Biochar, Vermicompost and Microorganisms an Organic Soil Amendment to Build the Soil Health and Enhance the Cotton Yield in Yavatmal and Amravati Districts of Maharashtra, India

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ABSTRACT

Cotton has been cultivated for over 6,000 years for various purposes, including food, fiber, and fuel. It is not only used in clothing, sheets, and towels, but also in the production of rope, paper, cooking oil, animal feed, packaging, and biofuels. Biochar has been identified as a potential tool for improving soil fertility, mitigating climate change, and serving as a long-term sink for atmospheric carbon dioxide. The application of biochar to soil indirectly improves soil health. Cotton is a significant cash crop grown extensively in the Vidarbha region of Maharashtra. A field experiment was conducted in the Yavatmal and Amravati districts of Maharashtra to assess the impact of biochar and vermicompost, along with biofertilizers on soil properties and cotton yield. The experiment consisted of two treatments: T_1, which involved the recommended dose of fertilizers (RDF), and T_2, which involved biochar @ 2.5 t ha^{-1}+ vermicompost @ 2.5 t ha^{-1}+*Azotobacter*@ 5 L ha^{-1} along with RDF. Both treatments received the recommended dose of fertilizers for cotton (100:50:50 NPK Kg ha^{-1}). The field experiment was conducted using a paired t-test and was replicated with 20 farmers, with each treatment applied to an area of 0.2 ha on each farmer's land.

The results indicated that the application of biochar @ 2.5 t ha^{-1}+vermicompost 2.5 t ha^{-1}+*Azotobacter*@ 5 L ha^{-1} along withthe recommended dose of fertilizers @ 100:50:50 NPK Kg ha^{-1}, significantly enhances the soil's water holding capacity, cation exchange capacity, organic carbon, available nitrogen, phosphorous, and potassium content compared to the RDF treatment. Additionally, this treatment slightly decreases the soil's bulk density and increases its pH and electrical conductivity, although these effects werenot statistically significant. Moreover, the application of biochar @ 2.5 t ha^{-1}+vermicompost 2.5 t ha^{-1}+*Azotobacter*@ 5 L ha^{-1} along withthe recommended dose of fertilizers @ 100:50:50 NPK Kg ha^{-1}significantly boosts the yield of cotton. Based on these findings, it can be concluded that the combined application of biochar, vermicompost, and biofertilizers to cotton crops is crucial during the *Kharif* season to enhance soil health and maximize yield compared to the RDF treatment.

Keywords:*Biochar, Vermicompost, Biofertilizers,Soil health, Cotton, Yavatmal, Amravati.*

Introduction:

Maharashtra state exhibits significant diversity in crop production and cropping patterns due to its diverse agro-climatic conditions. The cropping pattern in the state varies across different regions. One of the prominent commercial crops in Maharashtra is cotton, which is predominantly cultivated under rainfed conditions in the Vidarbha region (Tupe and Joshi, 2019). Cotton,known as "the king of apparel fibers" holds, immense importance as a cash crop, providing a major portion of raw material for the textile industry and playing a crucial role in the global economic and social landscape (Hosamani*et al*., 2013). In India, cotton is cultivated across an area of 122.38 lakh ha, yielding a production of 361 lakh bales. In Maharashtra, cotton is grown on 41.19 lakh ha, producing 81 lakh bales (Anonymous, 2019). Notably, the Vidarbha region alone accounts for approximately 16.18 lakh ha of cotton cultivation, producing around 30.50 lakh bales. Yavatmal, a significant district in Maharashtra, is known for its substantial cotton production, with an area of 4,05,000 ha dedicated to cotton cultivation during the *Kharif* season (Tupe and Joshi, 2019). The primary purpose of cultivating cotton in this region is to obtain its fiber, which is utilized in the manufacturing of fabrics, thread production and extraction of oil from cotton seeds (Deshmukh *et al*., 2013).

Researchers and farmers have shown great interest in agricultural practices that enhance soil quality and sustainability. The significance of organic fertilizers in plant nutrition has become a global focus for agriculturists and soil scientists. Although chemical fertilizers have increased crop production and productivity, their continuous and imbalanced use can negatively impact production potential and soil health. This issue is particularly severe in intensively cropped soils, resulting in soil fertility deterioration, decreased productivity, and increased production costs. To improve soil health, it is essential to combine the use of chemical fertilizers with organic manure. Additionally, the use of biofertilizers not only supplements nutrients but also enhances the efficiency of applied nutrients. Neglecting environmental hazards and solely focusing on high yields through excessive use of chemical fertilizers can lead to further problems while attempting to solve existing ones.

The cotton crop holds significant importance for the farmers in the Vidarbha region, serving as the primary cash crop. However, the management of cotton crop residues poses a major challenge for farmers in the Yavatmal and Amravati districts. In order to prepare their fields for the next crop, farmers resort to burning these residues, which in turn contributes to global warming and the emission of greenhouse gases. To address this issue, the BAIF Development Research Foundation, Pune has established the Tulja Farmer Producer Company (FPC) in the Athmurdi village of Yavatmal district. This FPC is actively involved in the collection, processing, and conversion of cotton crop residues into biochar through pyrolysis. The resulting biochar is then sold back to its farmer members and other farmers for soil application, thereby reducing the practice of open burning.

This study aims to examine the effects of combined application of biochar andvermicompostin addition to biofertilizers on both soil properties and the yield of cotton crops.

Material and Methods:

1. Location, Climate and Agriculture:

The study was conducted in the Ralegaon and Kalamb blocks of the Yavatmal district, as well as the Morshi block in the Amaravati district. Amaravati district is situated at longitude 21.1162 ^{o}N and latitude 77.6536 ^{o}E, while Yavatmal district is located at longitude 20.3888 ^{o}N and latitude 78.1204 ^{o}E. The average annual rainfall in Amaravati district is 889 mm, whereas Yavatmal district receives rainfall ranging from 889 to 1095 mm, which is not evenly distributed throughout the district. Both districts experience irregular rainfall patterns and have a hot and dry climate in summer, with moderately cold winters. The primary crops grown in these districts include cotton, soybean, pigeon pea, wheat, and gram, and the soil type is predominantly black cotton soil (Anonymous (b), 2015).

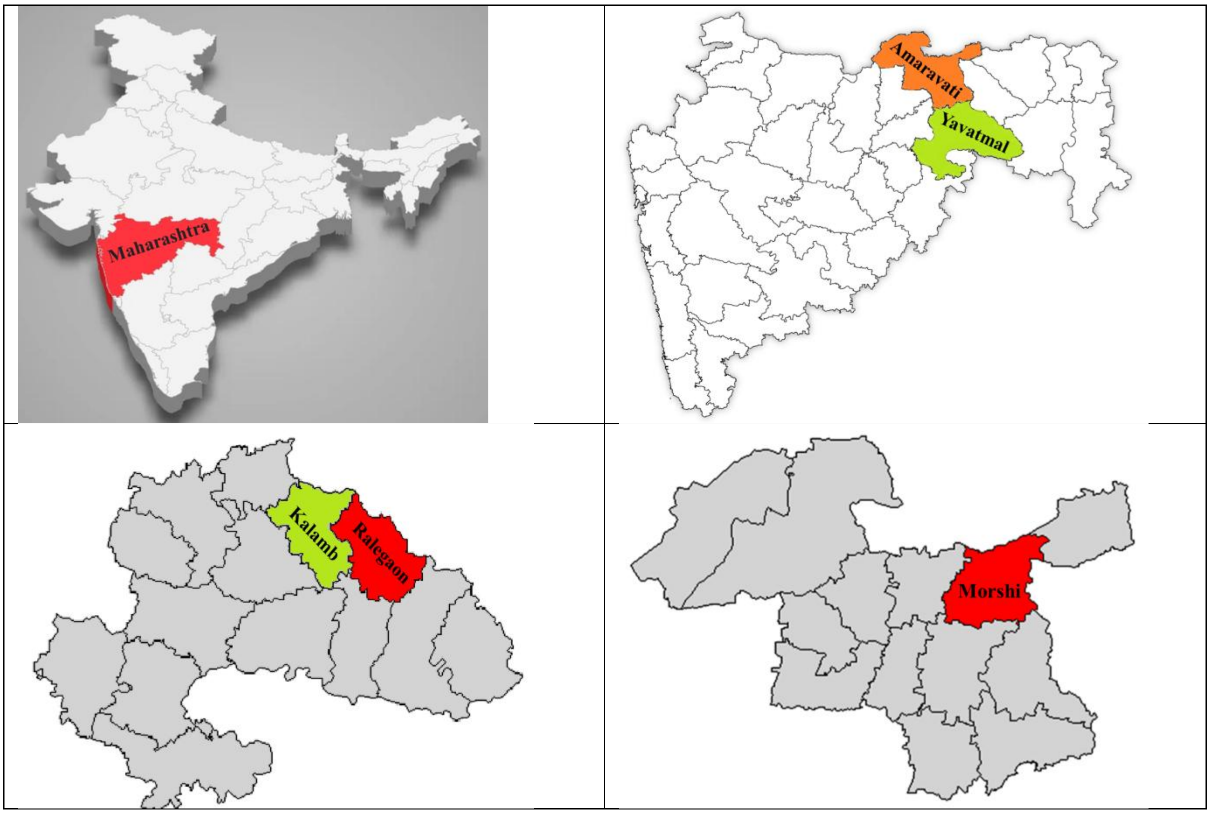

Fig. 1: Location map of study area

2. Study details:

2.1 Cultural practices:

Cotton *cv*. BG-II was taken as a test crop during the *Kharif* season of the year 2021. Prior to the experiment, the land was ploughed once with a mouldboardplough and then harrowed twice to achieve a fine tilth. The cotton was dibbled at a depth of 4 cm with a row-to-row distance of 90 cm and plant-to-plant distance of 45 cm, with two seeds hill^{-1}. Gap filling was conducted 10 days after sowing.

2.2 Treatment Details:

The experiment was undertaken with two treatments comprising T_1: Recommended dose of fertilizers (RDF) and T_2:biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + Azotobactor @ L ha^{-1} + RDF. In the treatment T_2, biochar, vermicompost and *Azotobacter*solution were mixed uniformly and applied in the plot before the second harrowing. The recommended dose of fertilizers for cotton (100:50:50 NPK Kg ha^{-1}) was applied to both treatments *i.e.* T_1 and T_2. Fifty percent of the recommended dose of nitrogen and a full dose of phosphorous and potassium were applied at the time of sowing and the remaining 50 per cent of nitrogen was applied after 30 days of sowing. The field experiment was laid out in paired t-testand was replicated with20 farmers.Each treatment was applied on a 0.2 ha area of each farmer. For the research trial biochar was prepared from cotton crop residues with the help ofTulja Farmers Producer Company (FPC) at Athmurdi village of Yavatmal district. Tulja FPC prepared biochar from cotton crop residues. The cotton residue was collected from farmers and subsequently cut into smaller fragments. These smaller residue fragments were then transferred to a charring kiln. Utilizing charring kilns with capacities of 10 Kg and 200 Kg, the pyrolysis process yielded a total of 6.72 tons of biochar from 27 tons of cotton residue. Following this, the biochar was further processed through grinding, resulting in a fine material weighing 5.6 tons, with a production recovery rate of 21 per cent.

The properties of cotton biocharused for the research trial are as follows: bulk density (0.28 g cm^{-3}), particle density (0.51 g cm^{-3}), water holding capacity (283%), pore space (52.4%), pH (9.15), electrical conductivity (1.49 dSm^{-1}), cation exchange capacity (51.3 cmol (P+) Kg^{-1}), carbon to nitrogen ratio (42.03), and total carbon content (66.83%). The soil in the experimental plots was slightly alkaline in pH(7.74), with normal electrical conductivity(0.324 dSm^{-1}), medium levels of available phosphorous (22.13 Kg ha^{-1}) and potassium (195.47 Kg ha^{-1}), and low levels of organic matter (0.407 %) and available nitrogen (237.87 Kg ha^{-1}).

2.3 Yield parameter:

The yield of cotton was measured in Kg plot^{-1} and converted it into bales per hectare (bales ha^{-1}). The Cotton Association of India considers 170 Kgs weight of cotton for bale size.

2.4 Soil properties:

Soil samples were collected both before and after harvest, following the standard procedure provided by Anonymous, 2011. The collected samples were then air-dried and ground to a size of less than 2 mm. Subsequently, the samples were analysed for various chemical and fertility parameters, including bulk density, water holding capacity (WHC), cation exchange capacity (CEC), pH, electrical conductivity (EC), organic carbon (OC), available nitrogen (N), available phosphorous (P_2O_5), and available potassium (K_2O) in the soil.The bulk density of soil was determined using themethod of Campbell and Henshall (1991).Water holding capacity of soil was estimated by themethod of Keen box (Piper, 1966).The cation exchange capacity (CEC) of soil was determined as per the procedure given by Chapman (1965). The pH (1:2.5) and electrical conductivity (1:2.5) of the soils were measured using the standard procedures described by Jackson (1973). The determination of organic carbon was carried out using the Walkley and Black method (Nelson and Sommers, 1996). Available nitrogen was estimated using the modified alkaline permanganate method (Sahrawat and Burford, 1982). The available phosphorous content of the soils was determined using Olsen's method, as outlined by Olsen and Sommers (1982). Finally, the available potassium was determined using the ammonium acetate method (Helmke and Sparks, 1996).

3. Statistical analysis:

The statistical analysis of experimental data was done by paired t-test given by Panse and Sukhatme (1985). In the t-teststar was used to show the flag level of significance. If a p-value is less than 0.05, it is flagged with one star (*). If a p-value is less than 0.01, it is flagged with two stars (**). If a p-value is less than 0.001, it is flagged with three stars(***). This research trial was conducted at a farmer'sfield therefore, data was tested at 5 per cent (0.05) level of significance.

Result and Discussion:

1. Effect on bulk density of soil:

Glimpses of the data presented in Table 1 revealed that the bulk density of soil ranged from 1.33 to 1.37 g cm^{-3} and did not exhibit any significant difference between the treatments. The application of biochar @ 2.5 t ha^{-1}+ vermicompost @ 2.5 t ha^{-1}+ azotobacter @ 5 L ha^{-1} in addition witha recommended dose of fertilizer (RDF), resulted in the lowest (1.33 g cm^{-3}) bulk density of soil. Conversely, the highest (1.37 g cm^{-3}) bulk density was observed in the plot where only RDF was applied.

The observed decline in bulk density can be attributed to various factors associated with the properties of biochar. These factors include particle size, active surface area, porosity and the relatively lower bulk density of biochar compared to soil. Additionally, the ability of biochar to form soil aggregates in conjunction with soil particles, leading to a decrease in bulk density, may also play a role. Previous studies by Tokova *et al*. (2020) have supported these potential causes. Furthermore, biochar acts as a substrate for soil fauna and its particles can be mixed with soil particles in the digestive tract of earthworms, resulting in the formation of agronomically valuable soil aggregates known as coprolites. These coprolites contribute to a more favourable soil structure, as highlighted by Simansky*et al*. (2019), and consequently lead to lower bulk density values. Moreover, the porous nature of biochar allows it to increase soil porosity upon addition, thereby reducing bulk density, as suggested by Nyambo *et al*. (2018).

Table. 1:Effect of biochar, vermicompost and biofertilizer on bulk density, water holding capacity and cation exchange capacity of the soil

Parameter	**Bulk Density (g cm^{-3})**	
Treatment	Recommended dose of fertilizers (RDF)	Biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + azotobacter @ 5 Lha^{-1}+ RDF
Mean	1.37	1.33
Variance	0.01	0.01
No. of observations	20	20
t-test value	1.21	
Standard error	0.03	
Parameter	**Water Holding Capacity (%)**	
Mean	27.67	29.79
Variance	3.78	4.72
No. of observations	20	20
t-test value	3.25*	
Standard error	0.65	
Parameter	**Cation Exchange Capacity(cmol (P^{+}) Kg $^{-1}$)**	
Mean	38.68	45.92
Variance	7.39	11.21
No. of observations	20	20
t-test value	7.51*	
Standard error	0.96	

2. Effect on water holding capacity of soil:

The results from the study indicated that, thewater holding capacity of experimental plots ranges from 27.67 to 29.79 per cent (Table 1). The soil amended with biochar @ 2.5 t ha^{-1} +

vermicompost @ 2.5 t ha^{-1}+ Azotobacter @ 5 Lha^{-1}along with RDF sowed significantly highest (29.79 %) water holding capacity of soiland the lowest (27.67 %) was observed in only RDFtreatment.

The moisture content in the soil is increased when biochar is applied in combination with vermicompost, *Azotobacter*and RDF, as compared to the RDF treatment. This can be attributed to the presence of more micropores in biochar-applied soils, which physically retain water, and improved aggregation that leads to the creation of more pore spaces due to increased earthworm burrowing. Another possible reason for the difference in water content between the biochar-treated plot and the RDF plot could be the variation in bulk density between the two treatments (Adekiya*et al.*, 2019). Additionally, Chan *et al*. (2008) have also reported that the water retention ability of biochar may be a result of an overall increase in the net soil surface area after biochar application.

3. Effect on cation exchange capacity of the soil:

Significantly higher cation exchange capacity of soil was observed in the biochar applied plots over RDF plot (Table 1). The cation exchange capacity of research plots varies from 38.68 to 45.92 cmol (P^+) Kg^{-1}. The application of biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + *Azotobacter* @ 5 Lha^{-1}along with RDF showed significantly highest (45.92 cmol (P^+) Kg^{-1}) cation exchange capacity of soil as compare with RDF treatment(38.68 cmol (P^+) Kg^{-1}).

The increase in cation exchange capacity in soil treated with biochar can be attributed to the presence of cation exchange sites on the surface of the biochar (Jones *et al*., 2012 and Sohi *et al*., 2010). Additionally, the abundance of cation exchange capacity in biochar-applied soils may be due to the interaction between metal cations in the soil and oxygen-active groups, such as $COOH^-$ or OH^-, present on the biochar surface, resulting in the formation of metal ion complexes. The negative charge of these ions contributes to the high cation exchange capacity of biochar (Gan *et al*., 2012). Bhattacharya *et al*. (2015) further confirmed that the cation exchange capacity of biochar has an impact on the soil's cation exchange capacity, leading to improvements in its physical and chemical properties.

4. Effect on soil pH:

The soils of the experimental location areslightly alkaline in nature, the application of biochar exhibited minimal impact on the soil's pH enhancement, with no notable disparity observed among the treatments (Table 2). The soil pH of the experimental plot ranges from 7.75 to 7.77. The lowest soil pH (7.75) was observed in the RDF treatment (T_1) whereas, the highest

(7.77) in the treatment of the application of biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + *Azotobacter* @ 5 Lha^{-1}along with RDF (T_2).

The application of biochar treatment observed that theslightincrement in soil pH as compared with RDF might be due to pH of biochar prepared from cotton crop residues is alkaline in nature.Nataraja *et al*. (2021) found that the pH levels of biochar derived from cotton crop residues ranged from 8.83 to 9.30. Similar results were observed by Pandian *et al*. (2016) in groundnut when applying *Prosopis* biochar @ 5 t ha^{-1} in sandy loam soil and Kannan *et al*. (2021) reported an increase in soil pH in *Vigna mungo* with the combined application of biochar and *phospho-bacteria* compared to biochar alone. The addition of vermicompost along with the biochar treatment did not significantly affect the results, as the acids released during its decomposition were not significant.

Table. 2: Effect of biochar, vermicompost and biofertilizer on soil pH, electrical conductivity (EC) and organic carbon (OC) of soil

Parameter	**pH**	
Treatment	Recommended dose of fertilizers (RDF)	Biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + azotobacter @ 5 Lha^{-1}+ RDF
Mean	7.75	7.77
Variance	0.30	0.32
No. of observations	20	20
t-test value	0.114	
Standard error	0.176	
Parameter	**Electrical conductivity (dSm^{-1})**	
Mean	0.320	0.334
Variance	0.001	0.001
No. of observations	20	20
t-test value	1.869	
Standard error	0.007	
Parameter	**Organic carbon (%)**	
Mean	0.415	0.472
Variance	0.002	0.001
No. of observations	20	20
t-test value	4.710*	
Standard error	0.012	

5. Effect on electrical conductivity (EC) of soil:

Thevariation inthe electrical conductivity of soil due to application of biochar, vermicompost and biofertilizers was observed from 0.320 to 0.334 dSm^{-1}(Table 2). The highest (0.334 dSm^{-1}) electrical conductivity of soil was found in the treatment of the application of biochar @

2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + Azotobacter @ 5 Lha^{-1}along with RDF as compared with RDF treatment but it did not show a significant difference.

The increased electrical conductivity of biochar, vermicompost and azotobacter in combination with RDF treated plot as compared with RDF might be due to the higher electrical conductivity of biochar and releasing the different soluble salts in soil during the decomposition of vermicompost.The application of biochar in soil leads to an increase the electrolyte concentrationby the addition of soluble salts.

6. Effect on organic carbon (OC) content in soil:

All biochar-applied plots exhibited a significantly higher organic carbon content compared to the RDF plot, as shown in Table 2. The treatment involving the application of biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + *Azotobacter*@ 5 L ha^{-1} along with RDF displayed the highest organic carbon content (0.472 %), while the RDF plots recorded the lowest organic carbon content (0.415 %). The study demonstrated that the addition of fertilizers in conjunction with biochar and vermicompost resulted in an increase in organic carbon content in the soil. This increase can be attributed to the higher carbon content present in biochar, thereby enhancing the overall carbon content of the soil. These findings align with the research conducted by Oladele *et al*. (2019).

7. Effect on available nitrogen (N) content in soil:

The combinedapplication of biochar, vermicompost, and biofertilizers had a significant impact on the nitrogen content in the soil (Table 3). The nitrogen content ranged from 251.39 to 287.62 Kg ha^{-1}. The treatment that involved the application of biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + *Azotobacter*@ 5 L ha^{-1}, along withthe recommended dose of fertilizer (RDF) showed the highest (287.62 Kg ha^{-1}) nitrogen content in the soil compared to the RDF treatment (251.39 Kg ha^{-1}). This combined application increased the available nitrogen content in the soil by 14.42 percent compared to the RDF treatment. This increase can be attributed to the higher nutrient retention capacity and reduced nutrient leaching in the soils treated with biochar. Additionally, the efficient adsorption of ammonia (NH_3) on the surface of biochar may have reduced volatilization loss, leading to an increase in the available nitrogen content in the soil. The application of nitrogen-fixing biofertilizers in this treatment may have also contributed to the increase in nitrogen availability in the soil by fixing atmospheric nitrogen.

Table. 3: Effect of biochar, vermicompost and biofertilizer on available N, P_2O_5 and K_2O content in soil

Parameter	**Available Nitrogen (Kg ha^{-1})**

Treatment	Recommended dose of fertilizers (RDF)	Biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + azotobacter @ 5 Lha^{-1}+ RDF
Mean	251.39	287.62
Variance	229.69	230.95
No. of observations	20	20
t-test value	7.55*	
Standard error	4.80	
Parameter	**Available P_2O_5 (Kg ha^{-1})**	
Mean	28.60	35.84
Variance	4.03	6.82
No. of observations	20	20
t-test value	9.82*	
Standard error	0.74	
Parameter	**Available K_2O (Kg ha^{-1})**	
Mean	204.07	241.53
Variance	205.74	226.47
No. of observations	20	20
t-test value	8.06*	
Standard error	4.65	

8. Effect on available phosphorous (P_2O_5) content in soil:

The data presented in Table 3 demonstrates that the combination of biochar, vermicompost, and biofertilizers increases the phosphorous (P_2O_5) content in soil. The phosphorous content in soil ranged from 28.60 to 35.84 Kg ha^{-1}. The treatment with the highest phosphorous content (35.84 Kg ha^{-1}) was observed in the application of biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + *Azotobacter*@ 5 L ha^{-1} + RDF, while the lowest phosphorous content (28.60 Kg ha^{-1}) was recorded in RDF plots. The increased availability of phosphorous in biochar-applied plots may be attributed to its interaction with cations (Ca, Mg, Al, Fe) that affect phosphorous. Additionally, the adsorption and desorption abilities of biochar were found to influence the availability of soil phosphorous, as suggested by Kannan *et al*. (2021) in *Vigna mungo* with the application of red gram stalk biochar and *Phosphor-bacteria*. Bornemann *et al*. (2007) reported that the application of biochar with phosphorous helps protect it from precipitation in soil, thereby enhancing its availability compared to RDF plots. The higher carbon content of biochar may have stimulated microbial activity, converting insoluble phosphorous into a form that is readily available to plants.

9. Effect on available potassium (K_2O) content in soil:

Table 3 presents the available potassium content in soil, with the highest amount (241.53 Kg ha^{-1}) observed in soils treated with biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} +

Azotobacter@ 5 L ha^{-1} along with RDF. Conversely, the lowest amount of available potassium content in soil was observed in RDF plots (204.07 Kg ha^{-1}). The combined application of biochar and vermicompost, along with biofertilizers, resulted in an observed increase in the available potassium content in the soil. This increase can be attributed to the rise in organic matter content and cation exchange capacity of the soil. Consequently, the enhanced cation exchange capacity of the soil leads to a reduction in potassium leaching losses and an overall increase in potassium availability. Similar results were reported by Pandian *et al*. (2016), who found that the application of red gram and cotton stalk biochar increased the availability of potassium in groundnut soil.

10. Cotton Yield:

The examination of the data presented in Table 4 revealed that the application of biochar, vermicompost and azotobacter along with RDF, had a significant impact on the yield of cotton. The yield of cotton ranged from 9.36 to 10.66 bales ha^{-1}. As indicated by the findings, the application of biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1}+*Azotobacter*@ 5 L ha^{-1} along with RDF, resulted in the highest yield of cotton (10.66 bales ha^{-1}) compared to RDF alone (9.36 bales ha^{-1}). This could be attributed to the prevention of nutrient leaching in the biochar-treated plots, leading to increased nutrient retention in the soil and subsequently contributing to a higher yield. As a result, the retention of these nutrients in the soil was enhanced, leading to a higher crop yield. In a similar vein, Di *et al*. (2019) observed that the combined use of wheat straw biochar and vermicompost resulted in an increased rice yield compared to the application of vermicompost alone. Adekiya*et al*. (2020) also found that the application of hardwood biochar in conjunction with NPK fertilizer led to an augmented rhizome yield of ginger.

Table. 4: Effect of combined application of biochar and vermicompost along with biofertilizers on yield of cotton (bales ha^{-1})

Treatment	Recommended dose of fertilizers (RDF)	Biochar @ 2.5 t ha^{-1} + vermicompost @ 2.5 t ha^{-1} + azotobacter @ 5 Lha^{-1}+ RDF
Mean	9.36	10.66
Variance	0.99	1.37
No. of observations	20	20
T test value	3.79*	
Standard error	0.34	

Conclusion:

Based on the findings, it can be concluded that the application of biochar derived from cotton crop residues, in conjunction with vermicompost, biofertilizers and recommended dose of fertilizers, holds significant promise for carbon sequestration, enhancement of soil health, and increased cotton yield, particularly during the *Kharif* season.

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Conflict of Interest:

As authors, we affirm that we possess no conflict of interest.

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