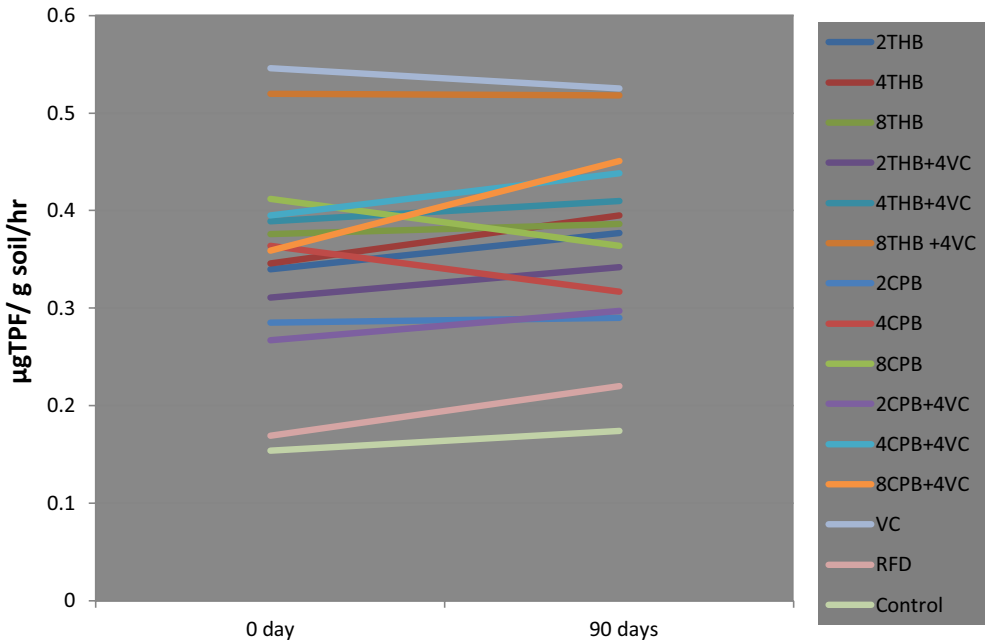


Fig. 5 Effect of tender coconut husk and coir-pith biochars on soil dehydrogenase enzyme activity in a 90-days incubation study

was performed factoring in pre-treatment data for pH, soil moisture and AM spore contents) are given in Table 5. All soil parameters showed increased value in all treatments at 50-days period compared to the start of the experiment except the pH which reduced significantly in the inorganic fertilizer application. A significantly high AM spore count and root colonization, and nodule dry weights were recorded in the tender coconut husk biochar at lower dose (2 t/ha) mixed with coconut leaf vermicompost as well as soil + vermicompost treatments. The plant dry weights in these treatments were marginally less than the inorganic fertilizer applied treatment. Addition of inorganic fertilizer reduced the mycorrhizal spore count, root colonization and nodule dry weight compared to all other treatments yet resulted in good plant growth and high plant dry weight than other treatments. Easy availability of required quantities of nutrients for the plants via inorganic fertilizer had resulted in highest plant dry weight even though there was significant reduction in AM spore numbers, root colonization, and nodule dry weight. In comparision, application of vermicompost was known to improve the mycorrhizal association and root nodulation in legumes (Maji et al. 2017).

Humic acid present in vermicompost is regarded to be the chemical that enhances the mycorrhizal and nodule association in legumes. Coconut leaf vermicompost also contains 10–13% humic acid (Gopal et al. 2010) and, therefore, was able to enhance these microbiological properties in the experiment. In another report, where cowpea was grown in soil amended with worm compost and biochar, no significant difference in mycorrhizal colonization was observed. However, when worm compost + biochar and 50% recommended dose of fertilizer was added, the above-ground biomass and nutritional factor were found to be the same as cowpea grown in soil with 100% recommended fertilizer dose. This proved that the positive effect of alternative soil amendments and AM fungi on plant yield nutrition could save on inorganic fertilizer cost in a significant manner (Cobb et al. 2018). It was also reported that biochar application improved nitrogen fixation by legumes, which also played a major role in improving plant growth (Yao et al. 2019). Our pot experimental results indicating that application of biochar along with vermicompost could give good crop growth were supported by the fact that biochar applications were found to be more effective for tropical soils than temperate ones (Jeffery et al. 2017).

3.5 Field study

The THB was taken up for the field study based on the positive results obtained from the biochar-soil incubation and pot studies carried out earlier. Combined application of the THB with coconut leaf vermicompost gave 1.814 kg of chilli fruits and application of vermicompost alone gave yield of 1.575 kg. The unamended plot yielded in 0.96 kg chilli. It was evident from the field trials that the addition of recycled coconut biomass residues via vermicompost or vermicompost mixed with biochar could increase the yield of chilli more than 50%, compared to the unamended treatment. Though the yield difference between the two amended treatments was small, the yield curve of the vermiompost + biochar-treated plants was more prolonged and sustainable (Fig. 6). Perhaps easily and quickly available nutrients triggered a quicker yield and quicker cessation of yield in soil treated with vermicompost, while, the biochar would have adsorbed the easily available nutrients from the vermicompost and released it slowly and sustainably in the soils applied with both these amendments. This clearly indicated that even at a low application rate of 2.0 t/

Table 5 Effect of application of tender coconut husk biochar alone and with coconut leaf vermicompost on arbuscular mycorrhizal (AM) sporulation, root colonization, nodule and plant dry weights

Treatments	pH	Soil moisture content (%)	AM spore count/10 g soil	AM root colonization (%)	Plant dry weight (g)	Nodule dry weight (g)
	Post	Post	Post	Post	Post	Post
THB-2	5.2^{b}	47.3^{bc}	22	63^{a}	0.61	0.02^{c}
THB-4	5.52^{a}	50.2^{b}	21	62^{a}	0.67	0.04^{ab}
THB2 + 4VC	5.56^{a}	68.9^{a}	26	65^{a}	0.72	0.05^{a}
THB4 + 4VC	5.47^{a}	70.1^{a}	22	61^{a}	0.70	0.03^{bc}
VC-4	5.49^{a}	65.1^{a}	28	63^{a}	0.68	0.05^{a}
RFD	4.66^{c}	41.4^{c}	17	43^{b}	0.75	0.001^{d}
Control	5.5^{a}	44.2^{bc}	24	61^{a}	0.55	0.04^{ab}
CD ($p = 0.05$)	0.31	8.6	NS	12.1	NS	0.017

The results (pH, SMC, AM spore counts) are data-assessed through co-variance analysis where the pre-treatment data was factored in with the post treatment observations. The pre-treatment data was collected on 1st day of the start of the experiment and post-treatment data (post) on 50th day when the experiment was closed. For all the means, $N = 3$ samples were used

THB tender coconut husk biochar, *VC* coconut leaf vermicompost, *RFD* recommended fertilizer dose. The biochars were added @ 2 and 4 t/ha and coconut leaf vermicompost at constant 4 t/ha

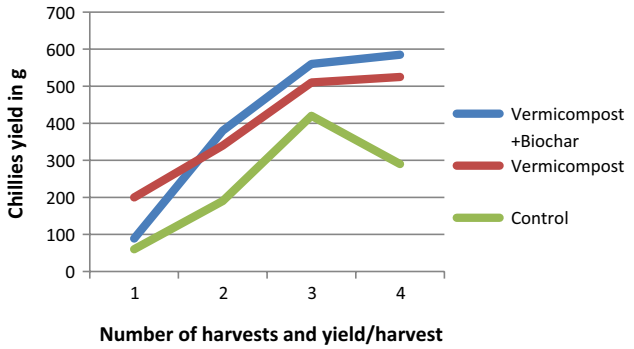


Fig. 6 Yield curve of chilli when applied with coconut leaf vermicompost and tender coconut husk biochar + vermicompost

ha biochar, the nutrient use efficiency was greatly improved. One of the main reasons of this result could be explained by the report of Hagemann et al. (2017) that the nutrient-rich organic coating of the biochars happening in presence of vermicompost which helped biochar-water interaction and better nutrient retention. More support to our results was from a 3 years field study in Northern Vietnam where biochar mixed with vermicompost had reduced nitrogen loss, soil erosion, improved water use efficiency, thereby, increasing the yield of maize (Doan et al. 2015). The combination of vermicompost + biochar was also seen to improve the groundwater quality as a result of reduced percolation of nitrogen in the agricultural fields. Increasing the amounts of biochar with different quantities of vermicompost had indicated increased yield in maize and cabbage but only up to a certain point. Though observations from our singular field study were very encouraging, it would need to be repeated to confirm the positive results of coconut waste biochar and coconut leaf vermicomposton the yield of vegetables.

4 Conclusions

Coconut biomass residues such as tender and mature coconut husks, coconut leaf petiole and coir pith were successfully recycled to biochars via pyrolysis using a simple charring kiln ideal for small and marginal farmers. Suitability of coconut biochars as soil amendment was established by seed germination and earthworm avoidance tests. The alkaline pH (> 7.5) of biochars made it an ideal input for humid tropical soils that are mostly acidic in nature. High potassium content (> 2.5%) makes them a very useful organic K source for plants; needed for their growth, yield and protection from pests and diseases. Application of biochar in graded doses with or without coconut leaf vermicompost improved the N, P and K contents in soil along with the promotion of soil microbiota and enzyme activities. It also showed plant growth promotion and enhanced mycorrhizal colonization and root nodulation in cowpea. Field trial with tender coconut husk biochar + coconut leaf vermicompost was able to improve chilli yield by 50% compared to non-amended soils. Our studies clearly prove that the voluminous lignin-rich biomass residues generated from coconut plantations could be easily converted to biochars, particularly tender coconut husk biochar, that can be added as amendment @ 2 t/ha along with coconut leaf vermicompost for aiding regenerative agriculture by enhancing soil health and fertility and improving crop yield.

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