STUDIES ON INFLUENCE OF BIOCHAR APPLICATION ON SOIL PROPERTIES AND PERFORMANCE OF WHEAT IN SODIC SOILS

by

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(J-20-D-425-A)

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Division of Soil Science and Agricultural Chemistry
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CERTIFICATE - I

This is to certify that the thesis entitled, **'Studies on Influence of Biochar Application on Soil Properties and Performance of Wheat in Sodic Soils'** submitted in partial fulfilment of the requirements for the degree of **Doctor of Philosophy in Soil Science and Agriculture Chemistry** to the Faculty of **Agriculture**, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, is original work and has similarities with published work not more than minor similarities as per UGC norms of 2018 adopted by the University. Further, the level of minor similarities has been declared after checking the manuscript with **Drill Bit** software provided by the University.

The work has been carried out by **Ms. Divya Chadha** under my supervision and guidance. No part of the thesis has been submitted for any other degree or diploma. It is further certified that help and assistance received during the course of thesis investigation have been duly acknowledged.

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ABSTRACT

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ABSTRACT

A pot and leaching experiment were conducted during 2022-2024, at the Division of Soil Science and Agriculture Chemistry to study the impact of biochar and various amendments on the soil health as well as growth and productivity of wheat (DBW-173). It was hypothesized that the application of biochar combined with other amendments can be beneficial for soil health and crop productivity in sodic soils. Four amendments (F_1-Control, F_2-FYM, F_3-FYM + Consortia, and F_4-FYM + Consortia + 50% Gypsum requirement (GR) and five biochar treatments (B_0- 0 t ha^{-1}, B_1 – 2.5 t ha^{-1} Biochar, B_2 – 5.0 t ha^{-1} Biochar, B_3 – 2.5 t ha^{-1} Acidified Biochar, B_4 – 5.0 t ha^{-1} Acidified Biochar) were tested. The consortia used was Halo-Mix. Results showed significant improvements in soil health with biochar and amendment treatments. Although acidified biochar applied at 5 t ha^{1} showed significant outcomes but the combination of FYM + Consortia + 50% GR with acidified biochar (F_4B_4) had the most beneficial effect, resulting in the lowest soil pH, electrical conductivity, exchangeable sodium, and sodium adsorption ratio, while enhancing soil fertility parameters like available nitrogen, phosphorus, potassium, calcium and magnesium. Biological parameters such as, dehydrogenase activity, alkaline phosphatase activity and bacterial count also improved significantly in sodic soil over corresponding control values. Dehydrogenase activity was highest in soils treated with 5 t ha^{-1} acidified biochar (B_4) combined with the of FYM + Consortia + 50% GR (F_4) showing the highest activity at 5.43 µg TPF g^{-1} hr^{-1}. Similarly, alkaline phosphatase activity increased with biochar application, with the highest values recorded under F_4 combined with B_4(20.30 µg PNP h^{-1} g^{-1}). In terms of bacterial populations, higher bacterial counts were observed with increasing biochar levels, especially when acidified biochar was used. The combination of 5 t ha^{-1} acidified biochar (B_4) and FYM + Consortia + 50% GR (F_4) yielded the highest porosity (59.77%) and the lowest bulk density (1.21 g cm^{-3}). The application of acidified biochar at 5 t ha^{-1} (B4) combined with F_4 resulted in the highest wheat growth, with plant height of 58.21 cm, number of grains per spike of 69.33, spike length of 12.73 cm, and root weight of 23.46 g and were significantly higher compared to the control treatments. Grain yield for B_4 + F_4 was 27.34 q ha^{-1}, significantly greater than the control (15.13 q ha^{-1}), while straw yield was 33.19 q ha^{-1} for B_4 + F_3 compared to 18.72 q ha^{-1} in the control. The highest test weight (43.81 g) and nitrogen uptake (43.01 kg ha^{-1}) were also observed in the B_4 + F_4 treatment. Nutrient uptake values for phosphorus, potassium, calcium, magnesium, and sulphur were enhanced with biochar and amendments, with the highest values recorded for the combination of B_4 + F_4 and B_3 + F_4. In the leaching studies, the acidified biochar at 5 t ha^{-1} (B_4) combined with treatment F_4 significantly decreased soil pH to 7.80, compared to the control's pH of 9.10. Furthermore, the highest values for exchangeable calcium and magnesium were observed with B_4 + F_4 and B_3 +F_4 with exchangeable calcium increasing to 44.45 meq/l, and exchangeable magnesium rising to 14.00 meq/lt. Available nutrients in soil leachate also showed significant trends, with available nitrogen, and potassium increasing in the B_3 + F_4 treatment. While available phosphorus was significantly increased under B_1 + F_4 treatment. Significant interaction effects between biochar levels and amendments were evident for ions ie., exchangeable potassium, calcium and magnesium particularly in the fourth leachates. In nutshell, the application of acidified biochar at a rate of 5 t ha^{-1}, in combination with other soil amendments, was found to have a positive impact on both soil health and crop productivity in sodic soils.

Keywords: Soil health, sodic soils, Acidified biochar, biochar, FYM, Microbial consortia, Gypsum

Signature of Major Advisor

Divya Chadha
Signature of student

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LIST OF ABBREVIATION AND SYMBOLS

Azo	*Azospirillium*
CFU	Colony-forming unit
CSSRI	Central Soil Salinity Research Institute
DHA	Dehydrogenase Activity
dS m^{-1}	desi Siemens per meter
DTPA	Diethylene Triamine Penta Acetic acid
EC	Electrical Conductivity
EC_e	Saturation extract electrical conductivity
ESP	Exchangeable Sodium Percentage
et al.	co-worker/and others
mha	million hectare
i.e.	*Id est*, that is
kg ha^{-1}	Kilogram per hectare
meq	Milliequivalent
mg kg^{-1}	Milligram per Kilogram
$molL^{-1}$	mole per litre
NA	Nutrient Agar
NaCl	Sodium Chloride
NS	Non-Significant
PDA	Potato Dextrose Agar
PNP	cpara-Nitrophenyl phosphate
PSB	Phosphorus Solubilizer Bacteria
q ha^{-1}	Quintal per hectare
SAR	Sodium Adsorption Ratio
TPF	Tri-phenyl Formazon
TTC	Triphenyl tetrazolium chloride
VAM	Vesicular-Arbuscular Mycorrhiza
Viz.	Vide licet, namely, Such as
%	Percentage
µg g^{-1}	Microgram per gram

CHAPTER I

INTRODUCTION

Biochar has gained significant attention as a sustainable soil amendment due to its ability to enhance soil fertility, improve water retention, and increase nutrient use efficiency. Its application is particularly relevant in the context of India, where an irreversible decline in the productive potential of 187.8 million hectares of arable land is believed to be caused by ongoing soil degradation. The inability to bridge soil nutrient shortfalls has been made more difficult by soil acidity, salinization, decreased soil organic matter, and micronutrient deficiencies. Soil salinity and sodicity are significant global issues that affect over 100 countries across every continent. Soils containing salts that are more soluble than gypsum and calcium carbonate, and have an impact on crop growth and yield, are referred to as salt-affected soils. The parameters used to categorize the salt-affected soils include exchangeable sodium percentage (ESP), electrical conductivity (EC), and soil response (pH). These characteristics divide salt-affected soils into two groups: sodic soils (pH greater than 8.5, EC less than 4.0 ds/m, ESP greater than 15) and saline soils (pH less than 8.5, EC greater than 4.0 ds/m, ESP less than 15) (Richards, 1954). It is estimated that 955 million hectares (mha) of land worldwide, or 7% of all arable land, are affected by salt (Flowers *et al*., 1997). In India, the states of Gujarat (2.23 mha), Uttar Pradesh (1.3 mha), Maharashtra (0.61 mha), West Bengal (0.44 mha), and Rajasthan (0.38 mha) account for approximately 6.73 mha of salt-affected soils. In the Ravi-Tawi Command area of the Jammu region, nearly 7,500 hectares of land are salt-affected, primarily sodic (Sharma *et al.*, 2011). This region, where wheat is the dominant crop during the rabi season, plays a crucial role in providing daily calories and protein to the local population. Water availability and soil quality are vital for the growth and development of wheat (Akhkha *et al.*, 2011; Iqbal *et al.*, 2012). However, the high salt content in the soil severely hampers wheat growth and productivity by creating osmotic stress, ion toxicity, and nutrient imbalances. Saline soils reduce the plant's ability to take up water due to a lowered osmotic potential, leading to physiological drought, even when moisture is available. Additionally, the accumulation of toxic ions such as sodium (Na^+) and chloride (Cl^-) interferes with essential metabolic processes, reducing photosynthesis and stunting growth. Research has shown that salinity and sodicity can significantly decrease wheat germination rates, biomass, and grain yield (Munns and Tester, 2008; Shrivastava and Kumar, 2015). Salt-affected soils have limited organic matter content and are vulnerable to erosion-related land degradation due to poor plant growth and reduced residue input (Rengasamy, 2006). Furthermore, osmotic stress inhibits the growth and activity of microorganisms in saline soils, while high pH and ion toxicities create unfavorable conditions for the microbial population in sodic settings (Marschner, 2012).

Reclamation of sodic soils is one of the world's most pressing issues facing humanity (Szaboles, 1994). Effective strategies for combating such soils include the use of salt-tolerant wheat varieties, proper irrigation management, and the application of both organic and inorganic soil amendments. These approaches are recommended to restore soil health and enhance crop productivity in areas affected by sodicity (Sharma and Minhas, 2005; Qadir *et al.*, 2007). Therefore, reclaiming soil impacted by salt is necessary to maintain appropriate fertility levels and enhance soil health. Gypsum is the most commonly used inorganic amendment for ameliorating sodic soils, as its effectiveness as a source of Ca^{2+} helps displace Na^{+} from clay surfaces (Gharaibeh *et al.*, 2010). In addition, adding organic materials such as compost and plant residues to soil amendments has been shown to significantly reduce soil sodicity and boost crop yields (Drake *et al.*, 2015; Ibrahim *et al.*, 2015). According to Melero *et al*. (2007), the application of organic matter has been a standard practice in areas affected by sodicity over the past few decades, playing a crucial role in rehabilitating soil and improving fertility. Organic matter is vital for maintaining soil structural stability and enhancing its physical, chemical, and biological properties. Studies have found that incorporating organic matter into salt-affected soils reduces the exchangeable sodium percentage (ESP) and electrical conductivity (EC), while also improving soil microbial biomass, enzymatic activity, aggregate stability, water infiltration, and water-holding capacity (El-Shakweer *et al.*, 1998; Wu *et al.,* 2015). However, research on the impact of stable organic additives, such as biochar, on the field restoration of saline-sodic soils remains limited.

Biochar, a substance resembling charcoal, is used in agriculture as a soil amendment. It is produced by pyrolyzing biomass—such as wood, manure, or leaves—in a closed container with limited oxygen, resulting in a carbon-rich product (Mohan *et al.*, 2006; Lehmann, 2007). Adding biochar to sodic soils has been suggested as a means to improve soil fertility and mitigate climate change. Biochar is a modern innovation in soil management, particularly for sequestering carbon dioxide and immobilizing contaminants. The application of biochar has been shown to improve nitrogen (N), phosphorus (P), and potassium (K) availability in sodic soils through various mechanisms. Biochar inherently contains variable amounts of these nutrients, depending on its feedstock and pyrolysis conditions, which directly contribute to soil nutrient pools upon application (Lehmann *et al*., 2011). The high cation exchange capacity (CEC) of biochar facilitates the retention of ammonium (NH_4^+) and potassium (K^+) ions in the soil, preventing their leaching and making them available for plant uptake (Glaser *et al*., 2002). Additionally, biochar enhances soil microbial activity, which plays a critical role in nitrogen mineralization and phosphorus solubilization, thereby improving their availability (Singh *et al.,* 2010). In sodic soils, the high sodium (Na^+) concentration can displace essential nutrients such as K^+, reducing their availability. Biochar mitigates this effect by adsorbing sodium ions and promoting their leaching, which helps restore soil nutrient balance (Chan *et al.,* 2008). Furthermore, biochar's porous structure improves soil aeration and water retention, creating favorable conditions for nutrient cycling and root growth. Phosphorus availability is further enhanced through biochar's interaction with soil minerals, as it can reduce P fixation by binding to calcium or aluminum in sodic soils, making P more accessible to plants (Yuan et al., 2011). These combined effects demonstrate biochar's potential to improve the nutrient status of sodic soils, thereby supporting sustainable soil fertility and crop productivity.

In addition to enhancing soil fertility, organic manure contributes to creating a safer and healthier soil environment (Lal, 2004). Farmyard manure (FYM), a mixture of animal feces, urine, and leftover roughages, is a key organic manure containing approximately 0.5% nitrogen, 0.2% phosphorus, and 0.5% potassium (Singh *et al*., 2010). FYM improves soil structure, water-holding capacity, and fertility, providing a better environment for root development (Sharma *et al.,* 2015). Its rich organic carbon content stimulates microbial activity, enhancing nutrient release, cycling, soil aggregation, and disease suppression, thereby supporting long-term soil health and productivity (Bhattacharyya *et al*., 2016; Ramesh *et al.,* 2018).

Another cost-effective approach to reclaiming salt-affected soils involves using microbial formulations. The growing understanding of microorganisms' role in sustainable agriculture has led to reduced dependence on chemical pesticides and fertilizers (Bünemann *et al*., 2018). Various government agencies and commercial producers offer a range of bioformulations, including Azotobacter, compost inoculants, phosphorus-solubilizing bacteria (Bio-phospho), and VAM inoculants (Goswami *et al*., 2018). However, many microbial strains currently available as biofertilizers struggle to perform effectively under salt stress. The activity of these microorganisms decreases when applied to salt- affected soils due to osmolysis, which disrupts their functions (Zahran, 1999). Salt stress also leads to the destruction of microbial communities and disrupts soil carbon cycling, further exacerbating soil degradation (Munns and Tester, 2008). To address the challenges posed by salt-affected soils, efforts have been made to develop halophile-based bioformulations that can replace conventional biofertilizer treatments. Halophiles are unique organisms that thrive in hypersaline conditions, requiring high salt concentrations for growth. While all living organisms require salts, halophiles are specialized to flourish in environments with extreme salinity. Based on their salt tolerance, halophiles are categorized as follows: mild halophiles grow best at 0.2-0.85 mol/L (2–5% NaCl), moderate halophiles grow best at 0.85–3.4 mol/L (5–20% NaCl), and extreme halophiles grow best at salt concentrations above 3.4–5.1 mol/L (20–30% NaCl). Halophiles, both prokaryotic and eukaryotic, can maintain osmotic pressure equilibrium and withstand the denaturing effects of salts. They produce compatible solutes such as glycine, betaines, and ectoines, which serve as stabilizers for enzymes, nucleic acids, membranes, and cells, while also offering protection against stressors like desiccation, freezing, and high salinity. Furthermore, halophilic bacteria can generate enzymes that function optimally in saline environments. These bacteria possess robust transport systems, often utilizing Na^+/H^+ antiporters to expel excess sodium ions from the cell (Oren, 2002). By enhancing microbial activity and organic acid synthesis, halophiles can indirectly boost crop productivity and promote plant growth under salt stress (Kumar *et al.,* 2014).

The growing demand for renewable energy alternatives is driven by the widespread decline in soil nutrient levels, global warming, and the need to ensure food security amidst climate change. The current lack of viable solutions is a global concern. Biochar technology, along with the application of organic manures and microbial formulations, is expected to play a significant role in developing an integrated strategy to address issues such as soil salinity and sodicity (Lehmann and Joseph, 2009). This integrated approach highlights the critical importance of biochar technology in promoting sustainable soil management and agricultural resilience.

Considering these factors, the present experiments were designed to investigate the effects of biochar application on soil properties and the performance of wheat in sodic soils, with the following specific objectives:

1. To study the impact of biochar application and other amendments on soil properties.
2. To evaluate wheat performance as influenced by biochar application and different amendments.
3. To ascertain the nutrient uptake by wheat crops as influenced by biochar application.
4. To study the influence of biochar and amendment applications on ion concentrations in leachate from sodic soils.

CHAPTER II

REVIEW OF LITERATURE

The addition of biochar, particularly when combined with farmyard manure (FYM), halophilic bioformulations, and gypsum, has demonstrated a significant positive impact on crop yield. This improvement is largely attributed to the synergistic effects of these amendments on the physical, chemical, and biological properties of salt-affected soils, ultimately promoting sustainable crop production. The present chapter provides a comprehensive discussion on the research conducted to fulfill the objectives of the study. The findings are organized under the following sub-headings for clarity and systematic presentation:

2.1 Salt-affected soils: An overview of the characteristics, classification, extent, and challenges associated with salt-affected soils, with an emphasis on their impact on agricultural productivity and soil health in arid and semi-arid regions.

2.2 Biochar production and characteristics: A detailed account of the biochar production process, including feedstock selection, pyrolysis conditions, and resulting physico-chemical properties that make biochar suitable for soil amendment purposes.

2.3 Influence of biochar on the salt-affected soils: A discussion on how biochar application influences the remediation of salt-affected soils by improving soil structure, reducing bulk density, increasing porosity, enhancing water retention, and buffering soil pH.

2.4 Effect of interaction of biochar, FYM, halophilic bioformulation and gypsum application on soil properties: An evaluation of the combined effect of these amendments on key soil properties such as pH, electrical conductivity (EC), organic carbon content, nutrient availability, microbial biomass, and enzymatic activities.

2.5 Effect of interaction of biochar, FYM, halophilic bioformulation and gypsum application on growth and yield parameters of wheat crop: Analysis of the impact of integrated soil management on wheat crop performance, including parameters like plant height, tiller number, biomass accumulation, grain yield, and harvest index.

2.6 Effect of biochar application and other amendments on nutrient uptake by wheat crop: Examination of how soil amendments influence the uptake of macro- and micronutrients by the wheat crop, contributing to improved nutritional status and productivity.

2.7 Effect of biochar and amendment applications on ion concentrations in leachate from sodic soils: Insights into the leaching behavior of harmful ions (e.g., Na^+, Cl^-, HCO_3^-) under the influence of biochar and other amendments, indicating their role in reducing sodicity and enhancing soil quality over time.

2.1 Salt affected soils

2.1.1 Genesis, characteristics and global distribution of salt-affected soils.

The parameters used to categorise the salt-affected soils include soil reaction (pHs), electrical conductivity (ECe) of soil saturation extract, exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR) (El-Ramady, 2022). These metrics (EC, pH, SAR or ESP) indicate whether a soil is saline, sodic, saline-sodic, or unaffected by salts (Mohamed, 2017). SAS are divided into two primary groups based on these characteristics: saline and sodic (Abrol *et al.,* 1980). Most food crops cannot be grown in saline soils because of the excess soluble salts that are present in them, which are indicated by ECe values above 4 dS m^{-1} at 25°C. Similarly, excess exchangeable sodium percentage (ESP>15) in sodic soils negatively impacts most crop plants' growth and development (Abrol *et al.*, 1988). In addition to the primary processes of physical and chemical weathering of rocks and primary minerals, uncontrolled irrigation and continuous or excessive fertilisation are also factors that contribute to the formation and/or accumulation of soluble salts in soils (Tedeschi & Dell'Aquila, 2005; Quantin *et al.*, 2008). Salinity development in perfectly normal soils can be caused by a variety of factors, including seepage from canals, irrigation with saline groundwater, development of saline creeps due to excessive leaching, ingress of sea water in coastal regions, congestion of natural drainage, waterlogging from faulty irrigation practices, and localised redistribution of salts. The predominant neutral soluble salts in saline soils are the chlorides and sulphates of Na^+, Ca^{2+}, and Mg^{2+}. Crops growing unevenly and white salt crusts on the surface are signs of a salinity issue (Singh *et al.,* 2009). The salinity issue is frequently made worse by high salt concentrations brought on by old marine deposits, inadequate drainage, and conditions with a shallow water table (Horney *et al.*, 2005). Alternate wet and dry seasons, groundwater containing carbonates and bicarbonates, desalinization, and the decrease of sulphate ions in anaerobic environments are the causes of the creation of sodic soils. These soils have poor physical qualities, limited water permeability, and clay dispersion due to high pH and abundant exchangeable sodium (Abrol *et al.*, 1988; Singh *et al.*, 2009).

Salinity is one of the main obstacles to sustainable food production in many parts of the world, as demonstrated by Sharma and Anshuman (2015). Researchers and policymakers are concerned about the food and nutritional security of a growing population as a result of the significant climatic variability, biodiversity loss, degradation of land and water, trade rules, and other factors that are changing the global landscape daily. Thus, the key difficulties for agriculture are guaranteeing sustainable agricultural output and paying growers a fair price, as a result of increased competition for productive lands and fresh water resources as well as widespread land use. Salinity and sodicity stressors affect an area of approximately 1125 million hectares worldwide (Hossain, 2019). The Middle East (189 m ha) has the highest concentration of salt-affected soils, followed by Australia (169 m ha) and North Africa (144 m ha). About 52 million hectares of South Asia, including India, are damaged by salt. The states of Gujarat (2.23 m ha), Uttar Pradesh (1.37 m ha), Maharashtra (0.61 m ha), West Bengal (0.44 m ha), and Rajasthan (0.38 m ha) combined account for about 75 % of the nation's salty and sodic soils. Overall, India has 6.73 million ha of salt-affected soils. About 2.95 million hectares (ha) of the 6.73 million ha of salt-affected soils in the nation fall into the saline category, and the remaining 3.77 million ha are classified as sodic (NRSA and Associates, 1996). The Indo- Gangetic plains of Haryana, Punjab, and Uttar Pradesh are home to the majority of the world's sodic soils. Parts of Jammu and Kashmir are also home to certain sodic soils. Saline soils, on the other hand, are limited to irrigated, semi-arid, and desert regions in Rajasthan, Gujarat,Karnataka, Andhra Pradesh, as well as portions of Punjab, Himachal Pradesh, and Jammu and Kashmir, which includes these states' Kandi belts. The effect of two significant irrigation projects on sodicity were documented by Sharma *et al.* (2011). These projects were implemented in the Jammu region and used water from the Ravi and Tawi rivers. It was noted that soils impacted by salt surfaced in Kathua, Samba, and Jammu. The pH, sodium adsorption ratio, and exchangeable sodium percentage in the command were determined to be up to 9.9, 25.30 m. eq. L^{-1}, and 78.41 m. eq. L^{-1}, respectively. 25000 ha of the approximately 75000 ha covered by the canal irrigation system were found to be sodic or flooded. According to reports, saline soils in the Kashmir valley and the Kandi belt of Jammu contain soluble salts with anions of Cl, NO3, SO4, and HCO3 in the range of 0.15 to 0.45 % (Gupta and Arora, 2016). By 2050, the country's current 6.72 million hectares of soil contaminated by salt are expected to have nearly tripled to 20 million hectares (Sharma and Singh, 2014).

As per the US Salinity Laboratory Staff, these soils have pH < 8.5, EC >4 dSm^{-1} at 25ºC and ESP <15 (Anonymous, 1954). In soil solution, the ratio of $[Na^{+}]/([Cl] + [SO^{-}_{4}])$ is less than 1.0. According to Bajwa (2002), neutral salts (Cl^{-} and $SO4^{2-}$) have substantially higher concentrations than alkali salts ($CO3^{2-}$ + $HCO3^{-}$). Soluble gypsum can also be present in small to significant amounts in a lot of salty soils. The white encrustation of salts on the soil's surface is a characteristic of these soils. Saline soils have a low relative proportion of Na^{+} ions compared to Ca^{2+} and Mg^{2+} ions. As a result, the exchange complex has low levels of adsorbed Na^{+} ions (ESP < 15). Clay particle flocculation is caused by the dominance of Ca^{2+} and Mg^{2+} ions in soil solution, on exchange sites, and high total soluble salt. The zeta potential of the soil exchange complex is lowered by the firmly adsorbed divalent (Ca^{2+} and Mg^{2+}) ions, which attract clay particles to one another and cause flocculation. The saline soils are aggregated and very porous as a result of the flocculation of clay particles.

As per the US Salinity Laboratory Staff, alkali soils are characterized by pH >8.5, ESP >15 and EC <4 dSm^{-1} (Anonymous, 1954). In soil solution, the ratio of $[Na^{+}]/([Cl] + [SO^{-}_{4}])$ is greater than 1.0. According to Odell (2000), sodic soils are problematic because of their high pH and Na^{+} levels, which contribute to clay swelling and dispersion and lower crop yields. Stimulating microbial communities in sodic soil to produce acid is one possible remediation technique. This raises the pH of the soil and releases calcium, which helps to stop soil dispersal.

2.2 Biochar production and characteristics

Biochar is being produced from biomass at a higher rate as a result of growing interest in using it for different purposes. The manufacturing method selected for biochar must be suitable for the type of biomass, and all other process parameters-such as heating rate, temperature, residence duration, etc.-must be at their ideal. Since they could have an impact on the chemical and physical states of biochar during the synthesis process, these variables are very important. Biochar can be manufactured commercially by a variety of thermo-chemical conversion processes, one of which is pyrolysis.

Pyrolysis is the term for the process of thermally breaking down organic molecules in an oxygen-free environment between 250 and 900 degrees Celsius (Osyai *et al*, 2014). This method offers an alternative for turning waste biomass into products with additional value, such as biochar, syngas, and bio-oil. Three phases make up the process of commercial biochar pyrolysis systems: (1) loss of moisture and some volatiles; (2) conversion of unreacted residues to volatiles, gases, and biochar; and (3) a gradual chemical rearrangement of the biochar (Demirbas, 2004). The first—and least likely—outcome of biomass exposed to fire is that it doesn't burn. The other two possibilities are that it is pyrolyzes to biochar or volatizes to carbon dioxide or a variety of other minor gas species (Graetz and Skjemstad, 2003). For the manufacture of biochar, a variety of reactor designs are utilised, including waggon reactors, bubbling fluidized beds, paddle kilns, and agitated sand rotating kilns. The kind and composition of biomass used during the pyrolysis process determines the biochar yield. The primary operating process parameter that determines product efficiency is temperature (Wei *et al*, 2019). In general, raising the temperature during the pyrolysis process results in a drop in the yield of biochar and an increase in syngas generation.

Table 2.1 Different types and products from pyrolysis

Types of pyrolysis	**Pyrolysis Temperature (0C)**	**Vapour residence time**	**Heating rate (0C/min)**	**Thermal decomposition product (%)**		
				Solid	**Liquid**	**Gas**
Slow pyrolysis	Low to moderate (300-500)	Long (5-20 min)	Slow (5-20)	35	30	35
Fast pyrolysis	Moderate (500)	Short (<5 sec)	Fast (50)	15-20	70-75	10-15
Gasification	Moderate to high (500-800)	Moderate (10-20 sec)	Moderate (20-30)	85	5	10

Source: Modified from Rishikesh *et al*, (2015) There are various pyrolysis procedures, including slow pyrolysis, quick pyrolysis, and gasification, depending on temperature and reaction time. While fast pyrolysis, on the other hand, relies on extremely rapid heat transfer, usually to fine biomass particles at less than 650ºC with a rapid heating rate (100–1000ºC/s), slow pyrolysis (heating for seconds or minutes) can be described as a continuous process, where purged (oxygen-free) feedstock biomass is transferred into an external heated kiln or furnace (gas flow removing volatile BC emerging at the other end) (Meyer *et al*, 2011). Unlike the other categories, gasification occurs in an aerobic environment. the reactor's architecture, and the production environment all affect the composition and properties of biochar (Ahmad *et al,* 2014). The most important factors affecting the adsorption characteristics of biochar are its chemical structure, porosity, the quantity of inorganic metals that were initially present in the feedstock (Kong *et al*, 2014), and the process conditions. Char and activated carbon have comparable surface heterogeneities (Ahmad *et al,* 2020). However, because of its large surface area, higher carbon content, high cation and anion exchange capacity, and stable structure (Kaetzal *et al*, 2018), biochar is said to perform better than activated carbon in the removal of various contaminants, including pathogenic organisms, organic matter, surfactants, nitrogen (N) (Dalahmeh *et al,* 2016), micropollutants (Nguyen *et al*, 2019), heavy metals (Enaime *et al*, 2020), and other pollutants. With micropores as large as 2 nm, mesopores ranging from 2 to 50 nm, and macrospores as small as 50 nm, biochar has a vast surface area and a uniformly distributed pore network. It has a particular adsorption impact on organic ammonia nitrogen and heavy metals in the water because of its huge specific surface area (Han *et al*, 2020). In certain instances, it was found that although the adsorption capacity of the biochar was greater than that of activated carbon, its surface area was less. This is because the swelling caused by the adsorption of water within the biochar increases its internal surface area, which raises the adsorption capacity. The adsorption characteristics of modified biochar and the influence of functional groups on the adsorption process have been examined in a number of research. Numerous functional groups have the ability to interact with one another and generate hydrogen bonds (Vijay *et al*, 2008). They have incredibly strong binding energy due to their hydrogen bonds, which makes them challenging to separate. Metal ion loading, oxidation, reduction, and microwave treatments are a few of the often employed modification methods (Yang *et al,* 2019). Many functional groups, including -CHO (aldehyde), -COOH (carboxyl group), and -OH (alcohol or phenol), are commonly present in modified biochar. When it comes to eliminating organic contaminants and hazardous metals from the environment, it performs remarkably well. Modified biochar operates on both physical and chemical adsorption throughout the adsorption processes (Cheng *et al,* 2021). However, the kind and characteristics of the deposited pollutant may affect the prevailing adsorption pathways. Structural advantages can be obtained by increasing the volume of pores and the specific surface area of biochar produced by the addition of iron oxides.

2.3 Influence of biochar on the salt-affected soils

According to Puga *et al.* (2015), biochar is a major source of mineral nutrients like Ca, Mg, K, and P that promote plant growth. Biochar can be used to recover degraded soils because of its significant adsorption capacity, which is determined by the production conditions and the source feedstock (Paz-Ferreiro *et al,* 2014). As a result, biochar improves plant production through secondary effects on mechanisms that alter the physical, chemical, and biological aspects of soils (Akhtar *et al,* 2015). In order to counteract greater exchangeable sodium in saline-sodic soils, the application of divalent cations like calcium and magnesium is essential, and biochar can be able to play a beneficial role in this regard. Furthermore, adding biochar to the saline soil improved crop growth by raising above-ground carbon sequestration. This, in turn, would result in additional soil carbon sequestration when the biomass was transformed into biochar. Therefore, adding biochar that has been pyrolyzed from plant wastes to soils could be an effective way to control carbon sequestration and reduce global warming without raising the amount of N2O produced in saline soils. Enhancements in the physical parameters of soil, such as bulk density, porosity, water holding capacity, aggregate stability, and hydraulic conductivity, have been documented in several research involving the application of biochar to soils (Uzoma *et al*, 2011). Jien and Wang (2013) discovered that a heavily weathered soil treated with 5% biochar had an increase in saturated hydraulic conductivity (Ks) due to an increase in macro aggregation of the soil. When it comes to saline-sodic soil restoration, improvements in the physical qualities of the soil are considered to be quite important. Moreover, addition of divalent cations such as Ca^{2+} and Mg^{2+} is necessary to offset Na^{+} on the exchange sites in a salt-affected soil. Therefore, biochar can possibly be a significant source of these cations (Singh *et al*, 2010) and thus could potentially help in remediation of the salt- affected soils.

2.4 Effect of biochar, FYM, halophilic bioformulations and gypsum application on soil properties.

Agbna *et al*. (2017) carried experiment on influence of biochar amendment on soil water characteristics under salinity stress. The rates at which the biochar was applied were 0%, 2%, and 4% w/w. The findings demonstrated that when the rate of biochar application increased, there was a considerable improvement in soil bulk density, field capacity, PWP, and soil organic matter. The pH and electrical conductivity of the soil were unaffected by the application of biochar, though.

Amin (2018) conducted pot experiment in El-Qusia, Assiut, Egypt to assess the effects of adding biochar (B) with farmyard manure (FYM) and poultry manure (PM) on some soil properties, phosphorus (P) availability, and barley growth in calcareous sandy soil. Control, B, B + FYM (1:1), B + PM (1:1), B + FYM (2:1), B + PM (2:1), FYM + B (2:1), and PM + B (2:1) were the treatments used in this investigation. The findings showed that in calcareous sandy soil, biochar increased the amount of soil organic matter (SOM) and the water holding capacity (WHC) when coupled with FYM and PM. In comparison to the control, the relative gains in WHC for B, B:FYM (1:1), B:PM (1:1), B:FYM (2:1), B:PM (2:1), B:FYM (1:2), and B:PM (1:2) were 7.3, 4.7, 14.1, 5.3, 16.9, 15.2, and 18.2%, respectively.

Anees *et al*. (2020) collected soil sample from the saline fields of Shadi Khel of Karak District of Pakistan, to study the complementary potential of chitinolytic and halotolerant bacterial strains (*Pseudomonas sp*., *Thalassobacillus sp*., and *Terribacillus sp*.) in promoting the phytoremediation of saline soil. The physico-chemical analysis of the samples were conducted to measure EC, pH, Na^+, Ca^{2+}/Mg^{2+}, and K^+ at the Soil and Water Testing Laboratory (Soil Fertility) Attock, Pakistan. Result obtained showed that the EC of the saline soils significantly decreased upon treatment with the chitinolytic and halotolerant bacterial strains ($p \leq 0.05$). Furthermore, the pH, organic matter content (%), saturation percentage, sodium adsorption ratio, cation contents, calcium carbonate, and exchangeable sodium percentage were recorded as around 7, 2%, 35-38%, 13, 28 m. eq. L^{-1}, 20 m. eq. L^{-1}, 21 m. eq. L^{-1}, 151 m. eq. L^{-1}, and 15% respectively.

Arora *et al*. (2016) isolated halophilic bacteria from saline soil from coastal Gujarat and sodic soil from Indo-Gangetic plains of Uttar Pradesh and inoculated the halophilic bacteria in seeds of wheat crop. Result obtained showed that there was increase in the microbial biomass carbon up to 137 µg g^{-1} as compared to 82 µg g^{-1} in control.

Bhullar *et al*. (2019) collected soil samples from on-going field experiment (since 2007) at Punjab Agricultural University, from different plots irrigated with water varying in residual sodium carbonate [0, (non-sodic), 6.5, and 10] after harvest of wheat in 2015 to study the beneficial effects of biochar on physicochemical properties in non-saline and non-sodic soils. Collected soil samples were incubated for 8 weeks with different rates of rice straw biochar (B0: control, B1: 1%, B2: 2%, B4: 4% w/w). Results revealed that both pH and SAR significantly decreased in the biochar amended sodic soils, whereas opposite trend was noticed in the amended control. Furthermore, at all SAR levels, NO3 – N concentrations were greater at differential biochar rates on day 14 and 56 of sampling; however, the results were contrary as far as NH4 + N was concerned. Therefore, they concluded that rice straw biochar can be used as an organic amendment for reducing adverse effects of sodicity on soil functions governed by their rate of addition.

Bayoumy *et al.* (2019) conducted two field experiments at two sites in Sakha Agric. Res. Station Farm, North Delta, during two successive winter seasons, 2017/2018 and 2018/2019 to study the effect of individual and combined applications of gypsum, compost tea and biochar on some soil properties and wheat (*Triticum aestivum*, L) productivity under saline and saline-sodic soils. Gypsum requirements (G), 400 L compost tea (C), 1 Mg biochar (B1) or 2 Mg biochar (B2) were applied. Results observed revealed that application of G+ C+ B2 decreased soil ECe by 28.06 and 13.16 %, SAR by 17.23 and 8.92 %, ESP by 17.23 and 8.92 % for site 1 and site 2, respectively as compared to the control. However, there was a slight rise in the sodium removal efficiency (RSE%) with various treatments in the following order: In comparison to the original soil; G+C+B2 > G+C+B1 > G+C > G+B2 > G+B1 > G > C+B2> B2 > C+B1 > C > B1. Additionally, during the two growing seasons, the application of various soil amendments increased soil porosity and lowered bulk density of the soil.

El-Gamal *et al*. (2020) conducted a lysimeter experiment during two consecutive seasons of winter 2017/2018 and summer season 2018 for wheat and soybean at EL-Gemmieza

Agriculture Research Station, El Gharbiya Governorate to study the influence of sulphur and biochar on soil proprieties. Results indicated that the application of sulphur or biochar, both separately and in combination, increased available N, P, K, cation exchange capacity, total porosity, organic matter, exchangeable Ca, Mg, and K. However, in sandy and calcareous soils, EC, pH, bulk density, and soil hydraulic conductivity significantly decreased. Conversely, with clay soil, various treatments resulted in a large increase in soil hydraulic conductivity.

Gandahi *et al*. (2015) conducted experiment at Sindh University on impact of rice husk biochar and macronutrient fertilizer on fodder maize and soil properties. They observed that the application of BC at all levels had a good impact on the parameters of the soil, including organic matter, pH, and EC.

Huang *et al.* (2022) found that applying biochar boosted the soil's organic matter, humic acid, total nitrogen, and total phosphorus levels, as well as its ability for cation exchange, indicating an improvement in the soil's nutritional conditions. Under salt stress, the application of biochar altered the bacterial community structure and further enhanced soil bacterial abundance.

Khan *et al*. (2022) conducted an experiment in a 4×3 factorial scheme in North Western part of Pakistani 2012, by growing *Sorghum bicolor* (L. Moench) with four treatments of organic amendments, *i.e.,* control, FYM, BC, and FYM+BC, and three treatments of sowing techniques, *i.e.,* sowing on ridges (RG), raised beds (RB), and flat beds (FB) to evaluate the combined effects of organic amendments and seed placement techniques on *Sorghum bicolor* (L. Moench) growing in a saline-sodic soil (EC 8.2 dS m^{-1}, SAR 22.4). The results showed a significant decrease in the salinity indicators of sodium adsorption ratio (SAR) and electrical conductivity (EC) of the soil with concomitant significant increase in total nitrogen (N), available phosphorus (P), and potassium (K) contents in RG-sown plots by the application of FYM+BC. Under organic amendments, however, the pH of the soil stayed constant for all seeding methods. Therefore, they concluded that applying FYM+BC together to sorghum seeded using the RG planting method may be a more effective way to reduce salt stress and boost crop production than applying FYM and BC separately or sowing seeds on RB or FB.

Mahmoud *et al*. (2017) investigated the effects of applied biochar (wood sawdust and maize stalk) at levels of 5, 10 and 19 ton ha^{-1}, on selected physical properties of saline sodic soil, and on wheat yield. The results revealed that the addition of biochar had significant positive effects on the saturated hydraulic conductivity (Ks), infiltration rate (IR), and available water capacity (AWC). The treatment of 19 ton ha^{-1} of maize stalk biochar showed the highest increases in Ks by 127.6%, AWC by 72.8% and IR by 125% relative to the control. Based on the results of the current study, it is concluded that very large amounts of biochar would have to be applied in order to markedly change the soil physical properties and to improve the wheat yield in the salt affected soils.

Mahmoud *et al*. (2019) conducted an experiment in 2013-2014 and 2014-2015 growing season for maize in saline-sodic soil at Agricultural Faculty Farm, Tanta University. The results indicated that biochar application significantly increased soil organic matter (SOM), microbial biomass (C), cation exchange capacity (CEC), exchangeable cations, available phosphorus concentration, fertility index but decreased electrical conductivity (EC), and exchangeable sodium percentage (ESP) of the studied soil. In comparison to the control, the treatment with 19 tonnes ha^{-1} of wood sawdust biochar demonstrated the largest reductions in EC, which was 62.0%, ESP, which was 74.5%, and exchangeable Na, which was 67.4%. According to their findings, biochar can enhance soil fertility and reclaim saline-sodic soils.

Pandey *et al.* (2023) conducted an experiment in the net house of the Department of Agricultural Chemistry and Soil Science at Anand Agricultural University, Anand in the kharif season of 2018 to study the impact of biochar and farmyard manure (FYM) on physical and chemical aspects of saline soil. The results revealed that the presence of biochar significantly affected the availability of nitrogen and phosphorus in the soil post-harvest. Notably, the application of biochar at 7.5 t ha^{-1} resulted in a considerable drop in soil pH, electrical conductivity (EC), and exchangeable sodium percentage (ESP) (B4). Furthermore, similar to the benefits seen at 5 t ha^{-1}, biochar improved the physical characteristics of the soil at this level (7.5 t ha^{-1}) by lowering bulk density and increasing water retention. Furthermore, treatment F3 (FYM @ 10 t ha^{-1}) showed a significant increase in organic carbon, cation exchange capacity (CEC), and accessible NPK, comparable to treatment F2 (FYM @ 5 t ha^{-1}). They concluded that adding biochar can improve the physical and chemical characteristics of soils impacted by salt.

Sahay *et al*. (2018) conducted a field experiment during the kharif season of 2017 at the village Munshikhera of Unnao, India to study the impact of two halophilic bioformulations, halophilic azotobacter (Halo-Azo) and halophilic phosphate solubilizing bacteria (Halo-PSB) with effective salt tolerant variety of rice (CSR 36) on crop productivity and soil fertility in sodic soil. Soil samples were collected and analyzed for pH, electrical conductivity (EC), organic carbon, available nitrogen and available phosphorus. The results indicated that the inoculation of halophilic bioformulations increased the content of available phosphorus, available nitrogen, and organic carbon to 20, 9.9, and 16.8%, respectively.

Wu *et al*. (2014) carried out experiment on furfural and its biochar improve the general properties of a saline soil at Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai, China with five treatments *i.e*., control, 2, 5 and 5% furfural and biochar. According to the findings, biochar significantly lowered pH, raised soil organic carbon content and cation exchange capacity, and improved the soil's availability of phosphorus.

Xiao *et al.* (2020) demonstrated the effectiveness of potassium- rich biochar in alleviating the problem in wheat-maize rotation in the Yellow River Delta region. Results indicated that adding biochar at 0, 3, 6, and 12 t ha^{-1} decreased soil bulk density (BD) and increased saturated hydraulic conductivity (Ks) in a soil with a 2.8% salt content through rotational tillage with straw returning, with or without fertilisers. Biochar decreased soil BD by 9.1% and 14.5%, increased Ks by 82.7% and 91.2%, and decreased sodium adsorption ratio (SAR) by 64.9% and 92.8% at a dose of 12 t ha^{-1} and by wheat and maize harvests, respectively, in contrast to the control (CK). They observed that by reducing BD, increasing Ks, and decreasing SAR, biochar alleviated soil compaction and salt stress. Their outcome suggests that the conversion of local bio-waste into biochar as a soil amendment is of agronomic and environmental benefits.

Zhang *et al*. (2020) collected saline-alkali soil samples from the coastal area of Haixing County of Hebei Province, China in order to study the reclamation potential of biochar (BC, wheat straw biochar applied at 1% by weight), gypsum (G, 0.4% by weight), and gypsum coupled with biochar (GBC). Results revealed that the addition of gypsum (G and GB) significantly enhanced the removal of exchangeable Na^{+} and reduced leachate SAR. The soil pH, exchangeable sodium percentage (ESP), SAR, and alkalinity values following gypsum application were significantly lower than those following the CK and BC treatments. Their findings suggested that over a brief time, co-applying gypsum and biochar might enhance the hydraulic conductivity of saline-alkali soil and reduce leaching-induced sodicity.

2.5 Effect of biochar, FYM and gypsum application on growth and yield parameters of wheat crop.

Ahmad *et al*. (2020) conducted a pot experiment in the soil science department's wire house at Islamia University of Bahawalpur to assess the effects of biochar sourced from various sources combined with the nutrient-solubilizing, acid-producing *Bacillus sp*. ZM20 on the biological properties of the soil and the growth of maize (*Zea mays* L.) crops in a natural environment. Along with a control, several biochar treatments were utilised, including Egyptian acacia (*Vachellia nilotica* L.) biochar, wheat (*Triticum aestivum* L.) straw biochar, and farm-yard manure biochar with and without *Bacillus sp*. ZM20. The application of biochar from various sources, with and without *Bacillus sp.* ZM20, considerably improved fresh and dry biomass, 1000 grain weight, and grain yield, according to the results of the pot trial. Additionally, it was found that applying biochar in conjunction with *Bacillus sp.* ZM20 was more successful than applying biochar alone. The treatment where *Bacillus sp.* ZM20 and wheat straw biochar (0.2%) were administered together showed the highest increase in grain production (25.77%). Compared to all other treatments, the combination application of wheat straw biochar (0.2%) inoculated with *Bacillus sp.* ZM20 proved to be the most efficient in enhancing the biological soil characteristics, plant growth, yield, and quality of the maize crop.

Arif *et al*. (2012) conducted an experiment on effect of biochar, FYM and mineral nitrogen alone and in combination on yield and yield components of maize at Pakistan. The results revealed that the plant height and number of row ear^{-1} was found non significant due to biochar application as compared to control. But the higher ear length and grain per ear were found under the treatment of biochar application @ 30 t ha^{-1} as compared to control.

Arora *et al.* (2016) observed that the plant growth promoting halophilic bacteria helps in bio-remediation of salt affected soils and thereby improves the agricultural crop yields. Bio- inoculation of seeds of wheat with plant growth promoting halophilic bacteria resulted in increase of 18.1 and 24.2 % in grain and straw yield, respectively under sodic conditions.

Arun Kumar *et al.* (2019) conducted a field experiment during summer season of 2018 on sandy loam soil at Zonal Agricultural and Horticultural Research Station, University of Agricultural and Horticultural Sciences, Navile, Shivamogga, Karnataka to study the effect of biochar, FYM and NPK fertilizers integration on growth and yield of aerobic rice. The study had 16 treatments, which included two levels of FYM at 5 and 10 t/ha and four levels of coconut shell biochar at 2, 4, 6, and 8 t/ha. These treatments were administered to the soil both singly and in combination. With the exception of the absolute control, all treatments received the same application of the suggested fertiliser dose (100, 50, and 50 kg/ha). When compared to RDF alone and RDF+FYM 10 t/ha applied treatments, at all growth stages, the results demonstrated a significant increase in plant height, number of tillers/hill, number of panicles/hill, number of grains/panicle, and 1000-grain weight when 8 t coconut shell biochar/ha and 10 t FYM/ha were combined with the recommended dose of fertilisers. This was demonstrated by the significantly higher grain (6184 kg/ha) and straw (7724 kg/ha) yields as well as the aerobic rice crop's overall uptake of macronutrients in the FYM 10 t/ha with RDF applied treatment and the 8t coconut shell biochar treatment.

Khan *et al.* (2020) conducted a field experiment during Fall 2015-16 and 2016-17 at Agriculture Research Station (ARS) Swabi Khyber Pakhtunkhwa Pakistan, to enhance N availability from organic and inorganic N sources via biochar (0, 10, 20 and 30 tons ha^{-1}) under four levels of N (0, 90, 120 and 150 kg ha^{-1}). Farmyard manure (FYM), poultry manure (PM), and urea provided the necessary nitrogen (N). The findings shown that, in comparison to the control, the application of 20 and/or 30 t BC ha^{-1} considerably delayed booting, anthesis, and physiological maturity in wheat. It also increased leaf area (LA), leaf area index (LAI), plant height, and the number of tillers and spikes m^{-2}. On the other hand, wheat's booting, anthesis, and physiological maturity were delayed by the treatment of 150 kg N ha^{-1} as urea, FYM, and PM, which also raised the height of the plants and their m^{-2} spikes. Similarly, increased LA, LAI, tillers, and spikes m^{-2} over control plots were obtained with 120 and 150 kg N ha^{-1} applied from PM, FYM, and urea. Therefore, 20 t BC ha^{-1} plus 120 kg N ha^{-1} from organic or inorganic sources should be applied to wheat as this combination improved wheat growth and development.

2.6 Effect of biochar application and other amendments nutrient uptake by wheat crop.

Bekele *et al.* (2021) carried out a field experiment at Werer Agricultural Research, Ethiopia, in the 2016–2017 and 2018 cropping seasons, with the goal of improving saline– sodic soils by applying gypsum and charcoal, and consequently raising wheat grain production. The findings showed that the treatment of gypsum and biochar had a discernible impact on grain production, thousand seed weight, and the number of seeds per panicle. When compared to biochar, gypsum application generally outperformed it on most crop characteristics. The treatment with 100% gypsum application yielded the maximum grain yield as well.

Elangovan (2014) conducted a field experiments during 2011-12 to study the effect of biochar with and without FYM and inorganic fertilizers on soil productivity at Coimbatore, on an Inceptisol which having pH 8.68. The results revealed that among the biochar levels, the application of biochar recorded higher N, P and K uptake by cotton and it increased with increasing levels, significantly maximum N, P and K uptake was observed in biochar @ 10 t ha^{-1} level as compared to control.

El-Gamal *et al.* (2020) studied the effects of sulphur and biochar on the productivity of wheat and soybean yields in soils with different texture classes by conducting a lysimeter experiment for wheat and soybean at EL-Gemmieza Agriculture Research Station, El Gharbiya Governorate, over the course of two consecutive seasons, the summer of 2018 and the winter of 2017/2018. The results showed that applying sulphur or biochar, both separately and together, enhanced grain and straw yields. Additionally, all applications of sulphur and biochar considerably raised the concentration of N, P, and K as well as the uptake of wheat and soybean. Wheat and soybean (grain and straw) yields were significantly increased by applying charcoal and sulphur (T4) together.

Mahmoud *et al.* (2017) conducted a field experiment at the EL-Gemmieza Agriculture Research Station El Gharbiah Governorate, Egypt to investigate phosphogypsum (PG) and biochar (B), applied individually and their mixture at rates of 5 and 10 Mg ha^{-1} with recommended nitrogen fertilizer for maize plants, on soil physical properties in Vertic Torrifluvents and on nutrients uptake. Results showed that the combination of biochar and PG at 10 Mg/ha for each produced the largest increase in N uptake (86.3%) over the control. With PG, biochar, and PG mixes, the amount of P and K absorbed by maize plant grain rose dramatically.

Panda *et al*. (2017) carried out a pot experiment during the Rabi season of 2014 at the Indian Institute of Soil Science (ICAR), Bhopal, to assess the impact of inorganic fertilisers, farmyard manure (FYM), and Subabul (*Leucaena Leucocephala*) biochar in combination with organic resources on the biomass production of barley (*Hordeum vulgare* L.). The yield of barley biomass and some yield components showed a substantial response to the applications of FYM and biochar, according to the results. When soil + NPK + FYM 1% + Biochar 3% (T13) was applied, the total fresh biomass production (32.6 g pot^{-1}) and dry biomass yield (6.18 g pot^{-1}) were highest compared to the control (17.5 g pot^{-1}) T1. Both T11 (31.3 g pot^{-1}) and T12 (32.4 g pot^{-1}) treatments had significantly higher recorded values than the control (T1) and significantly at par with each other. We draw the conclusion that applying organic amendments maximises barley plant biomass.

Rehmat *et al*. (2021) conducted a pot experiment in rain protected wire house at Institute of Soil and Environmental Sciences (ISES), University of Agriculture, Faisalabad. to evaluate the effect of halotolerant phosphorus solubilizing bacteria (PSB) and organic manures (PM and FYM) in mineralization of phosphorus under salinity stress. For this purpose, PSB-coated maize seedlings were simply compared, under salt stress (7dSm^{-1}), with non-inoculated PSB and organic manures (PM and FYM). The findings showed that, in comparison to the control group and plants under salt stress, the inoculation of PSB and the application of organic manures (PM and FYM) improved P uptake (35.4% and 28.7%) and maize growth.

Singh *et al*. (2021) conducted a field experiment on maize/cotton-wheat cropping system in 2014 at Punjab Agricultural University (PAU), Ludhiana, India to evaluate four rates of rice straw biochar and four levels of saline water on crop growth in the cotton-wheat system. The study's findings showed that applying biochar (2–8 t ha^{-1}) to salty water-irrigated plots increased seed cotton and wheat grain yield by 6–23% and 13–27%, respectively, as compared to unmodified plots.

Sun *et al*. (2019) conducted a pot experiment to evaluate the effects of biochar applied at various rates (*i.e*., 0, 5, 10, 20, 30, 40 and 50 t ha^{-1}) on the nitrogen use efficiency (NUE), GY and amino acid (AA) contents of wheat plants in saline soils.

The results showed that the application of 5–20 t ha^{-1} biochar increased wheat NUE by 5.2-37.9% and thus increased wheat GY by 2.9-19.4%. However, excessive biochar applications (more than 30 t ha^{-1}) had negative effects on both the NUE and GY of wheat. Biochar had little influence on leaf soil and plant analyzer development (SPAD) values, the harvest index or yield components. The AAs were significantly affected by biochar, depending on the application rate. Among the application rates, 5-30 t ha^{-1} biochar resulted in relatively higher (by 5.2–19.1%) total AA contents. Similar trends were observed for each of the 17 essential AAs.

2.7 Effect of biochar and amendment applications on ion concentrations in leachate from sodic soils.

El-Fattah (2012) a leaching experiment was carried out utilising the columns technique to assess the efficacy of gypsum, rice straw compost (RSC), water hyacinth compost (WHC), and their various combinations on the rehabilitation of clay saline-sodic soils. Egypt's El- Sharkia Governorate's Sahl El-Hossinia provided the soils for the collection. The study's findings demonstrated that, when compared to the control, all of the applied amendments significantly reduced EC, pH, SAR, and ESP, either individually or in combination. According to this study, applying gypsum in conjunction with WHC or RSC improved reclamation and resulted in greater reductions in salinity and sodicity.

El-Shazly (2021) carried out a column experiment in the winter of 2019–2020 at the Research Farm of the Port Saied Agricultural Research Station, Port Saied Governorate, North East Dealta, Egypt, to assess the efficacy of (FYM) and gypsum in the leaching columns-based reclamation of a saline sodic soil. Gypsum (FYM) is applied in two ways: by soaking or by mixing, and in three sizes. Samples of leachate were taken at the base of soil columns. EC, pH, Na, and ESP measurements were made on the samples. The findings showed that adding amendments lowered the pH, EC, and ESP of the soil. They came to the conclusion that the most effective soil amendment for lowering soil EC, pH, and ESP was a mixture of (FYM) + gypsum.

Linh (2023) conducted a soil column experiment utilising a saline soil sample from the rice cropping system to assess the potential reclamation of compost and biochar in a laboratory setting. Random soil samples were taken from a double rice cropping field in the Mekong River Delta at depths ranging from 0 to 20 cm and with a high electrical conductivity value (EC(1:5)>5.0 mS cm^{-1}). The 30-g dried soil weight served as the basis for the compost and biochar application rates. Ten t ha^{-1}, twenty t ha^{-1}, and forty t ha^{-1} of amendments were added to thirty g of soil, and they were all well mixed. Findings showed that from the first to the fourth wash, the EC value in the solution fell concurrently. In about 10 to 23 days, the treatments that included compost and charcoal decreased the EC value to less than 1.2 mS cm-

1. Over the course of ten days, the EC value for the treatments that included 2% biochar and 1% compost plus 1% biochar was less than 1 mS cm^{-1}. As a result, it was demonstrated that the addition of compost and biochar had an impact on lowering the EC in the soil and accelerating the salinization process.

Mohamed *et al.* (2015) conducted a soil column experiment to investigate the effect of gypsum, ground to varying degrees of fineness, on the reclamation of clayey saline-sodic soils. The saline-sodic soil utilised in this study was taken from Gelbana Village in Sahl El-Tins Plain, Sinai Governorate, Egypt, at a depth of 0–30 cm. The following treatments were included in the test: control (leaching without gypsum addition), small particles (<0.5 mm), medium particles (0.5-1 mm), and coarse particles (1-2 mm). Three different degrees of gypsum fineness (0.5, 0.5-1, and 1-2 mm) were evaluated. For the 30-cm soil matrix, the gypsum requirement (GR) to lower the initial ESP from 29.8 to 10 percentwas determined. The gypsum application and subsequent leaching improved reclamation and reduced both the salinity and sodicity. Both sodicity and salinity were found to decrease more when the gypsum particles were finer. This study advises that fine-particle gypsum be employed in the restoration of saline-sodic soils for increased reclamation efficiency.

Sadegh-Zadeh *et al.* (2018) conducted a leaching column experiment and saline-sodic soil samples were collected from the Karfun region, located in the Mazandaran Province, Iran to investigate the effects of adding various biochars and acidified biochars on selected characteristics of saline-sodic soil and rehabilitation of this soil. Rice straw (RSB) and dicer wood chips (DWCB) were combined to create biochars in a laboratory furnace for two hours at 300°C with restricted oxygen. The application of biochars and acidified biochars decreased the soil EC and sodium adsorption ratio, according to the results. The saline-sodic soil was remedied by the biochars, particularly the RSB, which has a high Ca^{2+} and Mg^{2+} content. It is possible to improve calcareous saline-sodic soil using RSB, acidified RSB, and acidified

DWCB, according to the findings.

Santos *et al*. (2021) carried out a laboratory column-leaching experiment to test the ability of biochars from sugarcane bagasse (SB), orange bagasse (OB), and corncob (CB) to remediate a highly degraded saline-sodic soil in the Northeast region of Brazil. The biochars were applied both alone and in combination with gypsum (G). They found that under the SB treatment, soil ECe, SAR, and ESP decreased to 3.42 dS m^{-1}, 1.64 (mmolc dm^{-3}) 0.5 and 4.86%, respectively; under the CB treatment, they decreased to 3.19 dS m^{-1}, 0.88 (mmolc dm^{-3}) 0.5 and 2.53%, respectively. Salinity indicators were not effectively reduced by orange bagasse biochar. Consequently, they came to the conclusion that applying SB and CB is a useful substitute for cleaning up saline-sodic soils and lessening the environmental effects of soil salinity.

Yue *et al*. (2016) conducted a soil column leaching experiment to evaluate the impacts of three biochars on promoting salt washing and then find possible biochars as saline soil conditioner. In April 2013, they procured a sample of Sitao area, Inner Mongolia, China, silt loam soil (Aridisol). Three types of biochar were introduced at a rate of 5% (w/w) to sulphate (SO4 2–) saline soil columns at soil depths ranging from 0 to 35 cm (0 to 13.8 in) and made from rice (*Oryza sativa* L.) straw (RSB), sunflower (*Helianthus annuus*) straw (SSB), and cow manure (CMB) through a slow pyrolysis process. The columns treated with biochar released efflux 24 to 40 days ahead of the control group that did not receive biochar (CK), according to the results. The EC values of the efflux were lowered to 5 dS m^{-1} in 56 to 62 days with the addition of biochar.

CHAPTER III

MATERIAL AND METHODS

The present investigation entitled “Studies on Influence of Biochar Application on Soil Properties and Performance of Wheat in Sodic Soils” was conducted during 2022-2024. The details of material used and methods adopted during the investigation have been presented under different headings.

3.1 General Description

3.1.1 Experimental Location and study area

The experiment was conducted at the Division of Soil Science and Agricultural Chemistry, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu (J&K). The study area lies in the subtropical zone of Jammu and Kashmir, at a latitude of 32.43° North and a longitude of 74.54° East which is located near the banks of the Tawi River. The river not only supports the irrigation systems in the surrounding areas but also influences the local microclimate. The northern part of the command area features a slightly hilly terrain with rolling topography and falls within the drought-prone Kandi belt of Jammu, whereas the southern part is relatively plain.

3.1.2 Climate and weather

The climate of study area was predominantly subtropical, with hot and dry early summers, hot and humid monsoon seasons, and cold and dry winters. The region normally receives 1,142 mm of rainfall annually, of which 70% falls between June and September during the Southwest monsoon season and the remaining 30% is received during October and May, mostly as a result of western disturbances. The amount of rain that falls here varies greatly and is not evenly distributed throughout the year. The weather conditions during the growing season of the test crop, wheat, are summarized in Figure 3.1, which provides detailed weather data for the full farming season.

3.1.3 Soil Types

The soils of experimental site are predominantly Inceptisols, with textures ranging from clay loam to sandy clay loam. Characterization of the salt-affected soils in the Ravi-Tawi command revealed that the salinity is primarily sodic in nature. Scattered patches of sodicity are present, especially in low-lying areas where water stagnation is a common issue. The pH of these sodic soils exceeds 10.0 in certain cases, accompanied by a high Exchangeable Sodium Percentage (ESP). Notably, the soils in Tarore exhibit very high levels of sodicity, with a pH of 9.9 and an ESP of 78.41. Out of the total 75,000 hectares under the canal irrigation system in the area, approximately 25,000 hectares are classified as waterlogged. Of this, an estimated 7,500 hectares are affected by sodic soils (Sharma *et al*., 2011).

3.1.4 Soil Types

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3.2. Experimental treatments

To study the impact of biochar application and amendments on soil properties, crop growth and yield, two experiments *i.e.*, Pot culture and Leaching were conducted. Both of them were conducted separately with the same set of treatments.

3.2.1 Pot Experiment

3.2.1.1 Soil collection for pots

To conduct the pot experiment, bulk soil was collected from the Organic Farming Research Centre (OFRC), Chatha of Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu (SKUAST Jammu).

After collecting the soil, it was ground and passed through 5 mm sieve and 12 kg of soil was filled in each pot. Sixty pots were taken and sodicity was artificially induced by preparing a solution of sodium bicarbonate with deionised water. A mixture of 24 g of sodium bicarbonate dissolved in 2 litre of water was poured in each of the sixty pots. This application was carried out thrice till the pH obtained was greater than

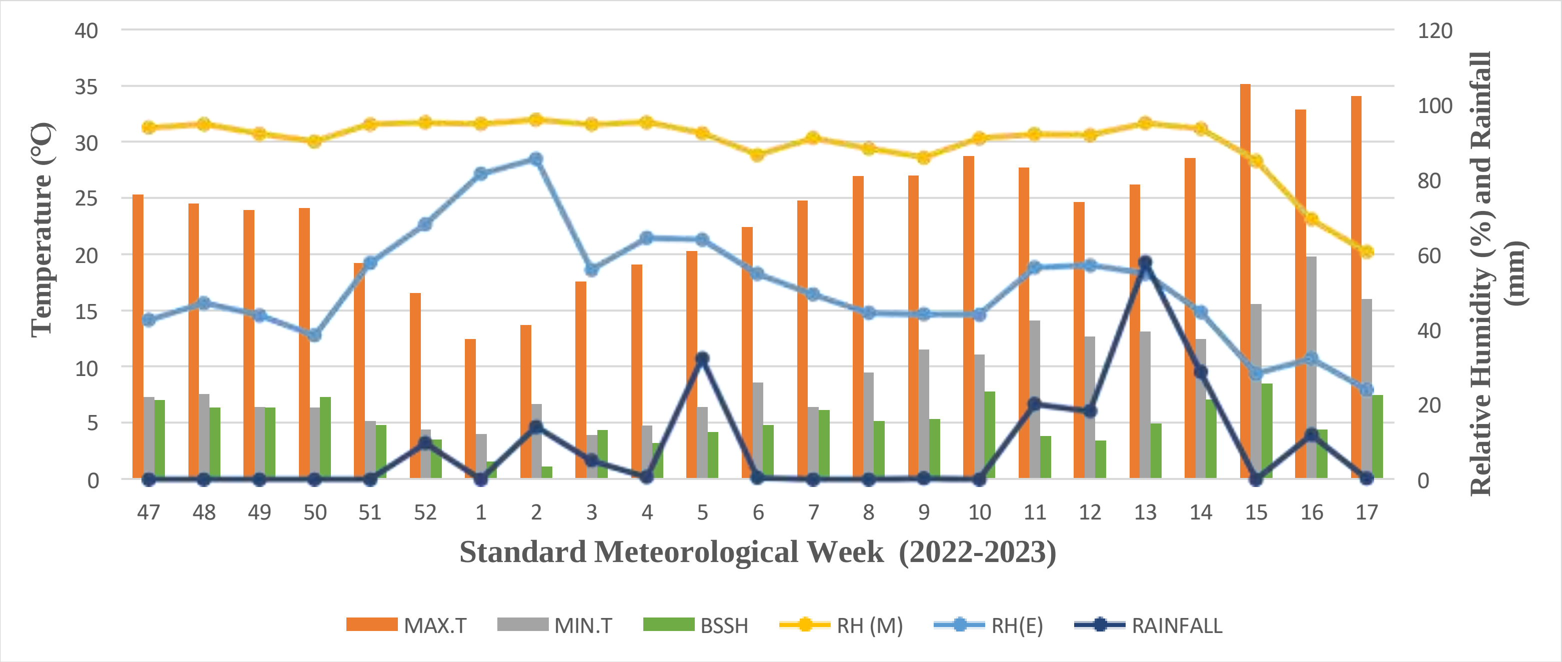

Fig. 3.1 Meteorological weekly data observed during wheat crop season (2022-23)

9. They were analysed over a fortnight and a constant pH of 9.46±(0.10) was obtained. The properties of soil type are presented in Table 3.1.

Table 3.1: Initial soil properties of potted soils.

Parameters	**Values**
Soil Type	Sodic
pH	9.46
EC (dS m^{-1})	1.02
Organic Carbon (g kg^{-1})	2.5
Available N (kg ha^{-1})	188.5
Available P (kg ha^{-1})	5.40
Available K (kg ha^{-1})	90.56
Exchangeable Ca (me/100g)	1.40
Exchangeable Mg (me/100g)	1.20
Exchangeable Na (me/100g)	8.20
Exchangeable Sodium Percentage (%)	68.03
Sodium Adsorption Ratio	38.17
Sand (%)	61.5
Silt (%)	15.0
Clay (%)	23.5
Texture	Sandy Clay Loam

3.2.1.2 Experimental design

The pot study was laid out in factorial completely randomized design (CRD).

Two factors were taken *viz*., Biochar and Soil Amendments.

3.2.1.3 Amendments

Four treatments were taken for amendments. These were control (F1), FYM (F2), FYM + Consortia (F3) and FYM + Consortia + 50% Gypsum (RDF) (F4).

3.2.1.4 Biochar

Two types of biochar were taken *ie*., normal biochar (pH 8.9) and acidified biochar (pH 5.4). The biochar was produced from the rice straw biochar (RSB) in a laboratory furnace under limited oxygen at 300°C for two hours. The acidified biochar was prepared by washing the RSB three times with 0.1 N HCl at 1:20 ratio (w/v), followed by deionized water and then dried in an oven for 48 h at 60°C (Sadegh-Zadeh *et al*. 2018). The biochar was designated as acidified rice straw biochar (ARSB).

There were total of 20 treatment combinations with 3 replications taking the number of pots to 60. A description of the treatments, factor wise, is given below in table 3.2. Table 3.3 below provides characterization of the biochar and FYM.

Table 3.2: Details of treatment combinations

FACTOR 1: Biochar

Rate of application (t ha^{-1})		
No Biochar	0 (B0)	
Normal Biochar	2.5 (B1)	5 (B2)
Acidified Biochar	2.5 (B3)	5 (B4)

FACTOR 2: Amendments	
F1	Control
F2	FYM
F3	FYM + Consortia*
F4	FYM + Consortia* + 50 % Gypsum (RDF)

*Consortia: (Halo-Mix) *ie.*, (Halo-Azo + Halo-PSB + Halo- Zinc inoculation)

Table 3.3: Characterization of biochar and FYM

Sr. No.	Components	Biochar	F.Y.M
1.	pH (1:10)	8.9	-
2.	EC (1:10)	0.49	-
3.	Nitrogen	0.09%	0.52%
4.	Phosphorus	0.15%	0.36%
5.	Potassium	0.5%	1.15%
6.	Total Carbon	53.5	16.39%
7.	Bulk density	0.28 g cm^{-3}	-

3.2.1.5 Bioformulation and its application

Bioformulation *i.e.* Halo-Mix (Halo-Azo, Halo-PSB and Halo-Zinc) were obtained from CSSRI, Lucknow. The seeds were soaked in a 100-fold diluted bioformulation for one hour and then inoculated in pots for planting. These strains were isolated from the salt-affected soils of the Indo-Gangetic plains at the ICAR-CSSRI, Regional Research Station, Lucknow (UP). These strains were characterized for their plant growth-promoting properties and evaluated for their efficacy under varying levels of salt stress. To facilitate their use as seed treatments, the selected strains of these beneficial soil microorganisms were cultured in the laboratory and prepared into standardized liquid bioformulations, named *Halo-Azo, Halo-PSB* and *Halo-Zinc*. These bioformulations can be conveniently used as seed treatments, seedling dips, or applied to the soil along with farmyard manure or compost. A 100 ml bottle is sufficient to treat seeds for one acre of land or for root dipping applications. Under salt-stress conditions, these bioformulations led to an increase in wheat yields by 11.5–14%. This approach provides a cost- effective and eco-friendly solution for the bioremediation of salt-affected soils, helping to optimize agricultural crop yields in degraded lands (Arora, 2020).

3.2.1.6 Plant material

The experiment was conducted using the wheat variety DBW 173, a high-yielding and disease-resistant variety known for its adaptability to different environmental conditions. In each experimental pot, ten wheat seeds were sown to ensure uniformity and adequate plant density for observing the effects of different treatments. The seeds were carefully placed at a recommended depth to encourage optimal germination. Throughout the duration of the study, proper cultural practices were followed to ensure healthy plant growth. These included regular watering, timely weeding, and the application of necessary fertilizers. The plants were monitored closely for any signs of disease or nutrient deficiency, and corrective measures were taken as needed. The care and attention given to the plants throughout the study aimed to provide a healthy and representative sample of wheat, enabling a thorough assessment of the impact of the treatments under investigation.

3.3 Soil sampling and analysis

3.3.1 Collection and preparation of soil samples

To study the impact of treatments on soil properties, soil samples from each experimental pot were collected at harvesting stage. Composite soil sample from 15 cm depth was collected from four points in each pot with the help of screw type auger. The soil samples, thus collected, were dried in shade, grounded, sieved through 2 mm sieve and stored in polythene bags for analysis of basic soil properties and nutrient status. However, fresh soil samples were used for estimation of soil biological properties.

Moisture correction was carried out for fresh soil samples, by keeping a replicate in the hot air oven and ascertaining the soil moisture content, which was then deducted from the weight taken for the analysis of biological properties.

3.3.2 Soil Chemical Properties

3.3.2.1 Soil pH

Soil pH was determined in 1: 2.5 soil water suspensions using digital pH meter following procedure as described by Jackson (1973).

3.3.2.2 Electrical conductivity

The electrical conductivity of the supernatant in the soil water extract was read with the help of digital EC meter Jackson (1967).

3.3.2.3 Organic carbon

It was determined according to wet digestion method of Walkley and Black (1934).

3.3.3 Soil nutrient status

3.3.3.1 Nitrogen

The available nitrogen (N) was estimated by alkaline potassium permanganate method as given by Subbiah and Asija (1956) and expressed in kg ha^{-1}.

3.3.3.2 Phosphorus

Available phosphorus in soil was determined by Stannous Chloride reduced ammonium molybdate method using Olsen's extractant (Olsen *et al.*, 1954) and determined on ultra violet visible spectrophotometer at 660 nm wave length and the results were expressed in kg ha^{-1}.

3.3.3.3 Potassium

Potassium was extracted with neutral normal ammonium acetate as per the procedure given by Jackson (1973). Potassium was estimated on the Flame Photometer and expressed in kg ha^{-1}.

3.3.4 Exchangeable ions

3.3.4.1 Exchangeable Calcium and Magnesium

The exchangeable calcium and magnesium were determined in the ammonium acetate extract used for exchangeable potassium.

3.3.4.1.1 Exchangeable Calcium

A known volume of soil extract was titrated with a standard EDTA (ethylene diamine tetra acetic acid) solution, using ammonium purpurate (Mure oxide) as an indicator in the presence of sodium hydroxide solution. The endpoint was indicated by a color change from orange-red to purple, as the calcium formed a complex with EDTA at a pH of approximately 12.0, as described by Jackson (1973).

3.3.4.1.2 Exchangeable Magnesium

A known volume of soil extract was titrated with a standard EDTA (ethylene diamine tetra acetic acid) solution, using Eriochrome Black T as an indicator in the presence of an NH_4Cl-NH_4OH buffer. The endpoint was determined by a color change from wine red to blue, which occurs at a pH of approximately 10.0, as described by Keeney and Nelson (1982).

3.3.4.2 Exchangeable Sodium

Exchangeable sodium in the soil was extracted using 1N neutral ammonium acetate and quantified on a flame photometer, as outlined by Ryan *et al*. (1986).

3.3.4.3 Carbonates and Bicarbonates

Carbonates and bicarbonates in the soil solution were determined by titrating a known volume of the soil solution against standard sulfuric acid, using phenolphthalein and methyl red as indicators, respectively, as described by Horneck and Hanson (2012).

3.3.4.4 Exchangeable Sodium Percentage

The exchangeable sodium percentage (ESP) measures the proportion of cation exchange sites occupied by sodium.

$$\text{ESP} = \frac{\text{Na}}{\text{CEC}} \text{ X } 100$$

3.3.4.5 Sodium Adsorption Ratio

Sodium adsorption ratio is a measure of the amount of sodium (Na) relative to calcium (Ca) and magnesium (Mg) in the water extract from saturated soil paste.

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

3.3.5 Soil biological properties

3.3.5.1 Dehydrogenase activity

Dehydrogenase activity was determined by monitoring the rate of production of triphenyl formazan (TPF) from tri-phenyl tetrazolium chloride (TTC), using the method given by Casida *et al*. (1964).

3.3.5.2 Phosphatase activity

The method of determination of alkaline phosphatase activity in soils followed was as suggested by Tabatabai and Bremner (1969). It involves colorimetric estimation of the *p*- nitrophenol released by phosphomonoesterases activity. The soil is incubated with buffer (at 11 for alkaline phosphomonoesterases activities) sodium *p*-nitrophenyl phosphate solution and toluene. Alkaline phenol has a yellow colour which is measured in colorimeter. The CaCl2 - NaOH treatment is used for extraction of *p*-nitrophenol.

3.3.5.3 Bacterial Count (cfu)

The serial dilution and plating techniques suggested by Subba Rao (1999), was employed for isolation and identification of viable bacteria count. Media were prepared for desired micro flora. The autoclaved and cooled medium was poured into sterile plates and allowed to solidify. One gram of soil was added to 9 ml sterile water blank and shaken for 15-20 minutes. Serial dilutions of 10^{-2} ,10^{-3}, 10^{-4}, 10^{-5}, 10^{-6} and 10^{-7} were prepared and 0.1 ml of aliquots of various dilutions were added, over cooled and solidified medium in petri plates. Pour plate method was employed. The plates were rotated for uniform distribution of bacterial cells in the aliquot under the media and allowed to solidify. After the media solidified, the plates were inverted and incubated at 28 °C for 3-4 days. The appearance of colonies on the surface of medium in the plates was observed. Viable count of microbes was noted using dilution plate technique by employing nutrient agar (NA), respectively. The population was expressed as colony forming units (CFU/g soil).

3.3.6 Soil physical properties

3.3.6.1 Bulk Density

Bulk density was determined from undisturbed soil samples using the core method (Blake and Hartge, 1986). The soil samples were dried in an oven at 105°C to a constant weight, and the bulk density was calculated using the following relationship.

$$\text{Bulk Density (g cm}^{-3}\text{)} = \frac{\text{Oven dry weight of soil}}{\text{Volume of soil}}$$

3.3.1.1 Porosity

Porosity is determined by dividing the volume of voids by the total volume of a material to calculate a percentage, as described by Black, (1965). It can be calculated using the following formula:

$$\textbf{Porosity (\%) = (Volume of Voids / Total Volume)} \times \textbf{100}$$

3.3.1.2 Infiltration rate

The infiltration rate was determined using the mini disk infiltrometer. The infiltrometer was first placed in water to ensure the mini disc was fully saturated, and then carefully filled with water to avoid air bubbles. At the start of the measurements, the disk infiltrometer was in full contact with the soil surface and measurements were continued for 10 to 15 minutes, depending on the treatment. The volume of water infiltrating and the position of the wetting front were recorded every 0.5 minute, as described by Luxmoore, (1981).

3.3.1.3 Soil moisture

Soil moisture content is determined by the oven drying method. In this method, a soil sample is collected in a moisture box and its wet weight is recorded. The sample is then dried in a hot air oven at 105°C until a constant weight is achieved, after which the dry weight of the sample is recorded (Black, 1965).

$$\textbf{Moisture content (on weight basis)} = \frac{\textbf{Wet weight – Dry weight}}{\textbf{Dry weight}} \times \textbf{100}$$

3.3.6.2 Water Holding Capacity

The water holding capacity is determined by using Keen Raczkowski box method (Keen and Raczkowski 1921) and calculated as:

$$\textbf{Water holding capacity (\%)} = \frac{\textbf{Wet wt. of soil – Oven dry wt. of soil}}{\textbf{Oven dry wt. of soil}} \times \textbf{100}$$

3.4. Collection of plant samples

Plant samples from each experimental pot were collected at harvesting stage. Plant sampling was done during the last week of April. The data on plant *i.e.* growth parameters and yield parameters were recorded and the procedures followed are described below:

3.4.1 Plant growth parameters

3.4.1.1 Height of plants

The height of plants (cm) was measured from the surface of soil to the tip of plant with the help of meter scale at harvesting stages.

3.4.1.2 Number of grains per spike

Ten effective spikes were randomly selected from the net area of each pot, threshed and the grains so obtained were counted and averaged to find out number of grains per spike.

3.4.1.3 Spike length (cm)

The spike length of wheat was measured by selecting representative plants at the harvest stage. The spikes (ears) were carefully removed from the plants, and the length was measured from the base of the spike (excluding the peduncle) to the tip of the longest awn or spikelet. Measurements were recorded in centimeters using a ruler or caliper.

3.4.1.4 Root weight

To calculate the root weight of wheat, representative plants were dug up, and the washed roots were weighed. The root dry weight was calculated using the formula:

Root Dry Weight = (Total Wet Weight / Root Sample Weight) × Oven Dry Weight of Root Sample.

3.4.1.5 Root : Shoot ratio

The root: shoot ratio is used as a measure to assess the overall health of the plants. To measure the root: shoot ratio, the plants were removed from the soil, and any loose soil was washed off. The plants were blotted to remove any free surface moisture. They were then dried in an oven set to low heat (100°F) overnight. After drying, the plants were allowed to cool in a dry environment. Once cooled, the plants were weighed on a scale. The roots were separated from the tops, and the roots and tops were weighed and recorded separately for each plant.

(Dry weight for roots/dry weight for top of plant = root/shoot ratio)

3.4.2 Yield attributes

3.4.2.1 Yield

After the harvesting of the wheat crop, the grain and straw yield per pot were carefully recorded to assess the productivity of the plants under the given experimental conditions. The grain yield was determined by threshing the harvested wheat plants to separate the grains from the straw, ensuring no loss of seeds during the process. The grains were then cleaned to remove any impurities, such as broken husks or chaff, and subsequently weighed using a precision scale. This provided an accurate measurement of the grain yield per pot.

Similarly, the straw yield was measured by collecting the remaining plant material, which included stems, leaves, and any non-grain portions left after threshing. The straw was allowed to air-dry or oven-dried at a specified temperature to ensure uniform moisture content across all samples. Once dried, the straw was weighed to determine its yield per pot. This comprehensive approach ensured that both grain and straw yields were accurately quantified, allowing for a reliable evaluation of the wheat crop's overall performance (Mason and Brennan, 1998).

3.4.2.2 Harvest index

The ratio of economic yield to the biological yield was computed to find out the harvest index by using the formula as given by Nichiporovich (1967):

$$\textbf{Harvest index (percent)} = \frac{\textbf{Economic yield (Grain)}}{\textbf{Biological yield (Grain + Straw)}} \times \mathbf{100}$$

3.4.2.3 1000- Grain weight

A random sample from bulk produce of each treatmental pot was taken out of which 1000-grains were counted and weighed. The weight so recorded was expressed in grams as test weight.

3.4.3 Plant analysis

The plant samples collected at harvest were washed with distilled water and dried in an oven at 65 ºC. These dried samples were powdered and analysed for the nutrients.

3.4.3.1 Total Nitrogen

Nitrogen content in samples was determined by digesting the sample using concentrated H_2SO_4 and digestion mixture consisting of K_2SO_4, $CuSO_4$ and Se and then distilled in an alkaline medium as per the standard procedure described by Jackson (1973).

3.4.3.2 Diacid digestion of plant samples for P and K

One gram of powdered plant samples were pre-digested with 10 ml of concentrated nitric acid and kept overnight. The samples were then digested with 10 ml of diacid mixture (HNO_3:$HClO_4$ in 10:4 ratio) until a white residue was left and the solution was clear. The residue was cooled, made up to a known volume with distilled water and used for further analysis.

3.4.3.2 Total Phosphorus

Phosphorus was estimated by Vanado-molybdate phosphoric acid yellow colour method. The intensity of yellow colour was read using a spectrophotometer at 430 nm wave length (Jackson, 1973).

3.4.3.3 Total Potassium

Potassium content in the digested sample was determined using flame photometer (Jackson, 1973).

3.4.3.4 Total calcium and magnesium

Calcium and magnesium in di-acid digested plant sample was estimated by complexometric titration method (Jackson, 1973)

3.4.3.5 Total Sulphur

Sulphur in the di-acid digested sample was quantified by using $BaCl_2$ to develop turbidity following estimation of the sample at 420 nm (Piper, 1966).

3.5 Statistical Analysis

The data recorded during the investigation was statistically analysed as prescribed by Fisher (1926) for Factorial Completely Randomized Design using

Microsoft 365 excel data tool.

3.6 Leaching experiment

3.6.1 Leachate procedure

The air-dried sodic soil, collected from the Chakrohi farm in Jammu with a bulk density of 1.5 g/cm³, was packed into 40 soil columns for the experiment. Each column was constructed using a grey PVC cylinder measuring 45 cm (14.7 in) in height and 7.62 cm (3 in) in inner diameter. To reduce interfacial tension, a 1 cm (0.4 in) layer of sand was added to the bottom of each column. A hard plastic beaker, connected to a plastic funnel lined with filter paper and securely sealed with tape, was used to collect the eluent at the base of the soil columns. The experiment utilized two types of biochar—normal biochar and acidified biochar—applied across four treatments: Control, FYM (Farmyard Manure), FYM + Consortia, and FYM + Consortia + 50% Gypsum RDF. Each treatment was replicated twice, with biochar applied at three different rates: 0 t ha^{-1}, 2.5 t ha^{-1}, and 5 t ha^{-1}. Eight of the forty PVC cylinders were filled with soil under various treatments but without biochar (0 t ha^{-1}) (Plate 3.1). Another eight cylinders were packed with soil containing normal biochar at 2.5 t ha^{-1} under the same treatments, and eight more were filled with normal biochar at 5 t ha^{-1} with the respective treatments. The remaining sixteen cylinders followed the same pattern but used acidified biochar. Specifically, eight cylinders contained acidified biochar at 2.5 t ha^{-1} with various treatments, while the other eight contained acidified biochar at 5 t ha^{-1} with the respective treatments. Deionized water (pH = 6.86) was added to each PVC cylinder in a volume of approximately 272.19 ml using a beaker. Electrical conductivity (EC) was measured every four days after collecting the eluent. The experiment was concluded after the fourth leaching, when the EC values had stabilized, followed by the analysis of the leachate. At the conclusion of the experiment, soil samples were collected from the columns, air-dried, and sieved through a 2 mm mesh to measure the concentrations of the primary salt ions. The layout of the experimental apparatus used in this study are illustrated in Plate 3.2.

3.6.2 Leachate Properties

3.6.2.1 pH

During the leaching process, the leachate (the liquid that drained out from the soil column or sample) was collected in a clean container. A calibrated pH meter was

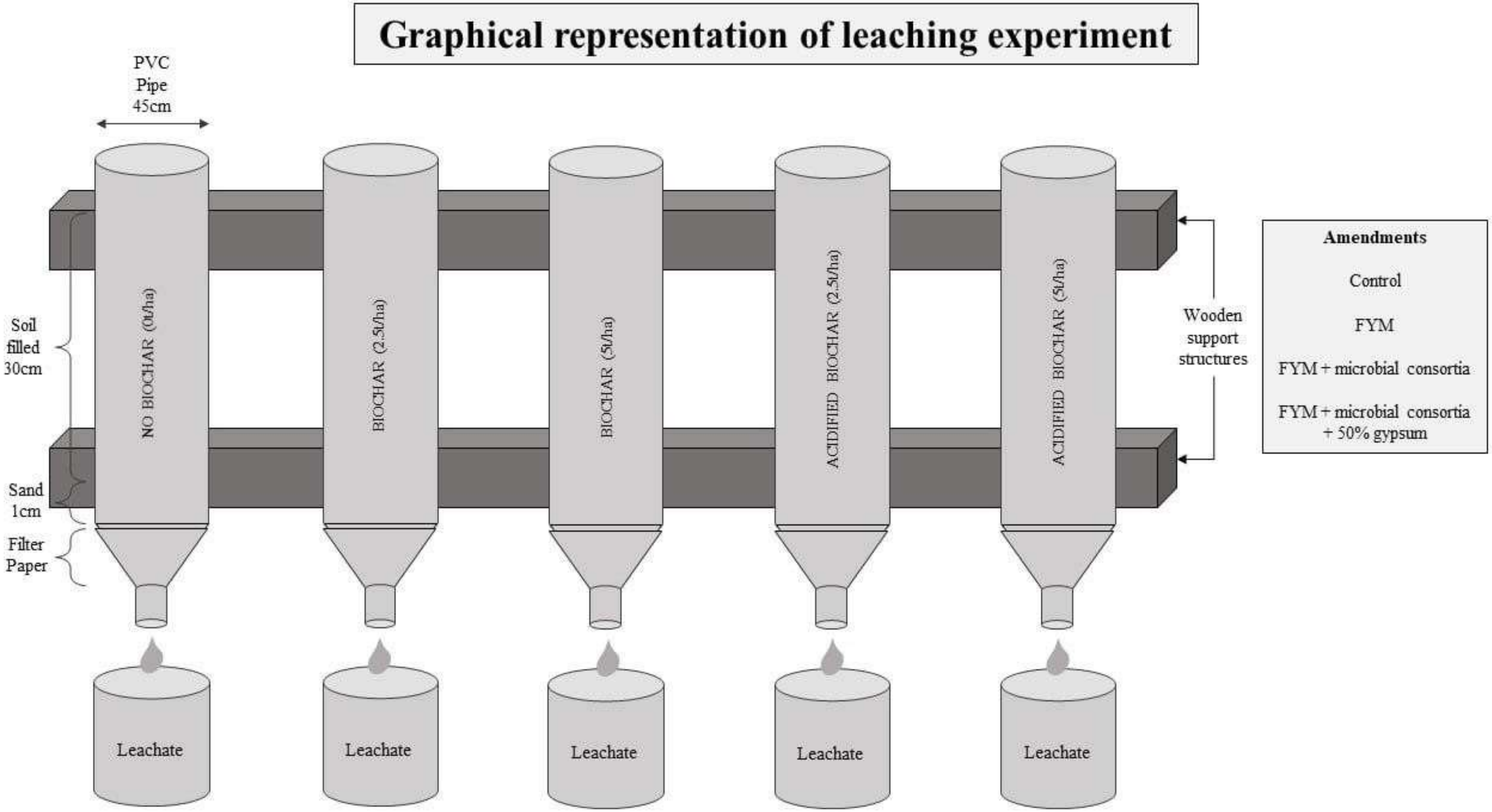

Plate 3.1 Graphical representation of Leaching experiment

Plate 3.2 Layout of the leachate experiment

used for accurate measurements. The meter was calibrated using standard buffer solutions (e.g., pH 4.0, 7.0, and 9.2) before each session to ensure accuracy. The electrode of the pH meter was rinsed with distilled or deionized water between samples to avoid cross-contamination. The pH electrode was immersed into the collected leachate, ensuring that it was completely submerged in the liquid. The leachate was gently stirred with the electrode to ensure uniformity and eliminate any bubbles around the electrode. The pH meter was allowed to stabilize before the reading was recorded. The pH values were recorded along with the corresponding time intervals or leachate volumes collected during the experiment (McLean, 1982).

3.6.2.2 Electrical Conductivity (EC)

A calibrated EC meter was used for accurate measurements of electrical conductivity. The EC meter was calibrated before use with standard conductivity solutions of known values to ensure reliable readings. The electrode was rinsed thoroughly with distilled or deionized water between samples to prevent cross-contamination. The electrode of the EC meter was immersed into the collected leachate, ensuring that the electrode was fully submerged without touching the sides or bottom of the container. The leachate was gently stirred with the electrode to ensure uniformity. The EC meter was allowed to stabilize, and the displayed value was recorded once it became steady (Rhoades and Miyamoto, 1990).

3.6.2.3 Calcium ions

The calcium concentration in the leachate was determined using a titrimetric method (EDTA titration). For the EDTA titration method, reagents such as a standardized EDTA solution, ammonium buffer (pH 10), and Eriochrome Black T indicator were prepared. A 25 mL aliquot of the filtered leachate was pipetted into a conical flask. Ammonium buffer was added to maintain a pH of 10, followed by a few drops of Eriochrome Black T indicator. The solution was titrated with the standardized EDTA solution until the color changed from wine red to pure blue, indicating the endpoint. The calcium concentration was calculated based on the volume of EDTA used (Sparks, 1996).

3.6.2.4 Magnesium ions

The magnesium concentration in the leachate was determined using a titrimetric method (EDTA titration). For EDTA titration, reagents such as a standardized EDTA solution, Eriochrome Black T indicator, and ammonium chloride-ammonium hydroxide buffer (to maintain a pH of 10) were prepared. A 25 mL aliquot of the filtered leachate was pipetted into a clean conical flask. An ammonium chloride-ammonium hydroxide buffer was added to maintain a pH of 10, followed by the Eriochrome Black T indicator. The solution was titrated with a standardized EDTA solution. In the presence of magnesium ions, the solution exhibited a wine-red color, which changed to blue at the endpoint. The magnesium concentration was calculated using the volume of EDTA consumed during the titration (Sparks, 1996).

3.6.2.5 Sodium ions

Sodium concentration was typically measured using flame photometry. The collected leachate was filtered through Whatman filter paper (or similar) to remove particulate matter. A clean aliquot of the filtered sample was introduced into the flame photometer. The sodium concentration was determined by measuring the emission intensity at the characteristic sodium wavelength (589 nm) and comparing it with the calibration curve (Sparks, 1996).

3.6.2.6 Potassium ions

The potassium concentration was determined using flame photometry. The leachate sample was filtered through Whatman filter paper (or a similar type) to remove particulate matter. A clean aliquot of the filtered leachate was introduced into the flame photometer, where the potassium concentration was determined by measuring the emission intensity at the characteristic potassium wavelength (766.5 nm). The intensity was compared to a calibration curve to determine the potassium concentration in the leachate (Sparks, 1996).

3.6.2.7 Carbonates

Carbonates in the leachate were determined using titrimetric methods (Horneck and Hanson, 2012). A known volume (usually 50 mL) of the filtered leachate was pipetted into a clean conical flask. A few drops of phenolphthalein were added as an indicator. The leachate was titrated with the standardized HCL solution. The titration process continued until the solution turned from pink (indicating basic conditions) to colorless, which indicated the complete neutralization of carbonates by HCl. The volume of acid consumed to reach the endpoint was recorded. For accurate measurement, the carbonate concentration was calculated as follows:

$$\text{Concentration of } CO_3^{2-} = \frac{\text{Vacid} \times \text{Cacid}}{\text{Vsample}}$$

Where:

- Vacid: the volume of acid used (in litres),
- Cacid: the concentration of the titrant acid (in mol/L),
- Vsample: the volume of leachate sample used (in litres).

3.6.2.8 Bicarbonates

Bicarbonates in the leachate were typically determined by titrimetric methods (Horneck and Hanson, 2012). A known volume (typically 50 mL) of the filtered leachate was pipetted into a clean conical flask. A few drops of phenolphthalein were added, which would remain pink in the presence of bicarbonate. The leachate was titrated with the standardized HCl solution.

The titration continued until the solution turned from pink to colorless, indicating that all bicarbonates had been neutralized by the acid. The volume of acid used to reach the endpoint was recorded. To ensure accurate results, the concentration of bicarbonate was calculated using the following formula:

$$\text{Concentration of } HCO_3^{2-} = \frac{\text{Vacid} \times \text{Cacid}}{\text{Vsample}}$$

Where:

- Vacid: the volume of acid used (in litres),
- Cacid: the concentration of the titrant acid (in mol/L),
- Vsample: the volume of leachate sample used (in litres).

3.6.2.9 Exchangeable Sodium Percentage (ESP)

The exchangeable sodium percentage (ESP) measures the proportion of cation exchange sites occupied by sodium.

$$\text{ESP} = \frac{\text{Na}}{\text{CEC x 100}}$$

3.6.2.10 Sodium Adsorption Ratio

Sodium adsorption ratio is a measure of the amount of sodium (Na) relative to calcium (Ca) and magnesium (Mg) in the water extract from saturated soil paste.

$$\mathrm{SAR} = [\mathrm{Na}^{+}] / [(\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}) / 2]$$

3.6.3 Column Soil Properties

Soil analysis of the column after the leaching process was carried out following procedures as mentioned for soil analysis for pot culture studies.

3.7 Statistical Analysis

A factorial completely randomized design (Fisher, 1926) was adopted for the experiment to systematically assess the effects of various treatments and their interactions. The collected data was subsequently utilized for statistical analysis to evaluate the significance of individual treatment effects and their combined interactions on the measured variables.

CHAPTER IV

RESULTS

The results pertaining to the present investigation on influence of biochar and amendments on soil properties and physiological parameters of wheat crop (pot experiment) and leaching experiment are presented in this chapter.

4.1 Chemical Parameters of pot experiment

The effect of biochars and different amendments on the basic soil properties and available nutrients is presented in this section under different sub-heads.

4.1.1 pH

The data on soil pH, as influenced by different levels of biochar treatments and other amendments in a wheat cropping system, are presented in Table 4.1. A significant variation in soil pH was observed among the treatments, demonstrating the impact of biochar and amendments on soil alkalinity. The application of acidified biochar at 5 t ha^{-1} (B4) consistently resulted in the lowest soil pH values, indicating its strong acidifying effect. The mean soil pH values for the biochar treatments B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 9.25, 9.04, 9.03, 8.52, and 8.22, respectively. Among the amendments, the mean pH values for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) were 9.23, 8.79, 8.68 and 8.54 respectively, with F3 and F4 significantly reducing soil pH compared to F1 and F2.

The interaction effect of biochar and amendments was also significant, with the lowest soil pH (7.77) recorded in the F4 treatment (FYM + Consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} (B4). In contrast, the highest soil pH was observed in the untreated control F1B0 (9.57).

4.1.2 Electrical Conductivity (EC)

The data on soil electrical conductivity (EC), influenced by different levels of biochar and amendments in a wheat cropping system, are presented in Table 4.2. The mean soil EC values for the biochar treatments B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.89 dS m^{-1}, 0.83 dS m^{-1}, 0.78 dS m^{-1}, 0.71 dS m^{-1}, and 0.67 dS m^{-1}, respectively. Similarly, among the amendments, the mean soil EC values were 0.86 dS m^{-1} for F1 (control), 0.78 dS m^{-1} for F2 (FYM), 0.76 dS m^{-1} for F3 (FYM + Consortia), and 0.71 dS m^{-1} for F4 (FYM + Consortia + 50% GR). The lowest soil EC (0.59 dS m^{-1}) was recorded under the combined treatment of F4 (FYM + Consortia + 50% GR) with acidified biochar applied at 5 t ha^{-1} (B4). This value was significantly lower than the EC observed in the control treatment F1B0 at 0.76 dS m^{-1}. Although the interaction effect of biochar levels and amendments on soil EC was found to be non-significant.

4.1.3 Organic Carbon (OC)

A perusal of the data presented in Table 4.3 reveals a significant impact of biochar levels and amendments on soil organic carbon (SOC) after the wheat harvest. The mean SOC values for the biochar treatments B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 1.25, 1.27, 1.50, 2.14 and 1.90 g kg^{-1}, respectively. Similarly, among the amendments, the mean SOC values for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) were 1.05, 1.42, 1.89 and 2.08 g kg^{-1}, respectively. Treatments F3 and F4 were significantly higher in SOC compared to F1 and F2, with F4 showing the highest SOC levels.

The interaction effect of biochar levels and amendments was found to be significant. The highest SOC value (2.99 g kg^{-1}) was recorded with the combined application of F4 (FYM + Consortia + 50% GR) and acidified biochar at 5 t ha^{-1} (B4), which was significantly higher than the control treatment (F1B0) at 1.08 g kg^{-1}.

4.1.4 Available Nitrogen

The data presented in Table 4.4 reveal significant variations in soil available nitrogen (N) as influenced by different levels of biochar and amendments. The mean soil available nitrogen for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 134.75, 170.94, 210.54, 233.74 and 245.31 kg ha^{-1}, respectively. These results indicate a progressive and significant increase in soil available nitrogen with higher levels of biochar application, particularly acidified biochar (B3 and B4), compared to the control (B0). Among the amendments, the mean soil available nitrogen values for

Table 4.1 Effect of different levels of Biochar and other amendments on pH of soil.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	9.57	9.17	9.20	9.17	9.05	9.23
FYM	**F2**	9.17	9.07	9.10	8.52	8.07	8.79
FYM+Consortia	**F3**	9.17	8.99	8.91	8.37	7.99	8.68
FYM+Consortia+50%GR	**F4**	9.10	8.94	8.90	8.01	7.77	8.54
Mean		9.25	9.04	9.03	8.52	8.22	

ANOVA	**CD**	**F Test**
B	0.20	S
F	0.18	S
B*F	0.39	S

Table 4.2 Effect of different levels of Biochar and other amendments on Electrical Conductivity (dS m^{-1}) of soil.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.96	0.90	0.86	0.80	0.76	0.86
FYM	**F2**	0.90	0.84	0.78	0.72	0.66	0.78
FYM+Consortia	**F3**	0.88	0.82	0.76	0.70	0.66	0.76
FYM+Consortia+50%GR	**F4**	0.83	0.77	0.71	0.65	0.59	0.71
Mean		0.89	0.83	0.78	0.71	0.67	

ANOVA	**CD**	**F Test**
B	0.04	S
F	0.03	S
B*F	0.07	NS

Table 4.3 Effect of different levels of Biochar and other amendments on soil organic carbon (g kg^{-1}) of soil.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	1.01	1.01	1.05	1.08	1.08	1.05
FYM	**F2**	1.27	1.27	1.60	2.06	2.15	1.42
FYM+Consortia	**F3**	1.33	1.36	1.66	2.45	2.65	1.89
FYM+Consortia+50%GR	**F4**	1.38	1.43	1.67	2.95	2.99	2.08
Mean		1.25	1.27	1.50	2.14	1.90	

ANOVA	**CD**	**F Test**
B	0.45	S
F	0.40	S
B*F	0.90	S

Table 4.4 Effect of different levels of Biochar and other amendments on soil available nitrogen (kg ha^{-1}) of soil.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	129.03	142.25	164.08	171.23	174.70	156.27
FYM	**F2**	136.03	155.97	210.18	237.97	264.73	200.98
FYM+Consortia	**F3**	135.63	161.50	224.60	251.88	260.47	206.82
FYM+Consortia+50%GR	**F4**	138.31	224.04	243.30	273.87	281.35	232.17
Mean		134.75	170.94	210.54	233.74	245.31	

ANOVA	**CD**	**F Test**
B	10.69	S
F	9.56	S
B*F	7.48	S

F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) were 156.27, 200.98, 206.82 and 232.17 kg ha^{-1}, respectively. The interaction effect of biochar levels and amendments was found to be significant. The highest soil available nitrogen (281.35 kg ha^{-1}) was recorded with the combined application of F4 (FYM + Consortia + 50% GR) and acidified biochar at 5 t ha^{-1} (B4), which was significantly higher than the control treatment (F1B0) at 174.70 kg ha^{-1}. The lowest soil available nitrogen (129.03 kg ha^{-1}) was observed in the untreated control (F1B0), which was significantly lower than all other treatments.

4.1.5 Available Phosphorus

The data presented in Table 4.5 show significant variations in soil available phosphorus (P) across different biochar levels and amendments. The mean soil available phosphorus for the biochar treatments B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 3.27, 6.15, 8.09, 10.06 and 11.81 kg ha^{-1}, respectively. These results indicate a significant increase in available phosphorus with the higher levels of acidified biochar (B3 and B4), with the highest available P observed in B4 (15.10 kg ha^{-1}). Similarly, the mean soil available phosphorus for the amendments F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) were 5.51, 7.21, 8.69 and 10.09 kg ha^{-1}, respectively. The highest soil available phosphorus (15.10 kg ha^{-1}) was recorded with the combination of F4 (FYM + Consortia + 50% GR) and acidified biochar at 5 t ha^{-1} (B4), which was significantly higher compared to the control 7.11 kg ha^{-1}. The interaction effect of biochar levels and amendments on soil available phosphorus was found to be non-significant. The lowest soil available phosphorus (2.00 kg ha^{-1}) was observed in the combination of F1B0.

Available Potassium

The data presented in Table 4.6 reveal significant variation in soil available potassium (K) across different biochar levels and amendments. The mean soil available potassium for the biochar treatments B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 113.93, 143.86, 158.57, 174.97 and 185.75 kg ha^{-1}, respectively. These values indicate a clear increase in available potassium as the biochar application rate increased, with the highest available potassium observed in B4 (194.35 kg ha^{-1}). Similarly, the mean values for the different amendments F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) were 144.67, 157.94, 155.22 and 163.82 kg ha^{-1}, respectively. The highest soil available potassium (194.35 kg ha^{-1}) was recorded with the combination of F4 (FYM + Consortia + 50% GR) and acidified biochar at 5 t ha^{-1} (B4), which was significantly higher than the control (168.66 kg ha^{-1}) and other treatments. The interaction effect of biochar levels and amendments on soil available potassium was non-significant,

4.1.6 Exchangeable sodium

The data presented in Table 4.7 show significant variation in soil exchangeable sodium (Na) across different biochar levels and amendments. The mean values for biochar treatments B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) 6.64, 5.14, 4.30, 3.37 and 2.15 meq/100g, respectively, indicating a decrease in exchangeable sodium as the biochar application rate increased. Similarly, the mean values for the amendments F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) were 6.16, 4.95, 3.64 and 2.53 meq/100g, respectively.

Among the treatments, soil exchangeable sodium was highest under F1 (control) and progressively decreased with the inclusion of amendments, particularly F4 (FYM + Consortia + 50% GR). The combination of F4 and acidified biochar at 5 t ha^{-1} (B4) resulted in the lowest soil exchangeable sodium, with a significantly lower value of 0.91 meq/100g compared to the control treatment (4.22 meq/100g). However, the interaction between biochar levels and amendments on soil exchangeable sodium was found to be non-significant.

4.1.7 Exchangeable calcium

The data presented in Table 4.8 reveal significant variation in soil exchangeable calcium (Ca) across the different biochar levels and amendments. The mean values for biochar treatments B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 3.34, 5.03, 5.73, 7.14 and 8.44 meq/100 g, respectively, showing a clear increase in exchangeable calcium as the application rate of biochar increased.

Table 4.5 Effect of different levels of Biochar and other amendments on soil available phosphorus (kg ha^{-1}) of soil.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	2.00	4.60	6.83	7.03	7.11	5.51
FYM	**F2**	4.00	5.07	5.80	9.15	12.03	7.21
FYM+Consortia	**F3**	3.23	8.00	7.97	11.27	13.00	8.69
FYM+Consortia+50%GR	**F4**	3.83	6.93	11.77	12.80	15.10	10.09
Mean		3.27	6.15	8.09	10.06	11.81	
ANOVA	**CD**	**F Test**					
B	1.47	S					
F	1.32	S					
B*F	2.95	NS					

Table 4.6 Effect of different levels of Biochar and other amendments on soil available potassium (kg ha^{-1}) of soil.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	108.23	130.71	147.33	168.40	168.66	144.67
FYM	**F2**	113.57	141.33	168.35	179.17	187.29	157.94
FYM+Consortia	**F3**	116.80	148.77	155.58	162.28	192.69	155.22
FYM+Consortia+50%GR	**F4**	117.12	154.63	163.40	190.01	194.35	163.82
Mean		113.93	143.86	158.57	174.97	185.75	
ANOVA	**CD**	**F Test**					
B	7.38	S					
F	6.60	S					
B*F	14.77	NS					

Table 4.7 Effect of different levels of Biochar and other amendments on soil exchangeable sodium (meq/100g) of soil.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	8.02	7.11	6.33	5.13	4.22	6.16
FYM	**F2**	7.39	6.00	5.08	3.88	2.39	4.95
FYM+Consortia	**F3**	6.24	4.43	3.60	2.81	1.10	3.64
FYM+Consortia+50%GR	**F4**	4.90	3.03	2.18	1.65	0.91	2.53
Mean		6.64	5.14	4.30	3.37	2.15	
ANOVA	**CD**	**F Test**					
B	0.59	S					
F	0.53	S					
B*F	1.19	NS					

Table 4.8 Effect of different levels of Biochar and other amendments on soil exchangeable calcium (meq/100gm) of soil.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	2.87	4.73	3.90	6.23	6.40	4.83
FYM	**F2**	2.60	5.30	5.87	6.17	6.90	5.37
FYM+Consortia	**F3**	3.30	4.73	6.37	8.60	9.60	6.52
FYM+Consortia+50%GR	**F4**	4.60	5.33	6.77	7.57	10.87	7.03
Mean		3.34	5.03	5.73	7.14	8.44	
ANOVA	**CD**	**F Test**					
B	0.61	S					
F	0.55	S					
B*F	1.22	S					

Similarly, the mean values for the amendments F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) were 4.83, 5.37, 6.52 and 7.03 meq/100 g, respectively. The application of treatment F4 (FYM + Consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} (B4) resulted in the highest soil exchangeable calcium, with a value of 10.87 meq/100 g, significantly higher than the control and other treatment combinations. The interaction between the biochar levels and amendments was found to be significant.

4.1.8 Exchangeable magnesium

The data presented in Table 4.9 indicate significant variations in soil exchangeable magnesium (Mg) across different biochar levels and amendments. The mean values for the biochar treatments B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.63, 1.78, 5.83, 5.57 and 6.05 meq/100 g, respectively, demonstrating a clear increase in exchangeable magnesium with the application of biochar. Similarly, the amendments F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) resulted in mean exchangeable magnesium values of 3.43, 3.21, 3.36 and 5.89 meq/100 g, respectively. The application of treatment F4 (FYM + Consortia + 50%GR) combined with acidified biochar at 5 t ha^{-1} (B4) resulted in the highest soil exchangeable magnesium, with a value of 10.87 meq/100 g, which was significantly higher than the control treatment (B0), which had a value of 6.40 meq/100 g. The interaction effect between biochar levels and amendments was found to be significant.

4.1.9 Bicarbonates

The data presented in Table 4.10 reveal significant differences in soil bicarbonate levels across the various biochar treatments and amendments. The mean bicarbonate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 78.92, 61.60, 43.05, 31.83, and 24.09 mg kg^{-1}, respectively, indicating a decrease in bicarbonate content with increasing biochar levels. Similarly, the amendments F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) resulted in mean bicarbonate values of 61.80, 47.91, 44.82, and 37.07 mg kg^{-1}, respectively.

Among the treatments, the application of F4 (FYM + Consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} (B4) resulted in the lowest soil bicarbonate level (17.27 mg kg^{-1}), which was significantly lower than the control treatment (35.27 mg kg^{-1}) and other treatments. However, no significant interaction was observed between the biochar levels and amendments on soil bicarbonates after the wheat harvest.

4.1.10 Carbonates

No carbonates were detected in the soil during the analysis.

4.1.11 Exchangeable sodium percentage (ESP)

The data presented in Table 4.11 reveal significant differences in exchangeable sodium percentage levels across the various biochar treatments and amendments. The mean exchangeable sodium percentage values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 57.30, 38.92, 25.36, 20.29 and 12.99 %, respectively, indicating a decrease in exchangeable sodium percentage with increasing biochar levels. Similarly, the amendments F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) resulted in mean bicarbonate values of 41.88, 35.75, 27.68 and 18.59 %, respectively.

Among the treatments, the application of F4 (FYM + Consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} (B4) resulted in the lowest exchangeable sodium percentage (3.91 %) which was significantly lower than the control treatment (24.74 %) and other treatments. However, no significant interaction was observed between the biochar levels and amendments on exchangeable sodium percentage after the wheat harvest.

4.1.12 Sodium adsorption ratio (SAR)

The data presented in Table 4.12 reveal significant differences in sodium adsorption ratio levels across the various biochar treatments and amendments. The mean sodium adsorption ratio values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 32.27, 22.17, 14.72, 11.93 and 7.92 %, respectively, indicating

Table 4.9 Effect of different levels of Biochar and other amendments on soil exchangeable magnesium (meq/100gm) of soil.

Treatment		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.27	1.33	5.60	4.47	5.47	3.43
FYM	**F2**	0.30	1.60	5.93	4.13	4.07	3.21
FYM+Consortia	**F3**	0.30	2.33	5.33	4.73	4.10	3.36
FYM+Consortia+50%GR	**F4**	1.63	1.83	6.47	8.93	10.57	5.89
Mean		0.63	1.78	5.83	5.57	6.05	
ANOVA	**CD**	**F Test**					
B	0.72	S					
F	0.65	S					
B*F	1.45	S					

Table 4.10 Effect of different levels of Biochar and other amendments on bicarbonates (mg kg^{-1}) of soil.

Treatment		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	87.80	78.00	61.87	46.07	35.27	61.80
FYM	**F2**	80.90	61.13	43.20	31.50	22.80	47.91
FYM+Consortia	**F3**	79.23	56.20	39.33	28.30	21.03	44.82
FYM+Consortia+50%GR	**F4**	67.73	51.07	27.80	21.47	17.27	37.07
Mean		78.92	61.60	43.05	31.83	24.09	
ANOVA	**CD**	**F Test**					
B	4.94	S					
F	4.42	S					
B*F	9.88	NS					

Table 4.11 Effect of different levels of Biochar and other amendments on Exchangeable Sodium Percentage (%).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	65.93	50.28	37.82	30.62	24.74	41.88
FYM	**F2**	65.43	43.15	28.37	25.65	16.15	35.75
FYM+Consortia	**F3**	57.57	35.45	21.93	16.28	7.15	27.68
FYM+Consortia+50%GR	**F4**	40.27	26.82	13.33	8.60	3.91	18.59
Mean		57.30	38.92	25.36	20.29	12.99	
ANOVA	**CD**	**F Test**					
B	3.69	S					
F	3.30	S					
B*F	7.39	NS					

Table 4.12 Effect of different levels of Biochar and other amendments on Sodium Adsorption Ratio (%).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	37.01	28.41	21.57	17.61	14.38	23.80
FYM	**F2**	36.74	24.49	16.37	14.88	9.66	20.43
FYM+Consortia	**F3**	32.42	20.26	12.83	9.73	4.72	15.99
FYM+Consortia+50%GR	**F4**	22.91	15.52	8.11	5.51	2.93	11.00
Mean		32.27	22.17	14.72	11.93	7.92	
ANOVA	**CD**	**F Test**					
B	2.03	S					
F	1.82	S					
B*F	4.06	NS					

a decrease in sodium adsorption ratio with increasing biochar levels. Similarly, the amendments F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) resulted in mean bicarbonate values of 23.80, 20.43, 15.99 and 11.00 %, respectively. Among the treatments, the application of F4 (FYM + Consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} (B4) resulted in the lowest sodium adsorption ratio (2.93 %) which was significantly lower than the control treatment (14.38 %) and other treatments. Furthermore, a non-significant interaction was observed between the biochar levels and amendments on sodium adsorption ratio.

4.2 Biological Parameters of pot experiment

The effect of biochar and different amendments on the soil biological properties is reported in various sub-sections below:

4.2.1 Dehydrogenase activity (DHA)

The mean dehydrogenase activity values for the various biochar treatments were 1.63 µg TPF g^{-1} hr^{-1} for B0 (control), 1.51 µg TPF g^{-1} hr^{-1} for B1 (2.5 t ha^{-1} biochar), 2.10 µg TPF g^{-1} hr^{-1} for B2 (5 t ha^{-1} biochar), 3.00 µg TPF g^{-1} hr^{-1} for B3 (2.5 t ha^{-1} acidified biochar), and 3.68 µg TPF g^{-1} hr^{-1} for B4 (5 t ha^{-1} acidified biochar). Similarly, the mean dehydrogenase activity values for the amendments were 1.58 µg TPF g^{-1} hr^{-1} for F1 (control), 2.00 µg TPF g^{-1} hr^{-1} for F2 (FYM), 2.96 µg TPF g^{-1} hr^{-1} for F3 (FYM + Consortia), and 3.00 µg TPF g^{-1} hr^{-1} for F4 (FYM + Consortia + 50% GR), indicating a clear trend of increased dehydrogenase activity with the addition of organic amendments. Among all treatments, the dehydrogenase activity was significantly highest under F4 compared to F1. Notably, the combination of F4 (FYM + Consortia + 50% GR) with B4 (5 t ha^{-1} acidified biochar) resulted in the highest dehydrogenase activity at 5.43 µg TPF g^{-1} hr^{-1}, which was significantly higher than the control treatment (2.25 µg TPF g^{-1} hr^{-1}). Furthermore, the interaction between different levels of biochar and amendments significantly influenced dehydrogenase activity after the wheat harvest.

4.2.2 Alkaline Phosphatase activity (PA)

The data presented in Table 4.14 demonstrate significant variations in alkaline phosphatase activity across different biochar levels and amendments. The mean alkaline phosphatase activity values for the biochar treatments were 4.09 µg PNP h^{-1} g^{-1} for B0 (control), 4.68 µg PNP h^{-1} g^{-1} for B1 (2.5 t ha^{-1} biochar), 6.83 µg PNP h^{-1} g^{-1} for B2 (5 t ha^{-1} biochar), 10.41 µg PNP h^{-1} g^{-1} for B3 (2.5 t ha^{-1} acidified biochar), and 16.24 µg PNP h^{-1} g^{-1} for B4 (5 t ha^{-1} acidified biochar). Similarly, the mean alkaline phosphatase activity values for the amendments were 4.85 µg PNP h^{-1} g^{-1} for F1 (control), 8.11 µg PNP h^{-1} g^{-1} for F2 (FYM), 9.63 µg PNP h^{-1} g^{-1} for F3 (FYM + Consortia), and 11.21 µg PNP h^{-1} g^{-1} for F4 (FYM + Consortia + 50% GR). Among all treatments, the highest alkaline phosphatase activity was observed in the F4 treatment compared to F1. Notably, the combination of F4 (FYM + Consortia + 50% GR) with B4 (5 t ha^{-1} acidified biochar) resulted in the highest alkaline phosphatase activity at 20.30 µg PNP h^{-1} g^{-1}, which was significantly higher than the control treatment (8.13 µg PNP h^{-1} g^{-1}). Furthermore, a significant interaction effect was observed between the different levels of biochar and amendments on alkaline phosphatase activity after the wheat harvest.

4.2.3 Bacterial count

The results presented in Table 4.15 indicate a clear influence of biochar levels and amendments on bacterial counts in the soil. The mean bacterial count values for the different biochar treatments were 6.00 CFU g^{-1} for B0 (control), 6.42 CFU g^{-1} for B1 (2.5 t ha^{-1} biochar), 10.83 CFU g^{-1} for B2 (5 t ha^{-1} biochar), 14.00 CFU g^{-1} for B3 (2.5 t ha^{-1} acidified biochar), and 16.25 CFU g^{-1} for B4 (5 t ha^{-1} acidified biochar), showing an increase in bacterial count with higher biochar levels, particularly with the use of acidified biochar. Similarly, the mean bacterial count values for the amendments were 6.13 CFU g^{-1} for F1 (control), 9.67 CFU g^{-1} for F2 (FYM), 11.93 CFU g^{-1} for F3 (FYM + Consortia), and 15.07 CFU g^{-1} for F4 (FYM + Consortia + 50% GR), indicating an increase in bacterial count with the addition of organic amendments. Among the treatments, the highest bacterial count was observed under F4 compared to F1. Notably, the combination of F4 (FYM + Consortia + 50% GR) with B4 (5 t ha^{-1} acidified biochar) resulted in the highest bacterial count at 22.00 CFU g^{-1}, which was significantly higher than the control treatment (10.00 CFU g^{-1}). However, the interaction between different levels of biochar and amendments on bacterial count after the wheat harvest was found to be non-significant.

Table 4.13 Effect of different levels of Biochar and other amendments on dehydrogenase activity (µg TPF g^{-1} hr^{-1}).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	1.53	1.30	1.73	1.95	2.25	1.58
FYM	**F2**	1.56	1.68	1.86	2.11	2.77	2.00
FYM+Consortia	**F3**	1.90	2.08	2.87	3.69	4.28	2.96
FYM+Consortia+50%GR	**F4**	1.53	1.83	1.93	4.25	5.43	3.00
Mean		1.63	1.51	2.10	3.00	3.68	
ANOVA	**CD**	**F Test**					
B	0.41	S					
F	0.37	S					
B*F	0.83	S					

Table 4.14 Effect of different levels of Biochar and other amendments on alkaline phosphatase activity (µg TPF g^{-1} hr^{-1}).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	2.73	2.83	4.73	5.80	8.13	4.85
FYM	**F2**	3.73	4.60	6.17	8.80	17.23	8.11
FYM+Consortia	**F3**	5.03	5.60	7.13	11.11	19.30	9.63
FYM+Consortia+50%GR	**F4**	4.87	5.67	9.30	15.93	20.30	11.21
Mean		4.09	4.68	6.83	10.41	16.24	
ANOVA	**CD**	**F Test**					
B	0.85	S					
F	0.76	S					
B*F	1.71	S					

Table 4.15 Effect of different levels of Biochar and other amendments on bacterial count (CFU g^{-1}).

Treatment		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	2.67	3.33	6.00	8.67	10.00	6.13
FYM	**F2**	5.33	5.67	10.33	11.67	15.33	9.67
FYM+Consortia	**F3**	7.33	6.67	11.33	16.67	17.67	11.93
FYM+Consortia+50%GR	**F4**	8.67	10.00	15.67	19.00	22.00	15.07
Mean		6.00	6.42	10.83	14.00	16.25	
ANOVA	**CD**	**F Test**					
B	1.41	S					
F	1.26	S					
B*F	2.81	NS					

Table 4.16 Effect of different levels of Biochar and other amendments on bulk density (g cm^{-3}).

Treatment		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	1.47	1.44	1.40	1.35	1.26	1.38
FYM	**F2**	1.38	1.37	1.33	1.33	1.31	1.34
FYM+Consortia	**F3**	1.32	1.32	1.32	1.27	1.27	1.30
FYM+Consortia+50%GR	**F4**	1.31	1.29	1.26	1.22	1.21	1.26
Mean		1.37	1.36	1.33	1.29	1.26	
ANOVA	**CD**	**F Test**					
B	0.02	S					
F	0.02	S					
B*F	0.04	S					

4.3 Physical Parameters of pot experiment

The effect of biochar and different amendments on the soil physical properties is reported in various sub-sections below:

4.3.1 Bulk density

The data presented in Table 4.16 demonstrate the effect of biochar levels and amendments on bulk density. The mean bulk density values for the biochar treatments were 1.37 g cm^{-3} for B0 (control), 1.36 g cm^{-3} for B1 (2.5 t ha^{-1} biochar), 1.33 g cm^{-3} for B2 (5 t ha^{-1} biochar), 1.29 g cm^{-3} for B3 (2.5 t ha^{-1} acidified biochar), and 1.26 g cm^{-3} for B_4 (5 t ha^{-1} acidified biochar), showing a decrease in bulk density with increasing biochar levels, especially with the use of acidified biochar. Similarly, the mean bulk density values for the different amendments were 1.38 g cm^{-3} for F1 (control), 1.34 g cm^{-3} for F2 (FYM), 1.30 g cm^{-3} for F3 (FYM + Consortia), and 1.26 g cm^{-3} for F4 (FYM + Consortia + 50% GR), indicating a decrease in bulk density with the addition of organic amendments. Among the treatments, bulk density was significantly lowest under F4 compared to F1. The combination of F4 (FYM + Consortia + 50% GR) with B4 (5 t ha^{-1} acidified biochar) resulted in the lowest bulk density of 1.21 g cm^{-3}, which was significantly lower than the control treatment (1.26 g cm^{-3}). Moreover, the interaction effect between biochar levels and amendments on bulk density was found to be significant.

4.3.2 Porosity

The results presented in Table 4.17 highlight the influence of biochar levels and amendments on soil porosity. The mean porosity values for the biochar treatments were 31.62% for B0 (control), 34.92% for B1 (2.5 t ha^{-1} biochar), 36.45% for B2 (5 t ha^{-1} biochar), 39.66% for B3 (2.5 t ha^{-1} acidified biochar), and 44.59% for B4 (5 t ha^{-1} acidified biochar), showing a progressive increase in porosity with higher biochar levels, particularly with the application of acidified biochar. Similarly, the mean porosity values for the amendments were 25.62 % for F1 (control), 32.06 % for F2 (FYM), 40.82 % for F3 (FYM + Consortia), and 51.28 % for F4 (FYM + Consortia + 50% GR). Among the treatments, the highest porosity was observed under F4 compared to F1. Notably, the combination of F4 (FYM + Consortia + 50% GR) with B4 (5 t ha^{-1} acidified biochar) resulted in the highest porosity at 59.77%, which was significantly higher than the control treatment (30.64%). Furthermore, the interaction effect between biochar levels and amendments on porosity after the wheat harvest was found to be significant.

4.3.3 Water holding capacity

The mean water holding capacity values for the biochar levels B0, B1, B2, B3, and B4 were 17.18, 18.10, 22.26, 24.36 and 27.10 %, respectively. Similarly, the mean water holding capacity values for the treatments with different amendments were 14.74, 19.89, 24.22 and 28.34 % for F1, F2, F3, and F4, respectively, as shown in Table 4.18. Among the treatments, water holding capacity was significantly highest under F4 compared to F1. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest water holding capacity (34.07 %), which was significantly highest than the control (19.28 %). However, the interaction effect of different levels of biochar and amendments on water holding capacity after the wheat harvest was found to be non-significant.

4.3.4 Soil Moisture

The data presented in Table 4.19 reveal the effects of biochar levels and amendments on soil moisture. The mean soil moisture values for the biochar treatments were 19.23% for B0 (control), 21.73% for B1 (2.5 t ha^{-1} biochar), 21.80% for B2 (5 t ha^{-1} biochar), 22.26% for B3 (2.5 t ha^{-1} acidified biochar), and 19.60% for B4 (5 t ha^{-1} acidified biochar), indicating slight variations in moisture content with different biochar treatments. Similarly, the mean soil moisture values for the amendments were 15.14% for F1 (control), 19.71% for F2 (FYM), 22.98% for F3 (FYM + Consortia), and 25.87% for F4 (FYM + Consortia + 50% GR), showing an increase in moisture content with the application of organic amendments. The combination of F4 (FYM + Consortia + 50% GR) with B3 (2.5 t ha^{-1} acidified biochar) resulted in the highest soil moisture at 30.20%, which was significantly higher than the control treatment (15.85%). However, the interaction effect between different levels of biochar and amendments on soil moisture after the wheat harvest was found to be non-significant.

Table 4.17 Effect of different levels of Biochar and other amendments on Porosity (%).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	20.88	23.89	27.40	25.30	30.64	25.62
FYM	**F2**	27.04	30.01	31.90	34.03	37.32	32.06
FYM+Consortia	**F3**	31.51	35.32	37.38	49.27	50.63	40.82
FYM+Consortia+50%GR	**F4**	47.03	50.44	49.13	50.03	59.77	51.28
Mean		31.62	34.92	36.45	39.66	44.59	
ANOVA	**CD**	**F Test**					
B	2.70	S					
F	2.41	S					
B*F	5.39	S					

Table 4.18 Effect of different levels of Biochar and other amendments on water holding capacity (%).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	10.62	10.25	15.62	17.95	19.28	14.74
FYM	**F2**	14.93	15.30	19.90	23.31	26.00	19.89
FYM+Consortia	**F3**	20.05	22.27	23.75	26.00	29.03	24.22
FYM+Consortia+50%GR	**F4**	23.13	24.57	29.77	30.17	34.07	28.34
Mean		17.18	18.10	22.26	24.36	27.10	
ANOVA	**CD**	**F Test**					
B	1.82	S					
F	1.62	S					
B*F	3.63	NS					

Table 4.19 Effect of different levels of Biochar and other amendments on soil moisture (%).

Treatment		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	12.45	14.42	17.69	15.85	15.27	15.14
FYM	**F2**	19.33	22.73	20.57	19.23	16.67	19.71
FYM+Consortia	**F3**	21.97	22.07	22.14	23.76	24.98	22.98
FYM+Consortia+50%GR	**F4**	23.15	27.68	26.82	30.20	21.49	25.87
Mean		19.23	21.73	21.80	22.26	19.60	
ANOVA	**CD**	**F Test**					
B	2.46	S					
F	2.20	S					
B*F	4.91	NS					

Table 4.20 Effect of different levels of Biochar and other amendments on Infiltration rate (cm hr^{-1}).

Treatment		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.02	0.02	0.09	0.52	0.21	0.17
FYM	**F2**	0.04	0.08	0.09	0.31	0.50	0.20
FYM+Consortia	**F3**	0.04	0.11	0.14	0.26	0.78	0.26
FYM+Consortia+50%GR	**F4**	0.05	0.13	0.13	0.31	0.92	0.31
Mean		0.04	0.08	0.11	0.35	0.60	
ANOVA	**CD**	**F Test**					
B	0.14	S					
F	0.12	NS					
B*F	0.10	S					

4.3.5 Infiltration rate

The data presented in Table 4.20 reveal the effects of biochar levels and amendments on infiltration rate. The mean infiltration rate values for the biochar treatments were 0.04 cm hr^{-1} for B0 (control), 0.08 cm hr^{-1} for B1 (2.5 t ha^{-1} biochar), 0.11 cm hr^{-1} for B2 (5 t ha^{-1} biochar), 0.35 cm hr^{-1} for B3 (2.5 t ha^{-1} acidified biochar), and 0.60 cm hr^{-1} for B4 (5 t ha^{-1} acidified biochar). Similarly, the mean infiltration rate values for the amendments were 0.17 cm hr^{-1} for F1 (control), 0.20 cm hr^{-1} for F2 (FYM), 0.26 cm hr^{-1} for F3 (FYM + Consortia), and 0.31 cm hr^{-1} for F4 (FYM + Consortia + 50% GR). The combination of F4 (FYM + Consortia + 50% GR) with B4 (5 t ha^{-1} acidified biochar) resulted in the highest soil infiltration rate at 0.92 cm hr^{-1} which was higher than the control treatment (0.21 cm hr^{-1}). However, the interaction effect between different levels of biochar and amendments on soil infiltration rate after the wheat harvest was found to be significant.

4.4 Physiological Parameters of pot experiment

4.4.1 Plant growth and Biomass

4.4.1.1 Plant Height

The mean plant height values for the different biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 16.29, 21.10, 23.71, 30.88 and 35.82 cm, respectively. Similarly, the mean plant height values for treatments with different amendments were 16.54, 21.01, 27.48 and 37.21 cm for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as presented in Table 4.21. Among the treatments, the application of F4 (FYM + consortia + 50% GR) in combination with acidified biochar at 5 t ha^{-1} (B4) resulted in the highest plant height of 58.21 cm, which was significantly higher than the control treatment (19.97 cm). The interaction effect of various biochar levels and amendments on plant height after the wheat harvest was found to be statistically significant.

4.3.1.2 Number of grains per spike

The mean number of grains per spike for the different biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were recorded as 8.00, 12.83, 15.08, 31.67, and

43.42, respectively, indicating a significant increase in grain numbers with higher biochar application rates. Similarly, the mean number of grains per spike for treatments with different amendments were 11.80, 17.00, 25.67, and 34.33 for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as presented in Table 4.22. Among the treatments, the combination of F4 (FYM + microbial consortia + 50% GR) with acidified biochar applied at 5 t ha^{-1} (B4) resulted in the highest number of grains per spike, reaching 69.33, which was significantly higher than the control treatment (20.67). The interaction effect of biochar levels and amendments on the number of grains per spike after the wheat harvest was found to be statistically significant. The lowest number of grains per spike was recorded in the control treatment (B0F1), where no biochar or amendments were applied.

4.3.1.3 Spike length

The mean spike length values for the different biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 2.71, 3.66, 4.12, 5.42, and 6.86 cm, respectively, indicating a consistent increase in spike length with higher biochar application rates. Similarly, the mean spike length values for treatments with different amendments were 3.26, 3.37, 4.42, and 7.16 cm for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as presented in Table 4.23. Among all treatment combinations, the application of F4 (FYM + microbial consortia + 50% GR) in conjunction with acidified biochar at 5 t ha^{-1} (B4) resulted in the highest spike length of 12.73 cm, which was significantly higher than the control treatment (B0F1), where a spike length of only 4.45 cm was recorded. The interaction effect of biochar levels and amendments on spike length after the wheat harvest was found to be statistically significant.

4.3.1.4 Root weight

The mean root weight values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 3.61, 5.52, 7.54, 9.74 and 15.24 g, respectively. Similarly, the mean root weight values for treatments with different amendments were 4.04, 7.59,

Table 4.21 Effect of different levels of Biochar and other amendments on plant height (cm).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	10.05	16.02	17.92	18.75	19.97	16.54
FYM	**F2**	15.61	18.65	20.19	23.77	26.80	21.01
FYM+Consortia	**F3**	18.31	23.02	26.01	31.75	38.32	27.48
FYM+Consortia+50%GR	**F4**	21.18	26.72	30.71	49.24	58.21	37.21
Mean		16.29	21.10	23.71	30.88	35.82	
ANOVA	**CD**	**F Test**					
B	2.53	S					
F	2.26	S					
B*F	5.05	S					

Table 4.22 Effect of different levels of Biochar and other amendments on number of grains per spike.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	5.00	8.00	10.00	15.33	20.67	11.80
FYM	**F2**	7.67	10.67	12.33	22.67	31.67	17.00
FYM+Consortia	**F3**	8.67	13.33	16.00	38.33	52.00	25.67
FYM+Consortia+50%GR	**F4**	10.67	19.33	22.00	50.33	69.33	34.33
Mean		8.00	12.83	15.08	31.67	43.42	
ANOVA	**CD**	**F Test**					
B	5.11	S					
F	4.57	S					
B*F	10.22	S					

Table 4.23 Effect of different levels of Biochar and other amendments on spike length (cm).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	2.07	2.85	3.11	3.84	4.45	3.26
FYM	**F2**	2.33	2.88	3.17	3.95	4.54	3.37
FYM+Consortia	**F3**	2.90	3.44	4.12	5.89	5.73	4.42
FYM+Consortia+50%GR	**F4**	3.54	5.45	6.08	8.00	12.73	7.16
Mean		2.71	3.66	4.12	5.42	6.86	
ANOVA	**CD**	**F Test**					
B	0.56	S					
F	0.50	S					
B*F	0.39	S					

Table 4.24 Effect of different levels of Biochar and other amendments on root weight (g).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	2.77	3.03	3.70	4.37	6.35	4.04
FYM	**F2**	3.17	5.59	7.32	9.62	12.24	7.59
FYM+Consortia	**F3**	3.93	6.35	8.81	11.40	18.92	9.88
FYM+Consortia+50%GR	**F4**	4.58	7.10	10.33	13.56	23.46	11.81
Mean		3.61	5.52	7.54	9.74	15.24	
ANOVA	**CD**	**F Test**					
B	2.05	S					
F	1.83	S					
B*F	4.09	S					

9.88 and 11.81 g for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.24. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in a root weight of 23.46 g, which was significantly higher than the control (6.35 g). The interaction effect of biochar levels and amendments on root weight after the wheat harvest was found to be significant. The lowest root weight was observed in the control treatment, where no biochar (B0) or amendments were applied.

4.3.1.5 Root:Shoot ratio

The mean root shoot ratio values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.64, 0.86, 1.26, 1.96 and 2.74, respectively. Similarly, the mean root shoot ratio values for treatments with different amendments were 0.68, 1.16, 1.71 and 2.41 for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.25. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in a root shoot ratio of 4.43 which was significantly higher than the control (1.30). The interaction effect of biochar levels and amendments on root shoot ratio after the wheat harvest was found to be significant. The lowest root shoot ratio was observed in the control treatment, where no biochar (B0) or amendments were applied.

4.4.2 Yield attributes and Yield of pot experiment

4.4.2.1 Grain Yield

The mean grain yield values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 12.35, 14.09, 16.04, 20.00 and 22.51 q ha^{-1}, respectively. Similarly, the mean grain yield values for the treatments with different amendments were 11.18, 16.37, 18.95 and 21.49 q ha^{-1} for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.26. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest grain yield of 27.34 q ha^{-1}, which was significantly higher than the control (15.13 q ha^{-1}). However, the interaction effect of different levels of biochar and amendments on grain yield after the wheat harvest was found to be non-significant.

4.4.2.2 Straw Yield

The mean straw yield values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 18.92, 20.39, 22.39, 26.36 and 28.55 q ha^{-1}, respectively. Similarly, the mean straw yield values for the treatments with different amendments were 15.53, 22.75, 26.54 and 28.47 q ha^{-1} for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.27. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest straw yield of 32.64 q ha^{-1}, which was significantly higher than the control (18.72 q ha^{-1}). However, the interaction effect of different levels of biochar and amendments on straw yield after the wheat harvest was found to be non-significant.

4.4.2.3 Harvest Index

The mean harvest index values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 35.88, 37.87, 39.36, 42.32 and 42.56, respectively. Similarly, the mean harvest index values for the treatments with different amendments were 35.91, 38.73, 40.88 and 42.86 for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.28. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest harvest index of 45.47, which was higher than the control (38.59). However, the interaction effect of different levels of biochar and amendments on harvest index after the wheat harvest was found to be non-significant.

4.4.2.4 Test weight

The mean test weight values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 31.26, 37.73, 39.26, 40.89 and 42.03 g, respectively. Similarly, the mean test weight values for the treatments with different amendments were 34.39, 37.90, 39.53 and 41.10 g for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.29. The

Table 4.25 Effect of different levels of Biochar and other amendments on root shoot ratio.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.30	0.40	0.50	0.90	1.30	0.68
FYM	**F2**	0.50	0.63	0.93	1.50	2.23	1.16
FYM+Consortia	**F3**	0.73	1.00	1.57	2.27	3.00	1.71
FYM+Consortia+50%GR	**F4**	1.04	1.40	2.03	3.17	4.43	2.41
Mean	0.64	0.86	1.26	1.96	2.74		
ANOVA	**CD**	**F Test**					
B	0.38	S					
F	0.34	S					
B*F	0.27	S					

Table 4.26 Effect of different levels of Biochar and other amendments on grain yield (q ha^{-1}).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	7.90	9.10	10.48	13.29	15.13	11.18
FYM	**F2**	11.92	13.25	15.18	19.31	22.17	16.37
FYM+Consortia	**F3**	13.24	15.36	18.22	22.52	25.40	18.95
FYM+Consortia+50%GR	**F4**	16.32	18.64	20.28	24.87	27.34	21.49
Mean		12.35	14.09	16.04	20.00	22.51	
ANOVA	**CD**	**F Test**					
B	1.12	S					
F	1.00	S					
B*F	2.23	NS					

Table 4.27 Effect of different levels of Biochar and other amendments on straw yield (q ha^{-1}).

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	12.16	13.10	14.93	18.72	18.72	15.53
FYM	**F2**	18.01	19.71	20.97	25.42	29.64	22.75
FYM+Consortia	**F3**	21.33	22.09	25.78	30.31	33.19	26.54
FYM+Consortia+50%GR	**F4**	24.18	26.66	27.88	31.00	32.64	28.47
Mean		18.92	20.39	22.39	26.36	28.55	
ANOVA	**CD**	**F Test**					
B	2.03	S					
F	1.82	S					
B*F	4.07	NS					

Table 4.28 Effect of different levels of Biochar and other amendments on harvest index.

Treatment		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	31.10	33.34	37.22	39.32	38.59	35.91
FYM	**F2**	34.19	37.07	37.04	42.57	42.80	38.73
FYM+Consortia	**F3**	37.27	39.91	41.04	42.83	43.37	40.88
FYM+Consortia+50%GR	**F4**	40.97	41.17	42.13	44.57	45.47	42.86
Mean		35.88	37.87	39.36	42.32	42.56	
ANOVA	**CD**	**F Test**					
B	1.46	S					
F	1.31	S					
B*F	2.93	NS					

Table 4.29 Effect of different levels of Biochar and other amendments on test weight (g).

Treatment		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	24.00	33.21	36.25	37.93	40.58	34.39
FYM	**F2**	27.76	38.65	40.38	41.57	41.15	37.90
FYM+Consortia	**F3**	34.54	39.49	39.90	41.19	42.55	39.53
FYM+Consortia+50%GR	**F4**	38.75	39.58	40.51	42.85	43.81	41.10
Mean		31.26	37.73	39.26	40.89	42.03	

ANOVA	**CD**	**F Test**
B	1.40	S
F	1.25	S
B*F	2.80	S

Table 4.30 Nitrogen uptake (kg ha^{-1}) of wheat as influenced by biochars and other amendments.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.49	0.79	1.99	6.59	13.56	4.69
FYM	**F2**	0.40	1.19	4.31	12.65	33.74	10.46
FYM+Consortia	**F3**	0.77	1.65	4.76	17.36	35.50	12.01
FYM+Consortia+50%GR	**F4**	1.09	3.35	9.86	28.66	43.01	17.19
Mean		0.69	1.75	5.23	16.31	31.45	

ANOVA	**CD**	**F Test**
B	2.38	S
F	2.13	S
B*F	4.77	S

application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest test weight of 43.81, which was higher than the control (40.58). However, the interaction effect of different levels of biochar and amendments on test weight after the wheat harvest was found to be significant.

4.5 Plant analysis of pot experiment

4.5.1 Nutrient uptake

4.5.1.1 Nitrogen uptake

The mean nitrogen uptake values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.69, 1.75, 5.23, 16.31 and 31.45 kg ha^{-1}, respectively. Similarly, the mean nitrogen uptake values for the treatments with different amendments were 4.69, 10.46, 12.01 and 17.19 kg ha^{-1} for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.30. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest nitrogen uptake of 43.01 kg ha^{-1}, which was significantly higher than the control (13.56 kg ha^{-1}). However, the interaction effect of different levels of biochar and amendments on nitrogen uptake after the wheat harvest was found to be significant.

4.5.1.2 Phosphorus uptake

The mean phosphorus uptake values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.24, 0.31, 0.36, 0.49 and 0.66 kg ha^{-1}, respectively. Similarly, the mean phosphorus uptake values for the treatments with different amendments were 0.20, 0.35, 0.43 and 0.66 kg ha^{-1} for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.31. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest phosphorus uptake of 1.29 kg ha^{-1}, which was higher than the control (0.31 kg ha^{-1}). However, the interaction effect of different levels of biochar and amendments on phosphorus uptake after the wheat harvest was found to be non-significant.

4.5.1.3 Potassium uptake

The mean potassium uptake values for the biochar levels B_0 (control), B_1 (2.5 t ha^{-1} biochar), B_2 (5 t ha^{-1} biochar), B_3 (2.5 t ha^{-1} acidified biochar), and B_4 (5 t ha^{-1} acidified biochar) were 19.99, 37.94, 67.03, 84.43 and 112.83 kg ha^{-1}, respectively. Similarly, the mean potassium uptake values for the treatments with different amendments were 30.06, 57.83, 70.49 and 99.39 kg ha^{-1} for F_1 (control), F_2 (FYM), F_3 (FYM + Consortia), and F_4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.32. The application of treatment F_4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest potassium uptake of 172.53 kg ha^{-1}, which was higher than the control (61.64 kg ha^{-1}). However, the interaction effect of different levels of biochar and amendments on potassium uptake after the wheat harvest was found to be non-significant.

4.5.1.4 Calcium uptake

The mean calcium uptake values for the biochar levels B_0 (control), B_1 (2.5 t ha^{-1} biochar), B_2 (5 t ha^{-1} biochar), B_3 (2.5 t ha^{-1} acidified biochar), and B_4 (5 t ha^{-1} acidified biochar) were 3.68, 6.95, 11.20, 23.07 and 49.01 kg ha^{-1}, respectively. Similarly, the mean calcium uptake values for the treatments with different amendments were 9.88, 14.36, 21.43 and 29.47 kg ha^{-1} for F_1 (control), F_2 (FYM), F_3 (FYM + Consortia), and F_4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.33. The application of treatment F_4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the highest calcium uptake of 69.40 kg ha^{-1}, which was higher than the control (27.98 kg ha^{-1}). The interaction effect of biochar levels and amendments on calcium after the wheat harvest was found to be significant.

4.5.1.5 Magnesium uptake

The mean magnesium uptake values for the biochar levels B_0 (control), B_1 (2.5 t ha^{-1} biochar), B_2 (5 t ha^{-1} biochar), B_3 (2.5 t ha^{-1} acidified biochar), and B_4 (5 t ha^{-1} acidified biochar) were 3.12, 6.98, 8.28, 18.61 and 31.60 kg ha^{-1}, respectively. Similarly, the mean magnesium uptake values for the treatments with different amendments were 10.76, 11.33, 14.64 and 18.22 kg ha^{-1} for F_1 (control), F_2 (FYM), F_3 (FYM + Consortia), and F_4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.34. The application of treatment F_4 (FYM + consortia + 50% GR) combined

Table 4.31 Phosphorus uptake (kg ha^{-1}) of wheat as influenced by biochars and other amendments.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.11	0.16	0.17	0.27	0.31	0.20
FYM	**F2**	0.21	0.27	0.31	0.49	0.46	0.35
FYM+Consortia	**F3**	0.24	0.34	0.40	0.57	0.59	0.43
FYM+Consortia+50%GR	**F4**	0.38	0.45	0.54	0.64	1.29	0.66
Mean		0.24	0.31	0.36	0.49	0.66	
ANOVA	**CD**	**F Test**					
B	0.20	S					
F	0.18	S					
B*F	0.39	NS					

Table 4.32 Potassium uptake (kg ha^{-1}) of wheat as influenced by biochars and other amendments.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	2.23	14.83	35.00	36.61	61.64	30.06
FYM	**F2**	18.03	30.44	61.47	80.07	99.12	57.83
FYM+Consortia	**F3**	22.69	47.47	71.11	93.14	118.02	70.49
FYM+Consortia+50%GR	**F4**	37.01	59.02	100.51	127.90	172.53	99.39
Mean		19.99	37.94	67.03	84.43	112.83	
ANOVA	**CD**	**F Test**					
B	13.82	S					
F	12.36	S					
B*F	27.63	NS					

Table 4.33 Calcium uptake (kg ha^{-1}) of wheat as influenced by biochars and other amendments.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	1.02	2.72	6.21	11.45	27.98	9.88
FYM	**F2**	2.75	5.75	11.70	16.04	35.54	14.36
FYM+Consortia	**F3**	4.43	8.68	10.92	20.00	63.12	21.43
FYM+Consortia+50%GR	**F4**	6.53	10.65	15.99	44.79	69.40	29.47
Mean		3.68	6.95	11.20	23.07	49.01	

ANOVA	**CD**	**F Test**
B	6.83	S
F	6.11	S
B*F	13.67	S

Table 4.34 Magnesium uptake (kg ha^{-1}) of wheat as influenced by biochars and other amendments.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.69	2.32	5.34	13.75	31.39	10.76
FYM	**F2**	1.97	5.75	6.60	16.04	26.29	11.33
FYM+Consortia	**F3**	3.86	8.68	8.46	20.75	31.43	14.64
FYM+Consortia+50%GR	**F4**	5.98	11.18	12.74	23.89	37.29	18.22
Mean		3.12	6.98	8.28	18.61	31.60	

ANOVA	**CD**	**F Test**
B	2.52	S
F	2.25	S
B*F	5.04	NS

with acidified biochar at 5 t ha^{-1} resulted in the highest magnesium uptake of 37.29 kg ha^{-1}, which was higher than the control (31.39 kg ha^{-1}). The interaction effect of biochar levels and amendments on magnesium after the wheat harvest was found to be non-significant.

4.5.1.6 Sulphur uptake

The mean sulphur uptake values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.59, 1.05, 2.05, 2.63 and 2.66 kg ha^{-1}, respectively. Similarly, the mean sulphur uptake values for the treatments with different amendments were 0.68, 1.98, 1.85 and 2.67 kg ha^{-1} for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.35. The application of treatment F4 (FYM + consortia + consortia) combined with acidified biochar at 2.5 t ha^{-1} resulted in the highest sulphur uptake of 4.09 kg ha^{-1}, which was higher than the control (0.97 kg ha^{-1}). The interaction effect of biochar levels and amendments on sulphur after the wheat harvest was found to be non- significant.

4.5 Leaching experiment

4.5.1 Soil leachate analysis

4.5.1.1 pH

The mean pH of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 8.96, 9.09, 8.99, 8.77 and 8.47, respectively. Similarly, the mean pH of soil leachate values for the treatments with different amendments were 9.26, 9.13, 8.69 and 8.35 for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.36. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the decrease of pH of soil leachate of 7.80, which was lower than the control (9.10). The interaction effect of biochar levels and amendments on pH of soil leachate was found to be non-significant.

4.5.1.2 Electrical conductivity

The mean EC of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.02, 0.07, 0.07, 0.03 and 0.04 dS m^{-1}, respectively. Similarly, the mean EC of soil leachate values for the treatments with different amendments were 0.05, 0.06, 0.06 and 0.03 dS m^{-1} for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR), respectively, as shown in Table 4.37. The interaction effect of biochar levels and amendments on electrical conductivity of soil leachate was found to be significant.

4.5.1.3 Exchangeable Sodium

The mean exchangeable sodium of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 9.19, 7.17, 7.17, 7.21 and 6.75 meq/l, respectively. Similarly, the mean exchangeable sodium of soil leachate values for the treatments with different amendments were 9.38, 8.12, 6.69 and 5.80 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.38. The interaction effect of biochar levels and amendments on exchangeable sodium of soil leachate was found to be significant.

4.5.1.4 Exchangeable calcium

The mean exchangeable calcium of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 3.89, 5.66, 6.40, 10.06 and 24.58 meq/l, respectively. Similarly, the mean exchangeable calcium of soil leachate values for the treatments with different amendments were 4.72, 7.55, 9.01 and 19.19 meq/l g for F1, F2, F3, and F4, respectively, as shown in Table 4.39. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the increase of exchangeable calcium of soil leachate of 44.45 meq/1, which was higher than the control (9.55 meq/l). The interaction effect of biochar levels and amendments on exchangeable calcium of soil leachate was found to be significant.

4.5.1.5 Exchangeable magnesium

The mean exchangeable magnesium of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 6.05, 4.39, 4.60, 9.25 and 6.15 meq/l, respectively. Similarly, the mean exchangeable magnesium of soil leachate values for

Table 4.35 Sulphur uptake (kg ha^{-1}) of wheat as influenced by biochars and other amendments.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.29	0.43	0.56	0.97	1.13	0.68
FYM	**F2**	0.52	0.75	3.70	2.27	2.64	1.98
FYM+Consortia	**F3**	0.62	0.81	1.70	3.17	2.96	1.85
FYM+Consortia+50%GR	**F4**	0.92	2.19	2.23	4.09	3.92	2.67
Mean		0.59	1.05	2.05	2.63	2.66	
ANOVA	**CD**	**F Test**					
B	0.83	S					
F	0.74	S					
B*F	1.66	NS					

Table 4.36 Effect of biochar and amendments on pH of soil leachate after fourth leaching.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	9.17	9.40	9.46	9.17	9.10	9.26
FYM	**F2**	9.18	9.07	9.35	8.92	9.16	9.13
FYM+Consortia	**F3**	9.01	8.95	9.01	8.64	7.84	8.69
FYM+Consortia+50%GR	**F4**	8.51	8.93	8.17	8.37	7.80	8.35
Mean		8.96	9.09	8.99	8.77	8.47	
ANOVA	**CD**	**F Test**					
B	0.32	S					
F	0.29	S					
B*F	0.65	NS					

Table 4.37 Effect of biochar and amendments on Electrical conductivity (dS m^{-1}) of soil leachate after fourth leaching.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.01	0.08	0.07	0.02	0.06	0.05
FYM	**F2**	0.02	0.08	0.10	0.02	0.06	0.06
FYM+Consortia	**F3**	0.01	0.13	0.06	0.07	0.02	0.06
FYM+Consortia+50%GR	**F4**	0.04	0.01	0.05	0.02	0.02	0.03
Mean		0.02	0.07	0.07	0.03	0.04	
ANOVA	**CD**	**F Test**					
B	0.01	S					
F	0.01	S					
B*F	0.02	S					

Table 4.38 Effect of biochar and amendments on exchangeable sodium (meq/l) of soil leachate after fourth leaching.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	9.75	10.04	9.41	8.95	8.73	9.38
FYM	**F2**	9.17	8.44	7.20	8.43	7.39	8.12
FYM+Consortia	**F3**	9.04	6.10	6.09	6.14	6.08	6.69
FYM+Consortia+50%GR	**F4**	8.81	4.10	5.98	5.32	4.78	5.80
Mean		9.19	7.17	7.17	7.21	6.75	
ANOVA	**CD**	**F Test**					
B	0.65	S					
F	0.59	S					
B*F	1.31	S					

Table 4.39 Effect of biochar and amendments on exchangeable calcium (meq/l) of soil leachate after fourth leaching.

Treatments		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	2.05	3.00	3.75	5.25	9.55	4.72
FYM	**F2**	3.20	3.55	3.95	6.75	20.30	7.55
FYM+Consortia	**F3**	3.50	5.20	4.35	8.00	24.00	9.01
FYM+Consortia+50%GR	**F4**	6.80	10.90	13.55	20.25	44.45	19.19
Mean		3.89	5.66	6.40	10.06	24.58	
ANOVA	**CD**	**F Test**					
B	3.37	S					
F	3.01	S					
B*F	6.73	S					

Table 4.40 Effect of biochar and amendments on exchangeable magnesium (meq/l) of soil leachate after fourth leaching.

Treatments		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	3.15	4.35	5.05	9.10	3.00	4.93
FYM	**F2**	2.80	4.35	1.95	6.90	8.30	4.86
FYM+Consortia	**F3**	9.75	3.65	6.00	7.00	11.10	7.50
FYM+Consortia+50%GR	**F4**	8.50	5.20	5.40	14.00	2.20	7.06
Mean		6.05	4.39	4.60	9.25	6.15	
ANOVA	**CD**	**F Test**					
B	1.97	S					
F	1.76	S					
B*F	3.94	S					

the treatments with different amendments were 4.93, 4.86, 7.50 and 7.06 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.40. The interaction effect of biochar levels and amendments on exchangeable magnesium of soil leachate was found to be significant.

4.5.1.6 Bicarbonates

The mean bicarbonates of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 42.37, 35.39, 43.44, 43.35 and 46.51 meq/l, respectively. Similarly, the mean bicarbonates of soil leachate values for the treatments with different amendments were 47.44, 45.06, 38.83 and 37.51 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.41. The interaction effect of biochar levels and amendments on bicarbonates of soil leachate was found to be significant.

4.5.1.7 arbonates

No carbonates were detected in the soil leachate during the analysis.

4.5.1.8 Exchangeable sodium percentage

The mean exchangeable sodium percentage of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 55.42, 46.66, 46.91, 46.35 and 44.17 %, respectively. Similarly, the mean exchangeable sodium percentage of soil leachate values for the treatments with different amendments were 58.92, 48.12, 44.54 and 40.02 % for F1, F2, F3, and F4, respectively, as shown in Table 4.42. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the decrease of exchangeable sodium percentage of soil leachate of 34.09 %, which was lower than the control (55.15 %). The interaction effect of biochar levels and amendments on exchangeable sodium percentage of soil leachate was found to be significant.

4.5.1.9 Sodium Adsorption Ratio

The mean sodium adsorption ratio of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 329.38, 251.93, 241.42, 183.42

and 144.01 %, respectively. Similarly, the mean sodium adsorption ratio of soil leachate values for the treatments with different amendments were 330.84, 275.07, 185.21 and 129.01 % for F1, F2, F3, and F4, respectively, as shown in Table 4.43. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in the decrease of sodium adsorption ratio of soil leachate of 73.28 %, which was lower than the control (253.38 %). The interaction effect of biochar levels and amendments on sodium adsorption ratio of soil leachate was found to be non- significant.

4.5.1.10 Available Nitrogen

The mean available nitrogen of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 47.26, 50.98, 53.19, 74.71 and 70.07 mg/kg, respectively. Similarly, the mean available nitrogen of soil leachate values for the treatments with different amendments were 51.04, 58.82, 61.40 and 65.71 mg/kg for F1, F2, F3, and F4, respectively, as shown in Table 4.44. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 2.5 t ha^{-1} resulted in the increase of available nitrogen of soil leachate of 97.37 mg/kg, which was higher than the control (45.71 mg/kg). The interaction effect of biochar levels and amendments on available nitrogen of soil leachate was found to be significant.

4.5.1.11 Available Phosphorus

The mean available phosphorus of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 6.08, 9.45, 6.29, 7.23 and 5.38 mg/kg, respectively. Similarly, the mean available phosphorus of soil leachate values for the treatments with different amendments were 3.64, 6.99, 7.34 and 9.57 mg/kg for F1, F2, F3, and F4, respectively, as shown in Table 4.45. The interaction effect of biochar levels and amendments on available phosphorus of soil leachate was found to be significant.

Table 4.45 Effect of biochar and amendments on Available Phosphorus (mg/kg) of soil leachate after fourth leaching.

Treatments		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	3.19	4.20	4.67	3.25	2.90	3.64
FYM	**F2**	7.27	4.15	9.44	7.11	6.97	6.99
FYM+Consortia	**F3**	8.34	11.06	5.59	4.01	7.70	7.34
FYM+Consortia+50%GR	**F4**	5.51	18.38	5.47	14.55	3.94	9.57
Mean		6.08	9.45	6.29	7.23	5.38	
ANOVA	**CD**	**F Test**					
B	2.02	S					
F	1.81	S					
B*F	4.04	S					

Table 4.46 Effect of biochar and amendments on Available Potassium (mg/kg) of soil leachate after fourth leaching.

Treatments		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.74	0.71	0.79	0.74	0.82	0.76
FYM	**F2**	0.95	1.02	1.07	1.04	1.00	1.02
FYM+Consortia	**F3**	0.86	1.04	0.89	1.00	0.98	0.95
FYM+Consortia+50%GR	**F4**	0.90	0.89	0.99	1.05	1.05	0.98
Mean		0.86	0.92	0.93	0.96	0.97	
ANOVA	**CD**	**F Test**					
B	0.08	NS					
F	0.07	S					
B*F	0.15	NS					

Table 4.41 Effect of biochar and amendments on bicarbonates (meq/l) of soil leachate after fourth leaching.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	50.31	24.00	32.95	65.00	64.95	47.44
FYM	**F2**	29.90	42.85	28.50	58.00	66.05	45.06
FYM+Consortia	**F3**	44.25	42.95	54.80	21.50	30.65	38.83
FYM+Consortia+50%GR	**F4**	45.00	31.75	57.50	28.90	24.40	37.51
Mean		42.37	35.39	43.44	43.35	46.51	
ANOVA	**CD**	**F Test**					
B	6.84	S					
F	6.11	S					
B*F	13.67	S					

Table 4.42 Effect of biochar and amendments on Exchangeable Sodium Percentage (%) of soil leachate after fourth leaching.

Treatments		Biochar			Acidified Biochar		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	60.69	62.13	58.15	58.48	55.15	58.92
FYM	**F2**	52.87	49.19	44.03	48.53	46.00	48.12
FYM+Consortia	**F3**	54.98	40.47	44.23	41.57	41.45	44.54
FYM+Consortia+50%GR	**F4**	53.13	34.86	41.23	36.82	34.09	40.02
Mean		55.42	46.66	46.91	46.35	44.17	
ANOVA	**CD**	**F Test**					
B	2.76	S					
F	2.47	S					
B*F	5.52	S					

Table 4.43 Effect of biochar and amendments on Sodium Adsorption Ratio (%) of soil leachate after fourth leaching.

Treatments		**Biochar**			**Acidified Biochar**		
			2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	448.78	382.92	326.12	242.99	253.38	330.84
FYM	**F2**	383.31	308.12	304.66	234.79	144.45	275.07
FYM+Consortia	**F3**	254.39	210.12	194.10	162.51	104.92	185.21
FYM+Consortia+50%GR	**F4**	231.02	106.56	140.81	93.38	73.28	129.01
Mean		329.38	251.93	241.42	183.42	144.01	
ANOVA	**CD**	**F Test**					
B	31.62	S					
F	28.28	S					
B*F	63.23	NS					

Table 4.44 Effect of biochar and amendments on Available Nitrogen (mg/kg) of soil leachate after fourth leaching.

Treatments		**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	9.75	69.74	39.11	45.71	74.33	51.04
FYM	**F2**	9.17	36.83	60.85	87.63	46.80	58.82
FYM+Consortia	**F3**	9.04	61.08	49.10	68.15	79.51	61.40
FYM+Consortia+50%GR	**F4**	8.81	36.28	63.69	97.37	79.63	65.71
Mean		47.26	50.98	53.19	74.71	70.07	
ANOVA	**CD**	**F Test**					
B	8.77	S					
F	7.84	S					
B*F	17.54	S					

4.5.1.12 Available Potassium

The mean available potassium of soil leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.86, 0.92, 0.93, 0.96 and 0.97 mg/kg, respectively. Similarly, the mean available potassium of soil leachate values for the treatments with different amendments were 0.76, 1.02, 0.95 and 0.98 mg/kg for F1, F2, F3, and F4, respectively, as shown in Table 4.46. The interaction effect of biochar levels and amendments on available potassium of soil leachate was found to be non-significant.

4.5.2 Leachate analysis

4.5.2.1 pH

The mean pH of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 7.87, 8.00, 7.69, 7.30 and 7.28, respectively. Similarly, the mean pH of the second leachate values for treatments with different amendments was 7.97, 7.73, 7.23 and 7.59 for F1, F2, F3, and F4, respectively, as shown in Table 4.47. The application of treatment F3 (FYM + consortia) combined with acidified biochar at 2.5 t ha^{-1} resulted in a significant decrease in the pH of the second leachate to 6.40. The interaction effect of biochar levels and amendments on pH of second leachate was found to be significant.

The mean pH of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 7.65, 7.88, 7.75, 7.62 and 7.21, respectively. Similarly, the mean pH of the third leachate values for treatments with different amendments was 7.91, 7.54, 7.55 and 7.50 for F1, F2, F3, and F4, respectively, as shown in Table 4.47. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} reduced the pH of the third leachate to 6.25. The interaction effect of biochar levels and amendments on pH of third leachate was also significant.

The mean pH of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and

B4 (5 t ha^{-1} acidified biochar) were 7.25, 7.60, 7.35, 7.26 and 7.12, respectively. Similarly, the mean pH of the fourth leachate values for treatments with different amendments was 7.60, 7.21, 7.35, and 7.09 for F1, F2, F3, and F4, respectively, as shown in Table 4.47. The application of treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} decreased the pH of the fourth leachate to 6.69. The interaction effect of biochar levels and amendments on pH of fourth leachate was significant.

4.5.2.2 Electrical conductivity (EC)

The mean EC of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.02, 0.01, 0.02, 0.03 and 0.03 dS m^{-1}, respectively. Similarly, the mean EC of the second leachate values for treatments with different amendments was 0.03, 0.02, 0.03 and 0.02 dS m^{-1} for F1, F2, F3, and F4, respectively, as shown in Table 4.48. The interaction effect of biochar levels and amendments on EC of second leachate was found to be non-significant.

The mean EC of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.03, 0.04, 0.04, 0.03 and 0.02 dS m^{-1}, respectively. Similarly, the mean EC of the third leachate values for treatments with different amendments was 0.02, 0.03, 0.03 and 0.05 dS m^{-1} for F1, F2, F3, and F4, respectively, as shown in Table 4.48. The interaction effect of biochar levels and amendments on EC of third leachate was non-significant.

The mean EC of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.05, 0.02, 0.02, 0.01 and 0.01 dS m^{-1}, respectively. Similarly, the mean EC of the fourth leachate values for treatments with different amendments was 0.03, 0.01, 0.02 and 0.02 dS m^{-1} for F1, F2, F3, and F4, respectively, as shown in Table 4.48. The interaction effect of biochar levels and amendments on EC of third leachate was significant.

Table 4.47 Effect of biochar and amendments on pH of leachate.

Second Leachate														**Third Leachate** **Fourth Leachate**					
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	8.08	8.01	7.99	7.99	7.77	7.97	8.00	7.95	8.02	8.06	7.50	7.91	7.20	7.69	7.98	7.80	7.19	7.60
FYM	**F2**	7.82	8.15	7.90	7.66	7.15	7.73	7.73	7.67	7.60	7.13	7.57	7.54	7.13	7.63	7.18	7.20	6.95	7.21
FYM+Consortia	**F3**	7.74	7.90	7.61	6.40	6.50	7.23	7.33	7.96	7.47	7.46	7.53	7.55	7.50	7.24	7.49	6.88	7.65	7.35
FYM+Consortia+50%GR	**F4**	7.84	7.96	7.29	7.14	7.71	7.59	7.55	7.96	7.91	7.85	6.25	7.50	7.03	7.85	6.75	7.15	6.69	7.09
Mean		7.87	8.00	7.69	7.30	7.28		7.65	7.88	7.75	7.62	7.21		7.25	7.60	7.35	7.26	7.12	

ANOVA	**CD**	**F Test**	**ANOVA**	**CD**	**F Test**	**ANOVA**	**CD**	**F Test**
B	0.33	S	**B**	0.24	S	**B**	0.28	S
F	0.29	S	**F**	0.22	S	**F**	0.25	S
B*F	0.66	S	**B*F**	0.49	S	**B*F**	0.57	S

Table 4.48 Effect of biochar and amendments on Electrical conductivity (dS m^{-1}) of leachate.

Second Leachate														**Third Leachate** **Fourth Leachate**					
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.03	0.02	0.02	0.03	0.05	0.03	0.01	0.02	0.04	0.03	0.02	0.02	0.10	0.02	0.02	0.02	0.01	0.03
FYM	**F2**	0.02	0.01	0.02	0.04	0.02	0.02	0.02	0.03	0.05	0.02	0.02	0.03	0.02	0.02	0.02	0.01	0.01	0.01
FYM+Consortia	**F3**	0.03	0.02	0.03	0.04	0.03	0.03	0.01	0.03	0.01	0.07	0.02	0.03	0.01	0.02	0.02	0.01	0.02	0.02
FYM+Consortia+50%GR	**F4**	0.02	0.01	0.03	0.01	0.01	0.02	0.06	0.08	0.07	0.01	0.01	0.05	0.06	0.01	0.01	0.01	0.01	0.02
Mean		0.02	0.01	0.02	0.03	0.03		0.03	0.04	0.04	0.03	0.02		0.05	0.02	0.02	0.01	0.01	

ANOVA	**CD**	**F Test**	**ANOVA**	**CD**	**F Test**	**ANOVA**	**CD**	**F Test**
B	0.01	NS	**B**	0.03	NS	**B**	0.01	S
F	0.01	S	**F**	0.23	NS	**F**	0.005	S
B*F	0.02	NS	**B*F**	0.06	NS	**B*F**	0.01	S

4.5.2.3 Exchangeable Sodium

The mean exchangeable sodium of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 3.88, 3.30, 2.92, 2.81 and 2.60 meq/l, respectively. Similarly, the mean exchangeable sodium of the second leachate values for treatments with different amendments was 3.43, 3.26, 3.01 and 2.71 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.49. The interaction effect of biochar levels and amendments on exchangeable sodium of second leachate was found to be significant.

The mean exchangeable sodium of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 2.50, 2.34, 3.23, 1.81 and 2.48 meq/l, respectively. Similarly, the mean exchangeable sodium of the third leachate values for treatments with different amendments was 2.64, 2.87, 2.55 and 1.83 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.49. The interaction effect of biochar levels and amendments on exchangeable sodium of third leachate was found to be significant.

The mean exchangeable sodium of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 2.44, 2.12, 2.62, 2.06 and 1.56 meq/l, respectively. Similarly, the mean exchangeable sodium of the fourth leachate values for treatments with different amendments was 2.11, 2.78, 1.87 and 1.89 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.49. The interaction effect of biochar levels and amendments on exchangeable sodium of fourth leachate was found to be non-significant.

4.5.2.4 Exchangeable Potassium

The mean exchangeable potassium of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.34, 1.54, 0.83, 1.90 and 0.91 meq/l, respectively. Similarly, the mean exchangeable potassium of the second leachate values for treatments with different amendments was 0.63, 1.38, 1.18 and 1.22 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.50. The interaction effect of biochar levels and amendments on exchangeable potassium of second leachate was found to be significant.

The mean exchangeable potassium of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.70, 1.61, 0.93, 1.83 and 1.12 meq/l, respectively. Similarly, the mean exchangeable potassium of the third leachate values for treatments with different amendments was 0.67, 1.67, 1.33 and 1.29 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.50. The interaction effect of biochar levels and amendments on exchangeable potassium of third leachate was found to be significant.

The mean exchangeable potassium of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.60, 1.28, 0.83, 1.62 and 0.98 meq/l, respectively. Similarly, the mean exchangeable potassium of the fourth leachate values for treatments with different amendments was 0.49, 1.48, 1.11 and 1.16 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.50. The interaction effect of biochar levels and amendments on exchangeable potassium of fourth leachate was found to be significant.

4.5.2.5 Exchangeable Calcium

The mean exchangeable calcium of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 12.96, 58.13, 53.50, 33.33 and 45.75 meq/l, respectively. Similarly, the mean exchangeable calcium of the second leachate values for treatments with different amendments was 22.86, 38.80, 35.77 and 65.50 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.51. The interaction effect of biochar levels and amendments on exchangeable calcium of second leachate was found to be significant.

The mean exchangeable calcium of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 11.64, 21.79, 14.73, 19.79 and 27.33

Table 4.49 Effect of biochar and amendments on exchangeable sodium (meq/l) of leachate.

Second Leachate													**Third Leachate** **Fourth Leachate**						
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	3.92	3.60	3.59	3.07	3.00	3.43	2.92	1.90	3.40	1.81	3.18	2.64	1.91	2.14	2.94	1.85	1.70	2.11
FYM	**F2**	3.91	3.55	3.19	2.86	2.79	3.26	2.33	3.42	4.87	1.64	2.10	2.87	3.39	2.77	2.82	3.32	1.62	2.78
FYM+Consortia	**F3**	3.86	3.19	2.68	2.71	2.60	3.01	2.40	2.21	2.75	2.17	3.23	2.55	2.19	1.91	2.30	1.60	1.38	1.87
FYM+Consortia+50%GR	**F4**	3.84	2.86	2.23	2.60	2.04	2.71	2.36	1.83	1.90	1.63	1.42	1.83	2.28	1.68	2.45	1.48	1.56	1.89
Mean		3.88	3.30	2.92	2.81	2.60		2.50	2.34	3.23	1.81	2.48		2.44	2.12	2.62	2.06	1.56	
ANOVA		**CD**	**F Test**					**ANOVA**		**CD**	**F Test**			**ANOVA**		**CD**	**F Test**		
B		0.06	S					**B**		0.46	S			**B**		0.54	S		
F		0.05	S					**F**		0.41	S			**F**		0.48	S		
B*F		0.12	S					**B*F**		0.91	S			**B*F**		1.08	NS		

Table 4.50 Effect of biochar and amendments on potassium (meq/l) of leachate.

Second Leachate													**Third Leachate** **Fourth Leachate**						
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	0.09	0.75	1.36	0.51	0.45	0.63	0.09	0.80	1.56	0.51	0.40	0.67	0.09	0.61	1.16	0.30	0.30	0.49
FYM	**F2**	0.39	1.55	1.27	2.20	1.47	1.38	1.42	1.65	1.27	2.60	1.40	1.67	1.24	1.20	1.27	2.37	1.32	1.48
FYM+Consortia	**F3**	0.32	1.95	0.29	2.50	0.84	1.18	0.44	2.00	0.48	1.78	1.97	1.33	0.30	1.60	0.47	1.23	1.97	1.11
FYM+Consortia+50%GR	**F4**	0.55	1.90	0.40	2.40	0.88	1.22	0.87	2.00	0.41	2.45	0.73	1.29	0.79	1.72	0.41	2.58	0.33	1.16
Mean		0.34	1.54	0.83	1.90	0.91		0.70	1.61	0.93	1.83	1.12		0.60	1.28	0.83	1.62	0.98	
ANOVA		**CD**	**F Test**					**ANOVA**		**CD**	**F Test**			**ANOVA**		**CD**	**F Test**		
B		0.26		S				**B**		0.21	S			**B**		0.22	S		
F		0.24		S				**F**		0.19	S			**F**		0.20	S		
B*F		0.53		S				**B*F**		0.43	S			**B*F**		0.44	S		

Table 4.51 Effect of biochar and amendments on exchangeable calcium (meq/l) of leachate.

Second Leachate														**Third Leachate** **Fourth Leachate**					
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	9.60	40.50	22.00	18.70	23.50	22.86	8.15	11.55	10.95	19.50	18.80	13.79	7.50	10.50	12.50	12.40	14.20	11.42
FYM	**F2**	13.00	55.50	50.00	36.50	39.00	38.80	11.40	14.80	13.00	10.75	24.45	14.88	11.20	10.50	62.70	51.55	41.50	35.49
FYM+Consortia	**F3**	14.25	53.50	59.50	14.60	37.00	35.77	11.25	31.60	12.35	29.75	32.00	23.39	18.75	12.00	14.50	26.95	44.85	23.41
FYM+Consortia+50%GR	**F4**	15.00	83.00	82.50	63.50	83.50	65.50	15.75	29.20	22.60	19.15	34.05	24.15	19.05	19.65	17.00	48.00	88.00	38.34
Mean		12.96	58.13	53.50	33.33	45.75		11.64	21.79	14.73	19.79	27.33		14.13	13.16	26.68	34.73	47.14	
ANOVA		**CD**		**F Test**				**ANOVA**		**CD**		**F Test**		**ANOVA**		**CD**		**F Test**	
B		7.30		S				**B**		4.90		S		**B**		6.18		S	
F		6.53		S				**F**		4.38		S		**F**		5.53		S	
B*F		14.60		S				**B*F**		9.80		NS		**B*F**		12.37		S	

meq/l, respectively. Similarly, the mean exchangeable calcium of the third leachate values for treatments with different amendments was 13.79, 14.88, 23.39 and 24.15 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.51. The interaction effect of biochar levels and amendments on exchangeable calcium of third leachate was found to be non-significant.

The mean exchangeable calcium of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 14.13, 13.16, 26.68, 34.73 and 47.14 meq/l, respectively. Similarly, the mean exchangeable calcium of the fourth leachate values for treatments with different amendments was 11.42, 35.49, 23.41 and 38.34 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.51. The interaction effect of biochar levels and amendments on exchangeable calcium of fourth leachate was found to be significant.

4.5.2.6 Exchangeable Magnesium

The mean exchangeable magnesium of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 12.89, 25.38, 24.08, 22.14 and 30.70 meq/l, respectively. Similarly, the mean exchangeable magnesium of the second leachate values for treatments with different amendments was 15.80, 17.91, 23.93 and 34.50 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.52. The interaction effect of biochar levels and amendments on exchangeable magnesium of second leachate was found to be significant.

The mean exchangeable magnesium of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 17.00, 19.11, 18.14, 23.85 and 25.86 meq/l, respectively. Similarly, the mean exchangeable magnesium of the third leachate values for treatments with different amendments was 14.19, 17.70, 20.76 and 30.52 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.52. The interaction effect of biochar levels and amendments on exchangeable magnesium of third leachate was found to be significant.

The mean exchangeable magnesium of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 14.25, 18.93, 23.56, 22.23 and 27.19 meq/l, respectively. Similarly, the mean exchangeable magnesium of the fourth leachate values for treatments with different amendments was 15.25, 20.65, 19.61 and 29.41 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.52. The interaction effect of biochar levels and amendments on exchangeable magnesium of fourth leachate was found to be significant.

4.5.2.8 Bicarbonates and carbonates

The mean bicarbonates of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 3.60, 3.25, 5.53, 4.75 and 4.30 meq/l, respectively. Similarly, the mean bicarbonates of the second leachate values for treatments with different amendments was 2.78, 4.26, 4.26 and 5.84 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.53. The interaction effect of biochar levels and amendments on bicarbonates of second leachate was found to be significant. The mean bicarbonates of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 2.56, 2.83, 2.63, 3.09 and 2.95 meq/l, respectively. Similarly, the mean bicarbonates of the third leachate values for treatments with different amendments was 2.02, 2.27, 3.34 and 3.61 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.53. The interaction effect of biochar levels and amendments on bicarbonates of third leachate was found to be non- significant.

The mean bicarbonates of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 2.49, 4.70, 2.79, 3.26 and 4.89 meq/l, respectively. Similarly, the mean bicarbonates of the fourth leachate values for treatments with different amendments was 2.01, 3.60, 4.11 and 4.78 meq/l for F1, F2, F3, and F4, respectively, as shown in Table 4.53. The interaction effect of biochar levels and amendments on bicarbonates of fourth leachate was found to be significant. No carbonates were detected during analysis.

Table 4.52 Effect of biochar and amendments on exchangeable magnesium (meq/l) of leachate.

Second Leachate														**Third Leachate** **Fourth Leachate**					
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	11.20	9.50	12.50	23.00	22.80	15.80	9.00	11.50	11.50	22.00	16.95	14.19	9.00	11.50	12.00	21.50	22.25	15.25
FYM	**F2**	10.00	17.50	18.50	17.05	26.50	17.91	21.50	14.00	13.00	22.50	17.50	17.70	14.00	16.50	34.00	18.75	20.00	20.65
FYM+Consortia	**F3**	12.85	22.00	31.30	19.00	34.50	23.93	18.50	17.50	18.00	22.80	27.00	20.76	14.00	12.50	19.50	22.55	29.50	19.61
FYM+Consortia+50%GR	**F4**	17.50	52.50	34.00	29.50	39.00	34.50	19.00	33.45	30.05	28.10	42.00	30.52	20.00	35.20	28.75	26.10	37.00	29.41
Mean		12.89	25.38	24.08	22.14	30.70		17.00	19.11	18.14	23.85	25.86		14.25	18.93	23.56	22.23	27.19	
ANOVA		**CD**		**F Test**				**ANOVA**		**CD**		**F Test**		**ANOVA**		**CD**		**F Test**	
B		5.81		S				**B**		4.13		S		**B**		5.36		S	
F		5.19		S				**F**		3.69		S		**F**		4.79		S	
B*F		11.61		S				**B*F**		8.25		S		**B*F**		10.72		S	

Table 4.53 Effect of biochar and amendments on bicarbonates (meq/l) of leachate.

Second Leachate														**Third Leachate** **Fourth Leachate**					
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	1.90	2.50	3.00	2.50	4.00	2.78	1.70	1.75	1.75	2.30	2.60	2.02	1.70	1.50	1.95	2.30	2.60	2.01
FYM	**F2**	4.00	3.00	6.80	4.00	3.50	4.26	2.65	2.05	2.10	2.35	2.20	2.27	2.60	2.55	3.30	3.05	6.50	3.60
FYM+Consortia	**F3**	4.00	3.50	3.30	6.00	4.50	4.26	2.75	3.75	3.75	3.20	3.25	3.34	2.15	4.75	3.75	3.20	6.70	4.11
FYM+Consortia+50%GR	**F4**	4.50	4.00	9.00	6.50	5.20	5.84	3.15	3.75	2.90	4.50	3.75	3.61	3.50	10.00	2.15	4.50	3.75	4.78
Mean		3.60	3.25	5.53	4.75	4.30		2.56	2.83	2.63	3.09	2.95		2.49	4.70	2.79	3.26	4.89	
ANOVA		**CD**		**F Test**				**ANOVA**		**CD**		**F Test**		**ANOVA**		**CD**		**F Test**	
B		1.12		S				**B**		0.52		NS		**B**		1.15		S	
F		1.00		S				**F**		0.46		S		**F**		1.03		S	
B*F		2.24		S				**B*F**		1.03		**NS**		**B*F**		2.29		S	

Table 4.54 Effect of biochar and amendments on Exchangeable Sodium Percentage (%) of leachate.

Second Leachate														**Third Leachate** **Fourth Leachate**					
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	15.87	6.62	9.09	6.93	6.04	8.91	14.79	7.53	12.53	4.18	8.13	9.43	11.09	8.66	10.26	5.13	4.56	7.94
FYM	**F2**	14.38	4.54	4.37	4.91	4.02	6.44	6.51	10.59	15.70	4.52	4.60	8.38	11.96	8.94	2.85	4.35	2.51	6.12
FYM+Consortia	**F3**	12.39	4.06	2.85	7.28	3.47	6.01	7.38	4.14	8.39	3.96	4.96	5.76	6.20	7.09	6.24	3.02	1.74	4.86
FYM+Consortia+50%GR	**F4**	10.41	2.04	1.88	2.65	163	3.72	6.21	2.84	3.45	3.14	1.83	3.50	5.42	2.95	5.07	1.84	1.24	3.30
Mean		13.26	4.31	4.55	5.44	3.79		8.72	6.27	10.02	3.95	4.88		8.67	6.91	6.11	3.59	2.51	
ANOVA		**CD**		**F Test**				**ANOVA**		**CD**		**F Test**		**ANOVA**		**CD**		**F Test**	
B		0.89		S				**B**		2.14		S		**B**		**2.27**		S	
F		0.80		S				**F**		1.92		S		**F**		**2.03**		S	
B*F		1.79		S				**B*F**		4.29		S		**B*F**		**4.54**		NS	

Table 4.55 Effect of biochar and amendments on Sodium Adsorption Ratio (%) of leachate.

Second Leachate														Third Leachate Fourth Leachate					
Treatments		**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**			**Biochar**			**Acidified Biochar**		
		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}		0t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	2.5t ha^{-1}	5t ha^{-1}	
		B0	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**	**B0**	**B1**	**B2**	**B3**	**B4**	**Mean**
Control	**F1**	1.22	0.72	0.86	0.68	0.62	0.82	1.01	0.57	1.02	0.40	0.75	0.75	0.70	0.64	0.84	0.45	0.40	0.61
FYM	**F2**	1.15	0.59	0.54	0.55	0.49	0.67	0.58	0.93	1.38	0.41	0.46	0.75	0.99	0.75	0.41	0.56	0.29	0.60
FYM+Consortia	**F3**	1.05	0.52	0.40	0.68	0.43	0.62	0.62	0.45	0.72	0.43	0.59	0.56	0.54	0.56	0.56	0.32	0.22	0.44
FYM+Consortia+50%GR	**F4**	0.95	0.35	0.29	0.38	0.26	0.45	0.57	0.33	0.37	0.33	0.23	0.32	0.52	0.32	0.51	0.24	0.20	0.36
Mean		1.09	0.54	0.52	0.57	0.45		0.63	0.57	0.87	0.39	0.51		0.69	0.57	0.58	0.39	0.28	
ANOVA		**CD**		**F Test**				**ANOVA**		**CD**		**F Test**		**ANOVA**		**CD**		**F Test**	
B		0.05		S				**B**		0.15		S		**B**		0.16		S	
F		0.04		S				**F**		0.13		S		**F**		0.14		S	
B*F		0.10		S				**B*F**		0.30		S		**B*F**		**0.32**		NS	

4.5.2.9 Exchangeable Sodium Percentage

The mean exchangeable sodium percentage of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 13.26, 4.31, 4.55, 5.44 and 3.79 %, respectively. Similarly, the mean exchangeable sodium percentage of the second leachate values for treatments with different amendments was 8.91, 6.44, 6.01 and 3.72 % for F1, F2, F3, and F4, respectively, as shown in Table 4.54. The interaction effect of biochar levels and amendments on exchangeable sodium percentage of second leachate was found to be significant.

The mean exchangeable sodium percentage of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 8.72, 6.27, 10.02, 3.95 and 4.88 %, respectively. Similarly, the mean exchangeable sodium percentage of the third leachate values for treatments with different amendments was 9.43, 8.38, 5.76 and 3.50 % for F1, F2, F3, and F4, respectively, as shown in Table 4.54. The interaction effect of biochar levels and amendments on exchangeable sodium percentage of third leachate was found to be significant.

The mean exchangeable sodium percentage of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 8.67, 6.91, 6.11, 3.59 and 2.51 %, respectively. Similarly, the mean exchangeable sodium percentage of the fourth leachate values for treatments with different amendments was 7.94, 6.12, 4.86 and 3.30 % for F1, F2, F3, and F4, respectively, as shown in Table 4.54. The interaction effect of biochar levels and amendments on exchangeable sodium percentage of fourth leachate was found to be non-significant.

4.5.2.10 Sodium Adsorption Ratio

The mean sodium adsorption ratio of the second leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1}acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 1.09, 0.54, 0.52, 0.57 and 0.45 %, respectively. Similarly, the mean sodium adsorption ratio of the second leachate values for treatments with different amendments was 0.82, 0.67, 0.62 and

0.45 % for F1, F2, F3, and F4, respectively, as shown in Table 4.55. The interaction effect of biochar levels and amendments on sodium adsorption ratio of second leachate was found to be significant.

The mean sodium adsorption ratio of the third leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.63, 0.57, 0.87, 0.39 and 0.51 %, respectively. Similarly, the mean sodium adsorption ratio of the third leachate values for treatments with different amendments was 0.75, 0.75, 0.56 and 0.32 % for F1, F2, F3, and F4, respectively, as shown in Table 4.55. The interaction effect of biochar levels and amendments on sodium adsorption ratio of third leachate was found to be significant.

The mean sodium adsorption ratio of the fourth leachate values for the biochar levels B0 (control), B1 (2.5 t ha^{-1} biochar), B2 (5 t ha^{-1} biochar), B3 (2.5 t ha^{-1} acidified biochar), and B4 (5 t ha^{-1} acidified biochar) were 0.69, 0.57, 0.58, 0.39 and 0.28 %, respectively. Similarly, the mean sodium adsorption ratio of the fourth leachate values for treatments with different amendments was 0.61, 0.60, 0.44 and 0.36 % for F1, F2, F3, and F4, respectively, as shown in Table 4.55. The interaction effect of biochar levels and amendments on sodium adsorption ratio of fourth leachate was found to be non-significant.

CHAPTER V

DISCUSSION

The results of present investigation entitled “Studies on Influence of Biochar Application on Soil Properties and Performance of Wheat in Sodic Soils” presented in the previous chapter are discussed here in the light of study duly supported by available relevant literature and shreds of evidence to establish cause and effect relationship. The entire discussion has been partitioned into following major parts:

5.1 Chemical Parameters

5.2 Biological Parameters

5.3 Physical Parameters

5.4 Physiological Parameters

5.5 Plant nutrient uptake

5.6 Soil Leachate Parameters

5.7 Leachate Parameters

5.1 Chemical Parameters

The chemical condition of soil plays a crucial role in soil-plant relationships by influencing the soil's ability to retain, supply, and cycle nutrients, as well as its impact on water movement and availability. The sodic soils used for sowing the wheat crop were analyzed for their chemical properties both before and after the crop was grown.

5.1.1 Soil pH and EC

The results from the study demonstrate the significant impact of biochar treatments and amendments on soil pH, which is a critical factor influencing nutrient availability, soil structure, and overall plant growth. Soil pH plays an essential role in determining the solubility of nutrients and their subsequent uptake by plants (Brady and Weil, 2016). The application of acidified biochar at 5 t ha^{-1} (B4) consistently resulted in the lowest soil pH values, indicating its strong acidifying effect, which is expected given that acidified biochar contains compounds that can lower the pH of the soil (Marschner, 2012). The lowest pH recorded in treatment F4B4 (7.77) suggests that the combination of FYM (Farmyard Manure), consortia, and 50% GR with acidified biochar created an optimal acidic environment for soil, likely enhancing nutrient availability for the wheat crop.

Soil pH levels are significantly influenced by biochar treatment, reflecting the combined effects of biochar's inherent properties and its interaction with other soil amendments. Specifically, acidified biochar treatments (B3 and B4) were more effective at reducing soil pH compared to non-acidified biochar treatments (B1 and B2). This observation aligns with the findings of previous studies, such as Gao and Zhang (2016), which highlighted that acidified biochar generally exerts a stronger acidifying effect on soil. In a similar context, Soothar et al. (2021) reported that the application of treatment B45S1 (45 g kg^{-1} biochar + 1% salt) resulted in a 7.7% reduction in soil pH in maize compared to the control. These results further emphasize the potential of acidified biochar treatments in modifying soil pH, contributing to improved soil conditions for crop growth.

The interaction between biochar and amendments further emphasizes the role of organic and inorganic materials in modifying soil pH. In particular, the amendment treatments F3 (FYM + Consortia) and F4 (FYM + Consortia + 50% GR) were significantly more effective at reducing soil pH compared to F1 and F2, demonstrating that a combination of organic matter and gypsum is beneficial in lowering pH in sodic or alkaline soils, which is consistent with research on the role of organic amendments in improving soil conditions (Lal, 2015). Moreover, the significant interaction between biochar and amendments suggests that their combined effects can lead to synergistic improvements in soil chemistry. The combination of acidified biochar with amendments such as FYM, consortia, and gypsum (i.e., F4B4) created a more acidic environment, likely enhancing the availability of essential micronutrients such as iron, zinc, and manganese, which are critical for plant growth (Brady & Weil, 2016). On the other hand, the untreated control (F1B0) maintained the highest pH (9.57), highlighting the inherent alkaline nature of the soil without any treatment.

Soil electrical conductivity (EC) is a crucial measure of soil salinity, indicating the concentration of dissolved salts in the soil solution. Higher EC values are typically associated with higher salinity, which can negatively impact plant growth by restricting water uptake and disrupting nutrient absorption (Munns and Tester, 2008). EC is commonly used to assess soil suitability for plant growth, as high salinity can lead to osmotic stress and reduced crop yield (Rengasamy, 2010). The results from the study highlight the significant impact of biochar and organic amendments on soil electrical conductivity (EC) in a wheat cropping system. The biochar treatments showed a decreasing trend in soil EC with the increase in biochar application rate, particularly with the acidified biochar treatments. The lowest EC value of 0.59 dS m^{-1} was observed with the 5 t ha^{-1} acidified biochar (B4), suggesting that the acidification process may enhance the biochar's ability to modify soil properties, including lowering EC. This is in line with the findings of Soothar et al. (2021), who observed a reduction in EC with the application of biochar in maize crops. Farid et al. (2025) also reported that the application of acid-modified biochar significantly reduced soil electrical conductivity (EC) in a wheat crop, suggesting that this treatment can effectively mitigate soil salinity. The reduction in EC observed in their study highlights the potential of acid-modified biochar to improve soil quality by enhancing ion exchange and adsorption of soluble salts, which is particularly beneficial in regions affected by soil salinization. This finding further supports the use of biochar as a valuable soil amendment to promote sustainable crop production and improve soil health in saline environments.

Among the amendments, the addition of FYM combined with Consortia and 50% gypsum (F4) resulted in the lowest EC of 0.59 dS m^{-1}, indicating that the combined organic amendments had a more pronounced effect on reducing EC compared to other amendment treatments, such as FYM alone (F2) or FYM + Consortia (F3). This finding suggests that the interaction between organic amendments and biochar may have a synergistic effect on soil salinity, which is consistent with the research by Zhang et al. (2017), who found that combined organic amendments improved soil structure and reduced EC. However, despite the significant differences in EC values across treatments, the interaction effect of biochar levels and amendments on EC was non- significant, indicating that each treatment independently influenced soil EC, rather than a combined effect of biochar and amendments.

5.1.2 Organic carbon

Soil Organic Carbon (SOC) plays a pivotal role in the management and improvement of sodic soils, which are often characterized by high sodium content that leads to poor soil structure, high pH, and low nutrient availability. Increasing SOC in sodic soils can provide significant benefits, including enhancing soil structure, reducing alkalinity, improving nutrient availability, and contributing to long-term soil fertility. The application of biochar levels and amendments had a significant impact on soil organic carbon (SOC) content after wheat harvest. The SOC values for biochar treatments ranged from 1.08 g kg^{-1} in the control (B0) to 2.99 g kg^{-1} in the treatment with 5 t ha^{-1} acidified biochar (B4), demonstrating a clear positive trend in SOC with increasing biochar application. The enhanced SOC in biochar-amended soils can be attributed to the carbon sequestration potential of biochar, which is known to improve soil organic matter (SOM) content by providing a stable matrix for carbon storage (Lehmann et al., 2011). Similarly, among the amendments, the addition of farmyard manure (FYM), consortia, and gypsum increased SOC, with F4 (FYM + Consortia + 50% GR) showing the highest SOC value of 2.99 g kg^{-1}. The results of this study align with previous research indicating that organic amendments, such as farmyard manure (FYM), enhance soil organic carbon (SOC) by adding both labile and stable organic matter (Lal, 2004). Similarly, El-Sharkawy (2022) found that rice straw biochar (RSB) was more effective than corn stalk biochar (CSMB) in increasing SOC. RSB increased SOC to 1.00% in the upper 0–20 cm soil layer, while modified rice straw biochar (RSMB) further enhanced SOC to 1.06%. These findings underscore the potential of rice straw-derived biochar, especially when modified, in improving SOC storage and soil fertility. The interaction between biochar and amendments significantly enhanced soil organic carbon (SOC) content, with the highest value (2.99 g kg^{-1}) achieved by combining farmyard manure + consortia + 50% GR (F4) and 5 t ha^{-1} acidified biochar (B4), which was significantly higher than the control and other treatments. This highlights the synergistic effect of biochar and organic amendments on SOC improvement. Zhou et al. (2021) similarly observed significant increases in organic matter (OM) with acidified straw-based biochar (ACSBC), reinforcing the long-term benefits of biochar for organic matter enhancement. These findings align with Soothar et al. (2021) and Farid et al. (2025), who also demonstrated that biochar and organic amendments contribute to increased SOC, improved soil fertility, and long-term carbon sequestration. Conversely, the untreated control (F1B0) exhibited the lowest SOC (1.01 g kg^{-1}), emphasizing the importance of biochar and amendments in improving soil quality.

5.1.2 Available Nutrients

A progressive and significant increase in soil-available nitrogen was observed with higher levels of biochar application, particularly with acidified biochar. Acidified biochar treatments (B3 and B4) significantly outperformed the control (B0), demonstrating the enhanced nitrogen availability resulting from the amendment effects and acidification of biochar. These findings align with previous studies, such as those by Smith et al. (2016) and Zhang et al. (2019), which highlighted the role of biochar in improving soil nutrient availability through enhanced nutrient retention and stimulation of microbial activity. El-Sharkawy et al. (2022) similarly reported that soil-available nitrogen significantly increased with the application of modified biochar treatments compared to unmodified biochar. According to their findings, the application of unmodified biochar resulted in soil-available nitrogen levels of 140–160 kg ha^{-1}, whereas modified biochar treatments, including acidified and nutrient-enriched biochar, achieved significantly higher levels of 180–220 kg ha^{-1}. The highest improvement was observed in acidified biochar treatments, which enhanced soil-available nitrogen by approximately 30–40% compared to unmodified biochar. These results further emphasize the potential of biochar modification as an effective strategy for optimizing soil nutrient availability and supporting sustainable agricultural practices.

Among the amendments, the addition of farmyard manure (FYM), microbial consortia and 50% gypsum resulted in significant improvements in soil available nitrogen compared to the control. The combination of FYM with microbial consortia (F3) and further enhancement with gypsum (F4) demonstrated the highest nitrogen levels, with F4 (281.35 kg ha^{-1}) showing the most significant improvement. This result underscores the synergistic effect of organic amendments and microbial consortia in enhancing nitrogen mineralization and availability, as reported by other researchers (Kumar et al., 2020; Liu et al., 2021). The interaction between biochar levels and amendments was found to be significant, with the highest soil available nitrogen (281.35 kg ha^{-1}) recorded for the combination of F4 (FYM + Consortia + 50% GR) and acidified biochar at 5 t ha^{-1} (B4). This value was significantly higher than the untreated control (F1B0), which recorded the lowest nitrogen level (129.03 kg ha^{-1}). These findings suggest that the combined application of higher levels of acidified biochar and nutrient-rich amendments maximized nitrogen availability, likely due to improved nutrient retention, microbial activity, and soil structure. Similar interaction effects of biochar and organic amendments have been reported by Qian et al. (2022) and Singh et al. (2018), further substantiating the present results.

The results demonstrated a significant increase in soil-available phosphorus (P) with higher levels of biochar application, particularly acidified biochar, with the highest phosphorus content of 15.10 kg ha^{-1} recorded in B4. This indicates that the acidification of biochar significantly enhances its ability to improve phosphorus availability, likely due to modifications in its surface properties, such as increased porosity and functional groups, which promote phosphorus retention and gradual release into the soil. Similar findings have been reported by El-Naggar et al. (2019) and Cui et al. (2021), who emphasized the role of acidified biochar in reducing phosphorus sorption and enhancing nutrient accessibility by mitigating the effects of fixation caused by aluminum and iron oxides in soils. Additionally, Taheri et al. (2023) demonstrated that soil treatment with biochar (B) and biochar combined with stimulants (BS) enhanced soil-available phosphorus by 60% and 96%, respectively, compared to the control. This remarkable improvement emphasizes the effectiveness of biochar and its modified forms in improving phosphorus availability in soils.

The combination of FYM with microbial consortia and gypsum (F4) exhibited the highest phosphorus levels, indicating the synergistic effect of organic amendments, microbial activity, and gypsum in enhancing phosphorus availability. The highest soil-available phosphorus (15.10 kg ha^{-1}) was recorded in the treatment combining F4 with 5 t ha^{-1} of acidified biochar (B4), which was significantly higher than the control treatment (F1B0) at 2.00 kg ha^{-1}. These results are consistent with previous studies, such as Singh et al. (2020) and Tang et al. (2022), which demonstrated that organic amendments combined with biochar could significantly enhance phosphorus cycling and availability in soils.

Although both biochar levels and amendments significantly influenced soil-available phosphorus, the interaction effect of these two factors was found to be non-significant. This suggests that while biochar and amendments individually improved phosphorus availability, their combined effects did not result in further significant increases. Nevertheless, treatments involving F4 and acidified biochar (B3 and B4) consistently showed higher phosphorus levels compared to other combinations, highlighting the positive effect of these treatments.

The results showed a significant increase in soil-available potassium with higher levels of biochar application, especially when acidified biochar was used. The highest potassium content was recorded in B4 (194.35 kg ha^{-1}), highlighting the positive effect of acidified biochar on potassium availability. Similar findings were reported by El-

Naggar et al. (2019) and Zhang et al. (2020), who observed that biochar, especially acidified biochar, enhances soil nutrient retention and improves potassium availability by reducing leaching and promoting nutrient exchange.

The inclusion of organic amendments, particularly FYM combined with consortia and gypsum, significantly enhanced soil-available potassium. The mean values for F1 (control), F2 (FYM), F3 (FYM + Consortia), and F4 (FYM + Consortia + 50% GR) were 144.67, 157.94, 155.22 and 163.82 kg ha^{-1}, respectively, indicating that organic matter and amendments improve soil fertility. This is consistent with findings by Noori et al. (2021), who observed similar improvements in nutrient availability with organic amendments. Additionally, Zhou et al. (2021) reported that potassium (K^+) significantly increased in all ACSBC treatments, except for the 1 t ha^{-1} rate. Higher biochar levels enhanced potassium availability, likely due to biochar’s ability to improve soil structure, increase cation exchange capacity (CEC), and enhance nutrient retention, supporting its role in promoting soil. The highest soil-available potassium, recorded at 194.35 kg ha^{-1}, was observed in the combination of F4 (FYM + Consortia+ 50% GR) and acidified biochar at 5 t ha^{-1} (B4), which was significantly higher than the control (168.66 kg ha^{-1}) and other treatments. The interaction between biochar levels and amendments was non-significant. This suggests that while biochar and amendments individually improved potassium availability, their combined effects did not result in further significant increases. Nevertheless, treatments involving F4 and acidified biochar (B3 and B4) consistently showed higher potassium levels compared to other combinations, highlighting the positive effect of these treatments.

5.1.2 Exchangeable ions (Sodium, Calcium, Magnesium, Bicarbonates, ESP and SAR)

The results indicate a significant reduction in soil exchangeable sodium with increasing biochar application rates and the inclusion of organic amendments. The biochar treatments showed a clear decrease in exchangeable sodium, with mean values decreasing from 6.64 meq/100g in the control (B0) to 2.15 meq/100g in the highest biochar application (B4). Similarly, organic amendments also reduced sodium levels, with the lowest mean value observed in F4 (FYM + Consortia + 50% GR) at 2.53 meq/100g. The combination of F4 and acidified biochar (B4) resulted in the lowest exchangeable sodium content of 0.91 meq/100g, significantly lower than the control treatment (4.22 meq/100g). This aligns with studies by Jeffery et al. (2011) and Zhou et al. (2021), which have reported the potential of biochar to reduce exchangeable sodium, particularly in saline or sodic soils, due to its ability to enhance soil structure and improve cation exchange capacity. However, the interaction between biochar and amendments on exchangeable sodium was non-significant, suggesting that each factor independently contributed to sodium reduction.

The results revealed a significant increase in soil exchangeable calcium (Ca^{2+}) with higher biochar application rates, particularly in acidified biochar treatments. The exchangeable calcium content increased from 2.87 meq/100 g in the control (B0) to 10.87 meq/100 g in the highest biochar treatment B4. The combination of F4 (FYM + Consortia + 50% GR) with acidified biochar at 5 t ha^{-1} (B4) resulted in the highest soil exchangeable calcium of 10.87 meq/100 g, significantly higher than other treatments. This finding suggests that biochar, particularly acidified forms, and organic amendments interact synergistically to enhance soil calcium availability, likely through mechanisms such as increased cation exchange capacity (CEC) and improved soil structure, as reported by Zhang et al. (2019) and Qian et al. (2021). The interaction between biochar and amendments on exchangeable calcium was significant, indicating that these factors worked together to enhance soil fertility. Conversely, the lowest exchangeable calcium was observed in the control treatment (B0), highlighting the beneficial effects of biochar and organic amendments on soil nutrient dynamics.

The results of this study demonstrate a significant increase in exchangeable magnesium (Mg^{2+}) with the application of biochar, especially acidified biochar. The mean exchangeable magnesium content increased from 0.63 meq/100 g in the control (B0) to 6.05 meq/100 g in the highest biochar treatment (B4), indicating a clear positive effect of biochar on magnesium availability. Similarly, organic amendments, particularly farmyard manure (FYM) combined with consortia and 50% GR (F4), contributed to a significant increase in exchangeable magnesium, with the highest value observed in F4 (10.57 meq/100 g). The combination of F4 (FYM + Consortia + 50%GR) and acidified biochar at 5 t ha^{-1} (B4) resulted in the highest exchangeable magnesium content of 10.57 meq/100 g, significantly higher than the control treatment (B0), which had a value of 5.47 meq/100 g. This suggests that biochar and organic amendments interact synergistically to enhance soil magnesium availability, likely through mechanisms such as increased cation exchange capacity (CEC) and improved soil structure. The significant interaction between biochar levels and amendments indicates that these factors work together to optimize soil nutrient dynamics. These findings align with previous research showing that biochar improves soil nutrient availability and fertility (Zhang et al., 2019; Qian et al., 2021). The enhancement of exchangeable magnesium through biochar and organic amendments suggests a potential strategy for improving soil fertility and promoting sustainable agricultural practices.

A decrease in soil bicarbonate content with increasing biochar levels, mean ranging from 78.92 mg kg^{-1} in the control (B0) to 24.09 mg kg^{-1} at the highest biochar level (B4). Amendments also influenced bicarbonate levels, with the lowest value (17.27 mg kg^{-1}) occurring in the combination of F4 (FYM + Consortia + 50% GR) and B4 (5 t ha^{-1} acidified biochar), significantly lower than the control treatment (35.27 mg kg^{-1}). Despite these changes, no significant interaction was observed between biochar levels and amendments on soil bicarbonates after the wheat harvest. This suggests that while both biochar levels and organic amendments influence bicarbonate content, their combined effects did not show a significant interaction in the context of soil bicarbonates after cropping. Additionally, the analysis revealed no detectable carbonates in the soil, indicating the absence of carbonate compounds. This suggests that the soil may have a low buffering capacity and could be potentially acidic, as carbonates typically play a key role in neutralizing soil acidity.

A decrease in exchangeable sodium percentage with increasing biochar levels, from mean 57.30% in the control (B0) to 12.99 % at the highest biochar level (B4). Amendments also impacted sodium percentages, with F4 (FYM + Consortia + 50% GR) showing the lowest mean value at 3.91 %, followed by other amendments. In contrast, El-Sharkawy et al. (2022) reported that the cotton stalk-modified biochar (CSMB) treatment led to an increase in ESP, reaching 20.95% in the wheat crop. This increase in exchangeable sodium percentage indicates that CSMB may have contributed to a higher sodium content in the soil, which could affect its salinity and overall fertility. The contrasting findings between the two studies highlight the varying effects of different types of biochar and organic amendments on exchangeable sodium levels in soil. The combination of F4 and B4 resulted in the lowest exchangeable sodium percentage of 3.91 %, significantly lower than the control treatment (24.74 %) and all other treatments. Despite these differences, no significant interaction was observed between the biochar levels and amendments on exchangeable sodium percentage after the wheat harvest. This indicates that although both biochar levels and amendments influence exchangeable sodium content, their combined effects did not show a significant interaction in the context of sodium percentages after cropping.

A decrease in sodium adsorption ratio (SAR) with increasing biochar levels, mean values ranging from 32.27 % in the control (B0) to 7.92 % at the highest biochar level (B4). Amendments also influenced SAR, with the lowest mean value of 11.00 % observed in F4 (FYM + Consortia + 50% GR). Similarly, Taheri et al., (2023) reported a significant reduction in SAR with biochar treatments. Specifically, the application of 15 t ha^{-1} biochar led to a 14% reduction in SAR, while sulphur-modified biochar resulted in a 7% lower SAR compared to the control. This decrease in SAR suggests that both biochar treatments, including sulphur-modified biochar, effectively reduced the soil’s tendency to retain sodium, thereby improving soil structure and alleviating salinity issues. The combination of F4 and B4 resulted in the lowest SAR of 2.93 %, significantly lower than the control treatment (14.38 %) and other treatments. Additionally, a non-significant interaction was observed between biochar levels and amendments.

5.2 Biological Parameters

5.2.1 Enzymatic Activity (Dehydrogenase and alkaline phosphatase activity)

The application of both biochar and organic amendments led to significant improvements in soil microbial activity, particularly in dehydrogenase activity, which is a key indicator of microbial metabolic activity. The highest dehydrogenase activity was observed in the combination of F4 (FYM + Consortia + 50% GR) and B4 (5 t ha^{-1}acidified biochar), reaching 5.43 μg TPF g^{-1} hr^{-1}, which was significantly higher than the control treatment (2.25 μg TPF g^{-1} hr^{-1}). This enhancement in dehydrogenase activity can be attributed to the improved soil conditions facilitated by acidified biochar, which helps lower soil pH and creates a more favorable environment for microbial enzymes, as many of these enzymes, including dehydrogenase and phosphatase, function optimally at near-neutral pH levels (Zhang et al., 2019). In support of this, Taheri et al., (2023) reported that biochar and sulphur-modified biochar treatments significantly enhanced dehydrogenase activity in soil, with sulphur- modified biochar showing an 82% increase compared to the control treatment. This suggests that biochar amendments, particularly sulphur-modified biochar, promote microbial enzyme activity, which is essential for soil health and nutrient cycling. Furthermore, acidified biochar enhances nutrient availability by mitigating the toxic effects of sodium and increasing the solubility of phosphorus, thereby promoting phosphatase activity (El-Sharkawy et al., 2022). Biochar's role in improving soil structure by enhancing aeration and water infiltration also contributes to better microbial populations, further boosting enzymatic activity (Jien et al., 2020). These combined mechanisms significantly elevate microbial enzyme production, leading to higher dehydrogenase and phosphatase activities, which are vital for nutrient cycling and organic matter degradation in sodic soils (Taheri et al., 2023).

Similarly, alkaline phosphatase activity increased across biochar treatments, with the highest mean value (16.24 μg PNP h^{-1} g^{-1}) observed with B4 (5 t ha^{-1} acidified biochar). Amendments further boosted alkaline phosphatase activity, with F4 (FYM + Consortia + 50% GR) showing the highest mean value of 11.21 μg PNP h^{-1} g^{-1}. The combination of F4 and B4 resulted in the highest alkaline phosphatase activity at 20.30 μg PNP h^{-1} g^{-1}, significantly higher than the control treatment (8.13 μg PNP h^{-1} g^{-1}). Furthermore, a significant interaction between biochar levels and amendments was observed, highlighting the synergistic effects of these treatments in enhancing soil microbial activity after the wheat harvest.

5.2.2 Bacterial count

The application of both biochar and organic amendments resulted in increased bacterial counts in the soil, with the highest bacterial count observed in the combination of F4 (FYM + Consortia + 50% GR) and B4 (5 t ha^{-1} acidified biochar), reaching 22.00 CFU g^{-1}, significantly higher than the control treatment (10.00 CFU g^{-1}). Biochar treatments, particularly acidified biochar, enhanced bacterial populations, with B4 showing the highest mean bacterial count at 16.25 CFU g^{-1}. Organic amendments, especially F4, also boosted bacterial numbers, with the highest mean value of 15.07 CFU g^{-1} observed. Acidified biochar enhances bacterial counts in sodic soils through several mechanisms that improve soil conditions. By lowering the high pH typical of sodic soils, acidified biochar creates a more favorable, near-neutral pH, which supports the growth and activity of beneficial soil bacteria (Zhang et al., 2019). It also improves soil structure by increasing porosity, water retention, and aeration, which are essential for microbial survival and activity (Jien et al., 2020). Additionally, acidified biochar increases nutrient availability, particularly phosphorus, by reducing the toxic effects of sodium and enhancing nutrient solubility, further promoting microbial activity (El-Sharkawy et al., 2022). Moreover, acidified biochar increases the soil's cation exchange capacity (CEC), which helps in better nutrient retention and exchange, stabilizing the environment for bacterial populations (Taheri et al., 2023). The micro-pores present in biochar also provide a habitat for bacteria, offering protection from environmental stresses and facilitating bacterial colonization (Zhang et al., 2019). These combined effects create an optimal environment for microbial growth, resulting in increased bacterial counts in sodic soils treated with acidified biochar. Although bacterial count increased with both biochar and amendments, the interaction between biochar levels and amendments was found to be non-significant, indicating that each factor contributed independently to the bacterial population increase. These findings highlight the role of biochar and organic amendments in promoting microbial growth, which is crucial for soil health and nutrient cycling.

5.3 Physical Parameters

5.3.1 Bulk density and Porosity

The study observed a decrease in bulk density and an increase in soil porosity with the addition of biochar, particularly acidified biochar. The lowest bulk density (1.21 g cm^{-3}) was recorded with the combination of FYM + Consortia + 50% GR (F4) and 5 t ha^{-1} acidified biochar (B4), significantly lower than the control (1.26 g cm^{-3}). Acidified biochar reduces bulk density by creating air spaces within the soil, enhancing aeration and neutralizing sodium ions, which improves soil aggregation (Zhang et al., 2019; El- Sharkawy et al., 2022). Organic amendments also contributed to reduced bulk density, with the lowest mean value under F4 (1.26 g cm^{-3}).

The combination of F4 and B4 resulted in the highest porosity (59.77%), significantly greater than the control (30.64%). The increase in porosity is attributed to the pore spaces created by acidified biochar, which enhances water retention, nutrient movement, and root growth (Jien et al., 2020). This combination of reduced bulk density and increased porosity improves soil structure, supporting plant development and microbial activity. El-Sharkawy et al., (2022) similarly found that biochar treatments, particularly rice straw-modified biochar, significantly reduced bulk density and increased porosity, enhancing soil structure and porosity across seasons.

El-Sharkawy et al., (2022) observed that soil bulk density (BD) increased with depth in all treatments. The application of cotton stalk-modified biochar (CSMB) during the maize season resulted in the greatest decrease in bulk density, with an average value of 1.25 $g \cdot cm^{-3}$ compared to the control (1.33 $g \cdot cm^{-3}$), followed by rice straw-modified biochar (RSMB) with an average value of 1.27 $g \cdot cm^{-3}$. In the surface layer (0–20 cm), modified rice straw biochar was the most effective treatment, improving soil bulk density to 1.24 $g \cdot cm^{-3}$, compared to the control value of 1.30 $g \cdot cm^{-3}$. In the wheat season, soil bulk density decreased overall compared to the maize season, with the RSMB treatment achieving the lowest BD of 1.27 $g \cdot cm^{-3}$. The study also highlighted that the interaction between treatments, depth, and season significantly influenced total soil porosity ($p < 0.01$), with rice straw biochar showing a pronounced effect in increasing soil porosity, with average vertical values of 50.94% in the maize season and 52.07% in the wheat season.

5.3.1 Water holding capacity, Soil Moisture and Infiltration rate

The application of biochar, especially acidified biochar, along with organic amendments, significantly improved key soil properties such as water holding capacity, soil moisture, and infiltration rates. The highest water holding capacity (34.07%) was recorded in the combination of FYM + Consortia + 50% GR (F4) with 5 t ha^{-1} acidified biochar (B4), which was significantly higher than the control treatment (19.28%).

Likewise, the combination of FYM + Consortia (F3) and 2.5 t ha^{-1} acidified biochar (B3) resulted in the highest soil moisture content (30.20%), compared to the control (15.85%). Infiltration rates were also significantly improved by biochar treatments, with the highest value of 0.92 cm hr^{-1} under F4 + B4, compared to the control (0.21 cm hr^{-1}). These improvements can be attributed to the porous structure of acidified biochar, which helps reduce soil compaction, enhance pore space, and improve water movement through the soil. Moreover, acidification of biochar lowers soil pH, alleviates sodium toxicity, and promotes better soil aggregation, which further enhances water retention and infiltration (Zhang et al., 2019; El-Sharkawy et al., 2022). These findings are consistent with previous studies that highlight the benefits of biochar, especially acidified versions, in improving soil structure, water retention, and infiltration, particularly in sodic soils (Zhao et al., 2022; Jien et al., 2020). In addition, also reported that biochar, particularly when modified with humic acid, significantly improved soil permeability They reported that the average infiltration rates for 1% humic acid–magnetic biochar and 5% humic acid–magnetic biochar were 11.43 mL/h and 25.08 mL/h, respectively, with the 5% humic acid–magnetic biochar showing the best effect, further supporting the idea that biochar enhances infiltration in saline- alkali and sodic soils.

5.4 Physiological Parameters

5.4.1 Plant growth and Biomass

The application of biochar, particularly acidified biochar, in combination with organic amendments such as FYM, consortia, and gypsum significantly enhanced various plant growth parameters, including plant height, number of grains per spike, spike length, root weight, and root-to-shoot ratio. The highest values for these parameters were observed with the application of 5 t ha^{-1} acidified biochar (B4) along with FYM + Consortia + 50% GR (F4), with plant height reaching 58.21 cm, number of grains per spike at 69.33, spike length of 12.73 cm, and root weight of 23.46 g, significantly higher than the control. These findings are consistent with Chunyu Li (2023), who observed enhanced plant height in wheat with the application of 5% humic acid–magnetic biochar, which reached 9.16 cm, indicating biochar's beneficial effects on plant growth. Moreover, Soothar et al., (2021) demonstrated that acidified biochar alleviates salinity stress, improving growth parameters in saline soils by enhancing soil properties such as nutrient availability, water retention, and root development. Biochar’s ability to improve soil structure and mitigate the toxic effects of sodium ions by lowering soil pH contributes to better plant performance under saline conditions. Farid et al. (2025) further supported these findings, showing that biochar improved plant growth, including increased plant height and spike numbers, especially with the higher rates of acid-modified biochar (10 g kg^{-1}). This effect was accompanied by improved root-to-shoot ratio and an grain-to-shoot ratio, highlighting biochar's role in enhancing soil properties and promoting optimal plant growth. Also, Zhou et al. (2021) observed that sorghum plant height was generally shorter without the application of acidified straw-based charcoal (ACSBC), but significant differences were found only in the 0.3 and 0.45 t ha^{-1} treatments whereas, root length was notably longer in the 1, 6, and 15 t ha^{-1} treatments compared to the non-ACSBC treatment, with the 6 t ha^{-1} treatment showing the most significant improvement (69% increase). While the spike length showed an S-shaped curve as the ACSBC dosage increased, no significant differences were observed between ACSBC and non-ACSBC treatments, except for the 0.6 and 1 t ha^{-1} treatments, which showed slight increases of 3.5% and 9.7%, respectively. These results emphasize the synergistic benefits of biochar and amendments in improving plant growth and soil health, particularly in sodic soils.

5.4.2 Yield Parameters

5.4.2.1 Grain and Straw Yield

The application of biochar and amendments significantly improved both grain and straw yields in sodic soils. The mean grain yield for different biochar levels ranged from 12.35 q ha^{-1} in the control treatment (B0) to 22.51 q ha^{-1} with 5 t ha^{-1} acidified biochar (B4). Similarly, the grain yield for different amendments varied from 11.18 q ha^{-1} in the control treatment (F1) to 21.49 q ha^{-1} with FYM + Consortia + 50% Gypsum (F4). The highest grain yield of 27.34 q ha^{-1} was recorded with the combined treatment of F4 + B4. For straw yield, biochar treatments ranged from 18.92 q ha^{-1} (B0) to 28.55 q ha^{-1} (B4), while the amendments showed a similar trend, with F4 resulting in the highest straw yield of 32.64 q ha^{-1}. The interaction between biochar levels and amendments on both grain and straw yields was found to be non-significant. Acidified biochar, in particular, has been shown to improve soil properties, enhancing both grain and straw yields in sodic soils by improving soil structure, water retention, and nutrient availability. The acidification process helps lower soil pH, reduces sodium toxicity, and promotes soil aggregation, leading to improved root penetration and plant growth (Zhao et al., 2022; El-Sharkawy et al., 2022). Additionally, acidified biochar enhances soil permeability, improving water infiltration and retention, which is crucial for optimal growth in saline and sodic environments (Chunyu Li, 2023). Zhou (2021) also observed a significant increase in sorghum yield when treated with acidified charcoal-treated biochar (ACSBC), with an average yield increase of 32.98%. The highest yields were achieved with 0.6 and 1 t ha^{-1} ACSBC treatments, leading to increases of 51.37% and 47.33%, respectively, highlighting the beneficial effects of biochar in enhancing yield under sodic soil conditions.

5.4.2.2 Harvest Index and Test weight

The application of biochar, especially acidified biochar, in combination with organic amendments such as FYM, consortia, and gypsum has shown significant improvements in harvest index and test weight in sodic soils. The harvest index values were notably higher in treatments with acidified biochar, ranging from 35.88 in the control (B0) to 42.56 with 5 t ha^{-1} acidified biochar (B4), with the highest value of 45.47 achieved when combined with FYM + Consortia + 50% GR (F4). This suggests that the acidified biochar treatment contributes to a more efficient allocation of plant resources towards grain production, improving the ratio of grain yield to total biomass. Similarly, the test weight, a measure of grain quality, showed a substantial increase, from 31.26 g in the control to 42.03 g with 5 t ha^{-1} acidified biochar, with the highest value of 43.81 g observed in the F4 + B4 treatment.

Zhou (2021) also found that acid-charcoal treated biochar (ACSBC) significantly enhanced the hundred-grain weight of sorghum, with the 0.6 t ha^{-1} ACSBC treatment resulting in a 56.17% increase over the non-ACSBC treatment. These results further support the notion that biochar, especially when acidified, improves grain quality by promoting better root development, nutrient uptake, and overall plant performance. The positive impact of ACSBC on soil properties such as water retention, nutrient availability, and soil aggregation likely contributes to the observed increases in seed weight and quality. The acidification process of biochar is critical in mitigating the negative effects of sodicity by reducing soil pH and alleviating sodium toxicity. By improving soil aggregation and water retention, acidified biochar creates a more favorable environment for plant roots, enabling them to penetrate deeper and access more nutrients. This, in turn, enhances plant growth and leads to higher seed production, as evidenced by the improved harvest index and test weight values. These findings are consistent with Zhao et al. (2022) and El-Sharkawy et al. (2022), who highlighted the role of biochar in improving soil health and crop productivity in challenging soil conditions, such as those found in sodic soils.

5.5 Plant nutrient uptake

5.5.1 Total Nitrogen, Total Phosphorus and Total Potassium

The application of biochar and amendments significantly influenced nitrogen, phosphorus, and potassium (NPK) uptake in wheat grown in sodic soils, highlighting the potential of integrated soil management for improving soil fertility and crop productivity. Nitrogen uptake increased with higher biochar levels, with the highest uptake (43.01 kg ha^{-1}) observed in treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1}, significantly outperforming the control (13.56 kg ha^{-1}). While phosphorus uptake remained relatively stable across treatments, the highest uptake (1.29 kg ha^{-1}) was also recorded for F4 with acidified biochar at 5 t ha^{-1}, exceeding the control (0.31 kg ha^{-1}), though the interaction effect of biochar and amendments was non-significant. Potassium uptake improved substantially with increasing biochar levels, with treatment F4 and acidified biochar at 5 t ha^{-1} resulting in the highest uptake (172 kg ha^{-1}) compared to the control (61.64 kg ha^{-1}), though the interaction effect was also non-significant. The enhanced nutrient uptake can be attributed to the positive effects of acidified biochar on sodic soil properties. Biochar improves soil structure, increases porosity, and reduces bulk density, thereby promoting root growth and nutrient availability. Its high surface area and cation exchange capacity (CEC) allow for the retention and gradual release of essential nutrients like nitrogen, phosphorus, and potassium, while its acidification enhances nutrient adsorption and availability. In sodic soils, biochar neutralizes pH, reduces exchangeable sodium percentage (ESP), and ameliorates overall soil quality. When combined with amendments such as FYM, microbial consortia, and gypsum, these effects are amplified. FYM adds organic matter, stimulates microbial activity, and provides additional nutrients, while gypsum supplies calcium to replace sodium on soil colloids, improving soil structure and nutrient dynamics. These findings align with previous studies (Glaser et al., 2002), which emphasize biochar's role in enhancing soil fertility, nutrient use efficiency, and productivity, particularly in degraded or sodic soils. Furthermore, Farid et al. (2025) reported that improvements in plant growth parameters were strongly correlated with increased NPK uptake, underscoring the critical role of these macronutrients in supporting plant development and sustainable agricultural practices.

5.5.1 Total Calcium, Total Magnesium and Total Sulphur

The application of biochar and amendments significantly influenced calcium, magnesium, and sulphur uptake in wheat grown in sodic soils, highlighting the role of integrated soil management in improving plant nutrient uptake and soil health. Calcium uptake increased with higher biochar levels, with the highest uptake (69.40 kg ha^{-1}) observed in treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1}, exceeding the control (27.98 kg ha^{-1}). The lowest calcium uptake was recorded in the control treatment with no biochar (B0) or amendments applied. Magnesium uptake also improved with increasing biochar levels, with treatment F4 and acidified biochar at 5 t ha^{-1} resulting in the highest uptake (37.29 kg ha^{-1}) compared to the control (31.39 kg ha^{-1}). Unlike calcium, the interaction effect of biochar levels and amendments on magnesium uptake was found to be non-significant, suggesting a synergistic relationship between these soil management practices. Sulphur uptake exhibited modest increases, with treatment F3 combined with acidified biochar at 2.5 t ha^{-1} achieving the highest uptake (4.09 kg ha^{-1}), which was significantly higher than the control (0.97 kg ha^{-1}). However, the interaction effect of biochar levels and amendments on sulphur uptake was non-significant.

The enhanced uptake of calcium, magnesium, and sulphur with the application of acidified biochar can be attributed to its beneficial effects on soil properties in sodic soils. Acidified biochar improves soil structure by reducing bulk density, increasing porosity, and enhancing root penetration, which facilitates nutrient absorption. Its high cation exchange capacity (CEC) promotes the retention and gradual release of calcium and magnesium ions, while its acidic nature neutralizes soil pH and increases the solubility and availability of sulphur. In sodic soils, biochar reduces the exchangeable sodium percentage (ESP), thus ameliorating soil salinity and improving the availability of essential nutrients. When combined with amendments such as FYM, microbial consortia, and gypsum, these effects are further enhanced. FYM contributes organic matter and microbial activity, which improves nutrient cycling, while gypsum provides calcium to displace sodium from soil colloids, improving soil structure and nutrient uptake.

These findings align with previous studies (Glaser et al., 2002; Mukherjee & Lal, 2013), which highlight the role of biochar in improving soil nutrient retention and plant growth in degraded soils. Farid et al. (2025) emphasized the positive correlation between soil amendments and enhanced plant growth parameters due to increased nutrient uptake. The results underscore the importance of acidified biochar in combination with organic and chemical amendments as an effective strategy for improving nutrient uptake and productivity in sodic soils.

5.6 Soil Leachate Parameters

5.6.1 pH and Electrical Conductivity

The pH and electrical conductivity (EC) of soil leachates are crucial indicators of soil quality in sodic soils. Increasing biochar levels (B0–B4) reduced soil pH significantly, with mean values decreasing from 8.96 to 8.47, while amendments (F1–F4) reduced pH from 9.26 to 8.35. The lowest pH (7.80) occurred with acidified biochar (5 t ha^{-1}) combined with FYM, microbial consortia, and 50% GR (F4). Acidified biochar reduced alkalinity by introducing H^+ ions, displacing Na^+ ions, and facilitating their leaching, while gypsum contributed Ca^{2+} to enhance soil structure. Li et al. (2022) found that biochar addition generally reduced the pH of soil leachate, with the humic acid–magnetic biochar group showing the greatest decrease. The magnetic modification and humic acid grafting treatments resulted in the lowest pH, highlighting the significant impact of humic acid–magnetic biochar on soil leachate pH.

Higher biochar application rates (B3 and B4) reduced soil EC from 0.03 and 0.04 dS m^{-1}, attributed to salt adsorption and immobilization. Amendments (F1–F4) also consistently reduced EC, with gypsum aiding sodium precipitation as sodium sulfate. These findings align with those of Sadegh-Zadeh et al. (2018), who reported that acidified dicer wood chips (DWCB) treated soils had lower pH. This result aligns with studies showing biochars can reduce pH in salt-affected soils with high exchangeable sodium percentage (ESP). The observed discrepancy may be due to the initial soil pH; soils with pH > 8, controlled by sodium carbonate, tend to decrease in pH as sodium is leached, whereas soils with pH < 8, controlled by calcium carbonate, behave differently. Additionally, acidified biochars were effective in lowering EC by improving soil porosity and enhancing salt leaching, although their impact on pH varied depending on soil conditions. Similarly, Santos et al. (2021) observed that soil electrical conductivity (ECe) was reduced by 90.5% in the sugarcane bagasse (SB) and corncob (CB) treatments compared to the control (CT), indicating a significant improvement in soil salinity with the application of these treatments.

5.6.2 Exchangeable Sodium and Bicarbonates

The mean exchangeable sodium values in soil leachate for different biochar levels (B0–B4) ranged from 9.19 meq/l (control) to 6.75 meq/l (5 t ha^{-1} acidified biochar). Similarly, for treatments with various amendments (F1–F4), exchangeable sodium values decreased from 9.38 meq/l in F1 to 5.80 meq/l in F4. Combining treatment F4 (FYM + consortia + 50% gypsum) with 5 t ha^{-1} acidified biochar reduced exchangeable sodium by 4.78 meq/l compared to the control (8.73 meq/l). Li et al. (2019) also reported that all treatments, including gypsum (GP), Polyhalite combined with fulvic acid (PLFA), and microporous potassium-silicon-calcium mineral fertilizer combined with furfural residue (MFFR), had significantly lower exchangeable sodium values than the control. Specifically, MFFA showed the lowest exchangeable sodium value of 0.49 cmol kg^{-1}, indicating the effectiveness of these treatments, particularly MFFA, in reducing exchangeable sodium in soil.

In terms of bicarbonates, soil leachate mean values for biochar treatments (B0–B4) ranged from 42.37 meq/l to 46.51 meq/l and for amendment treatments (F1–F4), values ranged from 47.44 to 37.51 meq/l. The combination of F3 and acidified biochar at 2.5 t ha^{-1} resulted in 21.50 meq/l reduction in bicarbonates compared to the control (65.00 meq/l). However, the interaction effect of biochar levels and amendments on both exchangeable sodium and bicarbonates was found to be significant. Sadegh-Zadeh et al. (2018) found that all treatments, except the control and acidified dicer wood chips (DWCB), showed decreasing Na^+ concentrations with increasing pore volume (PV), with the highest Na^+ levels in the first leachate. The control and DWCB had initially low Na^+ concentrations, which peaked at 1 PV before decreasing. The higher Na^+ concentrations in treatments like rice straw biochar (RSB), acidified rice straw biochar (ARSB) and ADWCB were linked to higher Ca^{2+}, Mg^{2+} and H^+ contents in these biochars, promoting Na^+ leaching. For $HCO3^-$, RSB maintained a constant level, while the control and DWCB showed a decrease, and ADWCB and ARSB saw an increase until plateauing.

5.6.3 Exchangeable Calcium and Magnesium

The exchangeable calcium and magnesium values in soil leachates were influenced by both biochar levels and amendments. For calcium, the values increased with higher biochar levels, with B4 (5 t ha^{-1} acidified biochar) reaching 44.45 meq/l, significantly higher than the control (9.55 meq/l). Similarly, treatment F4 (FYM + consortia + 50% GR) combined with acidified biochar at 5 t ha^{-1} resulted in an increase in exchangeable calcium to 44.45 meq/l, higher than the control (9.55 meq/l). For magnesium, B3 showed the highest exchangeable magnesium 14.00 meq/l. The increase in exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) in soil leachate with acidified biochar application is primarily due to ion exchange and the biochar's chemical properties. The lower pH of acidified biochar releases hydrogen ions (H^+), which displace sodium ions (Na^+) from soil colloids, promoting the leaching of excess sodium in sodic soils. Concurrently, calcium and magnesium ions from the biochar and soil amendments replace the sodium ions, increasing their concentration in the leachate. This process not only reduces soil alkalinity but also enriches the soil with essential nutrients, improving soil fertility and structure. Santos et al. (2021) reported that the Ca^{2+}:Mg^{2+} ratio in soil increased significantly after leaching, ranging from 1.52 to 21.3, with considerable variation among treatments. Before leaching, this ratio ranged from 1.30 to 1.71. Treatments like SB and SBG resulted in approximately six times more Ca^{2+} than Mg^{2+} in the soil solution, indicating that these biochars favored Mg^{2+} leaching over Ca^{2+}. In contrast, CB left 21 times more Ca^{2+} than Mg^{2+} in the soil, promoting an imbalanced cation ratio. Balanced concentrations of calcium and magnesium are crucial for proper plant growth and development. Similarly, Chaganti (2014) reported that amended soils had significantly higher soil exchangeable Ca^{2+} levels compared to control soils. On average, exchangeable Ca^{2+} concentrations were 26%, 36%, and 28% higher in biochar, biosolids compost, and greenwaste compost treated soils, respectively, than in the control soils. Organic amendments increased soil exchangeable Ca^{2+} by 8%, 16%, and 11% for biochar, biosolids compost, and greenwaste compost treated soils, respectively. Post-leaching, exchangeable Mg^{2+} concentrations did not differ statistically between treatments, although organic amendments tended to result in relatively higher concentrations than the control soils. However, compared to initial concentrations, all treatments showed lower exchangeable Mg^{2+} levels. Notably, compost treatments had a higher ability to retain

Mg^{2+}, losing only 21% of their initial exchangeable Mg^{2+} after leaching, while control and biochar-treated soils lost about 30%.

5.6.3 Exchangeable Sodium Percentage and Sodium Adsorption Ratio

The application of biochar and amendments significantly reduced exchangeable sodium percentage and sodium adsorption ratio (SAR) in soil leachate. For biochar treatments, the exchangeable sodium percentage decreased with higher biochar levels (B0-B1), from 55.42 % in the control to 44.17 % with 5 t ha^{-1} acidified biochar. The SAR also decreased across biochar treatments, with the lowest value (73.28 %) observed for 5 t ha^{-1} acidified biochar. The interaction of biochar and amendments on sodium adsorption ratio was non-significant. Acidified biochar has been shown to reduce exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) in soil leachate, particularly in sodic soils. The lower pH of acidified biochar releases hydrogen ions (H^+), which displace sodium ions (Na^+) from soil colloids, promoting the leaching of sodium from the soil. This reduces the ESP and SAR, which are key indicators of soil sodicity. In studies, the application of acidified biochar has led to significant decreases in both ESP and SAR, improving soil structure and reducing the negative effects of sodium on soil fertility. For instance, treatments with acidified biochar at 5 t ha^{-1} resulted in a reduction in both ESP and SAR in soil leachate, as observed in the work by Sadegh- Zadeh et al. (2018) and Santos et al. (2021). Sadegh-Zadeh et al. (2018) reported that acidified biochars, particularly RSB, ADWCB, ARSB, and DWCB, significantly reduced soil sodium adsorption ratio (SAR), with the greatest reduction observed in rice straw biochar (RSB) and acidified dicer wood chipper biochar (ADWCB) treatments. Acidified biochars enhanced the concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the soil solution, which helped replace sodium (Na^+) on exchange sites, promoting sodium leaching. The increased availability of hydrogen ions (H^+) in acidified biochars, especially in the ADWCB treatment, facilitated greater Na^+ displacement, leading to more substantial SAR reduction. Similarly, Li et al. (2019) found that the exchangeable sodium percentage (ESP) was significantly lower in the gypsum (GP), Polyhalite combined with fulvic acid (PLFA), and microporous potassium-silicon-calcium mineral fertilizer combined with furfural residue (MFFR) treatments compared to the control (CK) treatment. Specifically, the ESP decreased by 43.26%, 36.47%, and 25.86% in the GP, PLFA, and MFFR treatments, respectively.

5.6.4 Available Nitrogen, Phosphorus and Potassium

The mean available nitrogen (N), phosphorus (P), and potassium (K) in soil leachate increased with higher biochar and amendment levels. The highest nitrogen (97.37 mg/kg), phosphorus (18.38 mg/kg), and potassium (1.07 mg/kg) were observed. While the interaction of biochar and amendments was significant for nitrogen and phosphorus, it was non-significant for potassium. Yue et al. (2016) reported that after washing (CK), potassium (K^+) content increased by 42% to 115% in the upper two soil layers. This increase was attributed to the dissolution of soil minerals, such as carbonates, which released potassium into the soil solution. This suggests that washing or leaching processes can mobilize potassium bound within soil mineral matrices, enhancing its availability in the upper soil profile. Acidified biochar enhances the availability of nitrogen (N), phosphorus (P), and potassium (K) in soil leachate in sodic soils through multiple mechanisms. It improves soil structure by reducing bulk density and increasing porosity, thereby enhancing water infiltration and aiding in the leaching of excess salts, which lowers sodicity (Chaganti, 2014). The acidic nature of biochar reduces soil pH in alkaline sodic soils, increasing the solubility of phosphorus and promoting microbial activity essential for nutrient cycling, including nitrogen mineralization. Acidified biochar has a high surface area and cation exchange capacity (CEC), enabling it to adsorb and retain nutrients like ammonium (NH_4^+), potassium (K^+), and phosphate (PO_4^{3-}), which are released gradually into the soil. Furthermore, it binds sodium ions, preventing them from displacing essential cations such as potassium and magnesium (Yuan et al., 2011). Acidified biochar also supports beneficial microbial communities, including nitrogen-fixing and phosphorus- solubilizing organisms, which enhance nutrient availability. When combined with organic amendments like farmyard manure (FYM), it creates a synergistic effect by further boosting microbial activity and nutrient availability. By improving soil properties, minimizing nutrient loss, and directly contributing nutrients, acidified biochar effectively increases nitrogen, phosphorus, and potassium availability in sodic soils.

5.7 Leachate Parameters

5.7.1 pH and Electrical conductivity

The application of biochar and amendments significantly influenced the pH and EC of soil leachates. Acidified biochar at 2.5 t ha^{-1} (B3) combined with the F3 treatment (FYM + consortia) resulted in the lowest pH (6.40) for second leachate while acidified biochar at 5 t ha^{-1} (B4) combined with the F4 treatment (FYM + consortia + 50% GR) resulted in the lowest pH (6.25 and 6.69) for the (third and fourth leachates, respectively) and the mean value of EC for second leachate was recorded lowest at 0.01 dS m^{-1} under B1 at 2.5 t ha^{-1} biochar while the mean value of third and fourth leachate was observed under treatment B4 at 5 t ha^{-1} acidified biochar of 0.02, and 0.01 dS m^{-1} The application of biochar and various amendments significantly influenced both pH and electrical conductivity (EC) in leachates. In a study by Li et al. (2019), potassium-silicon-calcium mineral fertilizer combined with fulvic acid (MFFA) initially had the lowest pH (6.82) but exhibited the largest variation during leaching, while gypsum treatments maintained minimal pH changes, achieving the lowest pH by the fourth leachate. Conversely, potassium-silicon-calcium mineral fertilizer combined with furfural residue (MFFR) exhibited the highest pH (9.22). Regarding EC, MFFA showed the lowest initial value (62.98 dS m^{-1}), which increased significantly during leaching and remained the highest after four cycles. Similarly, Sadegh-Zadeh et al. (2018) found that rice straw biochar (RSB) had the highest pH in the final leachates, while distilled water carbonized biochar (DWCB) exhibited the lowest pH due to its limited sodium leaching ability. The control treatment showed a similar pattern to DWCB with low pH, and EC in both the control and DWCB treatments initially increased but later decreased as salts were removed. Santos et al. (2021) observed that the application of biochar and gypsum significantly impacted the time required to reduce leachate EC, with the treatments ranked as follows based on the time to reduce EC: soil+gypsum (CTG) < sugarcane bagasse biochar + gypsum (SBG) < sugarcane bagasse biochar (SB) < corncob biochar + gypsum (CBG) < orange bagasse biochar + gypsum (OBG) < corncob biochar (CB) < orange bagasse biochar (OB) < control (CT). The shortest time to reduce EC was seen for CTG (<15 minutes), while the longest was for the control (CT), taking 440 hours. These findings demonstrate the varying effects of different biochar types and amendments on soil pH and EC, highlighting the complex interactions between biochar, amendments, and leaching dynamics.

5.7.2 Exchangeable sodium and bicarbonates

Results showed that biochar application in fourth leachate, ie., acidified biochar at higher rates (5 t ha^{-1}), significantly reduced exchangeable sodium in leachates having mean value (1.87 meq/l), with treatment F3 (FYM + consortia) while bicarbonates remain high under treatment F4 combined with acidified biochar (4.78 meq/l). Significant interaction effects between biochar levels and amendments were observed for bicarbonates in second and fourth leachates. In particular, the highest exclusion of sodium occurred in the fourth leachate phase with F3 treatment, reducing sodium levels to 1.38 meq/l compared to the control (1.70 meq/l). Acidified biochar reduces sodium in leachates through several mechanisms. It increases the cation exchange capacity (CEC) of biochar, allowing it to adsorb sodium ions (Na^+) from the soil solution, which reduces their movement into leachates. The acidic functional groups on the biochar lower soil pH, reducing the solubility of sodium salts like sodium bicarbonate, causing them to precipitate and become less mobile. Additionally, acidified biochar improves soil structure by promoting aggregation and porosity, enhancing water infiltration and more effective leaching of sodium and bicarbonates.

Electrostatic interactions between biochar and sodium or bicarbonate ions further trap these elements on the biochar surface, limiting their movement. Sadegh-Zadeh et al. (2018) observed that the highest Na^+ concentrations occurred in the first leachate for most treatments, except for the control and DWCB. In these treatments, Na^+ concentrations initially increased, peaked at 1 PV, and then gradually decreased. Conversely, treatments like RSB, ARSB, and ADWCB exhibited higher initial Na^+ concentrations, which were associated with higher levels of calcium (Ca^{2+}), magnesium (Mg^{2+}), and hydrogen ions (H^+) in these biochars. The increased H^+ content in acidified biochars likely enhanced Na^+ leaching through two mechanisms: direct exchange on soil colloids and dissolution of calcite, which provides Ca^{2+} for Na^+ exchange. This finding is consistent with the results of Chaganti et al. (2015), who reported that amended soils, particularly those treated with biochars, lost significantly higher amounts of Na^+ compared to non-amended soils. In terms of bicarbonate concentrations (HCO_3^-), the RSB treatment maintained a constant level, while the control and DWCB treatments saw a decrease over time. For treatments like ADWCB and ARSB, HCO_3^- concentrations initially increased before stabilizing after 1 PV and 1.3 PV, respectively. These trends highlight the role of biochar, especially acidified biochar, in influencing both sodium and bicarbonate dynamics in sodic soils.

5.7.2 Exchangeable calcium, magnesium and potassium

The impact of biochar levels (B0 to B4) and amendments (F1 to F4) on exchangeable calcium, magnesium, and potassium in leachates across different phases were observed. For calcium, higher biochar levels, especially acidified biochar, generally resulted in higher exclusion of exchangeable calcium in leachates. The highest exclusion of calcium occurred in the control treatment for the second leachate, while significant interactions were observed between biochar levels and amendments in the third and fourth leachates. Magnesium levels showed a similar trend, with higher biochar levels causing higher exclusion exchangeable magnesium, and significant interactions found for the second and third leachates. For potassium, treatments with acidified biochar, especially when combined with organic amendments like FYM and consortia, showed higher exclusion of exchangeable potassium, particularly in the second, third, and fourth leachates. Acidified biochar enhances the leaching of calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+) in sodic soils through several mechanisms. The acidic functional groups on the biochar reduce soil pH, which increases the solubility of these cations, thus enhancing their mobility in the soil solution (Sadegh-Zadeh et al. (2018). Acidified biochar also has a higher cation exchange capacity (CEC), allowing it to adsorb and exchange cations like Ca^{2+}, Mg^{2+}, and K^+ with sodium (Na^+) ions from the soil colloids (Chaganti et al., 2015). This exchange process not only reduces the presence of harmful sodium but also mobilizes beneficial nutrients, enhancing their presence in the leachate. Furthermore, acidified biochar improves soil structure, promoting better water infiltration and more efficient leaching of these essential nutrients. The interaction between biochar and soil minerals further aids in the release of calcium, magnesium, and potassium, ensuring their enhanced presence in leachates from sodic soils. Sadegh-Zadeh et al. (2018) found that soils amended with biochar, except for DWCB, had high concentrations of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in the first leachate, which gradually decreased with increasing percolation volume. In contrast, the control and DWCB treatments showed initially low levels of these cations, which increased until peaking at 1 PV before declining slowly. This indicates that biochar amendments enhance the release of Ca^{2+} and Mg^{2+} in the initial leachates, potentially improving soil fertility in sodic soils. Similarly, Yue et al. (2016) reported that all three biochars (cow manure biochar, sunflower straw biochar and rice straw biochar) increased magnesium (Mg^{2+})

concentration and reduced calcium (Ca^{2+}) concentration in the first leachate. The addition of biochar sped up Mg^{2+} leaching while delaying Ca^{2+} leaching. Additionally, the addition of RSB biochar even resulted in a low sodium (Na^+) concentration in the effluent, likely due to the low Na^+ content in the added RSB. Potassium concentrations in the effluent remained very low and were generally unaffected by biochar addition.

5.7.3 Exchangeable Sodium Percentage and Sodium Adsorption Ratio

The application of biochar and amendments significantly impacted the exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) in the leachates. The ESP and SAR values in the second, third and fourth leachates were lower for treatments combined with FYM, consortia, and gypsum (F4), particularly with 5 t ha^{-1} acidified biochar, indicating enhanced leaching and reduction of sodium. The interaction effects of biochar levels and amendments were significant across all leachates, highlighting the importance of both biochar type and amendment in mitigating sodium levels in sodic soils. Acidified biochar helps reduce the exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) in leachates from sodic soils through multiple mechanisms. According to Sadegh-Zadeh et al. (2018), acidified biochars contain high concentrations of hydrogen ions (H^+), which lower the soil pH and promote the displacement of sodium (Na^+) from soil colloids, enhancing its leaching. Furthermore, acidified biochar has a high cation exchange capacity (CEC), which allows it to adsorb sodium ions, decreasing their mobility in the soil solution and reducing their presence in leachates. Additionally, the presence of calcium (Ca^{2+}) and magnesium (Mg^{2+}) from biochar and amendments like gypsum can displace sodium ions in the soil, which lowers both ESP and SAR by facilitating the exchange of sodium with calcium and magnesium ions (Sadegh-Zadeh et al. (2018); Yue et al., 2016). This process improves soil structure, enhances sodium leaching, and reduces the negative impact of sodium on soil permeability, ultimately decreasing both ESP and SAR levels in sodic soils. Zadeh et al. (2018) reported that the lowest sodium adsorption ratio (SAR) values were observed in the initial leachates of the control and DWCB treatments. These SAR values increased with an increasing percolation volume (PV), reaching a peak at 1 PV, before gradually decreasing in the subsequent leachates. In contrast, the highest SAR values were found in the initial leachates of RSB, ARSB, and ADWCB treatments, with SAR values decreasing as leaching continued. This suggests that biochar amendments, particularly acidified and rice straw-based biochars, influence SAR dynamics by affecting sodium retention and leaching in sodic soils over successive leaching phases.

CHAPTER VI

SUMMARY AND CONCLUSIONS

A study was conducted to evaluate the influence of biochar and soil amendments on the health and fertility of sodic soils under wheat cultivation. The study included four amendment treatments: Control, FYM (Farmyard Manure), FYM + microbial consortia, and FYM + consortia + 50% Gypsum Requirement (GR). Two types of biochar—Normal and Acidified—were applied at five levels: 0 t ha^{-1} (control), 2.5 t ha^{-1} (Normal Biochar), 5 t ha^{-1} (Normal Biochar), 2.5 t ha^{-1} (Acidified Biochar), and 5 t ha^{-1} (Acidified Biochar). The objective was to assess the individual and combined effects of biochar and amendments on improving soil physico-chemical and biological properties, enhancing nutrient availability, and boosting crop performance in sodic soils. Wheat was chosen as the test crop due to its sensitivity to sodicity and its relevance in saline-affected regions.

The study demonstrated notable improvements in soil health indicators and crop yield, particularly under combined treatments involving acidified biochar and integrated amendments. The key results and conclusions are summarized below.

6.1 Chemical parameters

The study demonstrated that biochar, particularly acidified biochar at 5 t ha^{-1}, significantly improved sodic soil properties by reducing pH, EC, ESP, and SAR, while enhancing soil organic carbon and nutrient availability. When combined with FYM, consortia, and gypsum (F4), acidified biochar (B4) showed the most effective results, including increased levels of nitrogen, phosphorus, potassium, calcium, and magnesium. These findings highlight the synergistic benefits of integrated amendments in restoring soil fertility and supporting sustainable wheat production in sodic soils.

6.2 Biological Parameters

The study showed that biochar, especially acidified biochar, and organic amendments significantly enhanced microbial activity and soil enzyme functions. The combination of FYM + Consortia + 50% GR (F4) with 5 t ha^{-1} acidified biochar (B4) resulted in the highest dehydrogenase and alkaline phosphatase activities. Improved soil conditions under these treatments also led to increased bacterial counts. While both biochar and amendments independently promoted microbial growth, their interaction was not statistically significant.

6.3 Physical Parameters

The study found that acidified biochar, especially at 5 t ha^{-1} combined with FYM + Consortia + 50% Gypsum (F4), significantly improved sodic soil physical properties. This treatment reduced bulk density to 1.21 g cm^{-3} and increased porosity to 59.77%, enhancing soil structure, aeration, and conditions for plant and microbial growth. It also improved water holding capacity (34.07%), soil moisture, and infiltration rates (0.92 cm hr^{-1}), mainly due to biochar's porous nature. Additionally, acidified biochar helped mitigate sodium toxicity, further promoting better soil aggregation and water retention.

6.4 Plant Parameters

The study showed that acidified biochar combined with organic amendments (FYM, consortia, and gypsum) significantly enhanced plant growth in sodic soils. The best results—including increased plant height, grain number, root weight, and yields—were observed with 5 t ha^{-1} acidified biochar and FYM + Consortia + 50% gypsum. Improvements were linked to better soil structure, water retention, nutrient availability, and reduced sodium toxicity, leading to higher grain quality and overall crop performance under saline conditions.

6.5 Nutrient uptake

The study found that acidified biochar combined with organic amendments (FYM, consortia, and gypsum) significantly enhanced nutrient uptake in wheat grown in sodic soils. The highest uptake of nitrogen, phosphorus, potassium, calcium, and magnesium occurred with 5 t ha^{-1} acidified biochar plus FYM + consortia + 50% gypsum (F4 + B4). Improvements were attributed to better soil structure, increased cation exchange capacity, and enhanced nutrient availability due to biochar and amendments working synergistically.

6.6 Leaching Studies - Soil Characteristics after four Leachings

The study demonstrated that acidified biochar, especially at 5 t ha^{-1} combined with FYM, microbial consortia, and gypsum (F4), significantly improved sodic soil quality by reducing soil pH, electrical conductivity (EC), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR). These improvements were due to biochar’s acidic nature, which displaced sodium ions and enhanced sodium leaching. Biochar also increased exchangeable calcium and magnesium, improved nutrient availability (N, P, K), soil structure, porosity, and microbial activity. The results highlight acidified biochar as an effective, sustainable amendment for reclaiming sodic soils and enhancing fertility in salt-affected areas.

6.7 Leachate Parameters

The application of acidified biochar at 5 t ha^{-1} (B4) combined with FYM, consortia, and 50% gypsum (F4) significantly reduced soil pH and electrical conductivity in leachates, enhancing soil acidification and salt leaching. This treatment increased the exclusion of exchangeable sodium and bicarbonates while promoting the leaching of beneficial cations like calcium, magnesium, and potassium. Acidified biochar improved soil structure and nutrient mobility by displacing sodium ions with calcium and magnesium, leading to significant reductions in exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR), thus improving soil fertility and permeability.

Conclusion

The study concludes that applying acidified biochar at 5 t ha^{-1} combined with organic amendments (FYM, consortia, and gypsum) significantly improves sodic soil quality by reducing sodicity, enhancing nutrient availability, and improving soil structure. This combination lowers soil pH, EC, ESP, and SAR, promotes better water retention and infiltration, and supports healthier root growth and microbial activity. It also enhances the leaching of sodium and bicarbonates, facilitating the replacement of sodium ions with calcium and magnesium, thereby reducing sodium toxicity. The synergistic effects of biochar and amendments offer a sustainable approach for improving soil fertility and crop productivity in sodic soils.

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CERTIFICATE - IV

Certified that all necessary corrections as suggested by the external examiner and advisory committee have been duly incorporated in the thesis entitled **'Studies on Influence of Biochar Application on Soil Properties and Performance of Wheat"** submitted by **Ms. Divya Chadha**, Registration No. **J-20-D-425-A.**

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