Original Research Article

Characterisation of coconut shell biochar and its influence on soil biological properties, bioavailability of major nutrients and Soybean (*Glycine max* L.) yield in acidic soils of Eastern Dry zone of Karnataka

ABSTRACT

A two-season field study was conducted Eastern Dry Zone of Karnataka, to evaluate the influence of phosphorus-solubilizing bacteria (PSB) and zinc-enriched coconut shell biochar on soil biological properties, nutrient bioavailability and soybean (*Glycine max* L.) yield in acidic soils. Thirteen treatments, including a control, package of practice and various combinations of PSB and zinc-enriched biochar were assessed. The biochar was characterized for its physicochemical properties, including pH, electrical conductivity and nutrient composition. Results indicated significant improvements in soil dehydrogenase activity, phosphatase activity and major nutrient bioavailability (N, P, K and Zn) in treatments receiving 100 % NPK, PSB enriched FYM at 3.125 t ha^{-1} and different doses of zinc enriched Biochar at 5 t ha^{-1} compared to the control and package of practice. Soybean yield was maximized under treatments combining PSB-enriched FYM and zinc-enriched biochar, with the highest yield observed in T_6 (23.61 q ha^{-1}), outperforming the control (8.39 q ha^{-1}). The enhanced yield was attributed to improved soil health and nutrient dynamics, driven by synergistic interactions between PSB and biochar. These findings underscore the potential of PSB and zinc-enriched biochar as sustainable amendments for enhancing soil fertility, crop productivity, and nutrient use efficiency in acidic soils.

Key words: PSB enriched biochar, dehydrogenase, phosphorus, phosphatase, soybean yield.

Commented [u1]: I suggest the title: **Effect of coconut shell biochar on soil properties and Soybean (Glycine max L.) yield in the Acidic Soil of of Eastern Dry zone, Karnataka**

Commented [u2]: Write in digital

Commented [u3]: List the physical parameters

Commented [u4]: Write about the characterization of biochar

Commented [u5]: Write the

Commented [u6]:

Commented [u7]: Write a ltebit about the characterization of biochar

Commented [u8R7]:

Commented [u9R7]:

Commented [u10]: What are physicochemical charactersticks biochar

1. INTRODUCTION

Soybean (*Glycine max* L.) is a critical legume crop globally, providing a major source of protein and oil, especially in tropical and subtropical regions. In India, soybean cultivation is particularly important in the Eastern Dry Zone of Karnataka, where soils are predominantly acidic. Acidic soils, defined by low pH levels (generally <5.5), present significant challenges to crop growth due to their negative impact on nutrient availability, microbial activity, and overall soil health (Rohitha *et al.* 2022). In these soils, the bioavailability of essential macronutrients such as phosphorus (P) and micronutrients like zinc (Zn) is substantially reduced, often leading to deficiencies that limit plant growth, yield, and quality (Shome *et al*. 2022).

Commented [u11]: Reference

In acidic soils, the availability of phosphorus is often restricted because phosphorus reacts with iron and aluminium to form insoluble compounds that are unavailable to plants. Similarly, zinc deficiency is common, as its availability decreases in highly acidic conditions due to its strong association with soil particles (Urgessa 2021). This nutrient imbalance can result in reduced soybean growth, impaired photosynthesis, and lower yields. The microbial community in acidic soils also tends to be less active, with critical enzymes such as dehydrogenase and phosphatase showing reduced activity (Baruah and Gogoi, 2023) Dehydrogenase activity is an indicator of overall microbial activity and soil health, while phosphatase activity plays a vital role in releasing organic phosphorus from soil organic matter, making it available for plant uptake. Reduced activity of these enzymes in acidic soils further exacerbates nutrient limitations and hinders the soil's ability to support healthy plant growth (Bramarambika *et al*. 2024).

To address these soil fertility challenges, sustainable soil amendments are needed. Phosphorus-solubilizing bacteria (PSB) have gained attention as a promising biotechnological solution to improve the availability of phosphorus in soils. PSB can convert insoluble forms of phosphorus into plant-available forms, thus enhancing nutrient cycling and microbial activity. Furthermore, biochar, a carbon-rich by-product derived from the pyrolysis of organic materials such as coconut shells, has emerged as an effective soil amendment (Mousavi *et al*. 2022). Biochar improves soil structure, increases cation exchange capacity, and enhances nutrient retention, thereby fostering a more favourable environment for plant growth. When enriched with zinc, biochar can also help mitigate zinc deficiencies, making it a powerful tool for enhancing nutrient availability in acidic soils (Sousarae *et al*. 2024).

The combination of PSB and zinc-enriched coconut shell biochar offers a potential solution to the challenges posed by acidic soils. This research aims to investigate the effects of PSB and zinc-enriched biochar on soil biological properties, nutrient bioavailability and soybean yield in acidic soils of the Eastern Dry Zone of Karnataka. Specifically, the study will assess the impact of these amendments on soil microbial activity, particularly dehydrogenase and phosphatase enzymes and how they influence the bioavailability of major nutrients like nitrogen, phosphorus, potassium and zinc. The study also includes a detailed characterization of coconut shell biochar, providing insights into its properties and its role as a sustainable soil amendment in improving soil fertility and crop productivity.

Commented [u12]: Please review the current state of the art in this regard where is challenged?

Commented [u13]: Check is it proposal

2. MATERIAL AND METHODS

2.1 Description of the experimental site

The field experiment was conducted for two cropping seasons during rabi, 2022 and rabi, 2023 at ICAR-Krishi Vigyan Kendra, Hadonahalli, Bengaluru Rural District, Karnataka, India which lies in the Eastern Dry Zone of Karnataka. ICAR-KVK is situated at an altitude of 880.71 meters above mean sea level and located between 13° 37[1], North latitude and 77° 54[1] East longitudes. The experimental site having slightly acidic soil with uniform textural make up and well connected with the farm pond.

Commented [u14]: Prepare the study area map

2.2 Collection of initial soil sample and analysis

To know the initial soil fertility status, soil samples were collected from the experimental site (ICAR-KVK, Hadonahalli, Karnataka). Soil samples were taken randomly from the different parts of the field before sowing of soybean up to depth of 15 cm and a composite sample was prepared. The physico-chemical properties of experimental site is presented in **Table 1.**

The physical properties of soil, such as texture, bulk density, and maximum water holding capacity (MWHC), were determined using the International Pipette method and Keen Raczkowski Cup method (Piper, 1966). Physico-chemical properties like soil pH and electrical conductivity (EC) were measured using a glass electrode pH meter and conductometry (1:2.5 soil: water suspension), respectively (Jackson, 1973). Organic carbon content was determined by the wet oxidation method given by Walkley and Black (1934). Major nutrients such as available nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) were analysed using the alkaline potassium permanganate method (Subbiah and

Asija, 1956), Bray's extraction and colorimetry (Jackson, 1973) and ammonium acetate extraction with a flame photometer (Jackson, 1973), respectively. DTPA-extractable zinc (Zn) micro nutrient was analysed using an atomic absorption spectrophotometer given by Lindsay and Norvell (1978).

Table 1: Initial physico-chemical and biological properties of soil during 2022-23

Commented [u15]: Add one two columns and rating the status and use citation for each parameter rating

Sl, no	Soil parameters	Value
1.	Sand, Silt and Clay (%)	52.58, 21.84 and 25.57, respectively.
2.	Soil textural class	Sandy clay loam
3.	Bulk density (mg m^{-3})	1.45
4.	Maximum water holding capacity (%)	37.42 %
5.	Soil pH (1:2.5)	5.83
6.	EC (dS m^{-1})	0.14
7.	Organic carbon (%)	0.46
8.	Available N (kg ha^{-1})	278.12
9.	Available P_2O_5 (kg ha^{-1})	25.81
10.	Available K_2O (kg ha^{-1})	193.68
11.	DTPA Extractable Zn (mg kg^{-1})	1.36
12.	Dehydrogenase activity (µg TPF/g soil/24 hr)	36.53
13.	Phosphatase activity (µg PNP/g soil/hr)	18.81

2.3 Enrichment of biochar

This experiment investigated 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. 1 kg of PSB is 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 $ZnSO_4$. To facilitate microbial development and proliferation, enriched biochar was covered and kept under shade with optimum moisture level. This environment ensures optimal conditions for the PSB to establish themselves and potentially enhance the biochar's nutrient availability and plant growth-promoting properties.

Commented [u16]: How to you prepare the biochar write in detail the methodology

2.4 Details of treatments

The study consisted of 13 treatments, comprised of 3 replications with RDF, FYM, biochar and PSB enriched biochar. The treatments details are mentioned below:

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**-** FYM**-**6.25 t ha^{-1}, Biochar^{-1}0 t ha^{-1}, 30: 80: 37.5: 12.5 N: P_2O_5: K_2O: Zn kg ha^{-1}.

* $ZnSO_4$ – 12.5 kg ha^{-1} for all treatments except in absolute control

* NPK Provided through Urea, single super phosphate and Muriate of potash

2.5 Estimation of biological properties of soil

The dehydrogenase activity in the soil was determined by the procedure given by Casida *et al*. (1964). It is based on the principle that 2, 3, 5- Triphenyl tetrazolium chloride (TTC), used as electron acceptor in place of O_2 is reduced to triphenyl formazan (TPF). The quantity of TPF formed which is directly proportional to the dehydrogenase activity. The activity is expressed as µg of TPF formed g^{-1} soil 24 hr^{-1} at 37 ± 2°C. Activity of phosphatase enzyme estimated as per the procedure given by Eivazi and Tabatabai (1977). It involved the colorimetric estimation of p-nitrophenyl (PNP) released by phosphatase activity, when the soil incubated with buffer. The suspension was centrifuged, filtered and the intensity of yellow colour of the supernatant was measured using spectrophotometer at 420 nm wavelength.

field production. Doctoral dissertation. Iowa State University, Ames, Iowa.

2.6 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. 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.

3. RESULTS AND DISCUSSION

3.1 Characterization of coconut shell biochar

The biochar produced from coconut shells was characterized for various physical and chemical properties and the findings are summarized in Table 2. Relatively low bulk density (0.38 Mg m^{-3}) of coconut shell biochar suggests that it is highly porous, enhancing its potential for improving soil structure and water retention. This low bulk density is common for biochar due to its inherent porosity formed during pyrolysis. The biochar exhibits a high-water holding capacity (76.27 %), making it a suitable amendment for arid and semi-arid soils. Its high porosity and surface area contribute to this capacity. The water retention potential of biochar depends on its feedstock and pyrolysis conditions and coconut shell biochar seems to retain more water due to its fine pore structure (Liu *et al.,* 2017).

The alkaline pH (9.52) indicates that the biochar has a significant liming effect and can helps to neutralize acidic soils. This high pH is typical for biochar derived from biomass like coconut shells due to the concentration of alkaline minerals during pyrolysis (Liu *et al.,* 2017). However, it can be detrimental in soils that are already neutral or alkaline. The relatively high EC value (1.12 dS m^{-1}) indicates the presence of soluble salts in the biochar, which could affect plant growth if applied in large quantities (Rohitha *et al*. 2021). This is typical for biochar that retain salts from their feedstock. The very high total carbon content (77.42%) reflects the stability and recalcitrance of biochar as a soil amendment, contributing to long-term carbon sequestration. Such high carbon levels are typical for biochar produced from woody biomass like coconut shells.

The low total nitrogen content (0.24 %) is expected, as biochar is typically poor sources of nitrogen due to volatilization of nitrogen compounds during pyrolysis. This limits its direct fertilization potential but makes it a good soil amendment for improving nitrogen retention in soils. The phosphorus content (0.16 %) may contribute to soil phosphorus pools, but biochar is not generally a significant phosphorus source. However, biochar can help improve phosphorus availability by reducing its fixation in soil. The relatively high potassium content (0.82 %) indicates that coconut shell biochar could provide some potassium to soils. Potassium is often preserved in biochar during pyrolysis due to its high melting point. (Mousavi *et al.,* 2022)

The sulphur content suggests that biochar is not a significant source of sulphur. Sulphur is often volatilized during the pyrolysis process. The presence of exchangeable calcium and magnesium points to the potential of biochar to improve cation exchange capacity (CEC) and soil fertility. These elements are typically retained in biochar and can help buffer acidic soils. The biochar exhibits high concentrations of micronutrients, particularly iron (262.56 mg kg^{-1}) and manganese (141.27 mg kg^{-1}), suggesting its suitability for micronutrient-deficient soils. These micronutrients likely remain in biochar due to incomplete volatilization during pyrolysis at moderate temperatures (Rohitha *et al*., 2021).

Table 2: Physico chemical characterization of coconut shell biochar and standard methods employed.

Parameters	Value	Method employed
Bulk density (mg m^{-3})	0.38	Keen's cup method (Piper, 1966)
Maximum water holding capacity (%)	76.27	Keen's cup method (Piper, 1966)
pH (1:10)	9.52	Potentiometry (Jackson, 1973)
Electrical conductivity (d S m^{-1})	1.12	Conductometry (Jackson, 1973)
Total carbon (%)	77.42	Dry combustion method (CHNS) (Page *et al*.,1982)
Total Nitrogen (%)	0.24	Kjeldahl digestion and distillation method (Jackson, 1973)
Total Phosphorus (%)	0.16	Diacid digestion and spectrophotometry (Jackson, 1973)
Total Potassium (%)	0.82	Diacid digestion and flame photometry (Jackson, 1973)
Total Calcium (%)	0.46	Complexometric titration (Jackson, 1973)
Total Magnesium (%)	0.25	Complexometric titration (Jackson, 1973)
Total Sulphur (%)	0.16	Turbidimetry (Black, 1965)
Zinc (mg kg^{-1})	28.65	
Iron (mg kg^{-1})	262.56	Di-acid digestion and Atomic Absorption spectrophotometry (Jackson, 1973)
Copper (mg kg^{-1})	36.25	
Manganese (mg kg^{-1})	141.27	

Commented [u17]: Move this column in to the methods

3.2 Soil biological properties

The data on dehydrogenase and phosphatase activity in soil after harvest as influenced by application of PSB and Zinc enriched coconut shell biochar in acidic soil are presented in Table 3.

Commented [u18]: Remove

3.2.1 Dehydrogenase activity

The dehydrogenase activity (Table 3) varied from 36.83 to 48.35 µg TPF/g soil/24 hr across the treatments. The highest value was observed in treatment T_6 (100% NPK + PSB enriched FYM at 3.125 t ha^{-1} + 100 % Zn enriched Biochar at 5 t ha^{-1}) with 48.35 µg TPF/g soil/24 hr in 2023, followed by T_7 (100% NPK + PSB enriched FYM at 3.125 t ha^{-1} + 75% Zn enriched Biochar at 5 t ha^{-1}) with 48.17 µg TPF/g soil/24 hr. The control treatment (T_1: Absolute Control) recorded the lowest value at 36.83 µg TPF/g soil/24 hr. The pooled values also highlighted treatment T_5 (100% NPK + $ZnSO_4$ + PSB enriched Biochar at 10 t ha^{-1}) with a mean of 46.39 µg TPF/g soil/24 hr, indicating on-par values with T_3 (46.12 µg TPF/g soil/24 hr) and T_6 (47.00 µg TPF/g soil/24 hr).

The observed enhancements in dehydrogenase activity, particularly in treatments involving PSB and zinc-enriched biochar, highlight the importance of these amendments in promoting soil microbial activity. The highest values indicate that the synergistic effect of organic matter and micronutrients significantly improves microbial respiration and metabolic activity, which are essential for effective nutrient cycling (Pandey *et al*. 2025). Moreover, the results are consistent with previous studies demonstrating that the application of biochar and PSB can enhance soil microbial biomass and enzyme activities, thereby improving soil health and fertility. Such findings suggest that integrating these practices into soybean cultivation can lead to improved soil quality and crop productivity, particularly in nutrient-deficient soils. These finding are in line with Castaldi *et al.* (2008) and Deng *et al*., (2025).

3.2.2 Phosphatase activity

The phosphatase activity (Table 3) in soil varied from 19.77 to 27.81 µg PNP/g soil/hr in the pooled data. The highest phosphatase activity 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 a value of 27.81 µg PNP/g soil/hr, followed by T_8 (27.24 µg PNP/g soil/hr) and T_7 (27.22 µg PNP/g soil/hr). The next lower values were recorded in T_9 (27.12 µg PNP/g soil/hr) and T_4 (26.57 µg PNP/g soil/hr). The lowest activity was recorded in T_1 (Absolute Control), with a value of 19.77 µg PNP/g soil/hr, which was significantly lower than the highest value and T_2 (Package of Practice - 24.87 µg PNP/g soil/hr). Treatments T_7 and T_8 were on par with each other, exhibiting similar phosphatase activity around 27.24 µg PNP/g soil/hr.

Commented [u19]: Refine in short way as you cite the table write only the major finding to reduce redundancy

The higher values of phosphatase enzyme activity were recorded with biochar application in combination with FYM. Pandey *et al*., (2025) also reported that higher soil organic carbon contents may potentially explain increased enzyme activities. It is also due to the fact that due to addition of both biochar and FYM, there was a better root growth that contributed for higher phosphatase activity and it is well known that phosphatases are root originated. The increased pH values in the original low pH soil could also enhance the availability of nutrients and consequently increased soil microbial biomass. Activities of certain enzymes like, alkaline phosphatase, aminopeptidase and N- acetyl glucosaminidase have been reported to increase due to biochar application (Zhou *et al*., 2022).

Table 3: Influence of PSB and Zn enriched coconut shell biochar on dehydrogenase and phosphatase activity in post-harvest soil

Treatment details	Dehydrogenase activity (µg TPF/g soil/24 hr)			Phosphatase activity (µg PNP/g soil/hr)		
	2022	**2023**	**pooled**	**2022**	**2023**	**pooled**
T_1	37.42	36.83	37.13	20.09	19.45	19.77
T_2	40.20	41.72	40.96	24.06	25.68	24.87
T_3	45.26	46.99	46.12	21.72	22.33	22.03
T_4	42.66	44.28	43.47	25.70	27.43	26.57
T_5	45.53	47.26	46.39	24.97	26.65	25.81
T_6	46.55	48.35	47.45	26.90	28.72	27.81
T_7	46.42	48.17	47.30	26.33	28.11	27.22
T_8	46.12	47.88	47.00	26.35	28.13	27.24
T_9	42.21	43.83	43.02	26.23	28.00	27.12
T_{10}	44.92	46.69	45.80	24.41	26.05	25.23
T_{11}	46.39	48.17	47.28	25.23	26.93	26.08
T_{12}	46.26	48.03	47.15	25.43	27.14	26.28
T_{13}	46.33	48.09	47.21	25.16	26.85	26.01
S. Em ±	**0.76**	**0.81**	**0.79**	**0.57**	**0.63**	**0.60**
CD (*P=0.05*)	**2.23**	**2.36**	**2.29**	**1.67**	**1.83**	**1.75**

Commented [u20]: Please mean separation using the Duncan multiple range test (DMRT) for the whole table

3.3 Major nutrient status in post-harvest soil (N, P and K)

The available nitrogen (N) content (Table 4) varied across treatments, with pooled N values ranging from 276.19 kg ha⁻¹ to 324.96 kg ha⁻¹. The lowest N was recorded in T_1 (Absolute Control) with a pooled value of 276.19 kg ha^{-1}, while the highest N content 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 a pooled N value of 324.96 kg ha^{-1}. Other notable treatments included T_5 (100 % NPK + $ZnSO_4$ + PSB enriched Biochar at 10 t ha^{-1}) with 313.94 kg ha^{-1} and T_{10} (100 % NK + 75 % P + PSB enriched FYM at 3.125 t ha^{-1} + $ZnSO_4$) with 321.85 kg ha^{-1}. Treatments T2 (294.94 kg ha^{-1})**,** T_3 (298.42 kg ha^{-1})**,** and T_4 (297.10 kg ha^{-1}) were on par with T_9 (295.89 kg ha^{-1}). The differences among treatments were significant at the (P= 0.05) level, indicating the influence of various nutrient amendments on nitrogen availability in the soil.

The available phosphorus content (Table 4) varied significantly, with pooled P values ranging from 23.31 kg ha^{-1} to 40.35 kg ha^{-1}. The lowest P was recorded in T_1 (Absolute Control) at 23.31 kg ha^{-1}, while the highest was observed in T_5 (100 % NPK + $ZnSO_4$ + PSB enriched Biochar at 10 t ha^{-1})**,** with a pooled value of 40.35 kg ha^{-1}. Other notable treatments included T_4 (35.04 kg ha^{-1}) and T_3 (36.15 kg ha^{-1})**.** Treatments T_2 (31.04 kg ha^{-1}) and T_6 (33.99 kg ha^{-1}) were on par with T_9 (33.00 kg ha^{-1})**.** The differences among treatments were significant at the (P= 0.05) level, indicating that the application of various nutrient amendments significantly influenced phosphorus availability in the soil.

Table 4 presents the available potassium (K) content in kg ha^{-1} across different treatments. The K content varied from 189.43 kg ha^{-1} in T_1 (Absolute Control) to 258.90 kg ha^{-1} in T_5 (100 % NPK + $ZnSO_4$ + PSB enriched Biochar at 10 t ha^{-1})**.** The highest value was followed by T_4 (215.42 kg ha^{-1}) and T_3 (252.32 kg ha^{-1})**.** Lower values included T_2 (209.22 kg ha^{-1}) and T_6 (255.75 kg ha^{-1})**,** which were on par with T_9: 100 % NK + 75 % P + PSB enriched FYM at 6.25 t ha^{-1}+ $ZnSO_4$ (211.12 kg ha^{-1})**.** Significant differences among treatments were noted at the (P=0.05) level, indicating that potassium availability is markedly enhanced through the application of NPK fertilizers, particularly when combined with organic amendments like PSB-enriched biochar. These results highlight the critical role of potassium in promoting plant health and productivity, thereby emphasizing the necessity for optimized nutrient management strategies in agriculture.

The significant increase in available phosphorus content observed in the study can be attributed to the synergistic effects of NPK fertilizers, $ZnSO_4$, and PSB-enriched biochar, which enhance phosphorus solubilization and availability in the soil. PSB play a crucial role in increasing the bioavailability of phosphorus from insoluble forms, facilitating better uptake by plants, as supported by Babu *et al*. (2022). The elevated phosphorus levels in treatments incorporating organic and chemical amendments underscore the importance of balanced fertilization for optimizing crop nutrition. Similarly, the increase in nitrogen content in treatments like T_6 is likely due to the effects of PSB-enriched FYM and Zn-enriched biochar, enhancing nutrient cycling.

Biochar improves nutrient retention, which reduces leaching and promotes microbial biomass essential for mineralization, aligning with findings from Dangi *et al.* (2020). Superior nitrogen values from treatments combining organic and chemical amendments indicate effective nutrient management for optimal productivity. Furthermore, potassium content significantly influenced plant growth, with higher levels in treatments supplemented with NPK and biochar, enhancing enzymatic functions and osmotic regulation. These findings align with Zhang *et al*. (2020), who emphasized potassium critical role in photosynthesis and water-use efficiency and also demonstrated that organic amendments, such as biochar, enhance potassium retention in soils, thereby improving nutrient uptake.

Table 4: Impact of PSB and Zn enriched coconut shell biochar on N (kg ha^{-1}), P_2O_5 (kg ha^{-1}) and K_2O (kg ha^{-1}) in post-harvest soil

Treatment details	N (kg ha^{-1})			P_2O_5 (kg ha^{-1})			K_2O (kg ha^{-1})		
	2022	**2023**	**pooled**	**2022**	**2023**	**pooled**	**2022**	**2023**	**pooled**
T_1	277.34	275.03	276.19	23.79	22.82	23.31	192.31	186.54	189.43
T_2	286.77	303.12	294.94	28.56	33.53	31.04	192.65	225.79	209.22
T_3	290.15	306.69	298.42	33.26	39.05	36.15	232.34	272.30	252.32
T_4	288.87	305.34	297.10	32.24	37.85	35.04	198.36	232.48	215.42
T_5	305.24	322.64	313.94	37.12	43.58	40.35	238.40	279.40	258.90
T_6	315.96	333.97	324.96	31.27	36.71	33.99	235.50	276.01	255.75
T_7	310.78	328.49	319.64	31.86	37.40	34.63	231.40	271.20	251.30
T_8	311.60	329.36	320.48	32.56	38.23	35.39	233.20	273.31	253.26
T_9	287.69	304.09	295.89	30.36	35.64	33.00	194.40	227.84	211.12
T_{10}	312.93	330.77	321.85	33.42	39.24	36.33	228.40	267.68	248.04
T_{11}	308.62	326.21	317.42	29.68	34.84	32.26	231.50	271.32	251.41
T_{12}	309.42	327.06	318.24	30.13	35.37	32.75	230.40	270.03	250.21
T_{13}	305.06	322.45	313.75	31.25	36.69	33.97	242.30	283.98	263.14
S. Em ±	**8.66**	**9.09**	**8.88**	**0.89**	**1.03**	**0.96**	**6.32**	**7.31**	**6.82**
CD @ 5%	**25.28**	**26.55**	**25.91**	**2.60**	**3.02**	**2.81**	**18.46**	**21.35**	**19.90**

3.4 DTPA extractable Zinc micro nutrient status in post-harvest soil

The DTPA-extractable Zn concentration (Fig 1) in post-harvest soil ranged significantly among treatments, varying from 1.13 to 1.98 mg kg^{-1}. The highest Zn concentration was observed in T_6 (1.98 mg kg^{-1}), followed by T_{11} (1.92 mg kg^{-1}). These values were significantly higher than the control (T_1), which recorded the lowest concentration of 1.13 mg kg^{-1}. On-par values were seen in T_4 and T_7 (1.82

mg kg⁻¹), T_{13} (1.85 mg kg⁻¹), and T_{12} (1.88 mg kg⁻¹), which were higher than the control and comparable to the package of practice (T_2, 1.80 mg kg⁻¹). Lower Zn concentrations were recorded in treatments like T_3 (1.72 mg kg⁻¹), T_5 (1.73 mg kg⁻¹), and T_{10} (1.69 mg kg⁻¹), but they still surpassed the control treatment.

The significant improvement in zinc content in soil observed in T_{11} (1.98 mg kg⁻¹) and other enriched treatments could be attributed to the synergistic effect of PSB and Zn-enriched coconut shell biochar. Biochar serves as a slow-release carrier, enhancing the availability of zinc in the rhizosphere while improving soil properties such as cation exchange capacity and organic carbon content (Baruah and Gogoi, 2023). The role of PSB in solubilizing unavailable zinc through organic acid production further contributed to the increased zinc in post harvested soil (Shukla *et al*. 2025). Treatments combining PSB and enriched biochar exhibited superior results compared to the package of practice, indicating that integrated nutrient management strategies can outperform conventional practices in acidic soils. The relatively lower zinc concentration in control and treatments lacking biochar enrichment highlights the limited availability of zinc in the absence of targeted nutrient supplementation. Similar findings have been reported by Sousarae *et al*., (2024), emphasizing the role of biochar in improving nutrient dynamics and plant productivity.

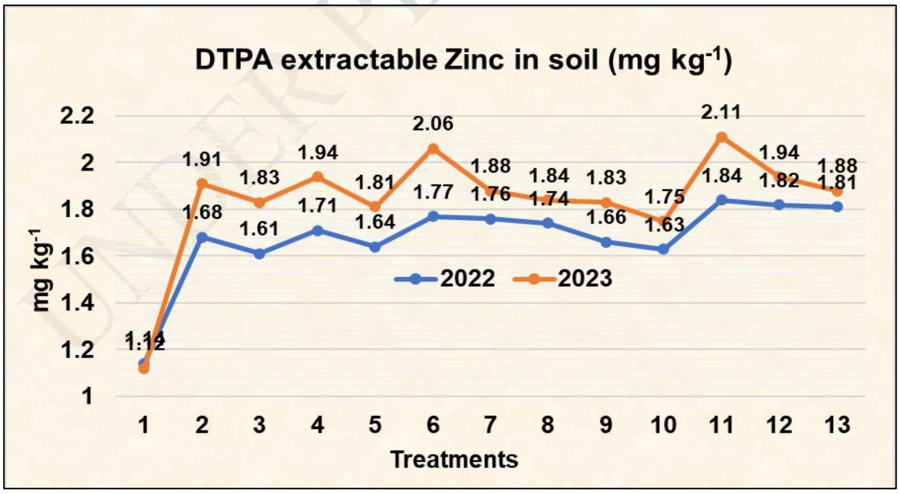

Fig 1: Impact of application of enriched biochar on DTPA extractable zinc content (mg kg⁻¹) in post-harvest soil

3.5 Soybean seed yield (q ha^{-1})

The pooled data for seed yield (Fig 2) revealed substantial differences among the treatments. The highest seed yield was recorded in T_6 (23.61 q ha^{-1}), followed by T_7 (22.91 q ha^{-1}) and T_8 (22.57 q ha^{-1}). In contrast, the control (T_1) had the lowest yield at 8.39 q ha^{-1}. Treatment incorporating PSB and Zn-enriched biochar, particularly T_6 and T_5, resulted in significantly higher seed yields compared to the control and the package of practice (T_2), which had a pooled yield of 15.49 q ha^{-1}. Other treatments such as T_3, T_4, and T_{10} also showed increased yields but were lower than those in T_6 and T_7. Notably, T_2 (package of practice) achieved a seed yield of 15.49 q ha^{-1}, indicating a substantial improvement over the control but still lower than those with biochar and Zn enrichment.

The data reveal that integrating PSB and Zn-enriched biochar substantially enhances Soybean seed yield. The significant yield increase in T_6 (23.61 q ha^{-1}), which combined PSB enriched FYM with 100% Zn-enriched biochar, demonstrates the synergistic benefits of these amendments. Treatments with lower levels of Zn-enriched biochar, such as T_5 (21.09 q ha^{-1}), also performed well, though not as high as T_6. This indicates that while higher levels of biochar provide optimal results, even partial Zn enrichment contributes positively to yield improvement. Soil was amended with biochar, compost, and their mixture at field level (Shravanilakshmi *et al.* 2025). They found that maize grain yield was significantly increased by 10–29% by organic amendments, which is consistent with the findings of this study. P availability was increased upon application of PSB enriched biochar due to reduced fixation of phosphorus. As residual nitrogen and cation exchange capacity increase in the soil, greater nutrients are provided to soybean, thus enhancing grain yield. These findings highlight the crucial role of PSB and Zn-enriched biochar in achieving higher seed yields, particularly in nutrient-deficient soils. The results advocate for incorporating such practices into soybean cultivation to enhance productivity and sustainability in agriculture. (Bramarambika *et al.* 2024 and Rohitha *et al*. 2022).

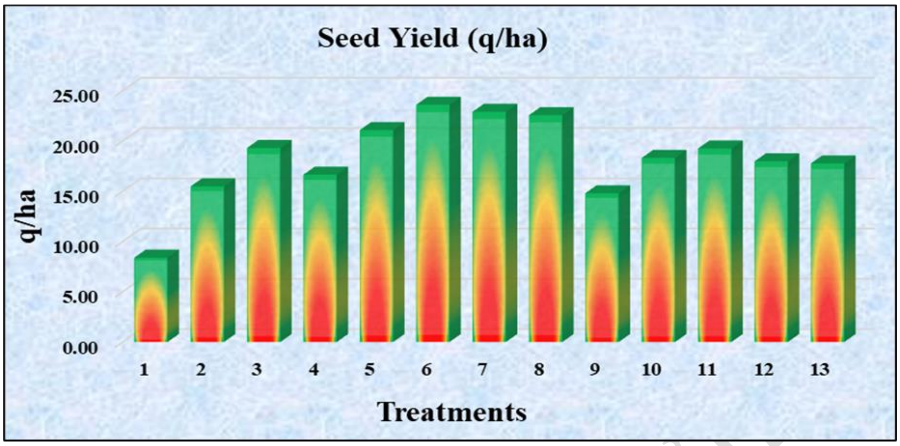

Fig 2: **Seed yield (q ha^{-1}) of soybean as influenced by the application of of PSB enriched coconut shell biochar in acidic soil (Pooled data 2022 and 2023)**

4. Conclusion

The enrichment of coconut shell biochar with phosphorus-solubilizing bacteria (PSB) and zinc sulphate ($ZnSO_4$) has demonstrated promising potential as an effective soil amendment for enhancing major nutrient availability and promoting crop growth. The combination of PSB and varying concentrations of $ZnSO_4$ in biochar significantly improved microbial activity, nutrient bioavailability, and overall soil health. This study highlights the synergistic effects of PSB and zinc-enriched biochar in addressing nutrient deficiencies in soils, particularly phosphorus and zinc in acidic conditions by reducing the fixation. The controlled environment facilitated optimal conditions for microbial proliferation, enhancing the biochar's efficacy as a sustainable and bioavailable source of essential nutrients. These findings suggest that PSB and $ZnSO_4$-enriched biochar could be a viable solution for improving soil fertility, boosting crop productivity, and fostering sustainable agricultural practices, particularly in nutrient-deficient and acidic soils.

5. References

Babu, S., Rathore, S. S., Singh, R., Kumar, S., Singh, V. K., Yadav, S. K., Yadav, V., Raj, R., Yadav, D., Shekhawat, K. & Wani, O. A. (2022). Exploring agricultural waste biomass for energy, food and feed production and pollution mitigation: A review. *Bioresource Technology*, 360: 127566.

Baruah, N., & Gogoi, N. (2023). Contrasting impact of soil amendments on bioavailability, mobility and speciation of zinc in an acidic sandy loam soil. *South African Journal of Botany*, *154*, 309-318.

Bramarambika, S., Mamatha, B., Jakir. H., Srinivas R. K. M, & Desai, N. (2024). The Effect of Coconut Shell Biochar on the Growth and Yield of Chilli (*Capsicum annum* L.) in Acidic Alfisols Soil. *Journal of Advances in Biology & Biotechnology*, 27(7), 203-211.

Casida Jr, L. E., Klein, D. A., & Santoro, T. (1964). Soil dehydrogenase activity. *Soil science*, 98(6), 371-376.

Dangi, S., Gao, S., Duan, Y., & Wang, D. (2020). Soil microbial community structure affected by biochar and fertilizer sources. *Applied Soil Ecology*, 150(2), 103452.

Deng, Z., Wang, J., Yan, Y., Wang, J., Shao, W., & Wu, Z. (2025). Biochar-based Bacillus subtilis inoculants promote plant growth: Regulating microbial community to improve soil properties. *Journal of Environmental Management*, *373*, 123534.

Eivazi, F. & Tabatabai, M. A. (1977). Phosphatases in soils. *Soil biology and Biochemistry*., 9(3), 167-172.

Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research*. John wiley & sons.

Jackson, M. L. (1973). Soil chemical analysis. Prentice Hall of India, New Delhi, 1: 485- 486.

Lindsay, W.L. & Norwell, W.A. (1978). Development of DTPA soil test for zinc, iron, manganese and copper, *Soil Science Society of American Journal.* **42**: 421-428.

Liu, N., Zhou, J., Han, L., Ma, S., Sun, X., & Huang, G. (2017). Role and multi-scale characterization of bamboo biochar during poultry manure aerobic composting. *Bioresource Technology*, *241*, 190-199.

Mousavi, R., Rasouli-Sadaghiani, M., Sepehr, E., & Barin, M. (2022). Effect of enriched biochar and Phosphate Solubilizing Bacteria (PSB) on the distribution of phosphorus forms in a saline and non-saline soil of lake Urmia Basin. *Applied Soil Research*, 10(3), 15-29.

Piper, C. S. (1966). *Soil and Plant Analysis, Hans Pub: Bombay*, **7**: 368-369.

Rohitha, D. S., Mamatha, B., DESAI, N., REDDY, K. S., & Prakasha, H. C. (2021). Physico-Chemical characterization of coconut shell biochar and its influence on growth of Soybean. *Mysore Journal of Agricultural Sciences*, *55*(1), 30-36.

Rohitha, D. S., Mamatha, B., Gayathri, B., Reddy, K. M., Desai, N., & Prakasha, H. C. (2022). Effect of coconut shell biochar on physical, chemical properties and available major nutrient status of acidic soil. *International Journal of Plant & Soil Science*, *34*(23), 1147-1153.

Shome, S., Barman, A., & Solaiman, Z. M. (2022). Rhizobium and phosphate solubilizing bacteria influence the soil nutrient availability, growth, yield, and quality of soybean. *Agriculture*, 12(8), 1136.

Shravanilakshmi, C. S., Kallimani., Vinoda, K. S., Doreswam, C., & Asha N N. (2025). Exploring silkworm litter as a liquid manure: a key to boost mulberry growth and productivity. *Journal of Advances in Biology and Biotechnology,* 28(1), 144- 154. https://doi.org/10.9734/jabb/2025/v28i11869.

Shukla, S., Kumar, S., Singh, P.K., Tripathi, K.M., Shukla, A.K. and Singh, J., (2025). Effect of recommended and graded doses of biochar with and without ZMB biofertilizer and zinc on the growth attributes of rice (*Oryza sativa* L.). *Journal of Advances in Biology & Biotechnology,* 28 (1), 265-80.

Sousaraei, N., Barani Motlagh, M., & Movahedi Naeini, S. A. (2024). Effect of co-application of zinc enriched biochar and foliar application of zinc on some physiological traits and the zinc uptake in wheat (Triticum aestivum L.). *Agricultural Engineering*, *47*(4), 467-490.

Subbaiah, A. Y. & Asija, G. K. (1956). A rapid procedure for the estimation of available nitrogen in soils. *Current Science,* 25, 270-280.

Urgessa, T. G. (2021). Effect of different source and rates of biochar application on selected physic-chemical properties of acidic soil in Western Ethiopia. *Modern Chemistry,* 13(1), 77-82.

Walkley, A. & Black, I. A., (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science,* **34**: 29–38.

Zhang, C., Li, X., Yan, H., Ullah, I., Zuo, Z., Li, L., & Yu, J. (2020). Effects of irrigation quantity and biochar on soil physical properties, growth characteristics, yield and quality of greenhouse tomato. *Agricultural Water Management*, *241*, 1-7.

Zhou, Y., Zhang, H., Li, M., Li, J. & He, M. (2022). Effects of biochar and phosphorus-solubilizing bacteria on the dynamics of soil microbial communities and enzyme activities. *Applied Soil Ecology*, 175(3), 104414.