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Do varied biochar quality parameters influence on maize growth and yield

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Abstract
In recent years, there has been a substantial increase in the widespread application of agrochemicals to enhance crop yields, there by posing a considerable risk to soil health. In this regard, biochar application has gained considerable interest due to its potential to enhance crop growth and yield and reducing use of agrochemicals. However, there is limited understanding how biochar produced at different temperature with varied quality parameters affects crop growth and yield. To study the impact of biochars from Simarouba seed coat produced at different pyrolysis temperatures (300 [BC_{300}], 400[BC_{400}], and 500°C [BC_{500}]), on maize growth and yield parametersa polyhouse pot experiment was conducted comprising 13 treatments with 3 replications each. Results showed that,T_5 (75% RDF + BC_{300} + 25% Simarouba cake on N basis + SSP), exhibited significantly higher plant height, number of leaves and leaf area plant^{-1} at 60 and 90 DAS, ultimately improving cob length (16.93 cm), cob girth (12.78 cm), number of seedscob^{-1} (474.90), test weight of kernels (24.03 g), grain yieldplant^{-1} (114.09 g), and total dry matter production plant^{-1} (207.21 g).Grain and stover yield ha^{-1} was calculated to be significantly higher in T_5 (6339 and 7762 kg respectively).25% RDF, 75% Simarouba cake on N basis and SSP when applied with BC_{300}(T_{11}) showed significantly higher organic carbon (0.51%), nitrogen (312.48 kg ha^{-1}), phosphorous (24.87 kg ha^{-1}), and secondary nutrient contents. Conversely, with BC_3 (T_{13}) significantly improved bulk density (1.38 dS m^{-1}), water holding capacity (42.98%) and potassium content (270.16 kg ha^{-1}) was found in post-harvest soil.

Keywords: Biochar, different temperatures, nutrient management, maize, growth and yield, soil properties

Introduction
The ongoing rapid growth in the global economy due to enhancing factors like industrialization, urbanization and burgeoning population is gradually reducing arable land. A key challenge for the agriculture sector is to feed the growing population, while at the same time to maintain soil health. In recent years, the extensive use of agrochemicals has risen significantly; posing a threat to soil health. Intensive crop farming on agricultural soils without organic matter addition is a major reason for deterioration of soil fertility and productivity (Lal, 2006) [21]. So, it becomes necessary to develop novel and environmentally benign technologies that improve soil health and resilience (Gisladottir & Stocking, 2005) [13]. Application of biochar to soils is one such approach to improve degraded soils (Coomes & Miltner, 2016) [8]. Biochar is a carbon-rich substance produced by pyrolysis of agricultural or forest biomass characterized by its porous structure, higher stability, and capacity to enhance soil quality and sequester carbon.

Simarouba (*Simarouba glauca* DC.) belonging to family Simaroubaceae, is a medium-sized multipurpose evergreen tree. The average yield of fruit from a 10-year-old plantation of Simarouba will be about 6000 to 8000 kg ha^{-1} (Joshi and Hiremath, 2001) [18]. Its seed consists of 71 per cent woody seed coat and 29 per cent kernel. The tree is having immense value in biodiesel production due to high oil content (61.04%) in its seed kernels (Dash *et al.*, 2008) [9]. After recovery of kernels for biodiesel production, seed shells obtained in huge quantity are considered as waste due to its slow decomposition rate. In this regard, thermochemical conversion of this waste-to-bioenergy can help to enhance the specie bio-energy value chain. The most popular, easy, and efficient method is pyrolysis *i.e.*, thermal decomposition of biomass at elevated temperatures in an inert atmosphere that produces three products: biochar, liquid-bio-oil, and gas-syngas.

Biochar application improves soil pH, available nutrients, and soil organic matter content and due to its porous nature, it helps to retain water and minerals in upper soil layer. Biochar treatments significantly increases soil cation exchange capacity (Laird *et al.*, 2010) [20] that helps to reduce leaching of the essential nutrients from plant root zone and keeps them accessible to the plants, improving their uptake. Biochar contains various nutrients essential for crop growth. Due to its physio-chemical characteristics, biochar promotes the growth of plant roots, enhancing the absorption of nutrients and water, ultimately increasing crop growth and yield. Nutrient contents in biochars are determined greatly by feedstock source and pyrolytic temperature (Ding *et al.*, 2016) [11]. The temperature at which pyrolysis occurs plays crucial role in deciding structure and physicochemical properties of biochar (Jindo *et al.*, 2014) [17]. Hence biochar produced at varied temperature resulted in varied quality biochar.

Biochar application integrated with inorganic and organic fertilizers, can significantly improve crop growth and yield (Dawar *et al.*, 2022; Bai *et al.*, 2022) [10, 4]. So, Biochar *via* pyrolysis from biowaste could be a promising option to use in integration with organic or inorganic fertilizers for enhancing soil productivity (Qian *et al.*, 2014) [30]. In the present study, biochars produced from simarouba seed coat at different temperature were applied in integration with different combinations of inorganic and organic (Simarouba seed cake) fertilizers. The present study aimed to examine the influence of the biochars on crop growth and yield parameters of maize crop as well as properties of post-harvest soils.

Materials and Methods

Biochar production

Slow pyrolysis of Simarouba seed coat (with moisture reduced to 6.28%, and shredded to size 0.2-2 mm) was performed in the fixed-bed tubular reactor at three different temperatures ranging from 300 to 500 °C with a constant heating rate of 10 °C min^{-1}. The reaction time was fixed for four hours and the material was run six times at three different temperatures that made up to a total of 18 runs. The treatment details are given below.

BC_{300}: Biochar produced at 300 °C

BC_{400}: Biochar produced at 400 °C

BC_{500}: Biochar produced at 500 °C.

Pot study

A pot experiment was conducted to know the effect of biochars produced at different temperatures on growth and yield parameters of maize (MAH 14-5). Total 13 treatments were taken (Table 1) with 3 replicates (for each replicate, 3 observations were taken). Study was conducted by filling 10 kg of soil collected from the Mahatma Gandhi Botanical Garden, UAS, GKVK, Bengaluru in each polybag. The collected soil was air-dried and ground to pass through 2-mm sieve. The soil was analysed for various physiochemical properties. The soil texture was sandy loam (60.73% sand; 20.41% silt; 16.86% clay) having pH 6.73; EC, 0.22 dS m^{-1}; organic carbon, 0.46 per cent; bulk density, 1.42 Mg m^{-3}; maximum water holding capacity, 39.70 per cent; available N, 328.70 kg ha^{-1}; available P, 27.51 kg ha^{-1} and available K, 286.32 kg ha^{-1}.The polybags were arranged in completely randomized design (CRD) in a polyhouse in the National Seed Project, UAS, GKVK, Bengaluru. For each polybag, biochars produced at different temperatures were applied at the rate 15 t ha^{-1}.To ensure crop nutrient requirement, different proportions of recommended doses of fertilizers (150 kg N ha^{-1}, 75 kg P_2O_5 ha^{-1}, 40 kg K_20 and 10 kg Zn ha^{-1} [POP, UASB, 2020]) and Simarouba seed cake (7.9% N and 1.07% P_2O_5) were given along with the biochars. N dose was given in two split doses (75 kg at sowing time and remaining 75 kg, 3 weeks after sowing). Two seeds were sown in each polybag and thinned to one seedling after one week of germination. Soil moisture content was maintained at field capacity to avoid draught stress to plants.

Growth and yield parameters of maize

Growth parameters including plant height, number of leaves and leaf area per plants were recorded at 30, 60 and 90 DAS. At the time of harvest, the plants were separated into leaf, stem, root, and cob and dried at 65 ^{0}C until they attained constant dry weight and the overall weight of all plant parts was recorded as dry matter production in g $plant^{-1}$. Yield parameters including number of cobs per plant, cob length, cob girth, number of rows per cob and number of seeds per cob were recorded at harvest of the crop. The harvested grains from cob of each plant were dried in an oven at 60 °C until constant weight was obtained and100 seeds were taken from produce of each treatment, weighed on electronic balance, and expressed as test weight of 100 kernels in grams. The grains from cob of each plant were weighed and the average weight was recorded as grain yield per plant (g) for each treatment. Grain yield ha^{-1} was computed from grain yield $plant^{-1}$, which was expressed in kg ha^{-1}. The dry weight of stover from each plant (g $plant^{-1}$) at harvest was recorded after complete sun-drying and expressed in kg ha^{-1}.

Analytical methods followed for the soil after the harvest of the crop

Soil bulk density (BD) and maximum water holding capacity (MWHC) was determined by using Keen's cup method given by Piper (1966) [29]. For determination of soil pH, potentiometry method suggested byJackson, 2005 [16]was used.Soil pH was measured using glass electrode digital pH meter. The same soil: water suspension (1:2.5) prepared for determination of pH was used for determination of soil electrical conductivity (EC) which was determined using conductivity bridge(Jackson, 2005) [16].The organic carbon in soils was determined by wet digestion method given by Walkley and Black, 1934 [37]. Alkaline potassium permanganate method was followed to estimate available nitrogen content in soils (Subbiah and Asija, 1956) [34]. Available phosphorus in soils was determined by Bray's method (Bray and Kurtz, 1945) [5] using spectrophotometer at 660 nm wavelength and the available potassium in soils was determined by flame photometric method using neutral normal ammonium acetate solution (Jackson, 2005) [16]. Exchangeable calcium and magnesium were extracted with neutral normal ammonium acetate and the content was determined by Versenate titration method. Available sulphur in the soils was extracted by turbidimetric method (0.15% $CaCl_2$) using spectrophotometer at 420 nm wavelength.

Table 1: Treatment details of study on the influence of biochars produced at different temperatures on growth and yield parameters of maize

T_1	Control – 100% RDF without Biochar
T_2	100%RDF+ BC_{300}
T_3	100% RDF + BC_{400}
T_4	100% RDF + BC_{500}
T_5	75% RDF + BC_{300}+ 25% Simarouba seed cake on N basis + SSP
T_6	75% RDF + BC_{400}+ 25% Simarouba seed cake on N basis + SSP
T_7	75% RDF + BC_{500}+ 25% Simarouba seed cake on N basis + SSP
T_8	50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP
T_9	50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP
T_{10}	50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP
T_{11}	25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP
T_{12}	25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP
T_{13}	25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP

Note: T = Treatment, RDF= Recommended doses of fertilizers (for maize), BC = Biochar @ 15 t ha, BC_{300}= Biochar obtained at 300 °C, BC_{400} = Biochar obtained at 400°C, BC_{500} = Biochar obtained at 500 °C, N = Nitrogen, and SSP = Single super phosphate (application of SSP is to balance P requirement of the crop).

Statistical analysis
The data on various parameters recorded during the investigation were tabulated and subjected to statistical analysis using one-way ANOVA. The critical difference (CD) was read at 0.05 probability.

Results and Discussion
a) Influence of application of biochars produced at different temperatures on growth parameters of maize
Plant height
Significant difference in maize plant height were observed at 60 and 90 days after sowing (DAS) as a result of the application of biochars produced at three different temperatures applied in integration with different levels of RDF and Simarouba seed cake (Table 2). At 30 DAS, there was no significant difference found in plant height of the crop.At 60 DAS, higher plant height, measuring 168.83 cm, was shown by T_5 (75% RDF + BC_{300}+ 25% Simarouba seed cake on N basis + SSP), which was on par with T_2 (100%RDF+ BC_{300}), measuring 166.77 cm. While the shorter plant height, measuring 134.40 cm, was observed in T_1*i.e.*, Control (100% RDF without biochar). At 90 DAS, T_5 showed significantly higher plant height (187.01 cm) which was on par with T_2 (185.13). Conversely, the shorter plant height *i.e.*, 148.66 cm was observed in T_1.

Number of leaves
At 30 DAS, the treatments showed no statistically significant variations on the number of leaves per plant (Table 3). But at 60 DAS, there was a noticeable variation in number of leaves per plant among the treatments. However, T_5, T_6 (75% RDF + BC_{400}+ 25% Simarouba seed cake on N basis + SSP), T_2, and T_3 (100%RDF+ BC_{400}) exhibited a significantly higher number of leaves per plant i.e., 10.56. The lowest leaf count per plant (8.89) was observed in T_1 and T_{13} (25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP). At 90 DAS, the higher leaf count per plant was observed in T_5 and T_6 (14.00). These values were on par with T_3 and T_6 (13.89). Conversely, lower leaf count was recorded in T_1 and T_{13} (12.45).

Leaf area per plant
Influence of the treatments on leaf area per plant of maize are mentioned in Table 4. At 30 DAS, there was no noticeable variations in the treatments. But there was significant difference in leaf area per plant among treatments at 60 DAS. At the time, significantly higher value was observed in T_5 (4304 cm^2) which was on par with T_2 (4258 cm^2). Conversely, lower value was seen in control treatment *i.e.*, T_1 (3512 cm^2). Similarly at 90 DAS, higher leaf area per plant was observed in T_5 (5361 cm^2) which was on par with T_2 (5316 cm^2). The lowest value was found in T_1 (4374 cm^2) *i.e.*, incontrol treatment.

Total dry matter production per plant (g)
The total dry matter production per plant after harvest showed a significant difference among the treatments in which the T_5 showed higher value *i.e.*, 207.21 g (Table 5). This was on par with T_2 (205.27 g). While the lower value *i.e.*, 156.45 g was observed in T_1 which was on par with T_{13} (158.61 g).

Studies have consistently demonstrated that the joint use of biochar, chemical fertilizers and organic manure results in improved nutrient retention and root development, resulting in increased nutrient uptake and plant growth (Dawar *et al.*, 2022; Badu *et al.*, 2019, Glaser *et al.*, 2015; and Partey *et al.*, 2014) [10, 3, 15, 28]. With increasing of pyrolysis temperature, plant nutrients in biochar become less available to plants (Tag *et al.*, 2016; Yuan *et. al.*, 2016; Zornoza *et al.*, 2016) [35, 41, 42]. Naeem *et al.* (2017) [25] reported that, higher nutrient concentrations in shoot and root of maize plants were observed with the wheat straw biochar produced at lower temperature compared to biochar produced at higher temperatures. This may be due to decrease in ion exchange functional groups with increase in pyrolysis temperature due to dehydration and decarboxylation (Glaser *et al.* 2002) [14]. So, the biochars produced at lower pyrolysis temperature can effectively improve crop growth and yield, when compared to biochars produced at higher temperatures.

Nitrogen is very essential for chlorophyll synthesis in leaves, which helps in more photosynthesis and production of dry matter. Initial requirement of N was met from the inorganic source and subsequent requirement of N from organic source assuring continuous N supply throughout different growth stage favouring increase in growth parameters. Maurya *et al.* (2022) [22], reported that maximum plant height and leaf area in wheat was observed with the treatment receiving, 75 per cent RDF and 25 per cent poultry manure. Similarly, Mishra *et al.* (2020) [23], observed that, application of 75 per cent RDF and 25 per cent neem oil cake on N basis showed maximum plant height, number of leaves and leaf area in okra ultimately increasing overall dry matter production. Furthermore, Paikara and Pandey (2018) [27] observed that, at 60 and 90 DAS, significantly superior leaf area index and crop growth rate of maize was noted in treatment receiving 75 per cent N through RDF and 25 per cent N through vermicompost ultimately producing higher dry matter production.

Table 2: Influence of biochars produced at three different temperatures on maize plant height

Treatment details	Plants height (cm)		
	30 DAS	60 DAS	90 DAS
T_1: Control (100% RDF without biochar)	21.67	134.40	148.66
T_2: 100% RDF + BC_{300}	23.00	166.77	185.13
T_3: 100% RDF + BC_{400}	22.45	159.20	178.49
T_4: 100% RDF + BC_{500}	21.67	152.30	168.85
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	23.45	168.83	187.01
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	22.67	162.97	180.56
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	21.67	156.07	172.22
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	20.56	143.80	163.41
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	20.56	143.70	163.27
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	20.56	141.87	160.98
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	20.22	140.47	160.88
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	19.56	139.73	157.42
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	20.11	136.03	152.79
S. Em±	0.93	0.86	0.97
C.D.@ 5%	NS	2.49	2.82
C.V (%)	2.24	3.09	2.60

Table 3: Influence of application of biochars produced at different temperatures on number of leaves plant^{-1} of maize.

Treatment details	No. of leaves plant^{-1}		
	30 DAS	60 DAS	90 DAS
T_1: Control (100% RDF without biochar)	5.56	8.89	12.45
T_2: 100% RDF + BC_{300}	6.56	10.56	14.00
T_3: 100% RDF + BC_{400}	6.56	10.56	13.89
T_4: 100% RDF + BC_{500}	6.34	10.11	13.34
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	6.56	10.56	14.00
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	6.56	10.56	13.89
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	6.34	10.11	13.67
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	6.34	10.11	13.34
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	6.34	9.89	13.34
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	5.67	9.67	13.00
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	5.56	9.11	12.67
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	5.56	9.11	12.67
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	6.56	8.89	12.45
S. Em±	0.31	0.11	0.12
C.D.@ 5%	NS	0.31	0.36
C.V (%)	2.69	3.17	2.61

Table 4: Influence of application of biochars produced at different temperatures on leaf area per plant of maize.

Treatment details	Leaf area per plant (cm^2)		
	30 DAS	60 DAS	90 DAS
T_1: Control (100% RDF without biochar)	1284	3512	4374
T_2: 100% RDF + BC_{300}	1383	4258	5316
T_3: 100% RDF + BC_{400}	1357	4133	5191
T_4: 100% RDF + BC_{500}	1345	4081	5135
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	1395	4304	5361
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	1371	4169	5230
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	1348	4118	5180
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	1328	4036	4903
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	1323	3886	4802
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	1309	3780	4645
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	1299	3659	4520
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	1297	3649	4498
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	1288	3533	4397
S. Em±	22.48	22.71	28.24
C.D.@ 5%	NS	66.02	82.10
C.V (%)	2.42	3.17	2.73

Table 5: Influence of application of biochars produced at different temperatures on total dry matter production per plant of maize

Treatment details	Total dry matter production per plant (g)
T_1: Control (100% RDF without biochar)	156.45
T_2: 100% RDF + BC_{300}	205.27
T_3: 100% RDF + BC_{400}	198.63
T_4: 100% RDF + BC_{500}	192.57
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	207.21
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	201.25
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	196.36
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	178.42
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	175.31
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	170.97
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	165.22
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	163.93
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	158.61
S. Em±	1.06
C.D.@ 5%	3.07
C.V (%)	2.02

b) Effect of application of biochars produced at different temperatures on yield parameters of maize

Number of cobs per plant

All the treatments showed one cob per plant irrespective of the application of biochars produced at different temperatures with integrated application of RDF and Simarouba seed cake in different proportions.

Cob length

A significant difference in the cob length of maize was observed among various treatments (Table 6). Longer cobs were observed in T_5 (16.93 cm), it was on par with T_2 (16.71 cm). While, the shorter cobs were found in $T_1$and T_{13} (14.19 cm).

Cob girth

There was a significant difference in cob girth between the different treatments (Table 6). The maximum cob girth was exhibited by T_5 (12.78 cm), it was on par with T_2 (12.68 cm). The minimum cob girth was found in T_1(11.40 cm).

Number of rows per cob

No significant difference was seen in number of rows per cob of maize among the treatments.

Number of seeds per cob

The number of seeds per cob exhibited significant variations among the treatments (Table 6). T_5 exhibited the maximum value among all treatments (474.90), was on par with T_2 (471.90). While, the minimum number of seeds per cob were found in T_1 (379.79).

Test weight of kernels

Test weight of 100 kernels showed a significant variation across the different treatments (Table 6). The T_5 showed the highest test weight (24.03 g) which was on par with T_2 (24.00 g) and T_6 (23.85 g). Lowest value for test weight was found in T_1 (22.95 g).

Grain yield per plant (g)

The grain yield per plant exhibited a noticeable variation across the different treatments (Table 6). The highest value was observed in T_5 (114.09 g) which was on par with T_2 (113.23 g). While the T_1 showed lowest grain yield per plant (87.15 g).

Though determining grain yield per hectare using grain yield per plant data obtained from a pot experiment may not precisely reflect real field conditions, conversions were employed to gain insights into grain yield per unit area under experimental conditions.

Grain yield per hectare

As there was a significant difference in grain yield per plant (Table 6) within given treatments, ultimately it showed a significant difference in the data of grain yield per hectare (Table 7). The higher value for grain yield per hectare was found in T_5(6339 kg ha^{-1}) which was on par with T_2 (6291 kg ha^{-1}). While the lower grain yield per hectare was found in T_1 *i.e.*, control, receiving only 100 per cent RDF (4842 kg ha^{-1}).

Stover yield per hectare

A notable variation was observed in the maize stover yield per hectare when using different temperature biochars in combination with various proportions of RDF and Simarouba seed cake application (Table 7). The higher stover yield was observed in T_5 (7762 kg ha^{-1}) which was on par with T_2 (7714 kg ha^{-1}). While, the lower stover yield was shown by T_1 (6265 kg ha^{-1}).

Table 6: Influence of application of biochars produced at different temperature on yield parameters of maize per plant

Treatment details	Cob length (cm)	Cob girth (cm)	No. of rows per cob	No. of seeds per cob	100 kernels weight (g)	Grain yield per plant (g)
T_1: Control (100% RDF without biochar)	14.19	11.40	12.00	379.79	22.95	87.15
T_2: 100% RDF + BC_{300}	16.71	12.68	14.00	471.90	24.00	113.23
T_3: 100% RDF + BC_{400}	16.53	12.48	14.00	460.12	23.62	108.66
T_4: 100% RDF + BC_{500}	16.03	12.24	13.33	438.56	23.42	102.69
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	16.93	12.78	14.00	474.90	24.03	114.09
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	16.55	12.53	14.00	461.56	23.85	110.09

T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	16.15	12.44	14.00	453.67	23.54	106.78
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	15.25	11.91	13.33	418.45	23.25	97.28
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	15.05	11.81	13.33	416.01	23.24	96.67
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	14.95	11.75	12.67	408.45	23.22	94.82
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	14.64	11.64	12.67	395.01	23.04	91.00
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	14.64	11.63	12.67	393.01	23.04	90.54
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	14.19	11.45	12.00	381.56	23.01	87.78
S. Em±	0.09	0.07	0.45	1.68	0.13	0.60
C.D.@ 5%	0.26	0.21	NS	4.89	0.38	1.74
C.V (%)	2.24	1.61	3.26	2.84	2.16	2.38

In the present study, significantly higher values of yield parameters such as cob length, cob girth, number of seeds per cob, test weight of 100 kernels, grain yield per plant, grain yield per hectare and stover yield per hectare were observed in treatment receiving, 75 per cent RDF + BC_{300}+ 25 per cent Simarouba seed cake on N basis + SSP (T_5). Studies have shown that the use efficiency of inorganic fertilizer and organic inputs was enhanced when applied with biochar (Glaser *et. al.*, 2015; Partey *et al.*, 2014) [15, 28] due to its higher porosity, water holding capacity and higher CEC. Dawar *et al.* (2022) [10] showed that treatment with combined application vermicompost, biochar and chemical fertilizers performed significantly better for improvement in maize plant height, 1000 grains weight, biological yield and grains yield compared to treatment receiving only chemical fertilizers and control. With increasing of pyrolysis temperature, plant nutrients in biochar become less available to plants (Tag *et al.*, 2016) [35], so the biochars produced at lower pyrolysis temperature effectively improve crop growth and yield, when compared to biochars produced at higher temperatures.

Enhanced yield parameters in T_5can also be attributed to continuous nutrient supply to plants throughout different growth stage (Initially from inorganic and subsequently from organic amendments) favouring increased growth parameters like leaf count and leaf area per plant that ultimately enhanced photosynthesis rate resulting in increase in the yield parameters of the crop (Mishra *et al.*, 2020; Paikara and Pandey, 2018) [23, 27]. Sowjanya *et al.* (2022) [33], reported that 75 per cent RDF N through inorganic fertilizer and 25 per cent equivalent N through poultry manure recorded higher cob length, cob girth, no. of grains per cob, and green cob yield in sweet corn.

Table 7: Effect of application of different temperature biochars on grain yield and stover yield of maize per hectare

Treatment details	Grain yield per hectare (kg)	Stover yield per hectare (kg)
T_1: Control (100% RDF without biochar)	4842	6265
T_2: 100% RDF + BC_{300}	6291	7714
T_3: 100% RDF + BC_{400}	6037	7460
T_4: 100% RDF + BC_{500}	5705	7129
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	6339	7762
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	6117	7540
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	5933	7356
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	5405	6828
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	5371	6794
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	5268	6691
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	5056	6479
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	5030	6454
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	4877	6300
S. Em±	33.31	33.38
C.D.@ 5%	96.83	97.02
C.V (%)	2.58	2.83

In the present study, T_5 showed 30.92 per cent higher grain yield per hectare (Table 7) when compared to control (T_1) *i.e.*, 100 per cent RDF without biochar. Therefore, integrated application of biochar produced at 300 °C, combined with 75 per cent RDF, and 25 per cent Simarouba seed cakecan help to reduce application of chemical fertilizers by 25 per cent and increase the grain yield by around 30 per cent per hectare of maize crop.

c) Influence of biochars produced at different temperatures on properties of post-harvest soils

Physical properties of soils

BD was found significantly lower in T_{12} and T_{13} (1.38 Mg m^{-3}) (Table 8). While MWHC was seen significantly higher in T_{13} (42.98%) which was on par with T_{12} (42.84%) and T_{11} (42.49%). This can be attributed to presence sufficiently porous C structure and oxygenated functional groups in the structureof high-temperature biochars (BC_{400} and BC_{500}) that provide room for more water. These results were supported by findings of Ghorbani *et al.* (2022) [12]. Further, along with the biochars, higher doses of organic input *i.e.*, Simarouba seed cakehelped in lowering BD by increasing soil pore space in the treatments. This could be due to the reason that the organic amendments and biochar would act as the cementing materials for forming the stable soil aggregates with increased diameter resulting in changed pore size distribution (Sharma*et al.*, 2019) [32].

Table 8: Influence of biochars produced at different temperatures on physical properties post-harvest soils

Treatment details	BD (Mg m^{-3})	MWHC (%)
T_1: Control (100% RDF without biochar)	1.42	39.81
T_2: 100% RDF + BC_{300}	1.41	40.20
T_3: 100% RDF + BC_{400}	1.40	40.44
T_4: 100% RDF + BC_{500}	1.40	40.56
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	1.41	40.78
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	1.40	41.15
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	1.40	41.29
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	1.40	41.56
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	1.39	42.05
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	1.39	42.21
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	1.39	42.49
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	1.38	42.84
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	1.38	42.98
S. Em±	0.01	0.24
C.D.@ 5%	0.03	0.68
C.V (%)	0.57	0.99

Chemical properties of soil

Application of biochars produced at different temperatureshad no significantimpact on soil pH and EC after the crop harvest. The soil pH ranged from 6.72 to 6.89. Higher pH (6.89) was observed in T_{13}. While, the lower pH (6.72) was seen in control *i.e*., T_1(Table9).There was a significant difference in OC content in post-harvest soils due to application of biochars produced at different temperatures. The soil OC ranged from 0.44 to 0.51 per cent. Higher OC (0.51%) was found in T_{11}. While, the lower OC (0.44%) was observed in T_1*i.e*., control. Application of biochar can result in a substantial increase in OC content of soil(Aon *et al*., 2015; Ouyang*et al*., 2014) [1, 26].It was observed that, pyrolysis temperature had a pronounced effect on biochar's ability to enhance SOC.This could be due to presence of more fraction of incompletely pyrolyzed feedstock materialin low-temperature biochars thanhigh-temperature biochars (Bruun *et al*., 2011) [6].The results of the study are in accordance with findings ofYin *et al.* (2014) [40]. Further, the organic amendment of Simarouba seed cake played important role in enhancing the OC content of soil. This increase in OC can be attributed to increase in the activity of beneficial soil microbes with increase in organic matter. Kannan *et al*., (2013) [19] reported that integration application of organic and inorganic nutrients in maize crop resulted in maximum soil organic carbon.

Table 9: Influence of biochars produced at different temperatures on chemical properties of post-harvest soils

Treatment details	pH	EC(dS m^{-1})	OC(%)
T_1: Control (100% RDF without biochar)	6.72	0.21	0.44
T_2: 100% RDF + BC_{300}	6.77	0.22	0.47
T_3: 100% RDF + BC_{400}	6.78	0.21	0.46
T_4: 100% RDF + BC_{500}	6.77	0.21	0.46
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	6.81	0.22	0.48
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	6.80	0.22	0.47
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	6.82	0.21	0.46
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	6.84	0.23	0.50
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	6.83	0.23	0.49
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	6.85	0.22	0.48
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	6.86	0.23	0.51
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	6.86	0.23	0.50
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	6.89	0.23	0.49
S. Em±	0.04	0.01	0.01
C.D.@ 5%	NS	NS	0.03
C.V (%)	0.95	4.83	3.18

Primary nutrient status of soil

The application of biochars produced at different temperatures in combination with various proportion of organic amendment (Simarouba seed cake) and RDF significantly impacted available nitrogen, phosphorous and potassium content (Table 10).

Higher N content was observed in T_{11} (312.48 kg ha^{-1}) followed by T_{12} (310.08 kg ha^{-1}). Similarly, Higher P content was observed in T_{11} (24.87kg ha^{-1}) followed by T_{12} (24.69kg ha^{-1}). While higher K content (270.16 kg ha^{-1}) was seen in T_{13}. This value was on par with T_{11} (269.41 kg ha^{-1}) and T_{12} (269.87 kg ha^{-1}). Conversely, lower N (281.36 kg ha^{-1}), P (17.80 kg ha^{-1}) and K (242.52 kg ha^{-1}) content was found T_1.

Biochar produced at lower temperature showed greater nutrient retention in soil. This may be due to presence of more C=O and C-H functional groups and exchange sites in the biochars after oxidation (Wu *et al.* 2012) [38]. At higher pyrolysis temperature, volatilization of N present in feedstock material occurs due to its sensitivity against increasing temperature (Chan & Xu, 2009) [7], ultimately reducing N content in biochar. Furthermore, organic input *i.e.*, Simarouba seed cake provides the substrate for microbial activities and enhances N mineralization. Slow-release of nutrients from organic manures ensures higher concentration of available soil N observed even after crop harvest. Further, application of biochar significantly increased soil P availability. This may be due to the enhanced microbial activity, changes in soil pH and reduced fixation of P with cations in soil (Atkinson *et al.* 2010) [2]. Naeem *et al.* (2017) [25] reported that, the available P was significantly higher in soil treated with low-temperature biochar while available K was higher in high-temperature biochar. The water-soluble K concentration of the biochars significantly increased with increasing temperature due to separating of K salts from organic materials (Tag *et al.*, 2016) [35]. Urmi *et al.* (2022) [36] reported that the treatments comprising of organic and inorganic fertilizers significantly increased the available N and P contents in the soil over control.

Secondary nutrient status of soil

Significantly higher exchangeable Ca content was found in T_{11} (3.60 c mol [p+] kg^{-1}) which was on par with T_{12} (3.58 c mol [p+] kg^{-1}), and T_{13} (3.56 c mol [p+] kg^{-1}) (Table 11). While the higher magnesium content was observed in T_{11} (1.47 c mol [p+] kg^{-1}) which was on par with T_{12} (1.45 c mol [p+] kg^{-1}), and T_{13} (1.44 c mol [p+] kg^{-1}). Highest sulphur content was observed in T_{11} (17.42 mg kg^{-1}) which was on par with T_{12} (17.39 mg kg^{-1}), T_{13} (17.35 mg kg^{-1}), T_8 (17.27 mg kg^{-1}), T_9 (17.24 mg kg^{-1}), and T_{10} (17.20 mg kg^{-1}).

Owing to its large specific surface area, cation exchange capacity and high pH value, biochar is considered as a good sorbent, which can adsorb nutrients and retain them in soil (Yao *et al.*, 2012; Mukherjee and Zimmerman 2013) [39, 24]. Ash residues in biochar are rich in available nutrients, especially in cationic elements such as Ca^{2+}, Mg^{2+}, Na^{2+} and K^+. Tag *et al.* (2016) [35] observed that the concentrations of water-soluble Ca and Mg decreased in biochar with increasing pyrolysis temperature indicating a tendency of these elements to become less available to plants. Further, integrated application of organic inputs with inorganic fertilizers help to increase soil CEC, contributing to higher base saturation of the soil. The results of the present study are in accordance with the findings of Urmi *et al.*, 2022 [36]. The positive effects of biochar amendment on the activities of sulphate-reducing bacteria (SRB) and thus microbial sulphate reduction were attributed to biochar-facilitated electron transfer (Sande, 2016) [31].

Table 10: Influence of biochars produced at different temperatures on primary nutrient status of post-harvest soils

Treatment details	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
T_1: Control (100% RDF without biochar)	281.36	17.80	242.52
T_2: 100% RDF + BC_{300}	285.07	19.37	244.60
T_3: 100% RDF + BC_{400}	284.39	19.13	247.32
T_4: 100% RDF + BC_{500}	283.85	18.97	252.96
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	293.28	21.77	253.04
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	294.36	21.70	254.15
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	292.97	21.43	261.48
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	304.73	23.33	262.48
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	303.38	23.05	264.76
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	302.83	22.85	265.16
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	312.48	24.87	269.41
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	310.08	24.69	269.87
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	309.85	24.53	270.16
S. Em±	1.07	0.43	1.19
C.D.@ 5%	3.11	1.24	4.69
C.V (%)	0.63	1.13	0.80

Table 11: Influence of biochars produced at different temperatures on secondarynutrient status of post-harvest soils

Treatment details	Ca [c mol (p+) kg^{-1}]	Mg [c mol (p+) kg^{-1}]	S [mg kg^{-1}]
T_1: Control (100% RDF without biochar)	3.09	1.29	16.55
T_2: 100% RDF + BC_{300}	3.39	1.34	16.88
T_3: 100% RDF + BC_{400}	3.36	1.34	16.85
T_4: 100% RDF + BC_{500}	3.35	1.33	16.82
T_5: 75% RDF + BC_{300} + 25% Simarouba seed cake on N basis + SSP	3.46	1.38	17.11
T_6: 75% RDF + BC_{400} + 25% Simarouba seed cake on N basis + SSP	3.43	1.37	17.07
T_7: 75% RDF + BC_{500} + 25% Simarouba seed cake on N basis + SSP	3.42	1.36	17.03
T_8: 50% RDF + BC_{300} + 50% Simarouba seed cake on N basis + SSP	3.54	1.43	17.27
T_9: 50% RDF + BC_{400} + 50% Simarouba seed cake on N basis + SSP	3.51	1.41	17.24
T_{10}: 50% RDF + BC_{500} + 50% Simarouba seed cake on N basis + SSP	3.49	1.40	17.20
T_{11}: 25% RDF + BC_{300} + 75% Simarouba seed cake on N basis + SSP	3.60	1.47	17.42
T_{12}: 25% RDF + BC_{400} + 75% Simarouba seed cake on N basis + SSP	3.58	1.45	17.39
T_{13}: 25% RDF + BC_{500} + 75% Simarouba seed cake on N basis + SSP	3.56	1.44	17.35
S. Em±	0.04	0.02	0.10
C.D.@ 5%	0.12	0.05	0.30
C.V (%)	2.00	1.99	1.00

Conclusion

From the experimental results, the study concludes that, there were significant variations in the growth and yield parameters of maize crop as well as properties of post-harvest soils due to application of biochars produced from simarouba seed coat at different temperatures. Among different treatments employed, integrated application of biochar produced at 300 °C, with 75 per cent RDF, and 25 per cent Simarouba seed cake (T_5), was found most efficacious. The treatment exhibited notable enhancement growth and yield parameters of the crop. Further, low-temperature (BC_{300}) biochar can help to improve soil OC, primary and secondary nutrient status (except K) while high-temperature biochar (BC_{500}) helps to improve soil physical properties and K content when applied with 25 per cent RDF, and 75 per cent Simarouba seed cake.The results of T_5in crop growth and yield were on par with T_2 where biochar produced at

300 °C and 100 per cent RDF was applied. Therefore, T_5 has been considered as best treatment which can help to reduce use of chemical fertilizers by 25 per cent and increase the grain yield by around 30 per cent per hectare of maize crop.

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