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PRODUCTION AND PHYSIO-CHEMICAL CHARACTERIZATION OF BIOCHAR OBTAINED FROM COFFEE PROCESSING WASTES AND CROP RESIDUES OF COFFEE PLANTATION

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Abstract– Biochar is a pyrogenous organic material obtained mostly from various plant based waste biomass through pyrolysis process. The production of biochar from various plant based waste biomass is a part of the modern agenda to recycle bio-wastes and its application in agriculture is reported to improve the soil health in several ways. The other potential benefit of biochar include pollution remediation due to its high cation exchange capacity and specific surface area. In the present study, production and physico-chemical characterization of biochars obtained from coffee processing waste biomass (cherry husk and parchment husk) and crop residues from coffee plantation (diseased uprooted coffee stem and pepper stem waste) were attempted following standard methodologies. The statistical analysis of the data on biochar yield and physico-chemical parameters (moisture, pH, fixed carbon level, ash and volatile matter) of the biochar produced in the present study indicated that among the four waste biomass studied, significantly (p=0.05) highest biochar yield (40.53%) and fixed carbon level (54.53%) were recorded in cherry husk waste biomass. While, biochar obtained from pepper stem waste showed significantly (p=0.05) highest pH level (10.85%) and lowest moisture level (3.59%). Significantly (p=0.05) highest volatile matter (66.3%) and ash (18.13%) contents were observed in the biochars obtained from pepper stem waste and cherry husk, respectively. These data indicated that biochar yield and physico-chemical parameters of the biochar primarily depends on the chemical nature of waste biomass or crop residues. Therefore, screening of biochar obtained from various waste biomass or crop residues is pre-requisite for assessing its agronomical and environmental potentials. The results of the present study has provided baseline information of biochars obtained from various coffee processing waste biomass as well as crop residues from coffee plantation.

INTRODUCTION

Coffee is reckoned to be the second largest traded commodity in the world after oil. Coffee is grown in about eighty countries, mostly in the developing countries and largely consumed in the developed countries. India is the seventh largest producer of coffee in the world with 4,59,895 hectares of land under coffee cultivation (Arabica-23,3081 hectare; Robusta-22,6814 hectare) with the total production of 2.98 lakh metric tonne of coffee bean during 2019-2020 harvest season (Anonymous, 2021). All over the world, coffee fruits are processed at the estate by either of the two methods *viz.* wet and dry. In India, about 80% of arabica and 15% of robusta coffees are wet processed. The remaining quantities are dry processed. Wet processed coffee fruits yield parchment coffee and dry processed coffee fruits results in cherry coffee (Anonymous, 2014).

Generation of by-products or residues is inherent in all agri-production sectors and coffee sector is no exception. Coffee being the second largest traded commodity in the world, it generates large amount of by-products or residues. It is estimated that over ten million tonnes of solid residues are generated yearly from coffee worldwide (Echeverria, 2017). There are three levels in coffee processing right from harvesting to consumption. Primary processing (occurring at the estate level), secondary processing (taking place at the coffee curing factories) and tertiary processing (includes activities like roasting of coffee bean, grinding & packaging of roasted coffee and industrial production of instant or soluble coffee). Coffee processing at the estate level generates two by-products *viz*. fruit skin (commonly known as pulp) and mucilage. Coffee processing at curing factories results in two more by-products (parchment husk from parchment coffee and cherry husk from cherry coffee). Spent coffee ground is yet another by-product generated during the industrial production of instant or soluble coffee. Coffee pulp is converted into compost or vermi-compost at the estate itself and the other coffee residues (parchment husk, cherry husk and spent coffee ground) are largely used as a source of fuel under Indian condition. The approximate yield of various by-products resulting during coffee processing along with total quantity of by-products produced annually in India are showed in Table 1.

Among the various pests affecting the coffee crop, coffee white stem borer (CWSB) is the most dreaded pest of arabica coffee in India. As the CWSB pest completes its lifecycle within the coffee stem, timely implementation of recommended pre-emptive measures are crucial to evade the pest infestation onto the coffee stem (Roobak *et al*. 2019). As per the current recommendation, the CWSB pest infested arabica plants should be uprooted and burnt immediately to avoid further spread of infestation within the coffee estate (Anonymous, 2014).

Pepper is grown as an inter-crop in coffee plantation and pepper vines are trained on the jungle trees available in the coffee orchard. The harvested green pepper is further processed to remove pepper seeds from the main stem of the pepper using deconer machine. The deconing of the harvested pepper result in the generation of pepper stem waste biomass (Anonymous, 2014).

In recent years, biochar is attracting interest worldwide because of its potential to improve soil health, in particular. Biochar is one of the most popular sources of soil ameliorant and produced from the pyrolysis or combustion of waste organic material under limited oxygen condition. Biochar is different from organic matter and it composed of aromatic carbon rings that are more stable in the soil (Maguire *et al*. 2010). Application of biochar in soil has been reported to influence several characteristics of soil such as electrical conductivity, pH, cation exchange capacity, nutrient level, porosity, bulk density, microbial community structures (El-Naggar *et al*. 2018; Sheng *et al.* 2018; Dai *et al*. 2020; Zeeshan *et al*. 2020) and maintains soil moisture, as its water holding capacity is high (Endriani *et al*. 2013). The changes brought out by the biochar in the soil environment enhances agricultural productivity. Further, owing to its unique specific surface properties and high cation exchange capacity, biochar displays exceptional efficiency in removing pollutants like herbicides, dyes, pesticides, antibiotics and heavy metals (Oliveira *et al*. 2017).

Reports on the production of biochar from coffee production system are indeed scarce and the published reports mostly relates to production of biochar from spent coffee ground (Lindiamara *et al*. 2019, Mauro *et al*. 2019, Naruephat, 2019, Pravin *et al*. 2019, Marinos *et al*. 2020, Silva *et al*. 2021[ab], Tran *et al*. 2021 and Xin *et al*. 2021). Nonetheless, very few reports are available on the production of biochar from cherry husk (Domingues *et al.* 2017; Kiggundu *et al*. 2019; Setter *et al*. 2020 and Silva *et al*. 2021[ab]), parchment husk (Lindiamara *et al*. 2019) and coffee chaff (Quosai *et al*. 2018). As in case of coffee, reports on biochar production of pepper stem waste biomass are also very limited (Jong-Hwan *et al*. 2015; Azri *et al*. 2022).

Globally, biochar production is increasing year on year, as the awareness and demand for biochar raises. Considering the growing importance of biochar worldwide and limited reports available on biochar production from coffee processing wastes and crop residues from coffee plantation, it is imperative to generate baseline data on the

Table 1. Approximate yield of various by-products (kg/tonne of primary product) and total quantity of by-products produced annually in India

Primary product	By-product	Yield	Annual production of by-products (MT)
Coffee fruit	Fruit skin/pulp	400-450	3 lakh
Parchment coffee	Parchment husk	150-200	30
Cherry coffee	Cherry husk	480-520	2 lakh
Roasted ground coffee	Spent coffee ground	2,000	2.3 lakh

production potential and physio-chemical characterization of biochar from coffee processing waste biomass and crop residues from coffee plantation. In this direction, the present investigation was aimed to generate baseline data on the production perspectives and physio-chemical characterization of biochar from diseased uprooted coffee stem, pepper stem waste, cherry husk and parchment husk. Transformation of coffee processing wastes and crop residues from coffee plantation into biochar will be more attractive in the context of sustainable production of coffee cultivation.

MATERIALS AND METHODS

Sample collection and pre-processing

The study was carried out at the research farm of Central Coffee Research Institute (CCRI) located at Chikkamagaluru district in Karnataka state during 2019-2020 coffee harvest season. The waste biomass for biochar production such as diseased uprooted coffee stem (CS) and pepper stem waste (PSW) biomass were collected from research farm at CCRI. The cherry husk (CH) and parchment husk (PH) were collected from M/s. Sargod coffee curing factory located at Chikkamagaluru district in Karnataka state. The diseased uprooted coffee stem (CS) were cut into small pieces using chain saw machine (STHIL brand) prior to charring. The other coffee waste biomass such as PSW, CH and PH were directly used for bio-charring process. The biochars obtained from CS, PSW, CH and PH were designated as CS-BC, PSW-BC, CH-BC and PH-BC, respectively.

Preparation of biochar

The biochar from coffee processing waste biomass and crop residues from coffee plantation was prepared following the protocol detailed in the CRIDA–NICRA research bulletin (Venkatesh *et al*. 2018). The waste biomass were pyrolyzed at 500 °C for about 30 minutes. The yield of the biochar was calculated as follows and the yield values were average of three independent batch trials.

Yield (%) = [Amount of biochar (kg) obtained at 500 °C÷Amount of fresh waste biomass (kg)] x 100

Analytical methods

All the waste biomass were grounded in a laboratory mixer and sieved using 1 mm size test sieve (M/s. Techno Instruments Company, Bangalore). A well homogenised sample portion was used for various analytical testing. The pH of the various biochars (5 gram sample in 50 ml double distilled water and allowed to stand for 30 minutes) was measured after calibrating the pH meter with the standard buffer solutions (Lab Man make pH meter model no. LMPH-10). The moisture content in the biochars was determined following the standard method (Anonymous, 2003). The volatile matter, ash and fixed carbon content in the biochars were estimated following the procedure detailed in Domingues *et al*. (2017). In brief, the waste biomass was oven dried at 105 °C for 1 hour and then heated in a covered crucible inside a muffle furnace at 950 °C for 6 minutes. The resulting loss of mass refers to volatile material (VM). The biochar was then returned to the muffle furnace and heated in an open crucible at 750 °C for 6 hours. The mass of material remaining after incineration refers to ash. Finally, the fixed carbon (FC) was determined by the following equation:

Fixed carbon (%) = [100 – (VM + Ash)]

Statistical analysis

The data were subjected to analysis of variance (ANOVA) according to least significant difference test to indicate statistically significant differences between variables following the Agress package (version 3.01 data entry module and version 7.01 ANOVA package for researchers).

RESULTS AND DISCUSSION

Biochar yield

The biochar yield levels recorded in the present study (21.95% to 40.53% at 500°C) are well within the range reported by Tomczyk *et. al*. (2020) for a variety of waste biomasses (corn stover-17%; dairy manure-97%). As seen in Table 2, among the four waste biomasses studied in the current study, the CH waste biomass has recorded significantly (p=0.05) highest biochar yield (40.53% at 500 °C), while Kiggundu *et al*. (2019) reported 29.9% of biochar yield in CH waste biomass at the pyrolysis temperature 550 °C. These results clearly indicated that biochar yield decrease with increasing temperature due to increased volatilization rate of organic molecules which occur at higher temperature (Ki *et al*. 2013; Bordoloi *et al*. 2016; Biswas *et al*. 2017).

The biochar yield from CS waste biomass registered in the present study (28.5% at 500 °C) was

Table 2. Biochar yield and moisture level in biochars obtained from crop residues of coffee plantation and coffee processing waste biomasses

Residue	Biochar yield (%)	Moisture level (%)
Coffee stem	28.50 ± 1.32	7.43 ± 0.32
Pepper stem waste	21.95 ± 2 .36	3.59 ± 0.24
Cherry husk	40.53 ± 2.36	6.15 ± 0.82
Parchment husk	30.03 ± 2.86	6.47 ± 0.45
CD (0.05)	4.89	1.09

close to the biochar yields reported for other woody stems such as bamboo stem (26.3% at 450 °C) by Yao *et al.* (2012) and mulberry stem (26.2% at 550 °C) by Zama *et al*. (2017). The biochar yield from PSW biomass observed in the current study was 28.5% at 500 °C when compared to the biochar yield of 23.6% reported by Jong-Hwan *et al*. (2015) in pepper stem waste at the pyrolysis temperature of 600 °C and the variation in biochar yield due to differences in the pyrolysis temperature. The data on biochar yield from pH waste biomass (30.03%) recorded in the present study could not be compared, as there are no published reports relating to biochar yield for PH waste biomass.

As reported in the literature, the biochar yield depends on various factors such as biomass type, moisture level available within the biomass, duration of pyrolysis, pyrolysis temperature as well as composition of the biomass in particular lingo-cellulosic content in the waste biomass (Kloss *et al*. 2012; Sun *et al*. 2014; Shariff *et al*. 2016). Demirbas *et al*. (2004) reported that high lignin content in the waste biomass result in higher biochar production. Though the CS waste biomass is reported to contain higher levels of lignin (28%) and 59% of cellulose (Antonia Amanda da Silva *et al*. 2014), as compared to CH and PH waste biomasses (Alves *et al*. 2017), the biochar yield was low in CS waste biomass. This may possibly be due to higher moisture content in the raw CS waste biomass. In the current study, the moisture content recorded in the raw (i.e. before charring) CS, CH, PH and PSW biomasses were 29.13%, 12.5%, 9,9% and 11.05%, respectively (data not shown). These results corroborates the previous findings that the moisture contained in the waste biomass not only increases the energy required to reach the pyrolysis temperature, it also inhibits the biochar formation (Tripathi *et al*. 2016). In the current study, the moisture level recorded in the CH-BC was 6.15% at the pyrolysis temperature of 500 °C, when compared to the moisture level of 4.64% reported by Kiggundu *et al*. (2019) in CH-BC at the pyrolysis temperature of 550 °C.

pH level

Inyang *et al*. (2010) and Lehmann *et al*. (2011) reported that the pH of the biochar is generally alkaline in nature and it ranges from 7.1 to 10.5. As depicted in Fig.1 among the four biomasses studied, the PSW-BC has recorded significantly (p=0.05) highest pH level (10.85 at 500 °C) when compared to the pH value of 9.46 (at 600 °C) reported by Jong-Hwan *et al*. (2015) in PSW-BC. The pH of the CH-BC (8.88 at 500 °C) and PH-BC (8.23 at 500 °C) recorded in the present study was comparable to the pH values reported for CH-BC (9.8 at 450 °C) by Domingues *et al.* (2017) and PH-BC (9.6 at 700 °C) by Lindiamara *et al.* (2019). The pH of the CS-BC was 9.57 was closer to the pH of the biochar obtained from mulberry wood (10.6 at 550 °C), as reported by Zama *et al.* (2017). The differences of pH level in biochar can result from biomass type and pyrolysis temperature. The pH values of biochars are positively correlated with the formation of carbonates and inorganic alkalis. The alkali salts starts separating from the waste biomass at 300 °C onwards and these groups are the main cause of alkaline pH (Yuan *et al*., 2011; Ding *et al*., 2014). The contents of total base cations and carbonates have been reported to increase with increasing temperature contributing to increased pH (Yuan *et al*. 2011).

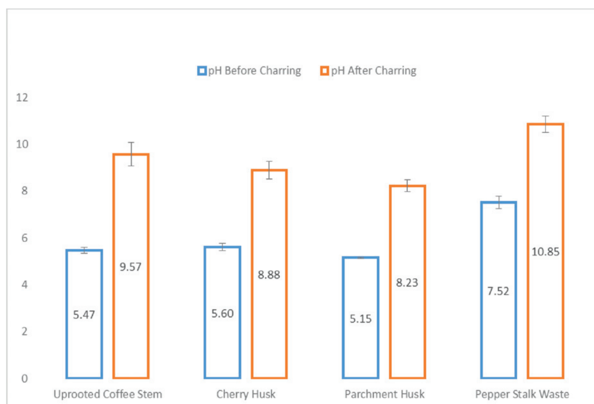

Fig. 1. Influence of various feed stocks on pH of the biochar obtained from crop residues of coffee plantation and coffee processing waste biomasses

Volatile matter

Volatile matter refers to the presence of organic material with low stability and an increase in the pyrolysis temperature results in the larger release of volatile matters causing formation of pores in the biochar (Shaaban *et al*., 2014; Tag *et al*., 2016). The range of volatile matter content registered in the present study (27.35% to 66.3% at 500 °C) are well within the limits reported by Tomczyk *et. al*. (2020) for a number of waste biomasses (pine bark-6% at 750 °C; municipal sewage sludge-87.5% at 900 °C). As seen in Table 3, significantly highest volatile matter content was observed in PSW-BC (66.3% at 500 °C), as compared to other waste biomass studied in the present study. Nguyen *et al*. (2020) reported that the biochar with high volume of pores are best-suited for decontamination process. Owing to the fact that the PSW-BC is relatively more porous in nature, Azri *et al*. (2022) employed PSW-BC for decontamination of pharmaceutical pollutants present in the waste water effluent.

As depicted in Table 3, the volatile matter content in CH-BC was to the tune of 27.35% (at 500 °C) as opposed to the report of Setter *et al.* (2020) who reported that the volatile matter content in CH-BC was 16.26% (at 500 °C). Domingues *et al.* (2017) reported that the volatile matter content in CH-BC ranged from 34.6% (at 350 °C) to 17.6% (at 750 °C). In the present study, the volatile matter content in CS-BC was to the tune of 36.48% (at 500 °C) when compared to the results of Zama *et al.* (2017) who reported that the volatile matter content in biomass derived from mulberry wood was 13.2% at 550 °C. While the volatile matter content in PH-BC was to the tune of 37.93% (at 500 °C) in contrast to the reports of Lindiamara *et al.* (2019) who reported that the volatile matter content in PH-BC was 54.6% at 700 °C. These results clearly indicated that loss of volatile matter increases with increasing pyrolysis temperature.

Ash content

The ash content relates to the mineral fraction that is concentrated during the pyrolysis process. The ash content of biochars increase with increasing pyrolysis temperature resulting from progressive concentration of inorganic constituents (Chen *et al.* 2008). Zama *et al.* (2017) demonstrated increases in Mg, Ca, K and P contents in biochars pyrolyzed at high temperature due to increased ash content. As seen in Table 3, among the four biomasses, CH-BC has registered significantly highest ash content (18.13 at 500 °C) when compared to the results of Domingues *et al.* (2017) who reported 12.9% of ash content in CH-BC at 450 °C. The data on ash content in PH-BC observed in the current study (12.6% at 500 °C) was in line with the reports of Lindiamara *et al.* (2019) who reported that the ash content in PH-BC was 13.6% at 700 °C clearly indicating that the ash content increase with increasing pyrolysis temperature. The ash content in PSW-BC (7.55% at 500 °C) was close to the ash content value (6.2%) reported by Park *et al*. (2021) in pepper stem waste biomass. The ash content in CS-BC (11.7% at 500 °C) was comparable to the ash content value (13.2% at 550 °C) reported by for mulberry wood by Zama *et al*. (2017). In the present study, the biochars derived from non-wood sources such as CH and PH have recorded comparatively higher ash content (18.13% and 12.6%, respectively) than the biochar derived from coffee stem (11.7%). This result corroborates with the results of Mukome *et al*. (2013) who opined that the biochars derived from woody waste biomass have lower ash content in comparison to the biochar derived from non-woody waste biomass.

Fixed carbon content

Fixed carbon content in biochar is generally determined by subtracting the volatile matter and ash content (Domingues *et al.* 2017). In the present study, the CH-BC has registered significantly highest (p=0.5%) fixed carbon content (54.53% at 500 °C), as compared to other biochars produced in this study. Available reports on fixed carbon content in CH-BC were in the order of 60.9% at 450 °C (Domingues *et al.* 2017), 63.73% at 450 °C (Kiggundu, *et al.* 2019), 67.11% at 530°C (Lima *et al*. 2018) and 68.59% at 500 °C (Setter *et al.* 2020). The fixed carbon content in CS-BC was found to be lower (51.82% at 500 °C) when compared to the

Table 3. Proximate analysis of biochars obtained from crop residues of coffee plantation and coffee processing waste biomass

Residue	Volatile matter (%)	Ash (%)	Fixed carbon (%)
Coffee stem	36.48 ± 3.76	11.7 ± 1.26	51.82 ± 0.91
Pepper stem waste	66.3 ± 2.53	7.55 ± 0.67	26.10 ± 0.71
Cherry husk	27.35 ± 2.94	18.13 ± 1.95	54.53 ± 1.10
Parchment husk	38.93 ± 1.71	12.6 ± 1.46	48.50 ± 1.32
CD (0.05)	5.33	2.65	2.29

fixed carbon content reported for other woody stems such as bamboo stem (76.9% at 450 °C) by Yao *et al*. (2012) and 70.8% at 450 °C in mulberry wood (Zama *et al.* 2017) indicating the biomass type may have a role in the fixed carbon content of the biochar. The fixed carbon content in PH-BC (48.5% at 500 °C) recorded in the current study was low when compared to the report of Lindiamara *et al.* (2019) who observed the fixed carbon content in PH-BC was 69.3% at 700 °C. Similarly, the fixed carbon content in PSW-BC (26.1% at 500 °C) was very low and this was in contrast to report of Jong-Hwan *et al*. (2015) who reported the fixed carbon content in PH-BC was 74.3% at 600 °C. The variations in fixed carbon content of biochar is primarily due to pyrolysis temperature and the fixed carbon content of increase with the increasing pyrolysis temperature (Chen *et al*., 2008; Fuertes *et al.,* 2010). The biochars derived from waste biomasses with high content of lingo-cellulosic component (such as CH, CS and PH) have recorded comparatively higher fixed carbon content (54.53%, 51.82% and 48.5% respectively) than the biochar derived from PWS (26.1%) and this result was in conformity with the findings of Mukome *et al*. (2013) who observed higher fixed carbon content in biochar from waste biomasses with high lingo-cellulosic contents.

CONCLUSION

The results of the present study has provided baseline information on the effect of various waste biomass (feed stocks) available in the coffee production system in respect of biochar yield and physio-chemical properties of biochar produced. The results also indicated that the pyrolysis temperature is very crucial in determining the physio-chemical properties of the biochar. The increase in pyrolysis temperature result in increase in the fixed carbon level, ash content and reduction in volatile matter content. It is proposed to further characterize the biochar from coffee processing waste biomass and crop residues from coffee plantation for other characteristics *viz*., cation exchange capacity (CEC), specific surface area, water holding capacity, neutralizing capacity and estimation of nutrient content in coffee biochar as future line of work.

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