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Influence of Enriched Biochar on Soybean Growth Traits, Quality Attributes and Economic Viability in Acidic Soil over Two Growing Seasons

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Abstract

A field experiment was conducted to evaluates the influence of enriched biochar on soybean growth traits, quality attributes and economic viability of soybean in acidic soils across two growing seasons (*Rabi* 2022 and *Rabi* 2023). This experiment was conducted in ICAR-KVK Hadonahalli, Bengaluru Rural. Thirteen treatments were replicated thrice, including an absolute control (T_1) and various combinations of recommended doses of fertilizers (NPK), farmyard manure (FYM), biochar, zinc sulphate ($ZnSO_4$) and phosphate-solubilizing bacteria (PSB). The results indicated that there was a non-significant improvement in germination percentage which ranged from 89.83 to 95.31 per cent and day to 50 per cent flowering ranged from 36.08 to 40.10 days. Compared to control, higher germination and days to 50 per cent flowering was recorded in T_6 (100% NPK + PSB enriched FYM at 3.125 t ha^{-1} + 100% Zn enriched Biochar at 5 t ha^{-1}). This treatment also recorded higher crude protein (36.48%) and higher oil content (21.70%), contributing to higher seed quality. Economic analysis revealed that treatments involving enriched biochar, especially T_5, T_6, T_7 and T_8, resulted in achieving higher gross and net returns. The benefit-cost ratio was most favourable in T_5, underscoring the economic advantage of integrating PSB-enriched biochar with conventional fertilizer practices. In conclusion, the study demonstrates that the application of enriched biochar, particularly when combined with PSB and $ZnSO_4$, not only improves soybean growth and quality in acidic soils but also enhances economic returns, offering a sustainable solution for soybean cultivation in challenging soil conditions.

Keywords : Enriched Biochar, Oil content. Germination, B:C ratio, PSB, Soybean

Soybean (*Glycine max* L.) is a vital oilseed crop globally, known for its high protein and oil content, with diverse applications in food, feed and industry. As demand increases, optimizing soybean cultivation in varied agroecological conditions is crucial. A major challenge in regions with acidic soils is maintaining nutrient availability and soil health, which are essential for high yield and quality. Acidic soils, common in tropical and subtropical areas, have low pH and often lack essential nutrients like phosphorus (P) and zinc (Zn) while containing toxic levels of aluminium (Al) and manganese (Mn) (Chintala *et al.,* 2014). These conditions can hinder soybean growth, resulting in reduced germination, delayed flowering, poor seed quality and lower economic returns. To counter these effects, soil management strategies, such as using organic amendments like farmyard manure (FYM) and biochar are essential (Hanumanta *et al*., 2024).

Biochar, a carbon-rich material from the pyrolysis of organic biomass, improves soil properties by buffering pH, retaining nutrients, reducing heavy metals in soil and enhancing microbial activity (Nandini and Prakasha, 2022; Bramarambika *et al.,* 2021). When enriched with nutrients like P and Zn, biochar can serve as a slow-release fertilizer. Additionally, incorporating phosphate-solubilizing bacteria (PSB) into FYM and biochar can further enhance nutrient availability, particularly phosphorus (Manikanta *et al*., 2024). While the benefits of biochar and PSB on soil health and crop yield are documented, limited research exists on their combined effects on soybean cultivation in acidic soils, especially regarding economic viability. This study aims to explore the influence of enriched biochar, alone and combined with other amendments, on soybean growth, seed quality and economic returns over two growing seasons (2022 and 2023).

The primary objectives include evaluating the impact of enriched biochar on soybean growth parameters, such as germination percentage and days to 50 per cent flowering and assessing seed quality, including crude protein and oil content. A comprehensive economic analysis was also conducted, examining the cost of cultivation, gross returns, net returns and benefit-cost ratio for each treatment.This research aims to provide insights into the potential of enriched biochar as a sustainable, economically viable solution for improving soybean productivity in acidic soils, contributing to sustainable agriculture and food security.

Material and Methods

The experiment was carried out at ICAR-KVK, located in Hadonahalli, Doddaballapura Taluk, Bengaluru Rural District, Karnataka, India, which falls under Eastern Dry Zone of Karnataka and is situated at 13° 37' North latitude 77° 54' East longitude and at an altitude of 880 meters above the mean s ea level. The chemical properties of the initial soil sample were as follows: the pH was 5.83, which was acidic in nature, electrical conductivity was 0.31 dS m^{-1}, available soil nitrogen, phosphorus and potassium content was 278.12, 25.81 and 193.68 kg ha^{-1}, respectively. The test crop selected was Soybean, variety JS-335. The experiment was carried out following randomized complete block design (RCBD) with thirteen treatments and three replications. Different methods followed for the soil analysis are indicated in the Table 1. The treatment details are mentioned below:

Treatment details

T_1	:	Absolute Control
T_2	:	Package of Practice (RDF+ FYM at 6.25 t ha^{-1})
T_3	:	100 % NPK + $ZnSO_4$ + Biochar at 10 t ha^{-1}
T_4	:	100 % NPK + $ZnSO_4$ + PSB enriched FYM at 6.25 t ha^{-1}
T_5	:	100 % NPK + $ZnSO_4$ + PSB enriched Biochar at 10 t ha^{-1}
T_6	:	100 % NPK + PSB enriched FYM at 3.125 t ha^{-1} + 100 % Zn enriched Biochar at 5 t ha^{-1}
T_7	:	100 % NPK + PSB enriched FYM at 3.125 t ha^{-1} + 75 % Zn enriched Biochar at 5 t ha^{-1}
T_8	:	100 % NPK + PSB enriched FYM at 3.125 t ha^{-1} + 50 % Zn enriched Biochar at 5 t ha^{-1}
T_9	:	100 % NK + 75 % P + PSB enriched FYM at 6.25 t ha^{-1} + $ZnSO_4$
T_{10}	:	100 % NK + 75 % P + PSB enriched Biochar at 10 t ha^{-1} + $ZnSO_4$
T_{11}	:	100 % NK + 75 % P + PSB enriched FYM at 3.125 t ha^{-1} + 100 % Zn enriched Biochar at 5 t ha^{-1}
T_{12}	:	100 % NK + 75 % P + PSB enriched FYM at 3.125 t ha^{-1} + 75 % Zn enriched Biochar at 5 t ha^{-1}
T_{13}	:	100 % NK + 75 % P + PSB enriched FYM at 3.125 t ha^{-1} + 50 % Zn enriched Biochar at 5 t ha^{-1}

Note : RDF=30:80:37.5:12.5 of N: P_2O_5: K_2O: Zn kg ha^{-1}, FYM-6.25 t ha^{-1}, Biochar at 10 t ha^{-1}

TABLE 1

Initial soil properties of experimental site and methods employed for analysis of soil samples

Soil properties	Method employed	Values	References
Physical analysis			
Texture	International Pipette method	Sandy clay loam	Piper, 1966
Bulk density (Mg m^{-3})	Keen Cup method	1.45	Piper, 1966
MWHC (%)	Keen Cup method	37.42 %	Piper, 1966
Chemical analysis			
Soil pH	Glass electrode pH meter (1:2.5) soil water suspension	5.83	Jackson, 1973
EC (dS m^{-1})	Conductometry (1:2.5 soil: water)	0.14	Jackson, 1973
Organic carbon (%)	Wet oxidation	0.46	Walkley and Blacks (1934)
Available N (kg ha^{-1})	Alkaline potassium permanganate method	278.12	Subbiah and Asija, 1956
Available P_2O_5 (kg ha^{-1})	Bray's extraction, (Spectrophotometer)	25.81	Jackson, 1973
Available K_2O (kg ha^{-1})	Ammonium acetate extraction (Flame photometer)	193.68	Jackson, 1973

Enrichment of FYM

Farm yard manure was enriched with PSB through a two-step process. Initially, finely decomposed FYM was collected which was available in ICAR-KVK Hadonahalli and foreign materials were removed. Subsequently, a PSB powder was purchased from the Department of Agricultural microbiology, UAS, GKVK, Bengaluru, at the rate of Rs.100 per kg. The matured PSB powder was then thoroughly mixed with the composted FYM in a predetermined ratio. For 200 kg of FYM 1 kg of PSB powder added in the ratio of 200:1. The mixture was incubated under shade conditions to allow for PSB colonization of the organic matter. This PSB enriched FYM was incorporated in the experimental field. (Lavanya and Sathish, 2020).

Enrichment of Biochar

This experiment investigates the potential of enriching coconut shell biochar with both phosphorus solubilizing bacteria (PSB) and zinc sulphate ($ZnSO_4$) to improve its beneficial effects on crops. The coconut shell biochar was purchased from Kalpatharu products, Tiptur, Tumakuru District of Karnataka. 1 kg of PSB was thoroughly mixed with 200 kg of biochar fostering a direct association between the bacteria and the biochar substrate. Additionally, the biochar is further enriched with three different concentrations of $ZnSO_4$ at 100, 75, and 50 per cent of recommended $ZnSO_4$. This allows for exploring the impact of varying zinc levels on the overall effectiveness of the enriched biochar. To foster microbial growth, enriched biochar is kept shaded and moist. This controlled environment promotes PSB colonization and potential nutrient release. Various enrichment methods and zinc concentrations are tested to determine the most effective biochar amendment for delivering phosphorus and zinc to crops. (Subedi, 2012).

Manures, Biochar and Fertilizer Application

Following a 15-day enrichment period, both enriched biochar and farm yard manure were applied to the designated field in accordance with the established treatment regime. The biochar was meticulously spread in a uniform layer across the entire area. Fertilizer application adhered to the recommendations outlined in the University of Agricultural Science, Bangalore POP with a total of 30 kg N, 80 kg P and 37.5 kg K per hectare, along with an additional 12.5 kg of Zinc Sulphate per hectare. Soybean growth parameters like germination percentage and days to 50 per cent flowering, quality attributes like crude protein and oil content of seed recorded as per the standard procedures. After harvesting of soybean crop pods, cost of cultivation, gross returns, net returns and B:C ratio were calculated.

Estimation of Oil Content (%) in Seeds of Soybean

Approximately 20 g of seeds drawn randomly from each treatment were oven dried at 55 ºC temperature. The oil contents were estimated by Nuclear Magnetic Resonance (NMR) instrument which is available at AICRP on Sunflower, ZARS, UAS, GKVK, Bengaluru. The principle of NMR is that a weighed sample is transferred to a cell and placed in the sample cavity in the magnet unit. After selection of instrument parameters, the instrument automatically sweeps through the resonance condition. Concurrently, the integrator stores information on the amount of energy absorbed by the sample. At the end of the cycle, the total energy absorption is proportional to the amount of mobile hydrogen or oil in the seeds estimated.

The bulk density and water holding capacity was calculated using the following formulae:

$$\text{B.D (Mg m}^{-3}\text{)} = \frac{\text{(Weight of Keen's cup + dry soil) - (Weight of Keen's cup)}}{\text{(Volume of Keen's cup)}} \times 100$$

$$\text{Water holding capacity (\%)} = \frac{\text{(Weight of saturated soil - Weight of oven dried soil)}}{\text{(Weight of oven dried soil)}} \times 100$$

Statistical Analysis

The data collected from the experiment at different growth stages were subjected to statistical analysis as described by Gomez and Gomez (1984). Statistical analysis was carried out by taking the average of five plants from each plot for growth, quality and yield attributes. The level of significance used in 'F' was P = 0.05. Critical difference (CD) values were calculated for the P = 0.05, whenever 'F' test was found significant. The results have been interpreted and discussed based on the pooled data of two years.

Results and Discussion

Growth Parameters of Soybean as Influenced by the Application PSB and Zinc Enriched Biochar to Acidic Soil

Germination (%) of Soybean

The germination percentage for various treatments was evaluated over two years (2022 and 2023) and presented as pooled data (Table 2), with rates ranging from 88.33 to 96.41 per cent. Absolute Control (T_1) had the lowest germination rates, averaging 89.83 per cent across the two years. In contrast, Treatment T_5 achieved the highest pooled germination percentage at 95.19 per cent, with individual year rates of 96.41 per cent in 2022 and 93.96 per cent in 2023. Treatments T_6 (100% NPK + PSB enriched FYM at 3.125 t ha^{-1} + 100% Zn enriched Biochar at 5 t ha^{-1}) and T_8 also demonstrated high germination percentages, with pooled averages of 95.3 and 94.96 per cent, respectively. Despite these variations, the overall mean germination across all treatments was 94.01 per cent and the F-test indicated that the differences between treatments were not statistically significant (NS) for either year or the pooled data.

Different nutrient management practices influenced crop germination rates, with the highest observed in treatments using PSB enriched biochar and FYM along with zinc-enriched fertilizers (T5 and T6). These amendments improved soil conditions, enhancing germination. However, non-significant F-test results suggest that while some treatments seemed more effective, the differences were not statistically robust due to data variability or external factors. The control had the lowest germination rates, underscoring the importance of nutrient management. Organic amendments like FYM and biochar, combined with NPK and zinc, appear beneficial, though the benefits were not statistically significant (Rafique *et al.*, 2017). Duan *et al.* (2024) also reported wheat-straw biochar performed better than rice-husk and sawdust-derived biochar regarding germination and agronomic parameters.

TABLE 2

Germination (%) and Day to 50% flowering as influenced by the application of PSB and Zn enriched biochar on soybean growth in acidic soil across two growing seasons 2022 and 2023

Treatments	Germination (%)			Days to 50% flowering		
	2022	2023	Polled	2022	2023	Polled
T_1	88.33	91.34	89.83	35.79	36.37	36.08
T_2	94.10	93.94	94.02	38.02	38.56	38.29
T_3	95.51	94.32	94.92	38.38	38.87	38.63
T_4	95.26	93.24	94.25	39.02	39.69	39.35
T_5	96.41	93.96	95.19	38.69	39.78	39.24
T_6	96.15	94.46	95.31	40.04	40.16	40.10
T_7	96.04	93.19	94.61	39.39	40.71	40.05
T_8	94.69	95.24	94.96	39.64	39.43	39.54
T_9	91.33	91.29	91.31	36.07	37.24	36.65
T_{10}	95.08	91.62	93.35	36.80	36.96	36.88
T_{11}	94.15	95.04	94.60	36.35	39.77	38.06
T_{12}	95.75	93.98	94.86	36.40	40.17	38.29
T_{13}	94.77	95.12	94.94	36.35	39.36	37.85
Mean	94.43	93.60	94.01	37.76	39.00	38.38
F-test	NS	NS	NS	NS	NS	NS
SE.m	2.05	2.60	1.98	1.92	2.06	1.98
CD (P = 0.05)	5.99	7.58	5.79	5.61	6.02	5.79

Note : S-Significant, NS-Non significant, CD: critical difference, SE.m: Standard error of mean

Days to 50 per cent Flowering

The number of days to 50 per cent flowering was evaluated over two years (2022 and 2023) across different treatments, with pooled data (Table 2) showing a range from 36.07 to 40.10 days. Absolute Control (T_1) had the earliest flowering, averaging 36.07 days, while Treatment T_6 took the longest, with a pooled average of 40.10 days. Other treatments, such as T_7 (100% NPK + PSB enriched FYM at 3.125 t ha^{-1} + 75 per cent Zn enriched Biochar at 5 t ha^{-1}), also showed later flowering, with average of 40.05. The overall mean days to 50 per cent flowering across all treatments was 38.38 days. Despite these variations, the F-test indicated that the differences between treatments were not statistically significant (NS) for either year or the pooled data.

Nutrient management practices, particularly in acidic soils, affect flowering timing. Treatments with enriched biochar and FYM (T_4, T_6) may delay flowering by improving soil health and nutrient availability, promoting prolonged vegetative growth. The control (T_1) showed earlier flowering, likely due to nutrient limitations. However, statistical analysis did not confirm significant differences. Biochar's ability to improve soil structure and nutrient retention may delay flowering, while nutrient limitations in the control may trigger earlier flowering as a survival response. These results are in line with the findings of Jahan *et al*. (2020) and Manu *et al.* (2020).

Quality Aattributes of Soybean Seed as Influenced by the Application PSB and Zinc Enriched Biochar

Crude Protein (%) and Oil Content (%) in Soybean Seed

The crude protein and oil content of soybean seeds (Table 3) were analysed across different treatments over two years (2022 and 2023), with the pooled data summarized for comparison. The crude protein content ranged from 26.94 to 36.47 per cent across all treatments. Absolute Control (T_1) had the lowest protein content, with a pooled average of 26.94 per cent. Treatment T_6 exhibited the highest crude protein content, with a pooled average of 37.11 per cent. The overall mean crude protein content across all treatments was 35.04 per cent and the F-test results indicated that the differences between treatments were statistically significant (S) for both years and the pooled data.

The oil content ranged from 16.78 to 21.51 per cent across the treatments (Table 3). Absolute Control (T_1) had the lowest oil content, with a pooled average of 16.78 per cent. Treatment T_6 also showed the highest oil content, with a pooled average of 21.41 per cent. The overall mean oil content across all treatments was 20.44 per cent. The F-test showed statistically significant (S) differences in oil content between treatments for 2022 and the pooled data, while the differences were not significant (NS) for 2023.

Improved oil and protein content in soybeans grown in acidic soils can be significantly enhanced by using NPK, PSB-enriched FYM and Zn-enriched biochar. These treatments work synergistically, providing

TABLE 3

Effect of PSB and Zn enriched biochar application on seed quality parameters like crude protein (%) and Oil content (%) in soybean growing two seasons 2022 and 2023

Treatments	Crude protein (%)			Oil content (%)		
	2022	2023	Polled	2022	2023	Polled
T_1	26.63	27.25	26.94	16.77	16.78	16.78
T_2	34.75	34.88	34.81	20.15	20.27	20.21
T_3	35.31	36.19	35.75	20.87	21.03	20.95
T_4	34.88	36.62	35.75	20.28	20.39	20.33
T_5	35.50	35.86	35.68	21.02	21.19	21.10
T_6	35.75	37.18	36.47	21.32	21.49	21.41
T_7	35.69	35.33	35.51	21.19	21.36	21.28
T_8	35.50	35.86	35.68	20.76	20.90	20.83
T_9	34.81	35.22	35.02	20.24	20.35	20.30
T_{10}	35.38	35.56	35.47	20.40	20.51	20.45
T_{11}	35.63	35.89	35.76	21.10	21.26	21.18
T_{12}	35.56	36.70	35.63	21.02	21.17	21.09
T_{13}	35.44	36.21	35.32	20.56	20.69	20.62
Mean	34.68	35.44	35.06	20.44	20.57	20.50
F-test	S	S	S	NS	NS	S
SE.m	0.93	1.01	0.95	0.79	0.82	0.75
CD (P = 0.05)	2.73	2.94	2.78	2.32	2.40	2.18

Note : S-Significant, NS-Non significant, CD: critical difference, SE.m: Standard error of mean essential nutrients, improving soil health and creating a more favourable environment for plant growth and metabolic process. These results are in line with the findings of Rohitha *et al.* (2021).

Number of Pods Per Plant

The Pooled data on number of pods per plant are represented in the Fig. 1. The number of pods per plant varied significantly across treatments, ranging from 18.72 (T_1) to 41.07 (T_6) in the pooled average. The highest number of pods was observed in T_6 (100% NPK + PSB enriched FYM at 3.125 t ha^{-1} + 100% Zn enriched Biochar at 5 t ha^{-1}) with 41.07, followed by T_7 (37.33) and T_8 (35.68), which were on par. The control treatment, T_1 (Absolute Control), recorded the lowest pod count at 18.72. The Package of Practice treatment, T_2(27.86), showed a slight improvement compared to the control but was lower than the enriched biochar treatments, underscoring the positive influence of biochar enrichment on pod formation in acidic soils. In contrast, the control consistently recorded the lowest number of pods across both years

The results indicate that biochar enrichment, especially with phosphorus solubilizing bacteria (PSB) and zinc (Zn), significantly enhanced the number of pods per plant in soybean grown in acidic soil. Treatment T_6 (100% NPK + PSB enriched FYM at 3.125 t ha^{-1} + 100% Zn enriched biochar at 5 t ha^{-1}) showed the highest pod count, suggesting that combining PSB with Zn-enriched biochar optimizes nutrient availability, particularly phosphorus and zinc, which are essential for reproductive growth in soybeans. The improved pod formation in enriched biochar treatments can be attributed to biochar's capacity to improve soil pH, cation exchange capacity and nutrient retention, which are critical in acidic soils (Nandini & Prakasha, 2022 and Hanumanta *et al.,* 2024) Studies have shown that biochar enhances root growth and microbial activity, further supporting nutrient uptake and pod development (Rohitha *et al.,* 2021). Compared to the Package of Practice (T_2), biochar-amended treatments showed superior pod counts, highlighting biochar's advantage in enhancing soybean productivity in challenging soil conditions.

Seed Yield (q ha^{-1})

The seed yield of soybean (Table 4) varied significantly across treatments in both years (2022 and 2023), as well as in the pooled data. In the control treatment (T_1), the lowest yield was recorded with an average of 8.39 q/ha across two years. The recommended dose of fertilizers (RDF) and

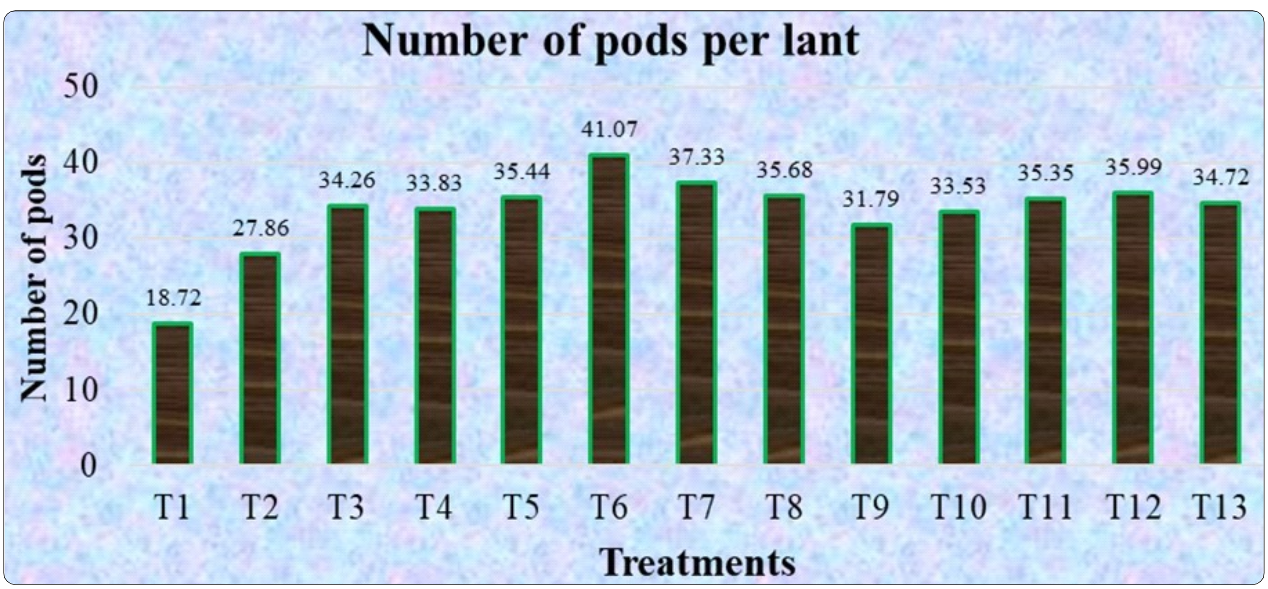

Fig. 1 : Effect of application of enriched coconut shell biochar number of pods per plant after harvest of Soybean (pooled data of 2022 and 2023)

TABLE 4

Effect of PSB and Zn enriched biochar application on seed yield (q/ha) of soybean grown in acidic soil across two growing seasons of 2022 and 2023 (pooled data)

Treatments Details	Seed yield (q/ha)		
	2022	2023	Pooled
T_1 : Absolute Control	8.53	8.24	8.39
T_2 : Package of Practice (RDF+ FYM at 6.25 t ha^{-1})	15.36	15.62	15.49
T_3 : 100 % NPK + $ZnSO_4$ + Biochar at 10 t ha^{-1}	18.76	19.86	19.31
T_4 : 100 % NPK + $ZnSO_4$ + PSB enriched FYM at 6.25 t ha^{-1}	16.49	16.81	16.65
T_5 : 100 % NPK + $ZnSO_4$ + PSB enriched Biochar at 10 t ha^{-1}	20.72	21.45	21.09
T_6 : 100 % NPK + PSB enriched FYM at 3.125 t ha^{-1} + 100 % Zn enriched Biochar at 5 t ha^{-1}	23.45	23.77	23.61
T_7 : 100 % NPK + PSB enriched FYM at 3.125 t ha^{-1} + 75 % Zn enriched Biochar at 5 t ha^{-1}	22.71	23.12	22.91
T_8 : 100 % NPK + PSB enriched FYM at 3.125 t ha^{-1} + 50 % Zn enriched Biochar at 5 t ha^{-1}	22.37	22.78	22.57
T_9 : 100 % NK + 75 % P + PSB enriched FYM at 6.25 t ha^{-1}+ $ZnSO_4$	14.28	15.32	14.80
T_{10} : 100 % NK + 75 % P + PSB enriched Biochar at 10 t ha^{-1} + $ZnSO_4$	18.72	19.80	19.26
T_{11} : 100 % NK + 75 % P + PSB enriched FYM at 3.125 t ha^{-1} + 100 % Zn enriched Biochar at 5 t ha^{-1}	17.98	18.66	18.32
T_{12} : 100 % NK + 75 % P + PSB enriched FYM at 3.125 t ha^{-1} + 75 % Zn enriched Biochar at 5 t ha^{-1}	17.55	18.41	17.98
T_{13} : 100 % NK + 75 % P + PSB enriched FYM at 3.125 t ha^{-1} + 50 % Zn enriched Biochar at 5 t ha^{-1}	17.32	18.22	17.77
Mean	18.02	18.62	18.32
F-test	S	S	S
SE.m0.51	0.53	0.52	
CD (P = 0.05)	1.48	1.53	1.51

FYM at 6.25 t ha^{-1} (T_2) produced a considerably higher yield of 15.49 q/ha, showing the benefits of nutrient application compared to the control. T_6 achieved the highest seed yield, with a pooled value of 23.61 q ha^{-1}. This was followed by T_7 and T_8, which yielded 22.91 q ha^{-1} and 22.57 q ha^{-1}, respectively. Among the treatments with reduced phosphorus (T_9 - T_{13}), seed yields were lower compared to treatments receiving 100 per cent P. T_9 produced 14.80 qha^{-1}, while the other treatments in this group showed moderate yields, ranging from 17.77 to 19.26 q ha^{-1}. The F-test was significant for all the treatments in both years and the pooled data.

The results demonstrate the significant impact of nutrient management on soybean seed yield in acidic soils. The highest yields were observed in treatments where PSB-enriched FYM and Zn-enriched biochar were applied with 100 per cent NPK. This reflects the synergistic effect of biochar and organic amendments in improving soil fertility and nutrient availability in acidic conditions. Biochar enhances soil structure, water retention and cation exchange capacity, while also serving as a carrier for Zn, which is essential for enzyme function and protein synthesis. The combined application of NPK, PSB-enriched FYM and Zn-enriched biochar significantly boosts soybean yields in acidic soils, with the greatest benefit seen from 100 per cent Zn enrichment in biochar (Mousavi *et al.,* 2022).

Effect of PSB and Zinc Enriched Biochar Application on Economic Viability of Soybean Cultivation in Acidic Soil

Economics

The economic analysis of different treatments shows a clear variation in cost of cultivation, gross returns (Table 5), net returns and benefit-cost (B:C) ratio (Table 6). The lowest cost of cultivation was recorded in the control treatment (T_1) with an average of Rs.32,942 ha^{-1}, while T_5 had the highest cost at Rs.60,830 ha^{-1}. The highest gross returns were observed in T_6, with pooled gross returns of Rs.127,153 ha^{-1} and a net return of Rs.73,140 ha^{-1}. The B:C ratio was also the highest in T_6 (2.35), followed by T_7 and T_8 with pooled B:C ratios of 2.28 and 2.25, respectively. The control treatment (T_1) had the lowest net returns and B:C ratio, highlighting the importance of nutrient application for profitability (Rohitha *et al*., 2021).

The results demonstrate that the combined application of NPK, PSB-enriched FYM and Zn-enriched biochar significantly enhances the economic returns of soybean cultivation in acidic soils. T_6, which had the highest gross and net returns along with the best B:C ratio, emphasizes the effectiveness of balanced nutrient management, particularly with Zn-enriched biochar. Biochar improves soil structure, nutrient retention and water holding capacity, while PSB-enriched FYM increases phosphorus availability, leading to better growth and higher yields (Nimbalkar *et al.,* 2023).

The study revealed that the combined application of 100% NPK, PSB-enriched FYM and Zn-enriched

TABLE 5

Effect of PSB and Zn enriched coconut shell biochar application on Cost of cultivation (Rs ha^{-1}) and Gross returns (Rs ha^{-1}) of Soybean (pooled data of 2022 and 2023)

Treatments	COC (Rs ha^{-1})			GR (Rs ha^{-1})		
	2022	2023	Polled	2022	2023	Polled
T_1	32,438	33,447	32,942	39,249	40,644	39,946
T_2	47,273	48,744	48,008	80,836	83,767	82,301
T_3	57,898	59,699	58,798	99,584	105,658	102,621
T_4	48,473	49,981	49,227	86,766	92,058	89,412
T_5	59,898	61,762	60,830	109,013	115,663	112,338
T_6	53,185	54,840	54,013	123,389	130,916	127,153
T_7	53,098	54,750	53,924	119,471	126,758	123,114
T_8	53,010	54,660	53,835	117,682	124,861	121,272
T_9	47,536	49,015	48,275	75,106	79,688	77,397
T_{10}	58,961	60,795	59,878	98,464	104,470	101,467
T_{11}	52,248	53,874	53,061	94,569	100,338	97,453
T_{12}	52,161	53,784	52,973	92,325	97,957	95,141
T_{13}	52,073	53,694	52,883	91,128	96,687	93,907

Note : S-Significant, NS-Non significant, CD: critical difference, SE.m: Standard error of mean

TABLE 6

Effect of PSB and Zn enriched coconut shell biochar application on Net returns (Rs.ha^{-1}) and Benefit cost ratio (Rs.ha^{-1}) of Soybean grown in two seasons (pooled data of 2022 and 2023)

Treatments	NR (Rs ha^{-1})			B:C ratio		
	2022	2023	Polled	2022	2023	Polled
T_1	6,812	7,197	7,004	1.21	1.22	1.21
T_2	33,563	35,023	34,293	1.71	1.72	1.71
T_3	41,686	45,959	43,823	1.72	1.77	1.74
T_4	38,293	42,078	40,185	1.79	1.84	1.82
T_5	49,116	53,902	51,509	1.82	1.87	1.85
T_6	70,204	76,076	73,140	2.32	2.39	2.35
T_7	66,373	72,008	69,190	2.25	2.32	2.28
T_8	64,672	70,201	67,437	2.22	2.28	2.25
T_9	27,571	30,673	29,122	1.58	1.63	1.60
T_{10}	39,504	43,675	41,589	1.67	1.72	1.69
T_{11}	42,321	46,464	44,392	1.81	1.86	1.84
T_{12}	40,164	44,173	42,168	1.77	1.82	1.80
T_{13}	39,055	42,993	41,024	1.75	1.80	1.78

Note : S-Significant, NS-Non significant, CD: critical difference, SE.m: Standard error of mean

biochar significantly improved soybean performance and recorded the highest seed yield, oil content, crude protein and economic returns. Germination percentage and days to 50 per cent flowering were positively influenced by balanced nutrient application, with biochar enhancing soil structure and nutrient availability. Economically, T_6 achieved the best benefit-cost ratio (2.35), indicating the superior profitability of this treatment in acidic soils for soybean cultivation. The reduced phosphorus treatments consistently showed lower economic returns, indicating that phosphorus plays a crucial role in maintaining both yield and profitability, particularly in acidic soils where phosphorus availability is often limited. Therefore, optimal phosphorus management, along with biochar and organic amendments, is essential for maximizing economic benefits in soybean cultivation.

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