Ph.D. Chingangbam Karuna Chanu 2026

ALLEVIATION OF ALUMINIUM TOXICITY OF MUNGBEAN IN ACID SOIL OF NAGALAND USING ORGANIC MATERIALS

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY

CHINGANGBAM KARUNA CHANU

Admn. No.: Ph-328/21 Regn. No. Ph.D./SS/00608

Department of Soil Science

School of Agricultural Sciences

Nagaland University, Medziphema Campus – 797106

Nagaland

June, 2026

ALLEVIATION OF ALUMINIUM TOXICITY OF MUNGBEAN IN ACID SOIL OF NAGALAND USING ORGANIC MATERIALS

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY

CHINGANGBAM KARUNA CHANU

Admn. No.: Ph-328/21 Regn. No. Ph.D./SS/00608

Department of Soil Science
School of Agricultural Sciences
Nagaland University, Medziphema Campus – 797106
Nagaland

June, 2026

ALLEVIATION OF ALUMINIUM TOXICITY OF MUNGBEAN IN ACID SOIL OF NAGALAND USING ORGANIC MATERIALS

BY

Name of Candidate – **Chingangbam Karuna Chanu**

Name of Supervisor – **Dr. P. K. Singh**

Submitted

In partial fulfilment of the requirements for the degree of Doctor of Philosophy in Soil Science of Nagaland University

Nagaland University

March, 2026

I, Chingangbam Karuna Chanu, hereby declare that the subject matter of this thesis is the record of work done by me, that the contents of this thesis did not form the basis of the award of any previous degree to me or to the best of my knowledge to anybody else, and that the thesis has not been submitted by me for any research degree in any other University/Institute.

This is being submitted to School of Agricultural Sciences, Nagaland University for the degree of Doctor of Philosophy in Soil Science.

(Chingangbam Karuna Chanu)

(Head) (Supervisor)

NAGALAND UNIVERSITY
Medziphema Campus
School of Agricultural Sciences
Medziphema – 797106, Nagaland

Dr. P. K. Singh
Professor and Head of Department
Department of Soil Science

CERTIFICATE – I

This is to certify that the thesis entitled **"Alleviation of Aluminium Toxicity of Mungbean in Acid Soil of Nagaland using Organic Materials"** submitted to Nagaland University in partial fulfilment of the requirements for the award of degree of Doctor of Philosophy in Soil Science, is the record of research work carried out by **Chingangbam Karuna Chanu**, Registration No. Ph.D./SS/00608, under my personal supervision and guidance.

The result of the investigation reported in the thesis has not been submitted for any other degree or diploma. The assistance of all kinds received by the student has been duly acknowledged.

Date :

Place : SAS, Medziphema

(Dr. P. K. Singh)
Supervisor

NAGALAND UNIVERSITY
Medziphema Campus
School of Agricultural Sciences
Medziphema – 797106, Nagaland

CERTIFICATE – II

VIVA VOCE ON THESIS OF
DOCTOR OF PHILOSOPHY IN SOIL SCIENCE

This is to certify that the thesis entitled **"Alleviation of Aluminium Toxicity of Mungbean in Acid Soil of Nagaland using Organic Materials"** submitted by **Chingangbam Karuna Chanu**, Admission No. Ph-328/21, Registration No. Ph.D./SS/00608, to the Nagaland University in partial fulfilment of the requirements for the award of degree of Doctor of Philosophy in Soil Science has been examined by the Advisory Board and External examiner on …………………………

The performance of the student has been found **Satisfactory/Unsatisfactory.**

Member	**Signature**
1. Prof. P. K. Singh (Supervisor)	……………………………..
2. Dr. P. K. Sharma (External examiner)	……………………………..
3. Dean. SAS, NU (Pro-Vice-chancellor Nominee)	……………………………..
4. Prof. Y. K. Sharma	……………………………..
5. Prof. A. K. Singh	……………………………..
6. Prof. Manoj Dutta	……………………………..
7. Dr. Debika Nongmaithem	……………………………..

Head
Department of Soil Science

Dean
School of Agricultural Sciences

ACKNOWLEDGEMENTS

It is with heartfelt gratitude that I express my deepest appreciation to my Research Advisor, Prof. P. K. Singh, Professor and Head, Department of Soil Science, School of Agricultural Sciences, Nagaland University. His invaluable and constructive guidance, constant encouragement, and scholarly advice— enriched by his breadth of knowledge and genuine interest—were instrumental in conducting this investigation.

I extend my sincere gratitude to the members of my Advisory Committee: Prof. Y.K. Sharma, Department of Soil Science; Prof. A.K. Singh, Department of Soil Science; Prof. Manoj Dutta, Department of Soil and Water Conservation; and Dr. Debika Nongmaithem, Assistant Professor, Department of Agronomy—for their thoughtful suggestions, critical evaluation, and constructive feedback at each stage of this research.

My appreciation also goes to Prof. Pauline Alila, Dean, School of Agricultural Sciences, Nagaland University, for her encouragement and for facilitating the resources required for this study.

I acknowledge the non-teaching staff for their steadfast administrative and technical support throughout the course of this investigation.

Special thanks are due to my friends and fellow scholars for their camaraderie, encouragement, and the spirit of community they offered during this demanding journey.

I am deeply indebted to my fiancé for his invaluable assistance throughout my journey. His constant encouragement and constructive insights were instrumental to the successful completion of this work. His unwavering belief in me provided the motivation I needed to navigate every challenge.

Finally, no words can fully capture my deepest gratitude to my beloved family, whose unconditional love, sacrifices, and enduring faith in me have been the bedrock of everything I have accomplished. I carry their blessings with me always.

Date: (Chingangbam Karuna Chanu)

Place:

WITH DEEPEST

GRATITUDE

TO

MY FAMILY

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

%	Percent
@	At the rate
^0C	Degree Celsius
Al	Aluminium
ANOVA	Analysis of variance
Ca	Calcium
C.D	Critical difference
Cm	Centimetre
CRD	Completely Randomized Design
Cv.	Cultivar
dS/m	Deci siemens per meter
DAS	Days after sowing
et al.	And others
EC	Electrical conductivity
FYM	Farmyard manure
Fig	Figure
G	Gram
Ha	Hectare
H_2SO_4	Sulphuric acid
hrs.	Hours
i.e.	That is
K	Potassium
Kg	Kilogram
mg/kg	Milligram per kilogram
Mg	Magnesium
MOP	Muriate of Potash
MSS	Mean Sum of Squares
N	Nitrogen
Na	Sodium
No.	Number
NS	Non-Significant
O.C.	Organic carbon
P	Phosphorus

P_2O_5	Phosphorus pentaoxide
pH	Potential of hydrogen
PM	Poultry manure
RA	Reserve acidity
RH	Relative humidity
RR	Rice residue
RDF	Recommended dose of fertilizer
SS	Sum of Squares
SEm±	Standard Error of the Mean
SSP	Single superphosphate
SR	Soybean residue
T	Tonnes
TPA	Total potential acidity
t/ha	Tonnes per hectare

ABSTRACT

The presented study entitled "**Alleviation of Aluminium Toxicity of Mungbean in Acid Soil of Nagaland using Organic Materials**" was conducted to evaluate the effect of aluminium (Al)-alleviating organic amendments on growth and yield, nutrient content and uptake, and soil chemical properties of mungbean (*Vigna radiata* L. var. HUM-12) in acid soil. A pot experiment was conducted during the summer seasons of 2023 and 2024 at the Experimental Farm, School of Agricultural Sciences (SAS), Nagaland University, Medziphema Campus, in a Completely Randomized Design (CRD) with 11 treatments and 3 replications. Treatments included wood ash (T_3: WA), poultry manure (T_4: PM), rice residue (T_5: RR), vermicompost (T_6: VC), soybean residue (T_{10}: SR), their combinations with wood ash (T_7 – T_9, T_{11}), an RDF control (T_1), and an absolute control (T_2).

The pooled results revealed that the combined application of wood ash + vermicompost under treatment T_9 consistently recorded the highest plant height (44.65 cm), number of branches per plant (4.72), number of leaves per plant (7.50), root length (19.38 cm), fresh root weight (2.90 g), dry root weight (0.63 g), relative root length (188.84 %), seed yield (26.29 g/pot), and stover yield (29.30 g/pot) at harvest. The highest harvest index (49.11%) was recorded under T_{11} (wood ash + soybean residue). The absolute control (T_2) recorded the lowest values across all growth and yield parameters, while T_6 (vermicompost) was the most effective treatment among the single amendments.

With respect to nutrient content in seed, treatment T_7 (wood ash + poultry manure) recorded the highest seed nitrogen (3.46 %), phosphorus (0.48 %), potassium (1.23 %), calcium (0.27 %), magnesium (0.22 %), and protein content (21.63 %), along with the lowest Al concentration (6.68 mg/kg) in plant tissue. T_9 (wood ash + vermicompost), however, was superior for stover nutrient content (in %) and total nutrient uptake (in mg/pot). The absolute control (T_2) recorded the lowest nutrient content and uptake across all parameters. Among single amendments, treatment T_4 (poultry manure) was the most effective for seed nutrient enrichment, while T_6 (vermicompost) was superior for total nutrient uptake (mg/pot).

Regarding soil chemical properties, T_9 recorded the highest soil pH (5.79), CEC [13.28 cmol (p^+) kg^{-1}] and organic carbon (1.63%), and also the lowest exchangeable Al [1.19 cmol (p^+) $kg^{-1]}$, total potential acidity [10.23 cmol (p^+) kg^{-1}], monomeric Al (0.29 ppm) and total Al (0.54 ppm) in soil solution. Treatment T_7 was superior for exchangeable base cations and base saturation (36.20%). The absolute control (T_2) recorded the most unfavourable soil chemical properties across all parameters. Among single-amendment treatments, T_3 (wood ash) was most effective for soil pH correction and Al toxicity reduction, while T_6 (vermicompost) excelled in improving organic carbon (%) and CEC [cmol (p^+) kg^{-1}].

Overall, the combined application of wood ash and vermicompost (T_9) is strongly recommended as the most effective and sustainable eco-friendly strategy for ameliorating Al toxicity, improving soil fertility and enhancing mungbean productivity in acid soils of Nagaland. The findings demonstrate that combined organic amendments offer a viable approach to improve acid soil chemistry, reduce aluminium stress, and support high legume yields under the agro-climatic conditions of the region.

***Keywords*:** Acid soil, Aluminium toxicity, Mungbean, Organic amendments, Soil properties, Nagaland

CHAPTER - I

INTRODUCTION

INTRODUCTION

Soil acidity is a widespread edaphic constraint affecting agricultural productivity across humid and sub-humid regions of the world. It is estimated that a significant proportion of the world's arable land is influenced by acidic soils, with particularly severe implications in tropical and subtropical ecosystems. In India, acid soils occupy nearly 49 million hectares, predominantly distributed in the eastern and north-eastern regions. The North-Eastern Hill (NEH) region, including the state of Nagaland, is characterized by high annual rainfall, steep slopes, intensive weathering, leaching of basic cations, and acidic parent materials, all of which contribute to the development of strongly acidic soils with low inherent fertility.

Acid soils are commonly associated with several chemical constraints, including low availability of essential plant nutrients such as phosphorus, calcium, magnesium, and molybdenum, along with increased solubility of potentially toxic elements, notably aluminium (Al) and manganese (Mn). Among these, aluminium toxicity is considered the most dominant factor limiting crop growth in acid soils. When soil pH falls below 5.5, aluminium-bearing minerals release Al^{3+} ions into the soil solution, which interfere with root cell division and elongation, disrupt membrane integrity, and inhibit the uptake of water and nutrients. The inhibition of root growth is often the earliest and most visible symptom of aluminium stress, leading to poor seedling establishment and reduced crop productivity.

Aluminium (Al) is the most abundant metal in the Earth's crust, constituting approximately 7% of its total mass, and occurs ubiquitously in soils in a variety of chemical forms (R'bia *et al.*, 2011). In soil environments, aluminium is primarily present as hydrous oxides, aluminosilicate minerals, sulphates, and phosphates. Under acidic soil conditions, a substantial proportion of the cation exchange capacity is satisfied by aluminium ions, resulting in high aluminium saturation. Although this fraction is commonly described as exchangeable Al^{3+}, it actually comprises a mixture of monomeric aluminium species, including Al^{3+}, $AlOH^{2+}$, and $Al(OH)_2^{+}$, with an average ionic charge ranging between 2 and 3 that decreases progressively with increasing soil pH (Wild, 1988). Because aluminium solubility is highly dependent on soil pH, any decline in pH leads to increased dissolution of aluminium-bearing minerals, whereas liming of acidic soils promotes the precipitation of soluble and exchangeable aluminium as less soluble hydroxy-aluminium compounds.

Aluminium toxicity is widely recognized as one of the most serious constraints to crop production in acid soils throughout the world (Foy, 1988). The earliest and most characteristic symptom of aluminium toxicity is inhibition of root growth, resulting in short, thickened, and stubby roots characterized by restricted elongation of the primary root axis and suppressed development of lateral roots (Foy, 1988). Root growth inhibition occurs as a result of disruptions in both cell elongation and cell division within the root meristematic tissues (Kochian, 1995). Because root growth is severely restricted, the capacity of plants to explore soil volume for water and essential nutrients is markedly reduced, often leading to nutrient deficiencies and moisture stress even under otherwise favourable conditions. In addition to its effects on root morphology, aluminium toxicity directly interferes with active ion uptake processes across the root plasma membrane (Kochian, 1995; Wright, 1989), particularly impairing the uptake of calcium and phosphorus, which are essential for normal plant growth and development (Huang *et al*., 1992; Mugwira, 1980).

In acidic soils, growth limitations are rarely due to aluminium toxicity alone but often result from the combined toxic effects of hydrogen (H^+), aluminium (Al^{3+}), and manganese (Mn^{2+}). These interacting chemical stresses further exacerbate nutrient imbalances and physiological dysfunctions in plants. It has been estimated that approximately 23% of cultivated soils in developing countries are constrained by aluminium toxicity, highlighting the global significance of this problem for food production and agricultural sustainability (Oluwatoyinbo *et al*., 2005). Moreover, continuous application of ammonium-based fertilizers under intensive agricultural systems accelerates soil acidification through nitrification processes, thereby increasing aluminium solubility and further intensifying aluminium toxicity over time.

The conventional and most widely practiced approach for correcting soil acidity involves the application of calcitic or dolomitic lime, which effectively neutralizes soil acidity, reduces aluminium solubility, and enhances plant growth (Bessho and Bell, 1992). However, in many developing regions where subsistence agriculture predominates, the use of lime is often limited by high cost, poor availability, and inadequate infrastructure for transport and application. In addition, liming may have unintended negative consequences, such as inducing deficiencies of essential nutrients including phosphorus, zinc, boron, and manganese due to changes in soil chemical equilibria (Ahmad and Tan, 1986). Long-term liming experiments conducted in cool, humid regions of Zaire and other tropical environments have further demonstrated that lime application alone is frequently insufficient to rehabilitate degraded or nutrient-depleted soils and sustain crop productivity in the long term (IBSRAM, 1989).

In view of these limitations, increasing attention has been directed toward alternative or complementary strategies for managing soil acidity and aluminium toxicity, particularly through the use of organic amendments. As early as the 1930s, studies reported that additions of organic matter could effectively reduce aluminium toxicity in soils (Mattson and Hester, 1933; Hester, 1935). Subsequent investigations confirmed that organic amendments substantially decrease both soluble and exchangeable aluminium in strongly acidic soils (Brogan, 1967; Hoyt and Turner, 1975). Soils rich in organic matter have consistently been observed to contain lower concentrations of soluble aluminium, suggesting a strong buffering and detoxifying role of organic matter against aluminium toxicity (Evans and Kamprath, 1970).

The ability of organic matter to detoxify aluminium is primarily attributed to a series of physicochemical processes, including complexation, chelation, adsorption, coagulation, and peptization reactions. Through these processes, aluminium ions become associated with organic molecules, forming stable aluminium–organic complexes that reduce aluminium activity in the soil solution to levels less harmful to plant roots (Mortenson, 1963; Bartlett and Riego, 1972; Cabrera and Talibudeen, 1977). During the decomposition of plant and animal residues, a wide array of organic compounds is released or synthesized by soil microorganisms, many of which possess a strong affinity for aluminium ions.

Soil organic matter–aluminium complexes can be broadly classified into two major categories: (i) well-defined biochemical compounds, such as low-molecular-weight organic acids, phenols, phenolic acids, hydroxamate siderophores, sugar acids, and polymeric phenols; and (ii) complex humic substances (Stevenson and Vance, 1989). Although the relative importance of these two groups varies with soil type, organic matter composition, and environmental conditions, humic substances are generally considered to play a dominant role in reducing aluminium phytotoxicity. This is largely due to their heterogeneous structure and high density of oxygen-containing functional groups, including carboxyl, phenolic, enolic, and hydroxyl groups, which provide numerous binding sites for polyvalent metal ions such as aluminium (Harper *et al*., 1995; Wong *et al*., 1995).

The interaction of aluminium with humic substances involves multiple, often overlapping mechanisms, including chelation, adsorption, complex formation, and coprecipitation (Haynes, 1984). Because these mechanisms frequently occur simultaneously and are difficult to distinguish experimentally, aluminium associated with organic matter is often broadly described as being "bound" to soil organic matter (Ritchie, 1989). Aluminium may form both soluble and insoluble complexes with humic materials, influencing its mobility, bioavailability, and phytotoxicity. Among the various organic ligands, low-molecular-weight organic acids—particularly hydroxy acids such as citric acid—are known to form especially strong and stable chelate complexes with Al^{3+}, thereby effectively reducing its toxicity to plant roots (Stevenson and Vance, 1989).

Numerous experimental studies have provided direct evidence for the role of organic compounds in alleviating aluminium toxicity. Suthipradit *et al*. (1990) demonstrated that the application of fulvic acid markedly reduced monomeric aluminium concentrations in solution and alleviated aluminium toxicity in soybean, cowpea, and green gram. Similarly, Hue *et al*. (1986) reported that low concentrations (5–50 μM) of soluble organic acids effectively detoxified aluminium and improved root growth in cotton seedlings, with citric, oxalic, and tartaric acids being the most effective. The incorporation of green manures and animal wastes into acidic soils has also been shown to reduce both total and monomeric aluminium concentrations in soil solution, thereby alleviating aluminium toxicity and enhancing crop growth (Asghar and Kanehiro, 1980; Hue and Amien, 1989; Hue, 1992; Wong *et al*., 1995).

In addition to their direct role in aluminium complexation, organic residue applications frequently lead to an increase in soil pH, further contributing to aluminium detoxification. Such increases in pH are attributed to the release of basic cations and the consumption of protons during the decomposition of organic materials (Hoyt and Turner, 1975; Hue, 1992; Lungu *et al*., 1993; Noble *et al*., 1996). The magnitude of pH increase depends on the nature of the residue, application rate, degree of decomposition, and the buffering capacity of the soil. At application rates of approximately 20 t ha^{-1}, increases in soil pH of 0.2–0.6 units are commonly observed, whereas higher application rates of 40–50 t ha^{-1} have been reported to raise soil pH by as much as 0.8–1.5 units (Berek *et al*., 1995; Iyamuremye *et al*., 1996; Noble *et al*., 1996).

In recent years, considerable emphasis has been placed on the use of specific organic amendments as either alternatives or complements to conventional liming for the management of soil acidity and aluminium toxicity. Organic materials such as wood ash, vermicompost, poultry manure, and crop residues have been widely reported to improve soil chemical properties by increasing soil pH, supplying base-forming cations such as Ca^{2+}, Mg^{2+}, and K^{+}, enhancing cation exchange capacity, and reducing aluminium activity in soil solution through complexation with organic ligands (Hue, 1992; Wong *et al*., 1995; Noble *et al*., 1996). Beyond chemical amelioration, organic amendments contribute to improvements in soil physical condition, microbial activity, and nutrient cycling, thereby creating a more favourable rhizosphere environment for plant growth and root development (Haynes and Naidu, 1998).

Among these organic amendments, wood ash—a by-product of biomass combustion—is particularly noteworthy due to its high content of calcium, potassium, and other basic cations, and its demonstrated liming potential comparable to that of conventional agricultural lime under certain soil conditions (Ohno and Erich, 1990; Demeyer *et al*., 2001). Organic manures and crop residues, in contrast, primarily contribute to aluminium detoxification through the formation of stable organo–aluminium complexes that reduce the concentration of toxic Al^{3+} species in soil solution (Stevenson and Vance, 1989; Wong *et al*., 1995). The combined application of wood ash with organic materials may therefore offer synergistic benefits by simultaneously neutralizing soil acidity and enhancing organic matter–mediated aluminium detoxification, leading to more sustained improvements in soil fertility and crop productivity (Noble *et al*., 1996; Haynes and Mokolobate, 2001).

Despite the growing interest in organic-based strategies for managing acid soils, systematic information on the relative effectiveness of different organic materials, applied either individually or in combination, in ameliorating aluminium toxicity in the acid soils of Nagaland remains limited. Furthermore, few studies have focused on the early root growth response of mungbean under aluminium stress, particularly under controlled incubation conditions that allow soil–amendment interactions to stabilize prior to crop establishment. Early root growth is widely recognized as a sensitive and reliable indicator of aluminium toxicity and its amelioration, as aluminium-induced inhibition of root elongation occurs rapidly and precedes visible shoot symptoms (Foy, 1988; Kochian, 1995). Nevertheless, this parameter remains underutilized in soil acidity research, especially in studies evaluating organic amendments and short-term bioassays, underscoring the need for comprehensive investigation in this context.

Mung bean (*Vigna radiata* L. Wilczek) popularly known as green gram, believed to be native crop of India, is a tiny circular shaped bean in green colour widely cultivated throughout Asia, including India, Pakistan, Bangladesh, Sri Lanka, Thailand, Laos, Cambodia, Vietnam, Indonesia, Malaysia, South China, and Republic of Formosa. This short-duration legume can grow under varying environmental conditions, and later it expands its reach to the USA, Australia, and Africa. In general, mung bean is a source of high-quality protein which can be consumed as whole grains, dhal, or sprouted form and is an excellent complement to rice in respect to balanced human nutrition. In addition to being the prime source of human food and animal feed, it plays an important role in maintaining the soil fertility by enhancing the soil physico-chemical properties and fixing atmospheric nitrogen.

Therefore, the present investigation entitled "**Alleviation of Aluminium toxicity of Mungbean in Acid Soil of Nagaland using Organic Materials**" is proposed to be undertaken with the following objectives:

1. **To evaluate the Al- detoxifying potential of different types of organic materials in acid soil**
2. **To study the effect of different aluminium alleviating organic materials on growth and yield of Mungbean in acid soil**
3. **To study the effect of different aluminium alleviating organic materials on nutrient content and uptake of Mungbean**
4. **To study the effect of different aluminium alleviating organic materials on the soil properties of an acid soil**

CHAPTER - II

REVIEW OF LITERATURE

REVIEW OF LITERATURE

Acid soils, which are characterized by low pH and high aluminium (Al) toxicity, represent one of the major soil constraints affecting crop production in tropical and subtropical regions of the world, including the north-eastern states of India. Mungbean [*Vigna radiata* (L.) Wilczek], is an important pulse crop widely cultivated in Nagaland; however, it is highly sensitive to aluminium toxicity, which adversely affects its root development, nutrient uptake, and overall productivity in acid soils. Organic materials such as wood ash, vermicompost, poultry manure, and crop residues have been reported to effectively ameliorate Al toxicity by raising soil pH, reducing exchangeable Al, improving cation exchange capacity, and enhancing nutrient availability. Hence, a brief review of the available literature with regards to the influence of different Al-alleviating organic materials on the growth and yield, nutrient content and uptake, and soil chemical properties of mungbean and other crops grown in acid soils are presented in this Chapter.

2.1 Effect of different aluminium alleviating organic materials on growth and yield of mungbean in acid soil

Hoyt and Turner (1975) added a large amount of Alfalfa meal, sucrose and peat moss to very acid soil to find their effects on yield of Barley and alfalfa grown in the greenhouse. Alfalfa meal was found to be the most effective. Its action was attributed primarily to complexing of exchangeable Al and, in consequence, decreasing toxic quantities of Al in the soil.

Adams (1981) reported that soil solution Al is toxic to plant root and is the major factor causing infertility in acid soils.

Pavan and Bingham (1982) showed that aluminium toxicity, often associated with low calcium availability in acid soils, adversely affects root growth and restricts the absorption of water and essential nutrients by plants. Inhibition of root development under Al stress ultimately leads to reduced plant growth and crop yields.

Blammey *et al*. (1983) found that inorganic monomeric species of Al have been shown to be toxic to root growth, whereas Al present in soluble organically complexed form is of low toxicity.

Abraham (1984) observed that increasing the concentration of aluminium in nutrient solution from 20 to 40 mg/L markedly inhibited root elongation in rice, reduced the number of productive tillers, and lowered both grain and straw yields. Aluminium stress also caused roots to become shortened and highly branched, which in turn reduced overall nutrient uptake by the plants.

Wright *et al*. (1985) reported that, in an incubation study, application of cow manure, either alone or in combination with lime, produced the greatest root growth (45 cm) in aluminium-sensitive barley. In contrast, individual applications of hog manure, gypsum, or EDTA resulted in rooting depths that were only 52.5–75 % of those achieved with the cow manure plus lime treatment. The enhanced root development was attributed to the complexation of aluminium by soluble organic constituents present in the manures, thereby reducing Al toxicity.

Hue *et al*. (1986) reported that the application of organic amendments such as manure and plant residues reduced exchangeable aluminium in acidic soils and improved crop growth. The improvement was mainly attributed to the formation of aluminium-organic complexes and the increase in soil pH following decomposition of organic materials.

Ryan *et al*. (1993) investigated the spatial sensitivity of plant roots to aluminium toxicity and demonstrated that the root apex is the primary site of Al injury. Their study showed that exposure to aluminium severely inhibited root elongation, with the most pronounced effects occurring near the root tip. The authors also highlighted the critical role of the root cap in aluminium perception and toxicity and reported that aluminium stress led to morphological abnormalities such as stunted, thickened, and discoloured roots. These findings provided fundamental insights into the mechanism of aluminium toxicity in roots under acidic soil conditions.

Berek *et al.* (1995) investigated the effects of six organic materials on the growth of soybean (*Glycine max* (L). Merr.) cv. Wilis resulting from the alleviation of aluminium toxicity on a red-yellow podzolic soil. They found that when organic materials were applied at 10 t/ha, all organic materials increased whole plant dry weight from 14 to 60%. Increasing the organic materials rate to 20 t/ha increased whole plant dry matter yield for *Imperata* tops, *Calopogonium* leaves, soybean tops and *Leucaena* leaves, relative to yield with 10 t/ha, had no effect for rice straw, and decreased dry matter yield for sugarcane leaves. The three leguminous materials strongly depressed monomeric Al concentrations in the soil solution, whereas the three non-leguminous materials only produced moderate depression.

Ginting *et al.* (1998) investigated the effect of aluminium phytotoxicity on the growth of soybean (*Glycine max* (L.) Merr.) cv. 'Forest' in nutrient solutions (pH 4.25) and its alleviation by organic anions. This study has shown that some organic anions and humic acid are effective complexors allowing soybean growth in nutrient solutions with a high concentration of Al. Citrate and oxalate proved to be the most effective. While stability constant data provided a guide to the effectiveness of the various organic anions, it is clear that the anions (particularly oxalate, tartrate and malate) provide additional benefits to plant growth.

Neogy *et al*. (2002) conducted a laboratory experiment to evaluate the effect of aluminium toxicity on the growth of mungbean (*Vigna radiata* L.). The results indicated that increasing concentrations of aluminium significantly reduced seed germination, root length, shoot length, leaf area, and biomass production of mungbean seedlings. The reduction in plant growth was mainly attributed to the toxic effects of aluminium on root development and physiological processes in plants.

Kochian *et al*. (2004) reported that aluminium toxicity is one of the major constraints limiting crop growth in acid soils because it inhibits root elongation and reduces nutrient uptake. The authors also suggested that organic compounds and soil amendments capable of binding aluminium ions can significantly reduce aluminium toxicity and improve crop growth.

Shamshuddin *et al*. (2004) demonstrated that severe acidity and aluminium toxicity in acid sulfate soils significantly restricted plant growth, with shoot biomass and height negatively correlated with Al concentration in plant tissues and soil solution. Application of organic materials, particularly peat alone or in combination with other residues, effectively reduced aluminium toxicity and improved growth, with critical toxicity thresholds identified at 10 µM for Al^{3+} and 15 µM for combined Al hydroxy species.

Kumawat (2006) reported that the application of organic manures significantly improved the growth and yield attributes of mungbean. Among the different organic manures, vermicompost recorded higher plant height, number of branches, dry matter accumulation, chlorophyll content, nodulation, number of pods per plant, seeds per pod and test weight, which resulted in significantly higher seed and straw yield compared to FYM and control.

Zheng (2010) reported that high concentrations of soluble aluminium (Al^{3+}) in acid soils impair root elongation by damaging the cellular organization of the root apex, thereby restricting water and nutrient uptake and adversely affecting overall plant growth and development.

Adeleke and Akinrinde (2011) evaluated the direct and residual effects of fertilizers on the growth and yield of cowpea and soybean grown with or without Al treatment on an alfisol. They found that the organo mineral fertilizer promoted crops performance better than the other fertilizer materials while the application of inorganic or organic fertilizers with 50µM $AlCl_3$ proved most effective. Organic fertilizer had the highest residual effects equivalent to that of organo mineral fertilizer applied with 50 µM $AlCl_3$ confirming that organic based fertilizers could be used to minimize the deleterious influence of Al toxicity on the production of these legumes in acid soils.

Oluwaseun and Akinrinde (2013) investigated the direct and residual effects of different fertilizer materials on the growth and yield of soybean grown with or without Al treatment on an Alfisol. The investigation involved a greenhouse (5 kg soil/pot) experiment with two factors: fertilizer types - control, organic fertilizer (OF), inorganic fertilizer (IF) and OF + IF mixture at ratio 1:1 and Al treatment (0, 50, 100 and 150µM $AlCl_3$). It is evident from this work that Al toxicity (induced with 150µM) reduced the growth and yield of soybean while low and moderate Al application rates (50 and 100µM) enhanced the performance of crop. Also, organic fertilizer proved to have the highest residual effects among the various fertilizer treatments confirming that organic based fertilizers could be used to minimize the deleterious influence of Al toxicity on the production of soybean in acid soils.

Gill *et al.* (2015) observed that the application of wood ash improved crop yield compared to the control and fertilizer treatments. The increase in yield was attributed to improved soil fertility and nutrient availability resulting from wood ash application.

Agegnehu *et al*. (2016) reported that the application of organic amendments such as compost and manure significantly improved soil fertility and crop productivity. The authors observed that organic materials enhanced soil biological activity, increased nutrient availability, and improved plant growth and yield in degraded soils.

Jaiswal *et al.* (2018) reviewed the recent findings on the effect of aluminium (Al) on the functioning of legumes and their associated microsymbionts. They discussed that with 40% of the world's arable land consisting of acid soils and Al toxicity being associated with low pH, global legume production is likely to be hugely constrained. This is because Al toxicity in soils can inhibit root elongation, lateral root development, root hair growth, rhizobial infection of the roots, Nod factor production and nodule development, resulting in low N_2 fixation and decreased crop yield. Therefore, selecting legume/rhizobia symbioses that are tolerant of Al toxicity is the easiest way to increase crop yields in Al-rich acidic soils.

Olubode *et al.* (2018) observed that the improvement in soil fertility due to the application of wood ash and cow dung resulted in higher pod number and grain yield of soybean grown in acid soil. The highest yield was recorded with wood ash applied at 5 t/ha, demonstrating the positive effect of organic amendments on legume productivity.

Rahman *et al*. (2018) reported that aluminium toxicity severely affects plant growth and yield in acidic soils by restricting root growth and nutrient uptake. The authors emphasized that the application of organic amendments and mineral nutrients can alleviate aluminium toxicity by improving soil chemical properties and reducing the activity of toxic aluminium ions in the soil.

Sultana *et al*. (2019) reported that soil acidity severely limits crop productivity in the Old Himalayan Piedmont Plain of Bangladesh and that integrated application of lime and organic manures significantly improves soil chemical properties and crop yields. Their study showed that poultry manure was more effective than farmyard manure in enhancing soil fertility and crop performance, owing to its higher nutrient content and faster mineralization under acidic conditions. Although the maximum yield response was observed in wheat, significant residual benefits were recorded in mungbean, indicating improved soil conditions and nutrient uptake following poultry manure application. The enhanced performance of mungbean was attributed to improved soil pH, organic matter status and nutrient availability. The authors concluded that moderate liming combined with poultry manure is an efficient strategy for improving productivity of cropping systems on acidic soils.

Das and Ganesan (2022) studied aluminium stress tolerance in mungbean seedlings and reported that aluminium toxicity significantly reduced root growth and overall plant development. The study also found that mungbean plants release organic acids such as malate under aluminium stress conditions, which help detoxify aluminium in the rhizosphere and improve plant tolerance to acidic soils.

Joshi *et al.* (2022) conducted a field experiment to evaluate the effect of different organic nutrient management practices on growth and yield of mungbean. The results indicated that the application of vermicompost @ 2 t/ha along with Panchgavya @ 4% at 15, 30 and 45 days after sowing significantly improved growth attributes such as plant height, number of leaves, number of branches and leaf area per plant. The treatment also recorded higher SPAD value, seed yield (908 kg ha^{-1}) and benefit–cost ratio compared to other treatments.

Liu *et al*. (2023) investigated the effect of exogenous organic acids such as oxalic acid, malic acid, and citric acid on aluminium toxicity in mungbean seedlings under controlled conditions. The study revealed that application of organic acids significantly improved root elongation and fresh weight of mungbean plants under aluminium stress. The improvement in plant growth was attributed to the ability of organic acids to chelate aluminium ions and reduce their toxicity in the rhizosphere.

Jalal *et al*. (2024) conducted a field study on mungbean and reported that the application of biochar significantly enhanced plant growth, nodulation, and grain yield under acidic soil conditions. The improvement was attributed to increased soil pH, enhanced nutrient availability, and reduced aluminium toxicity in the rhizosphere.

Yadav *et al.* (2024) reported that the application of organic nutrient sources significantly improved the growth and yield attributes of mungbean in south-eastern Rajasthan. The combined application of 50 % nitrogen through FYM and 50 % nitrogen through vermicompost along with vermiwash spray recorded higher plant height, number of branches, effective nodules, pods per plant, seeds per pod, test weight and seed yield compared to the control.

2.2 Effect of different aluminium alleviating organic materials on nutrient content and uptake of mungbean in acid soil

Demeyer *et al*. (2001) reviewed the effects of wood ash on soil properties and nutrient uptake, noting its high alkalinity and richness in base cations such as Ca, Mg, and K. Wood ash application increased soil pH, reduced exchangeable acidity and aluminium toxicity, and improved the availability of essential nutrients in acid soils. The authors concluded that wood ash can serve as an effective alternative or supplement to lime when applied judiciously.

Rout *et al.* (2001) discussed the aluminium toxicity and problems concerning tolerance and ecological performance. Differential tolerance of plant genotypes to aluminium stress is a more promising approach to increase our understanding of aluminium tolerance in plants. Induction of Al tolerance and its characterization are also reviewed. The cytogenetic effects of aluminium on plants are discussed in depth. Efforts have been made to compare the relative sensitivity of various plant species including micro- and macro-flora to aluminium, and uptake and transport of aluminium are taken into account with phytotoxicity and their interactions with nutrients. Present knowledge concerning the physiology and biochemistry of aluminium with regard to phytotoxicity is discussed and offers some ways for increasing the Al tolerance. This review shows the complexity of the toxicity mechanisms of trace elements.

Yadav (2001) reported that the application of 20 kg N through vermicompost significantly increased nitrogen content in seed and straw and protein content of cowpea compared to the same nitrogen dose applied through urea and FYM

Fageria *et al*. (2002) reported that aluminium toxicity in acid soils interferes with nutrient uptake by damaging root tissues and disrupting membrane transport systems. Their study indicated that the presence of toxic Al^{3+} ions significantly reduced the uptake of phosphorus, calcium, and magnesium in crops grown under acidic soil conditions.

Kumari and Kumari (2002) reported that the application of enriched compost significantly increased the uptake of nitrogen, phosphorus, potassium, calcium and magnesium by blackgram.

Neogy *et al*. (2002) reported that increasing concentrations of aluminium significantly reduced seed germination, root length, shoot growth, and biomass production in mungbean (*Vigna radiata* L.). The study revealed that aluminium toxicity adversely affected root development, which ultimately reduced nutrient absorption by mungbean seedlings grown under acidic conditions.

Netwal (2003) observed that the application of vermicompost at 5 t/ha significantly increased nitrogen, phosphorus and potassium content in seed and straw as well as their uptake by cowpea compared to control, FYM (5 t/ha) and 2.5 t/ha vermicompost

Kochian *et al*. (2004) reported that aluminium toxicity in acid soils primarily inhibits root elongation and interferes with nutrient uptake processes in plants. The authors emphasized that organic compounds and soil amendments capable of chelating aluminium ions play a crucial role in reducing aluminium toxicity and improving plant nutrient uptake.

Vasanthi and Subramanian (2004) reported that the application of vermicompost at 2 t/ha along with 100 % recommended NPK resulted in higher crude protein, nitrogen, phosphorus and potassium concentration and uptake in black gram compared to the application of chemical fertilizers alone.

Kumawat (2006) observed that the application of organic manures increased the nitrogen, phosphorus and potassium concentration in seed and straw of mungbean. Vermicompost recorded the highest nutrient content and total uptake of nitrogen, phosphorus and potassium by the crop compared to FYM and control.

Ramesh *et al.* (2006) reported that the application of organic manures such as cattle dung, vermicompost and poultry manure improved the protein content of pigeon pea seed, with the highest protein content recorded under cattle dung followed by vermicompost and poultry manure.

Raghawendra and Kedar (2008) conducted an investigation during 2004–2006 at Kanpur to study the effect of vermicompost on chickpea. The results revealed that the application of vermicompost at 2 t/ha resulted in higher total nitrogen (86.32 kg/ha) and phosphorus (9.88 kg/ha) uptake by chickpea grown in sandy loam soil.

Agegnehu *et al*. (2016), in a field experiment, reported that the application of compost and organic amendments significantly increased soil fertility and nutrient uptake in crops. The study indicated that organic amendments improved soil pH, increased microbial activity, and enhanced nutrient availability in acidic soils.

Otieno and Zingore (2018), in a greenhouse pot study, reported that the combined application of farmyard manure (FYM) and lime significantly enhanced the uptake of nitrogen, phosphorus, and potassium in plants grown on acid soils, with shoot uptake of N, P, and K increasing by 2.36, 0.04, and 1.15 per cent, respectively, compared to the control. The improved nutrient uptake under these conditions was closely associated with reduced aluminium interference in nutrient absorption and the creation of a more favourable root environment.

Jalal *et al*. (2024), in a field study on mungbean, reported that biochar application significantly improved nodulation, plant growth, and nutrient uptake in mungbean. The authors attributed the improvement to increased soil fertility, improved soil structure, and reduced metal toxicity in the rhizosphere.

2.3 Effect of different aluminium alleviating organic materials on the soil properties of an acid soil

Thomas (1975) reported that Al extracted by IN KCl was found to be lower as organic matter content increased at any given pH level. The effect of organic matter on the exchangeable Al was found to be greater at the lower pH values (£ 3.5) whereas increase in organic matter from 1 to 2 per cent decreased the exchangeable Al from 6.0 to 4.2 meg/100 g of soil.

Bloom *et al.* (1979) studied the variation of solution $A1^{3+}$ activity with pH, the effect of suspending salt solution cation on $A1^{3+}$ activity, and the buffering intensity were determined for salt solution suspensions of three soil samples and an Al substituted peat that contained one equivalent of $A1^{3+}$ for each equivalent of carboxyl groups. It was concluded that hydrolysis of organically bound Al is a major source of buffering in the pH range of 4 to 5 for dilute salt suspensions of acid soils and that exchange of Al ions from organic matter exchange sites controls the relationship between pH and Al^{3+} activity in acid soils that have a low amount of permanent charge CEC relative to the quantity of organic matter.

Asghar and Kanehiro (1980) evaluated the effects of sugarcane trash and pineapple residue on soil chemical properties during a four-month incubation study. Addition of organic residues increased soil pH and reduced redox potential, particularly in the early incubation period. The decline in extractable aluminium was closely associated with the rise in soil pH, indicating a potential role of organic residues in alleviating aluminium toxicity in acid soils. However, increased availability of manganese at higher residue rates highlighted the risk of Mn toxicity, emphasizing the need for careful management of organic amendments.

Wahab and Lugo-López (1980) investigated the role of organic matter in immobilizing aluminium in an acid Ultisol using ground coffee leaves and pangola grass. Their results showed that soils with high exchangeable Al severely restricted plant growth, while the addition of organic materials reduced soil acidity and exchangeable Al, leading to improved biomass production. Coffee leaves were more effective than pangola grass in alleviating aluminium toxicity, highlighting the potential of organic amendments for managing Al toxicity in acid soils.

Wong (1981) reported that organic amendments such as peat, manure, and compost contain humic and fulvic acids rich in functional groups, particularly carboxyl groups, which contribute significantly to soil acidity buffering. These functional groups are capable of consuming protons and forming stable complexes with Al^{3+} ions at the prevailing soil pH, thereby reducing aluminium activity and toxicity in acid soils.

Pavan (1983) investigated the relationships between different forms of aluminium and soil chemical properties in acid soils of Paraná State, Brazil. The study showed that increasing soil pH reduced exchangeable and soluble aluminium, while higher CEC and organic matter content promoted Al complexation, thereby decreasing the activity of toxic Al^{3+} in soil solution and alleviating aluminium toxicity.

Ahmad and Tan (1986) carried out a greenhouse experiment to compare the effects of organic matter and lime on soybean [Glycine max (L.) Merr.] plants grown under increasing Al stress in a Bradson (Typic Hapludults) soil. Treatments, replicated three times, were 0, 25, 50, and 100 mg Al kg^{-1} pot^{-1}, 0, S, and 10% wheat (*Triticum aestivum* L.) straw, and the equivalent of 0,1, and 2 Mg CaCO3 ha^{-1}. They found out that lime alone yielded good results, but lime in the presence of organic matter was more effective in reducing the effect of Al toxicity.

Alva *et al.* (1986) established a suitable aluminium index to predict Al toxicity to plants grown in nutrient solutions with a wide range of properties. The results have shown firstly that nominal Al concentration in solution is of little value as an index of Al toxicity of the solution. Secondly, where considerable quantities of polymeric Al species are present in solution, total Al concentration in solution is also of little value as an index. Thirdly, where the effects of Al are studied in solutions of differing ionic strength, the concentration of monomeric Al in solution is a poor index of Al toxicity. The best index of Al toxicity, as measured by root growth of soybean, subterranean clover, alfalfa, and sunflower, proved to be $\sum a_{\text{Al mono}}$., which takes account of Al precipitation and polymerization as well as the effects of ionic strength in assessing Al.

Hue *et al*. (1986) examined the influence of organic acids on aluminium toxicity in acid subsoils using split-root experiments with cotton. The study showed that several low-molecular-weight organic acids reduced Al phytotoxicity by forming stable Al–organic complexes, with acids such as citric and oxalic being particularly effective. Detoxification efficiency depended on molecular structure and the ability to form stable chelates with Al. Soil solution analyses indicated that a large proportion of total Al occurred in organically complexed, non-toxic forms, especially in forest soils, while root growth was closely related to monomeric Al rather than total Al concentration. The results demonstrate that organic ligands play a key role in lowering Al activity and toxicity in acid soils.

Bruce *et al.* (1988) concluded that soil Al saturation was not a good predictor of Al toxicity, but soil solution measurements were. The activities of Al^{3+} and $AlOH^{2+}$ gave the best associations with RRL, and values corresponding to 90% RRL were 4µm and 0.5 µm respectively. The results suggested that Al $(OH)_3^{o}$, Al $(OH)_2^{+}$ and $AlSO_4^{+}$ were not toxic species.

Hue and Amien (1989) conducted a greenhouse experiment to evaluate "liming" potential of different green manures. Biomass production and chemical composition of the soil indicated that (i) Cowpea and Leucaena were more effective than guinea grass in detoxifying Al (ii) reduction of soluble Al at increased pH as a result of manure additions was the major mechanism for Al detoxification, and (iii) complexation of soluble Al by organic molecules also contributed to the detoxification.

Stevenson and Vance (1989) demonstrated that humic and fulvic substances present in organic materials possess reactive functional groups, including carboxyl and phenolic groups, which dissociate under acidic soil conditions and develop negative charges. These charged sites effectively bind aluminium ions and neutralize protons, leading to a reduction in exchangeable aluminium and improved chemical conditions in acid soils.

Ohno and Erich (1990) evaluated the effect of wood ash application on soil pH and soil test nutrient levels to assess its suitability as an alternative liming material. Their laboratory incubation study showed that wood ash significantly increased soil pH, with calcium carbonate equivalence ranging from 26 to 59%, indicating considerable variability in acid-neutralizing capacity among ash sources. Application of wood ash enhanced the availability of base cations, particularly calcium, magnesium, and potassium, with calcium exhibiting the highest release into soil solution. Wood ash also altered the exchangeable cation balance by increasing calcium dominance, especially in soils initially low in exchangeable Ca. Although aluminium was not directly measured, the increase in soil pH and exchangeable Ca implies a reduction in aluminium solubility and potential toxicity**,** supporting the role of wood ash in ameliorating acid soils.

Suthipradit *et al*. (1990) studied the role of fulvic, malic and oxalic acids in alleviating the toxic effects of aluminium (AI) on tap-root elongation of soybean cv. Fitzroy, cowpea cv. Vita 4, and green gram cv. Berken. Treatments consisted of a factorial combination of four AI concentrations (0, 12.5, 25 and 50 μM as $AI(NO_3)_3$. $9H_2O$) and two concentrations either of malic or oxalic acid (0, 50 μM) or fulvic acid (0, 65 mg L^{-1} of organic carbon). They found that fulvic acid completely alleviated the toxic effect of AI at all concentrations on soybean and cowpea and at concentrations <25 μM on greengram.

Kretzschmar *et al*. (1991) reported that application of crop residues effectively reduced aluminium (Al) toxicity in acidic sandy soils by increasing soil pH and decreasing labile Al concentrations in the soil solution. Long-term residue incorporation significantly lowered soluble Al compared with residue-removed soils, while short-term incubation with millet straw reduced both total and labile Al by more than 40%. Although pearl millet showed inherent tolerance to Al, residue addition markedly enhanced root growth through chemical amelioration of soil acidity. These results indicate that crop residues mitigate Al toxicity primarily by reducing Al activity in soil solution rather than through direct effects on plant tolerance.

Alter and Mitchell (1992) investigated the potential of vermicompost extract to inhibit aluminium activity in aqueous solutions. Their study demonstrated that soluble organic constituents present in vermicompost effectively interacted with Al^{3+} ions, thereby reducing aluminium availability and toxicity. The findings indicate that organic compounds derived from vermicompost can form stable complexes with aluminium, highlighting the role of organic amendments as effective aluminium inhibitors and supporting their use in the management of aluminium toxicity in acid soil environments.

Bessho and Bell (1992) carried out a soil incubation and short-term root growth experiment to investigate the effects of organic matter applications on Al toxicity alleviation in a highly weathered acid soil. It has been shown that plant material alleviated Al toxicity in a highly weathered acid soil; however, a very high rate of application was required. In the case of test soil, to lower the Al^{3+} activity to 10µ M (a critical level for 10% reduction in RRL of Mungbean in this experiment), 14 t/ha and 42 t/ha of legume leaves and Barley straw, respectively were required, whereas only 0.75 t/ha was required for $CaCO_3$.

Clapham and Zibilske (1992) demonstrated that wood ash, particularly when applied in combination with lime, was effective in increasing soil pH and reducing soil aluminium levels in acid soils. Soil Al decreased linearly with increasing rates of wood ash in ash–lime admixtures, indicating amelioration of aluminium toxicity. Wood ash application also improved the availability of several nutrients, especially Ca, K, and P, and enhanced plant dry matter yield, supporting its use as a complementary liming amendment rather than a complete lime substitute.

Wong and Swift (1995) studied the amelioration of phytotoxicity with organic matter in strongly weathered soil. The main components of the soil organic matter are humic substances and the effect of adding a sample of humic acid on the activity of Al^{3+} was investigated. The addition of the humic acid to an Oxisol from Burundi and an Ultisol from Cameroon decreased the activity of aluminium in the pH range 3.2 to 4.6. In both soils, plots of Al^{3+} against pH were linear. They concluded that decrease in exchangeable aluminium saturation will further ensure lower Al^{3+} activities.

Qin and Chen (1998) reported that the addition of organic matter reduced the activity of highly reactive aluminium in acidic soils, suggesting that organic amendments can modify aluminium chemistry through complexation and buffering effects, thereby lowering the concentration of phytotoxic Al^{3+} species.

Nkana *et al*. (1998) compared the chemical effects of wood ash and $CaCO_3$ on ryegrass growth in tropical acid Kandiudult soils under greenhouse conditions. The study showed that wood ash amendments, applied to achieve target soil pH values of 5.5–6.5, produced higher biomass than lime or untreated soils. Wood ash application improved soil chemical properties by increasing effective cation exchange capacity and supplying Ca and K, while simultaneously reducing aluminium and manganese toxicity. These liming-like effects, combined with nutrient supplementation, indicate that wood ash can function both as an acidity neutralizer and as a nutrient source, thereby effectively ameliorating aluminium toxicity in tropical acid soils.

Hue and Licudine (1999) reported that the application of chicken manure and sewage sludge effectively increased soil-solution pH and calcium concentration, while simultaneously reducing soil-solution aluminium and the percentage of aluminium saturation in the subsoil, particularly at depths below 15 cm. These findings highlight the potential of organic amendments to alleviate subsoil aluminium toxicity by improving chemical conditions beyond the surface layer.

Whalen *et al*. (2000) reported that the application of farmyard manure (FYM) to acid soils resulted in an immediate increase in soil pH. They observed that the reduction in aluminium toxicity following FYM application was primarily due to the complexation of Al by soluble organic constituents present in the manure. In their study, application of FYM at a rate of 40 g kg^{-1} soil increased soil pH from 4.8 to 6.0, demonstrating the effectiveness of organic amendments in ameliorating soil acidity.

Haynes and Mokolobate (2001) reviewed the phenomenon and mechanisms involved in amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues. They found that additions of organic residues to acid soils can reduce Al toxicity (thus lowering the lime requirement) and improve P availability. The practical implication of the processes discussed is that organic residues could be used as a strategic tool to reduce the rates of lime and fertilizer P required for optimum crop production on acidic, P-fixing soils.

Judge (2001) investigated the ameliorative effects of poultry manure (PM) on acid soil through a leaching study and observed notable reductions in exchangeable aluminium across different soil depths. Exchangeable Al decreased by 0.66 cmol kg^{-1} in the 5–15 cm layer, 0.22 cmol kg^{-1} in the 15–25 cm layer, and 0.17 cmol kg^{-1} in the 25–35 cm layer, demonstrating that surface-applied PM can alleviate subsoil acidity by promoting downward movement of ameliorating components.

Liu and Hue (2001) reported that conventional surface application of liming materials such as limestone, burnt lime, or dolomite is largely ineffective in mitigating subsoil acidity, while deep ploughing or the use of specialized machinery to incorporate lime into deeper soil layers is often impractical. However, the combined application of lime and compost was found to significantly reduce exchangeable Al^{3+} concentrations not only in the surface soil but also in deeper layers. Moreover, the simultaneous application of lime with organic amendments, rather than their separate application, improved calcium availability in the lower soil horizons.

Shen and Shen (2001) conducted a pot experiment to investigate the effects of organic materials on the alleviation of Al toxicity in acid red soil. Ground wheat straw, pig manure or $CaCO_3$ were mixed with the soil and incubated, at 85% of water holding capacity and 25°C, for 8 weeks. After the incubation, 14 seedlings of mung bean (*Phaseolus aures* Roxb) were allowed to grow for 12 days. Results showed that application of organic material or $CaCO_3$ increased soil pH and decreased soil monomeric inorganic Al concentrations. Growth of mungbean seedling was improved substantially by the application of organic material or $CaCO_3$. Pig manure or wheat straw was more effective in ameliorating Al toxicity than was $CaCO_3$.

Muhrizal *et al.* (2003) carried out an experiment to determine the efficacy of organic matter to ameliorate acid sulfate soil. The results showed that Al was reduced substantially by addition of organic materials especially green manure and green manure in combination with peat. The ability of peat or its mixture with green manure, chicken dung and palm oil mill effluent is shown by a better growth of mungbean on the soil treated with them compared to that without. Soils treated with these materials have less Al^{3+} activities resulting from Al being complexed by the organic materials and/or precipitation of Al when soil pH increases due to the organic materials treatment.

Senkiw (2004) reported that a 9-week incubation of acid soils with alkaline humic substances increased pH in both surface (4.8 → 5.2) and subsurface (3.45 → 4.29) horizons. Furthermore, the initial exchangeable aluminium concentration in the subsurface soil (106 mg /kg) was completely eliminated, highlighting the effectiveness of humic-based organic amendments in ameliorating soil acidity and reducing aluminium toxicity.

Qin and Chen (2005) investigate the effect of both the long term and the short-term application of organic manure on the aluminium toxicity of the soil. They found that the long-term application of manure may have an even stronger effect. In contrast to barnyard manure, green manure (legumes) significantly alleviated aluminium toxicity after a short period of application; the low molecule organic acids released during the decomposition of green manure may play an important role. Furthermore, the ash elements in the manures also decrease the content of E-Al to some extent. Thus, the application of organic manure may be an effective and economical method for the reclaiming red soils through the detoxification of aluminium and providing nutrients to crops.

Kumawat (2006) reported that the application of organic manures improved soil fertility after harvest of mungbean. The application of FYM and vermicompost increased soil organic carbon and the availability of nitrogen and phosphorus in the soil compared to the control.

Naramabuye and Haynes (2006) conducted an incubation experiment to investigate the effect of the addition of two rates of a range of organic amendments to an acid soil on pH and exchangeable and soluble Al. The wastes included plant materials (maize, sorghum, kikuyu grass, soybean, red clover residues, and acacia prunings), animal manures (kraal, pasture and feedlot cattle, pig, and layer and broiler poultry), household compost, sewage sludge, and an industrial waste, filter cake. From this study, they conclude that addition of all the organic amendments increased soil pH and decreased exchangeable Al and AlMono in solution, at least during the 6-month incubation period used. Thus, organic amendments constitute not only soil conditioners and nutrient sources, but also liming materials.

Naramabuye and Haynes (2007) carried out an incubation experiment of 6 months duration to investigate the liming effects of five organic manures (poultry, pig, and cattle manure, soybean residues, and sewage sludge) when added to an acid soil at a rate of 10 mg/g. Manure additions resulted in a decrease in the percentage of Alt present in solution as Almono, and this was attributed to complexation of Al by soluble organic matter originating from the manures. It was concluded that organic wastes can act as liming materials when added to acid soils and that the resulting increase in pH and decrease in Almono concentrations might provide a window of opportunity for establishment and early growth of crop plants.

Tang *et al*. (2007) conducted a pot experiment to study the effect of feedlot manure (FM) and poultry litter (PL) on soil Al status and wheat growth. Custer, an acid susceptible wheat cultivar (*Triticum aestivum* L. var. Custer), was planted in a manure amended Teller (fine-loamy, mixed, thermic Udic Argiustoll) fine sandy loam soil and relationships between soil pH, organic carbon (OC), and P added in the manure, 0.01 mol L^{-1} $CaCl_2$ extractable Al (Al_{CaCl2}), 1.0 mol L^{-1} KCl exchangeable Al (Al_{KCl}), and wheat growth were investigated. Poultry litter and FM significantly increased soil pH, reduced Al_{CaCl2} and Al_{KCl}, and improved wheat growth. These two animal manures have the potential to reduce Al toxicity in acidic soils but need to be further evaluated at a field scale.

Vieira *et al*. (2008) evaluated the transformation of Al in an acidic sandy Alaquod soil amended with composts (10 and 50 g/kg soil of yard waste. yard + municipal waste. GreenEdge, and synthetic humic acid) based on soil Al fractionation by single and sequential extractions. Though the organic compost amendments increased total Al in soil, they alleviated Al potential toxicity in acidic soil by increasing soil pH and converting exchangeable Al to organically bound and other noncrystalline fractions, stressing the benefits of amending composts to improve acid soil fertility.

Bougnom *et al*. (2009) assessed composts amended with wood ash as a means of improving tropical acid Oxisols and Ultisols under greenhouse conditions. Compost application increased soil pH, organic matter, and nutrient availability, while significantly reducing exchangeable aluminium, ammonium-N, iron, and manganese. Moderate ash addition (8%) produced favourable changes in several soil chemical properties, although plant biomass response was limited due to excessively high soil pH. Overall, the study indicates that composts with wood ash addition can improve soil chemical conditions and reduce aluminium availability in acid tropical soils when applied at appropriate rates.

Vieira *et al*. (2009) demonstrated that application of organic composts to an acidic sandy soil markedly improved soil fertility and reduced aluminium phytotoxicity. Compost additions significantly increased Mehlich-3 extractable Ca, Mg, P and K, while total aluminium in soil solution remained largely unchanged. However, soil solution pH increased and the activity of toxic Al species declined to below critical levels due to the formation of stable aluminate and humic acid–Al complexes. The study highlighted that organic composts can effectively mitigate aluminium toxicity and enhance nutrient availability in acid soils, although excessive application may increase the risk of nutrient leaching.

Ch'ng *et al*. (2014) demonstrated that in acidic soils, iron (Fe) and aluminium (Al) strongly immobilize soluble inorganic phosphorus, thereby limiting its availability to plants. Although liming can reduce Fe and Al activity and improve phosphorus availability, it is often economically unviable and environmentally undesirable. To address this limitation, the study evaluated the use of organic amendments, particularly compost and a compost–biochar mixture, as alternatives for mitigating P fixation. The application of these organic materials significantly increased total phosphorus, available phosphorus, soluble inorganic phosphorus, as well as aluminium-, iron-, calcium- and residual-bound inorganic phosphorus fractions, along with organic phosphorus. These improvements were attributed to an increase in soil pH and a reduction in exchangeable Fe, exchangeable Al, and exchangeable acidity following organic amendment application.

Gill *et al.* (2015) reported that the application of wood ash significantly improved soil chemical properties by increasing soil pH and the availability of nutrients such as P, K, Ca, S and micronutrients. The study also indicated that wood ash can effectively mitigate soil acidity and enhance soil fertility.

Behera *et al*. (2016) reported that, in a 50-day incubation study on an acid soil, the combined application of calcium silicate with farmyard manure effectively ameliorated soil acidity. Exchangeable acidity declined from 1.12 to 0.67 cmol$_{(+)}$ kg^{-1}, while exchangeable Al^{3+} and H^{+} were reduced from 0.56 to 0.47 cmol$_{(+)}$ kg^{-1} and from 0.53 to 0.20 cmol$_{(+)}$ kg^{-1}, respectively, indicating the effectiveness of integrating organic amendments with alkaline materials in mitigating aluminium toxicity in acid soils.

Panda *et al*. (2017) evaluated the effect of maize, wheat, rice, and soybean residues on soil acidity in an Alfisol of northwest India. Incorporation of the residues increased soil pH without significantly affecting electrical conductivity. Among the treatments, soybean and maize residues caused a marked reduction in soil solution Al^{3+} concentration during incubation, indicating decreased aluminium toxicity. The study demonstrates that crop residues, particularly soybean residue, can effectively ameliorate soil acidity and reduce phytotoxic aluminium in acid soils.

Bandyopadhyay *et al*. (2018) investigated soil acidity across major landforms along an altitudinal sequence in Nagaland, India, and reported that soils are predominantly acidic, with pH-dependent acidity dominating over exchangeable acidity. A strong positive correlation between exchangeable aluminium percentage and exchangeable acidity indicated the central role of aluminium in controlling soil acidity. High aluminium saturation was linked to intense weathering of aluminium-rich parent materials, while elevated organic carbon in forested hills and piedmonts increased pH-dependent acidity through variable charge development. The study identified exchangeable aluminium percentage as a reliable indicator of soil acidity, highlighting the risk of aluminium toxicity in Nagaland soils and the need for appropriate amelioration strategies.

Bekele *et al*. (2018) carried out a two-month incubation study on Dystric Nitisol soils to examine the impact of lime, vermicompost, and phosphorus fertilizer on soil chemical properties. The results indicated that the combined application of lime

(4 t $CaCO_3$ /ha) and vermicompost (7.5 t /ha) led to the greatest improvement in soil pH, increasing it from 4.83 in the control to 6.05, and markedly decreased exchangeable aluminium from 1.70 to 0.09 cmol kg^{-1}, demonstrating the effectiveness of organic amendments in reducing aluminium toxicity in acid soils.

Olubode *et al.* (2018) reported that the application of wood ash and cow dung significantly improved soil chemical properties in acid soil. Wood ash applied at 5 t/ha increased soil pH, organic carbon and microbial population compared to the control, indicating its potential as an effective organic amendment for improving soil fertility in acidic soils.

Kidanemariam *et al*. (2020) investigated the individual and combined effects of lime and vermicompost on soil chemical properties and barley productivity in acidic soils of the northwestern highlands of Ethiopia. The study demonstrated that vermicompost application, particularly when combined with lime, significantly increased soil pH, organic carbon, cation exchange capacity, and exchangeable base cations, while markedly reducing exchangeable acidity and aluminium. Both the main and interaction effects of vermicompost and lime contributed to improved nutrient availability and enhanced crop yield, with the highest grain yield obtained under integrated application. These results indicate that vermicompost plays an important role in ameliorating aluminium toxicity in acid soils by improving soil chemical conditions, especially when used in conjunction with liming materials.

Lauricella *et al*. (2020) evaluated the effectiveness of thirteen organic amendments, including manures, composts, biochars, and plant residues, in comparison with four inorganic amendments (lime, dolomite, gypsum, and KH_2PO_4) for alleviating soil acidity in two soils differing in pH buffering capacity. Application of organic amendments increased soil pH (measured in $CaCl_2$) by up to 0.32 and 0.62 units in the two soils, respectively. Among the organic materials, poultry manure, poultry litter biochar, and biosolids produced greater shoot growth responses than lime, indicating their superior potential in improving soil chemical conditions and reducing acidity-related constraints.

An and Park (2021) assessed the effects of wood ash (WA) and nitrogen fertilization on soil chemical properties and the growth of *Zelkova serrata* across different soil types, including acidic forest soils. Wood ash application significantly increased soil pH, organic matter, available phosphorus, and exchangeable base cations (Ca^{2+}, Mg^{2+}, and K^{+}), with the most pronounced improvements observed in acidic soils. Moderate WA rates enhanced biomass production and foliar Ca, K, and P concentrations, indicating improved soil fertility and nutrient availability. Although aluminium was not directly measured, the marked increase in soil pH and base saturation implies a likely reduction in aluminium solubility and toxicity, highlighting the indirect role of wood ash in alleviating acidity-related aluminium stress.

Islam *et al*. (2021) reported that organic amendments can effectively ameliorate both surface and subsoil acidity through multiple mechanisms. These include proton consumption by functional groups associated with organic materials, decarboxylation of organic acid anions during decomposition, and specific adsorption of organic molecules via ligand exchange, which leads to the release of OH^{-} ions. Additional OH^{-} ions are generated during reduction reactions in localized anaerobic microsites. The released hydroxyl ions subsequently react with exchangeable H^{+} and Al^{3+} ions, resulting in the formation of insoluble aluminium hydroxide and thereby reducing aluminium toxicity.

Zhang *et al*. (2023) evaluated rice-straw hydrochar as an amendment for alleviating aluminium toxicity in acidic red soils and compared its effects with pyrochar. Application of both materials significantly enhanced maize root elongation and reduced root Al accumulation by lowering total Al and the proportion of toxic Al^{3+} species in soil solution. Unlike pyrochar, hydrochar did not markedly improve soil pH buffering or cation exchange capacity but substantially increased dissolved organic carbon, which reduced Al activity through Al–DOC complexation and adsorption. Although hydrochar was less effective than pyrochar, the study demonstrated its potential as a cost-effective organic amendment for mitigating Al toxicity in acidic soils.

Terefe *et al*. (2024) evaluated the effects of vermicompost and lime, applied individually and in combination, on soil chemical properties and malt barley productivity in an acidic soil of northwest Ethiopia. The study demonstrated that vermicompost application, particularly when integrated with lime, significantly increased soil pH, organic carbon, total nitrogen, and available phosphorus, while markedly reducing exchangeable acidity and aluminium toxicity. The combined application of 5.31 t /ha vermicompost and 3.24 t /ha lime resulted in the highest improvement in soil fertility parameters and crop productivity. These findings highlight the effectiveness of vermicompost as an organic amendment for mitigating aluminium toxicity in acid soils, especially when used in conjunction with liming materials.

CHAPTER - III

MATERIALS AND METHODS

MATERIALS AND METHODS

The presented study entitled "***Alleviation of Aluminium toxicity of Mungbean in Acid Soil of Nagaland using Organic Materials***" was conducted at the experimental farm of the School of Agricultural Sciences (SAS), Medziphema Campus, Nagaland University. The same experimental protocol was followed in two trials, which were conducted separately during the years 2023 and 2024. The materials used and the methods followed for the execution of the experiment are detailed in this chapter under the following headings.

3.1 Experimental site

In accordance with the objectives of the study entitled "***Alleviation of Aluminium Toxicity of Mungbean in Acid Soil of Nagaland using Organic Materials***", a pot experiment was carried out at the Experimental Farm of the School of Agricultural Sciences (SAS), Medziphema Campus, Nagaland University. The experimental site is located at 20°45′43″ N latitude and 93°53′04″ E longitude, with an altitude of 310 m above mean sea level.

3.2 Climatic conditions

Medziphema falls under the humid sub-tropical climatic zone, characterized by moderate temperatures and medium to high annual rainfall, ranging from 200 to 250 cm. The mean maximum temperature during the summer season varies from 21°C to 32°C, while in winter it ranges between 13°C and 26°C, rarely falling below 8°C. The meteorological data recorded throughout the experimental period are presented in Table 3.1 and graphically illustrated in Figure 3.1.

3.3 Experimental details

3.3.1 Soil

Soil samples were collected from the surface layer (0–15 cm) of the experimental field of the School of Agricultural Sciences (SAS), Medziphema, Nagaland, for the pot experiment. The collected soil was air-dried and gently crushed to remove large aggregates and ensure uniformity. Thereafter, the soil samples were analysed for their chemical properties, and the results are presented in Table 3.2 and Table 3.3.

Table 3.1 Meteorological data recorded during the period of crop investigation (March to May) for both years 2023 and 2024

Month		Temperature (ºC)		Relative Humidity (%)		Total Rainfall (mm)
		Max	**Min**	**Max**	**Min**	
2023	**March**	29.1	14.7	92	53	76.0
	April	32.7	17.7	87	50	68.0
	May	32.8	20.8	86	56	86.3
2024	**March**	28.3	13.1	91.55	53.55	4.9
	April	31.6	16.4	90.3	51.65	11.3
	May	33.35	21	86	54.75	9.05

.

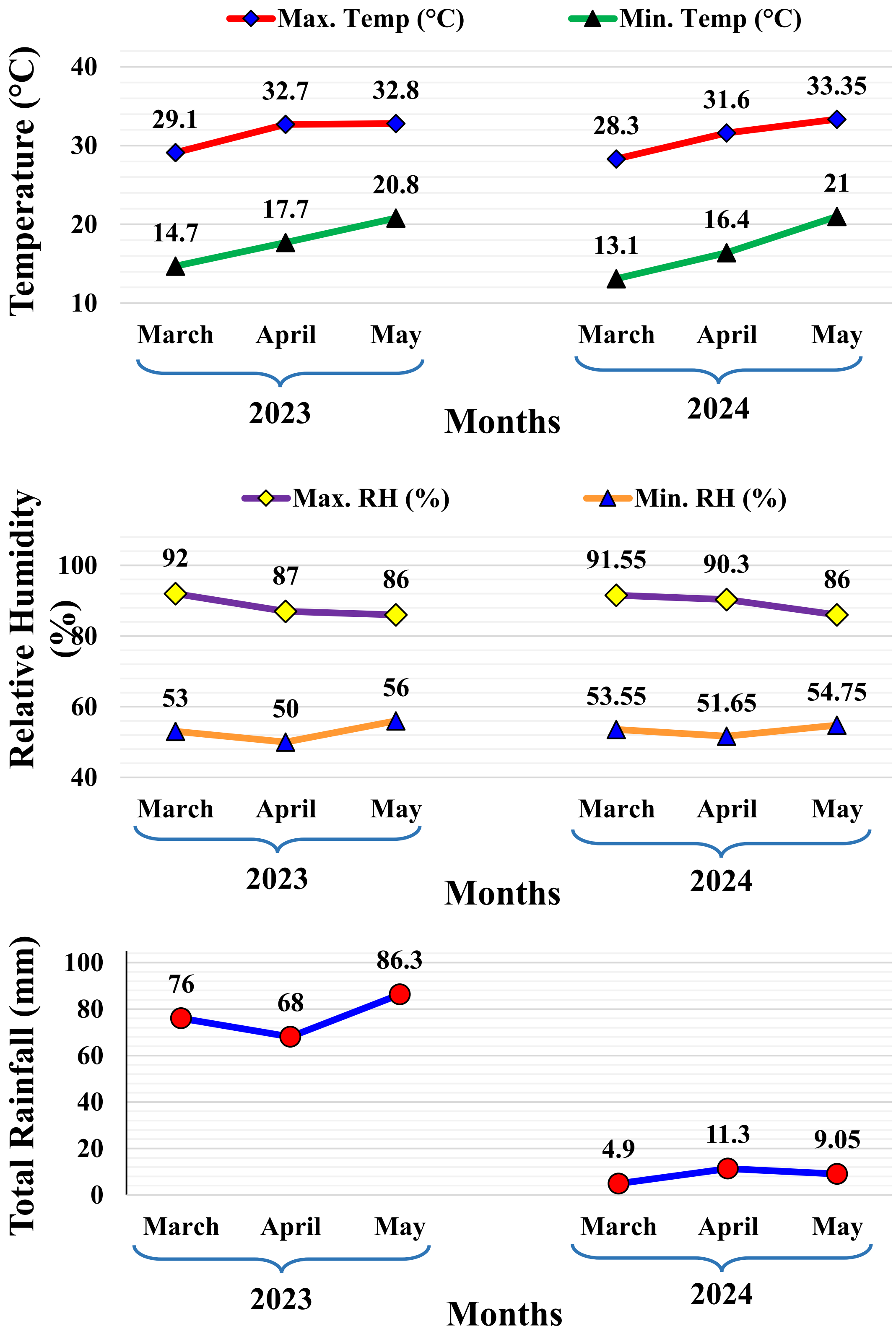

Fig. 3.1 Meteorological data recorded during the period of crop investigation (March to May) for both years 2023 and 2024

Table 3.2 Initial chemical properties of the soil used in the experiment

Sl.	Soil Parameters	Methods	2023	2024
1.	Soil pH	Soil: Water suspension (1:2.5) using glass electrode pH meter (Richards, 1954)	4.76	4.78
2.	EC (dS/m)	Conductivity bridge (Richards, 1954)	0.06	0.07
3.	CEC [cmol(p^+) kg^{-1}]	1N NH_4OAc at pH 7.0 (Chapman, 1965).	10.8	10.9
4.	ECEC [cmol(p^+) kg^{-1}]	Ex. bases + Ex. acidity	4.76	4.85
5.	Ex. Al [cmol(p^+) kg^{-1}]	NaF solution (4%) in 1 N KCL (Baruah and Barthakur, 1997)	2.13	2
6.	Ex. acidity [cmol(p^+) kg^{-1}]	1N KCl solution titrated against 0.1N NaOH sol. (Baruah and Barthakur, 1997)	2.75	2.63
7.	Ex. H [cmol(p^+) kg^{-1}]	Exchangeable acidity - Exchangeable Al^{3+}	0.62	0.63
8.	TPA [cmol(p^+) kg^{-1}]	$Bacl_2$ - triethanolamine extract buffered at pH 8.0-8.2 (Baruah and Barthakur, 1997)	14.2	14
9.	Reserve acidity [cmol(p^+) kg^{-1}]	TPA- Ex. acidity	11.57	11.37
10.	Al saturation (%)	Exchangeable Al /Effective CEC X 100	44.7	41.2
11.	Ex. Ca [cmol(p^+) kg^{-1}]	Versanate method (Black, 1965)	1.3	1.4
12.	Ex. Mg [cmol(p^+) kg^{-1}]	Versanate method (Black, 1965)	0.5	0.6
13.	Ex. K [cmol(p^+) kg^{-1}]	Neutral normal ammonium acetate extractable K - water soluble K.	0.13	0.13
14.	Ex. Na [cmol(p^+) kg^{-1}]	Neutral normal ammonium acetate extractable Na - water soluble Na.	0.08	0.09
15.	Base saturation (%)	Sum of basic cations/CEC X 100	18.61	20.37
16.	O.C (%)	Walkley and Black rapid titration method (1934)	1.17	1.2

Table 3.3 Initial forms of aluminium in the experimental soil

Sl.	Soil Parameters	Methods	2023	2024
1.	Exchangeable aluminium (KCl extractable Al) (mg/kg)	Colorimetric method (Chen and He, 1985)	149.24	149.24
2.	Organic bound aluminium (Pyrophosphate extractable Al) (mg/kg)		182.62	186.6
3.	Amorphous aluminium (Acid ammonium oxalate extractable Al) (mg/kg)		3197.19	3130.35
4.	Cumulative amorphous and crystalline aluminium (Dithionate citrate bicarbonate extractable Al) (mg/kg)		4513.52	4487.01
5.	Crystalline aluminium (mg/kg)	Amorphous aluminium minus dithionate citrate bicarbonate extractable Al	1316.33	1356.66

3.3.2 Chemical analysis of organic materials

The organic materials used in the experiment were analyzed for their chemical properties, and the analytical data are presented in Table 3.4

Table 3.4 Chemical properties of organic materials used in the experiment

Sl.	Parameters	Wood Ash		Poultry Manure		Vermicompost		Rice Residue		Soybean Residue	
		2023	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**	**2023**	**2024**
1	Total Organic carbon (%)	0.85	0.94	28.67	30.08	20.14	19.13	38.32	39.56	42.38	42.15
2	Total Nitrogen (%)	0.25	0.22	2.82	2.88	1.79	1.82	0.56	0.59	1.48	1.43
3	Total Phosphorus (%)	0.27	0.31	2.17	2.13	1.04	1.09	0.22	0.22	0.4	0.45
4	Total Potassium (%)	3.12	3.21	1.82	1.91	1.11	1.1	0.89	0.91	1.07	1.03
5	Total Calcium (%)	18.32	19.13	1.94	2.01	1.43	1.5	0.69	0.72	0.9	0.86
6	Total Magnesium (%)	1.46	1.38	0.75	0.7	0.51	0.55	0.34	0.32	0.38	0.4

3.3.3 Treatment details

T_1 : Control

T_2 : Absolute control

T_3 : Wood ash @ 2t ha^{-1}

T_4 : Poultry manure @ 2t ha^{-1}

T_5 : Rice residues @ 2t ha^{-1}

T_6 : Vermicompost @ 2t ha^{-1}

T_7 : Wood ash@2t ha^{-1} + Poultry manure @ 2t ha^{-1}

T_8 : Wood ash @ 2t ha^{-1} + Rice residues @ 2t ha^{-1}

T_9 : Wood ash @ 2t ha^{-1} + Vermicompost @ 2t ha^{-1}

T_{10} : Soybean residue @ 2t ha^{-1}

T_{11} : Wood ash @ 2t ha^{-1} + Soybean residue @ 2t ha^{-1}

3.3.4 Treatment application and soil incubation

The air-dried soil was placed in polyethylene bags and treated with organic materials, applied either individually or in combinations as per the treatment details. The recommended dose of nitrogen, phosphorus and potassium ($N:P_2O_5:K_2O$) at 25:50:25 kg ha^{-1} was applied through urea, single superphosphate (SSP) and muriate of potash (MOP)**,** respectively. On a soil weight basis, the corresponding quantities of fertilizers applied per polyethylene bag were 0.27 g urea, 1.53 g SSP and 0.20 g MOP**.**

All organic materials were applied uniformly at the rate of 2 t ha^{-1}**,** which corresponded to 9.82 g per polyethylene bag. The fertilizers and organic amendments were thoroughly mixed with the soil prior to incubation. The absolute control treatment did not receive any fertilizers or organic materials.

Following treatment application, the soils were incubated for four weeks at room temperature to allow adequate interaction between the soil and the applied organic amendments.

3.3.5 Pot experiment

A pot experiment was conducted to evaluate the ameliorative effects of selected organic materials, applied individually as well as in combination, on aluminium toxicity in acid soil. The treated soils were incubated for a period of four weeks prior to sowing in order to allow adequate interaction between the soil and the applied organic amendments. The experiment was carried out under ambient field conditions, with the pots maintained outdoors and exposed to natural environmental conditions throughout the experimental period.

3.3.5.1 Design and Layout of Experiment

The experiment was laid out following a Completely Randomized Design (CRD) with eleven treatments, each replicated three times. Thus, a total of thirty-three pots were used for the study. The experimental units were grouped into three replications, with each replication consisting of eleven pots representing the individual treatments. The schematic representation of the experimental layout is presented in Fig. 3.2.

Crop	Mungbean
Variety	HUM- 12
Season	Summer
Experimental design	Completely Randomized Design
Number of treatments	11
Number of replications	3
Total number of pots	33
Weight of soil in each pot	11 kg

3.3.6 Cultivar description

The mungbean (*Vigna radiata* L. Wilczek) variety **HUM-12**, also registered as *Malviya Janchetna*, was developed from the cross **HUM-5 × DPM 90-1** at the Institute of Agricultural Sciences, Banaras Hindu University, Varanasi. This variety was officially registered under Certificate of Registration No. 50 of 2009 by the Protection of Plant Varieties and Farmers' Rights Authority (PPV&FRA), Government of India, and has been commercialized since 2003. It is characterized by medium plant height,

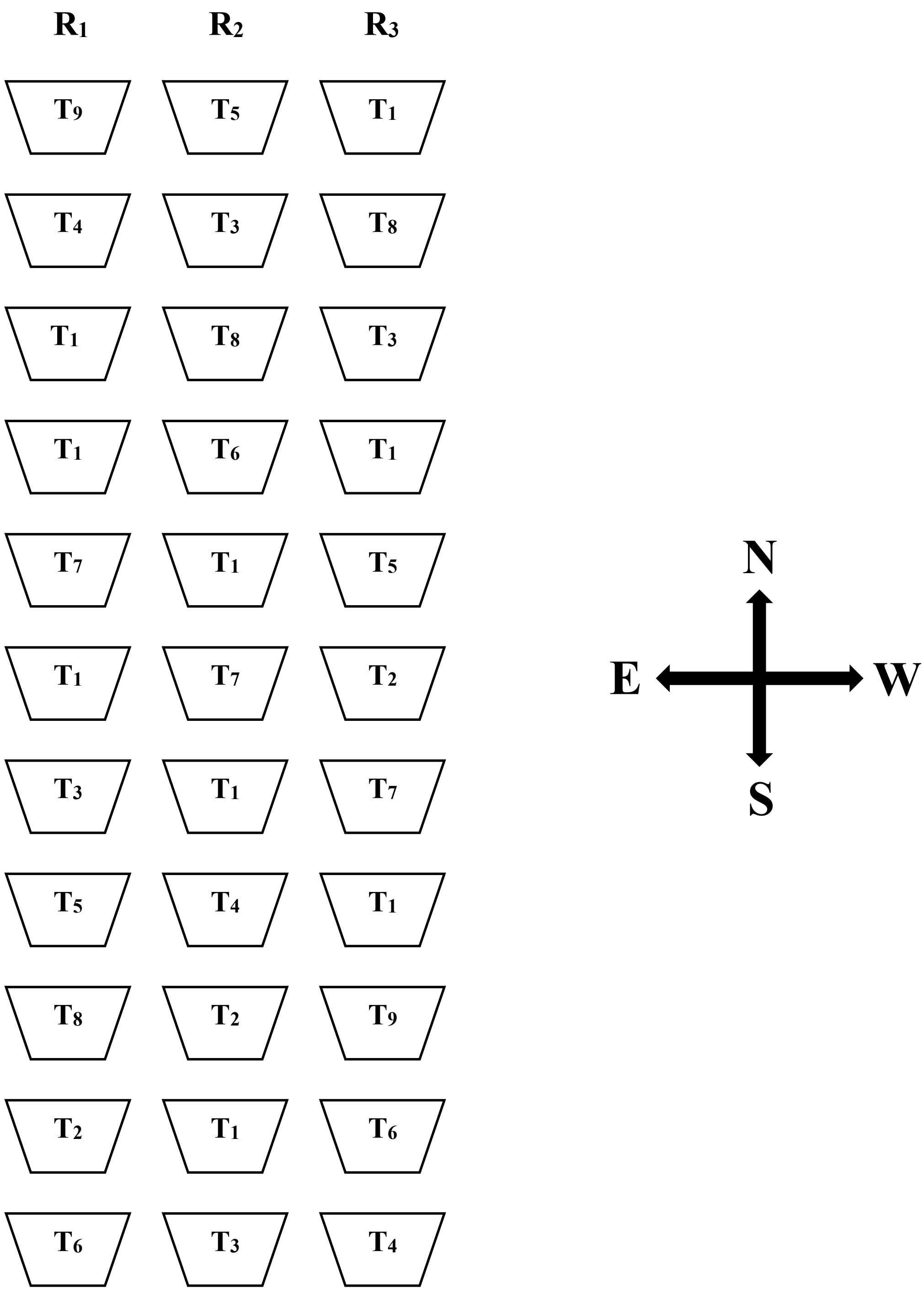

Fig 3.2: Layout of the Experiment

early maturity, increased branching, dark leaves, brownish-black mature pods, and a slightly curved pod tip**.**

3.4 Details of crop raising

3.4.1 Preparation of pots

The pots used for the experiment were thoroughly cleaned to remove any adhering soil or contaminants and were allowed to air-dry for two days prior to use. After completion of the four-week soil incubation period, all pots were uniformly filled with 11 kg of the incubated soil. Soil filling was carried out on 20 March 2023 for the first trial and on 14 March 2024 for the second trial. The soil in each pot was gently levelled to maintain a uniform soil surface and ensure consistency among treatments.

3.4.2 Seed rate and sowing

Seeds of mungbean (*Vigna radiata L.*) cv. HUM-12 were soaked in water for 24 hours prior to sowing to ensure uniform and rapid germination. Five healthy and uniform seeds were sown per pot at a depth of 1.5 cm. Sowing was carried out on 21 March 2023 for the first trial and on 15 March 2024 for the second trial. After establishment, thinning was performed at 15 days after sowing**,** retaining three plants per pot for subsequent growth and observations.

3.4.3 Irrigation

Irrigation was provided manually as and when required to maintain optimum soil moisture throughout the crop growth period. Care was taken to avoid moisture stress and waterlogging in the pots.

3.4.4 After-care

Uniform after-care practices were followed for all treatments throughout the crop growth period of mungbean (*Vigna radiata* L.) cv. HUM-12. Hand weeding was carried out at 20, 30 and 45 days after sowing (DAS) to control weed growth in the pots. The crop was regularly monitored for insect and pest incidence. Insect pests were managed through hand picking and spraying of imidacloprid 17.8 SL and neem oil at 30 and 45 DAS, following recommended plant protection practices.

3.4.5 Harvesting and Threshing

Harvesting of pods was done in two to three pickings. The first picking was followed by the second and third pickings as the pods matured. After completion of the final pod picking, the crop was harvested at ground level for recording stover yield. The harvested pods were dried for 5–10 days and then threshed. After threshing, the seeds were manually separated and cleaned.

3.5 Biometric observation

3.5.1 Growth parameters

3.5.1.1 Plant height (cm)

Plant height of mungbean (*Vigna radiata* L.) cv. HUM-12 was measured from the ground level to the tip of the main shoot at 25 days after sowing (DAS), 50 DAS and at harvest. Observations were recorded from the plants maintained in each pot, and the average plant height was computed from the replications for statistical analysis.

3.5.1.2 Number of branches per plant

The number of branches per plant was recorded at 25 days after sowing (DAS), 50 DAS and at harvest. The average number of branches per plant was computed from observations recorded in three replications.

3.5.1.3 Number of leaves per plant

The number of leaves per plant was recorded at 25 days after sowing (DAS), 50 DAS and at harvest. The average number of leaves per plant was computed from observations recorded in three replications.

3.5.2 Yield parameters

3.5.2.1 Number of pods per plant

The number of pods per plant was determined by counting all pods on the tagged plants in each treatment. The mean number of pods per plant was worked out using data from three replications.

3.5.2.2 Pod length (cm)

Pod length was measured by randomly selecting five pods from the tagged plant in each treatment. Measurements were recorded in centimetres, and the mean pod length was calculated based on the average of five pods across three replications.

3.5.2.3 Number of seeds per pot

The number of seeds per pod was determined by counting the seeds in the five pods selected for pod length measurement under each treatment. The average number of seeds per pod was calculated and the mean value was worked out based on three replications.

3.5.2.4 Seed yield (g/pot)

Pods were harvested separately from each pot at maturity and dried under ambient conditions. The dried pods were manually threshed and cleaned to obtain seeds. The seed yield obtained from each pot was recorded in grams, and the mean seed yield was calculated from three replications.

3.5.2.5 Stover yield (g/pot)

After the final pod picking, plants from each pot were harvested at ground level. The harvested plant material was dried under ambient conditions to a constant weight, and the stover yield per pot was recorded in grams. The mean stover yield was calculated from three replications.

3.5.2.6 Harvest index (%)

Harvest index was calculated using the data on seed yield and stover yield. In this study, seed yield was considered as the economic yield, while the sum of seed and stover yield was taken as the biological yield. Harvest index for each treatment was computed using the following formula, and the mean harvest index was calculated from three replications:

$$\text{Harvest index}(\%) = \frac{\text{Economic yield (seed yield)}}{\text{Biological yield (seed yield + stover yield)}} \times 100$$

3.5.3 Root parameters

3.5.3.1 Root length (cm)

Root length was measured at 48 hours after sowing to assess early radicle emergence and initial root growth. At this stage, root length was recorded from the point of seed attachment to the tip of the primary (radicle) root. Subsequent measurements were taken at 30 days after sowing and at harvest, where root length was measured from the collar region to the tip of the longest root.

3.5.3.2 Fresh and dry root weight (g)

Fresh root weight was recorded at 48 hours after sowing, 30 days after sowing, and at harvest. At each stage, plants were carefully uprooted, and roots were gently washed under running water to remove adhering soil particles. The roots were blotted dry using absorbent paper and weighed immediately to record fresh root weight. For dry root weight, the same root samples were oven-dried at 65 ± 2 °C until constant weight was attained and then weighed.

3.5.3.3 Relative root length (%)

Relative root length was determined at 48 hours after sowing, 30 days after sowing, and at harvest. It was calculated by expressing the root length of plants under each treatment as a percentage of the root length recorded under the absolute control at the corresponding stage.

$$\text{Relative root length}(\%) = \frac{\text{Root length under treatment}}{\text{Root length under absolute control}} \times 100$$

3.6 Plant analysis

The mungbean seed and stover samples were thoroughly washed with deionized water to remove surface contaminants, initially sun-dried, and then oven-dried at 70 °C until a constant weight was attained. The dried samples were ground into a fine powder and stored in properly labelled polyethylene bags for further analysis.

3.6.1 Nitrogen content in seed and stover (%)

One gram (1 g) of the powdered sample was digested with concentrated H_2SO_4 in the presence of a digestion mixture ($CuSO_4$ + K_2SO_4) until the digest became clear with a bluish-green colour. After digestion, the sample was carefully diluted with distilled water to a known volume. A measured aliquot of the digest was then transferred to a Micro-Kjeldahl distillation unit, where the liberated ammonia was distilled and absorbed in boric acid containing a mixed indicator. The absorbed ammonia was subsequently titrated against standard 0.1 N H_2SO_4, and the nitrogen content was calculated following the procedure described by Black (1965).

3.6.2 Digestion of plant sample for P, K, Ca, Mg and Al

Half a gram (0.5 g) of the powdered sample was pre-digested overnight with concentrated HNO_3. The pre-digested material was then subjected to wet digestion using a di-acid mixture of HNO_3 and $HClO_4$ (10:4, v/v) on a hot plate until a clear, colourless digest with thread-like fumes was obtained. After complete digestion, the residue was dissolved in 6 N HCl, filtered through Whatman No. 42 filter paper, and transferred into a 100 mL volumetric flask. The final volume was made up to 100 mL with double-distilled water, and the extract was stored for subsequent analysis.

3.6.3 Phosphorus content in seed and stover (%)

Phosphorus content in the mungbean seed and stover samples was determined using the vanadomolybdophosphoric yellow colour method as outlined by Jackson (1973).

3.6.4 Potassium content in seed and stover (%)

The aliquot after digestion for estimation of potassium was diluted to the desired level and were analysed using flame photometer as described by Chapman and Pratt (1961)

3.6.5 Calcium content in seed and stover (%)

The Calcium content in seed and stover was analysed with the digested aliquot and determined by versenate (EDTA) method (Gupta, 1999)

3.6.6 Magnesium content in seed and stover (%)

The Magnesium content in seed and stover was analysed with the digested aliquot and determined by versenate (EDTA) method (Gupta, 1999)

3.6.7 Aluminium content in seed and stover (mg/kg)

The aluminium content in seed and stover was determined using an Atomic Absorption Spectrophotometer following the method described by Page *et al.* (1982).

3.6.8 Nutrient uptake

Uptake of different nutrients was computed separately for seed and stover by multiplying the respective nutrient concentrations with their corresponding seed and stover yield data.

For N, P, K, Ca and Mg uptake in seed and stover

$$\text{Nutrient uptake (mg/pot)} = \frac{\text{Nutrient content (\%)} \times \text{Dry matter yield (g/pot)} \times 1000}{100}$$

For Al uptake in seed and stover (mg/kg)

$$\text{Aluminium uptake (mg/pot)} = \frac{\text{Al content (mg/kg)} \times \text{Dry matter yield (g/pot)}}{1000}$$

3.6.9 Protein content in seed and stover (%)

Protein content in mungbean seed and stover was calculated by multiplying their respective nitrogen contents by a conversion factor of 6.25, using the following formula:

$$\text{Protein content (\%)} = \text{Nitrogen content (\%)} \times 6.25$$

3.7 Soil solution analysis

After sowing, the pots were irrigated, and a small V-shaped furrow was gently created in the soil without disturbing the sown seeds to facilitate soil solution collection. After 48 hrs of equilibration, the soil solution that accumulated in the furrow was collected in situ using a syringe. Gentle suction and pressure were applied to obtain sufficient volume. The collected soil sample was used for analysis of the following parameters:

3.7.1 pH of soil solution

The pH of the soil solution was measured using a digital pH meter following the electrometric method described by Jackson (1973)

3.7.2 Calcium (ppm)

Calcium in the soil solution was determined by EDTA titration method using mureoxide indicator as described by Black (1965)

3.7.3 Magnesium (ppm)

Magnesium in the soil solution was determined by EDTA titration method using EBT indicator as described by Black (1965)

3.7.4 Potassium (ppm)

Potassium in the soil solution was determined using a flame photometer following the method described by Jackson (1973)

3.7.5 Monomeric aluminium (ppm)

Monomeric aluminium in soil solution was determined by the pyrocatechol violet (PCV) colorimetric method. The PCV reagent (0.0375%) was prepared by dissolving 77 mg of pyrocatechol violet in 200 mL deionized water. Hexamine buffer (15%) was prepared by dissolving 75 g hexamine in 400 mL deionized water, adding 16 mL concentrated ammonia solution, adjusting the pH to 6.2 with 5 M HCl, and making the volume up to 500 mL. An iron interference reagent was freshly prepared by dissolving 100 mg 1,10-phenanthroline and 500 mg ascorbic acid in 100 mL deionized water.

A standard calibration curve was prepared using aluminium concentrations of 0, 2, 5, 10, 15, 20 and 25 µM by pipetting 3.0 mL of each standard into a 10 mL vial, followed by the addition of 0.50 mL iron interference reagent, 0.20 mL PCV reagent and 1.0 mL hexamine buffer. Absorbance was recorded at 585 nm.

For soil solution analysis, 3.0 mL of sample filtered through a 0.22 µm membrane filter was treated with the same reagents, and absorbance was measured at 585 nm after 60 seconds. Monomeric aluminium concentration was calculated from the standard calibration curve. This method is described by Kerven *et al*. (1989).

3.7.6 Total aluminium (ppm)

Total aluminium in the soil solution was determined after acid digestion followed by estimation using an Atomic Absorption Spectrophotometer (AAS), as described by Page *et al*. (1982)**.** Soil solution samples were acid-digested to convert all forms of aluminium into soluble form. After digestion, the samples were diluted to a known volume with deionized water and analysed for aluminium concentration using AAS. The total aluminium content was calculated using standard aluminium solutions.

3.8 Soil solid phase analysis

After harvest, the soil from each pot was collected, air-dried under shade, gently ground, and passed through a 2-mm sieve for subsequent laboratory analysis. The processed soil samples were then used for the estimation of the following parameters:

3.8.1 Soil pH

Soil pH was determined in a soil–water suspension (1:2.5) using a glass electrode pH meter following the procedure described by Richards (1954).

3.8.2 Electrical conductivity (dSm^{-1})

Electrical conductivity of the soil was obtained in soil water (1:2) extract using conductivity meter as described by Richard (1954).

3.8.3 Cation exchange capacity [cmol (p^+) kg^{-1}]

The cation exchange capacity (CEC) of the soil was determined using 1 N ammonium acetate (NH_4OAc) at pH 7.0 following the procedure described by Chapman (1965).

3.8.4 Effective cation exchange capacity [cmol (p^+) kg^{-1}]

The effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable bases (Ca, Mg, K and Na) and exchangeable acidity (H + Al), using the values obtained from their respective determinations.

3.8.5 Exchangeable aluminium [cmol (p^+) kg^{-1}]

Exchangeable aluminium in the soil was determined using 1 N KCl as the extractant. An aliquot of the extract was treated with 5 mL of 4% sodium fluoride (NaF) solution and titrated against 0.1 N HCl until the disappearance of the pink colour, following the procedure described by Baruah and Barthakur (1997).

3.8.6 Exchangeable acidity [cmol (p^+) kg^{-1}]

Exchangeable acidity in the soil was determined by using 1N KCl as extractant and then the extract was filtered, boiled and titrated against 0.1 N NaOH using phenolphthalein indicator as described by Baruah and Barthakur (1997).

3.8.7 Exchangeable H^+ [cmol (p^+) kg^{-1}]

Exchangeable hydrogen (H^+) was calculated as the difference between exchangeable acidity and exchangeable aluminium.

$$\text{Exchangeable } H^+ = \text{Exchangeable acidity} - \text{Exchangeable } Al^{3+}$$

3.8.8 Total potential acidity [cmol (p^+) kg^{-1}]

Total potential acidity of the soil was determined using barium chloride–triethanolamine ($BaCl_2$ – TEA) extract buffered at pH 8.0–8.2, following the method described by Baruah and Barthakur (1997).

3.8.9 Reserve acidity [cmol (p^+) kg^{-1}]

Reserve acidity of the soil was calculated as the difference between total potential acidity and exchangeable acidity.

$$\text{Reserve acidity} = \text{Total potential acidity} - \text{Exchangeable acidity}$$

3.8.10 Aluminium saturation (%)

Aluminium saturation was calculated as the percentage of exchangeable aluminium (Al^{3+}) in relation to the effective cation exchange capacity (ECEC) of the soil, using the following formula:

$$\text{Aluminium saturation (\%)} = \frac{\text{Exchangeable Al}}{\text{Effective CEC}} \times 100$$

3.8.11 Exchangeable calcium [cmol (p^+) kg^{-1}]

Exchangeable calcium in the soil was extracted with neutral normal ammonium acetate and determined by titration with 0.01 N EDTA (versenate) using murexide indicator, following the procedure described by Black (1965).

3.8.12 Exchangeable magnesium [cmol (p^+) kg^{-1}]

Exchangeable magnesium [cmol(p^+) kg^{-1}] was extracted with neutral normal ammonium acetate and determined by titration with 0.01 N EDTA (versenate) using Eriochrome Black T (EBT) indicator, following the procedure described by Black (1965).

3.8.13 Exchangeable potassium [cmol (p^+) kg^{-1}]

Exchangeable potassium [cmol(p^+) kg^{-1}] was estimated as the difference between neutral normal ammonium acetate-extractable potassium and water-soluble potassium, following the procedure described by Jackson (1973).

3.8.14 Exchangeable sodium [cmol (p^+) kg^{-1}]

Exchangeable sodium was extracted with neutral normal ammonium acetate (1N NH_4OAc) at pH 7.0 and the sodium concentration in the extract was determined using a flame photometer, following the procedure described by Jackson (1973).

3.8.15 Base saturation (%)

Base saturation was calculated as the percentage of the cation exchange capacity occupied by exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) using the following formula:

$$\text{Base saturation (\%)} = \frac{\text{Sum of basic cations}}{\text{CEC}} \times 100$$

3.8.16 Organic carbon (%)

Organic carbon in soil was determined by Walkley and Black's method (Walkley and Black, 1934). The principle is to oxidize the organic carbon present in organic matter with potassium dichromate in presence of sulphuric acid and to titrate the residual $K_2Cr_2O_7$ solution with standard ferrous ammonium sulphate. The result was expressed in percentage.

3.8.17 Forms of Aluminium

3.8.17.1 Exchangeable aluminium (KCl extractable Al)

KCl-extractable aluminium was extracted by shaking the soil sample with 100 mL of 1 M KCl solution (pH 7.0) for one hour on a mechanical shaker following the method described by Black (1965). The suspension was then filtered through Whatman No. 42 filter paper, and the filtrate was preserved for aluminium analysis.

3.8.17.2 Organic bound aluminium (Pyrophosphate extractable Al)

Pyrophosphate-extractable aluminium was extracted by shaking 1 g of soil with 60 mL of 0.1 M sodium pyrophosphate ($Na_4P_2O_7$) solution overnight on a mechanical shaker. The extract was centrifuged and evaporated to dryness. The dried residue was oxidized twice with 5 mL of concentrated nitric acid (16 M), followed by treatment with 10 mL of 6 M hydrochloric acid and evaporation to dryness. The final residue was dissolved in 10 mL of 0.6 M hydrochloric acid, filtered, and the filtrate was made up to volume in a 250 mL volumetric flask for aluminium analysis (Agriculture Canada, 1984).

3.8.17.3 Amorphous aluminium (Acid ammonium oxalate extractable Al)

One gram of soil was shaken for four hours with 60mL of 0.2 M acid ammonium oxalate solution on a mechanical shaker. The extract was centrifuged and evaporated to dryness. The residue was moistened with distilled water, treated with 10 mL of 6 M HCl, and evaporated to dryness. The final residue was dissolved in 10 mL of 0.6 M HCl, filtered, and the filtrate was preserved for subsequent aluminium determination (Agriculture Canada, 1984).

3.8.17.4 Cumulative amorphous and crystalline aluminium (Dithionate citrate bicarbonate extractable Al)

One gram of soil was treated with 40 mL of 0.3 M sodium citrate and 5 mL of 0.1 M sodium bicarbonate solution. The mixture was heated for 15 minutes, after which 2 g of sodium dithionite was added and the suspension was shaken for 15 minutes under hot conditions. The extract was centrifuged, and the process was repeated. The combined extract was oxidized with 5 mL of 16 M HNO_3, followed by treatment with 10 mL of 6 M HCl and evaporation to dryness. The residue was dissolved in 10 mL of 0.6 M HCl, filtered into a 250 mL volumetric flask, and the filtrate was preserved for subsequent aluminium determination (CSSC Subcommittee on Methods of Analysis, 1978).

3.8.17.5 Crystalline aluminium (Amorphous aluminium minus dithionate citrate bicarbonate extractable Al)

Crystalline aluminium was calculated by subtracting the Dithionite–Citrate–Bicarbonate (DCB) extractable aluminium from the total amorphous aluminium content.

$$\text{Crystalline Al} = \text{Amorphous Al} - \text{DCB} - \text{extractable Al}$$

Procedure for Colorimetric Determination of Aluminium

Aluminium present in all soil extracts was determined by the colorimetric method described by Chen and He (1985).

Reagents

a) **Calcium chloride–hydroxylamine hydrochloride solution**
One gram of $CaCO_3$ (AR) was dissolved in 25 mL of distilled water. About 1.5 mL of 12 N HCl was added dropwise until complete dissolution. The solution was heated gently to evaporate CO_2, cooled, and 2 g of hydroxylamine hydrochloride was added. The final volume was made up to 250 mL with distilled water.

b) **Potassium ferricyanide solution [$K_3Fe(CN)_6$]**
0.3 g of potassium ferricyanide was dissolved in distilled water and diluted to 250 mL

c) **Alizarin Red-S solution**
0.31 g of Alizarin Red-S was dissolved and the volume was made up to 250 mL with distilled water.

d) **Sodium acetate–thioglycolic acid buffer**
35.8 g of hydrated sodium acetate ($NaOAc \cdot 3H_2O$) or 21.7 g of anhydrous sodium acetate was dissolved in distilled water. Two millilitres of thioglycolic acid were added and the volume was made up to 250 mL.

e) **Standard aluminium solution (500 mg L^{-1})**
840.12 mg of aluminium ammonium sulphate [$AlNH_4(SO_4)_2 \cdot 12H_2O$] was dissolved and made up to 100 mL with distilled water.

f) Working standard aluminium solution (5 mg L^{-1})

10 mL of the 500 mg L^{-1} standard solution was diluted to 100 mL with distilled water.

Preparation of Standard Curve

For preparation of the standard curve, 0, 1, 2, 3, 4, 5, 6 and 7 mL aliquots of the 5 mg L^{-1} working standard solution were taken in 50 mL volumetric flasks. The same quantity of extracting solution as used for unknown samples was added. To each flask, 6.3 mL of calcium chloride–hydroxylamine hydrochloride solution was added, followed by 6.3 mL of potassium ferricyanide solution. Then, 5 mL of sodium acetate–thioglycolic acid buffer was added and allowed to stand for 10 minutes. Subsequently, 5 mL of Alizarin Red-S solution was added, the volume was made up to the mark, and the solutions were allowed to stand for 90 minutes. The absorbance was measured at 475 nm using a spectrophotometer, and a standard curve was prepared by plotting optical density against aluminium concentration.

Determination of Aluminium in Unknown Samples

Appropriate aliquots of soil extracts were taken in 50 mL volumetric flasks. To each flask, 6.25 mL of calcium chloride–hydroxylamine hydrochloride solution was added, followed by 6.25 mL of potassium ferricyanide solution. Five millilitres of sodium acetate–thioglycolic acid buffer was then added and allowed to stand for 10 minutes. Subsequently, 5 mL of Alizarin Red-S solution was added, the volume was made up to the mark, and the solutions were allowed to stand for 90 minutes. Absorbance was measured at 475 nm, and aluminium concentration in the unknown samples was determined using the standard curve.

3.9 Statistical analysis

The data related to each character was analyzed statistically by applying the technique of analysis of variance (Cochran and Cox, 1957) and the significance of different source of variations was tested using Fisher Schedecor 'F' test at 0.05 level of probability.

PLATE 1 Soil sample collection

PLATE 2 Preparation of soil samples for incubation

PLATE 3 General view of the experimental site

CHAPTER - IV

RESULTS AND DISCUSSION

RESULTS AND DISCUSSION

A research investigation entitled "Alleviation of Aluminium toxicity of Mungbean in acid soil of Nagaland using organic materials" was undertaken during the summer seasons of 2023 and 2024 under acidic soil conditions of Nagaland. The observations recorded during the course of experimentation for both years were systematically compiled and subjected to appropriate statistical analysis to evaluate the magnitude of variation among different treatments. The experimental results have been presented in the form of relevant tables and figures and interpreted based on scientific reasoning, supported by experimental evidence and available literature, in order to draw logical and reliable conclusions of scientific and practical importance.

4.1 Effect of different aluminium-alleviating organic materials on growth and yield of mungbean in acid soil.

4.1.1 Growth parameters

The data recorded on growth parameters, namely plant height (cm), number of branches per plant, and number of leaves per plant, as influenced by different Al-alleviating organic materials at 25 days after sowing (DAS), 50 DAS, and at harvest stage, are presented and discussed in the following sections.

4.1.1.1 Plant height (cm)

The plant height (cm) as influenced by different organic materials is given in Table 4.1, and its graphical presentation has been shown in Fig. 4.1. The application of different organic materials significantly influenced plant height (cm) at all growth stages during both trials conducted in 2023 and 2024, as well as in the pooled analysis of the two years.

During the first trial (2023) at 25 DAS, treatment T_9 (wood ash + vermicompost) recorded the highest plant height (14.24 cm) among all the treatments, while the lowest value of 6.80 cm was observed under treatment T_2 (absolute control). Among the single amendments, treatment T_6 recorded the maximum plant height (12.58 cm). Similarly, at 50DAS, treatment T_9 (wood ash + vermicompost) registered the maximum plant

Table 4.1 Effect of different aluminium-alleviating organic materials on *plant height* of mungbean in acid soil

Treatments	Plant height (cm)								
	25DAS			50DAS			Harvest		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	7.98	8.17	8.08	19.26	19.91	19.59	31.85	31.71	31.78
T_2: Absolute control	6.80	6.62	6.71	16.55	16.77	16.66	24.09	24.14	24.12
T_3: WA @ 2t ha^{-1}	12.21	12.29	12.25	26.02	25.83	25.93	39.98	40.16	40.07
T_4: PM @ 2t ha^{-1}	11.77	11.63	11.70	24.02	23.83	23.93	38.51	38.53	38.52
T_5: RR @ 2t ha^{-1}	8.77	9.20	8.99	21.58	21.61	21.60	36.60	36.40	36.50
T_6: VC @ 2t ha^{-1}	12.58	12.60	12.59	27.32	27.71	27.51	40.81	41.30	41.05
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	13.34	13.67	13.51	30.75	31.64	31.20	42.91	42.95	42.93
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	12.31	12.30	12.30	26.16	26.21	26.19	40.54	40.88	40.71
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	14.24	14.42	14.33	32.60	33.13	32.86	44.61	44.68	44.65
T_{10}: SR @ 2t ha^{-1}	10.43	10.54	10.49	22.97	22.93	22.95	37.51	37.62	37.56
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	12.56	12.74	12.65	27.69	27.55	27.62	41.60	42.02	41.81
SEm±	0.13	0.28	0.15	0.46	0.38	0.30	0.30	0.53	0.30
CD at 5%	0.37	0.81	0.44	1.36	1.11	0.85	0.87	1.54	0.86

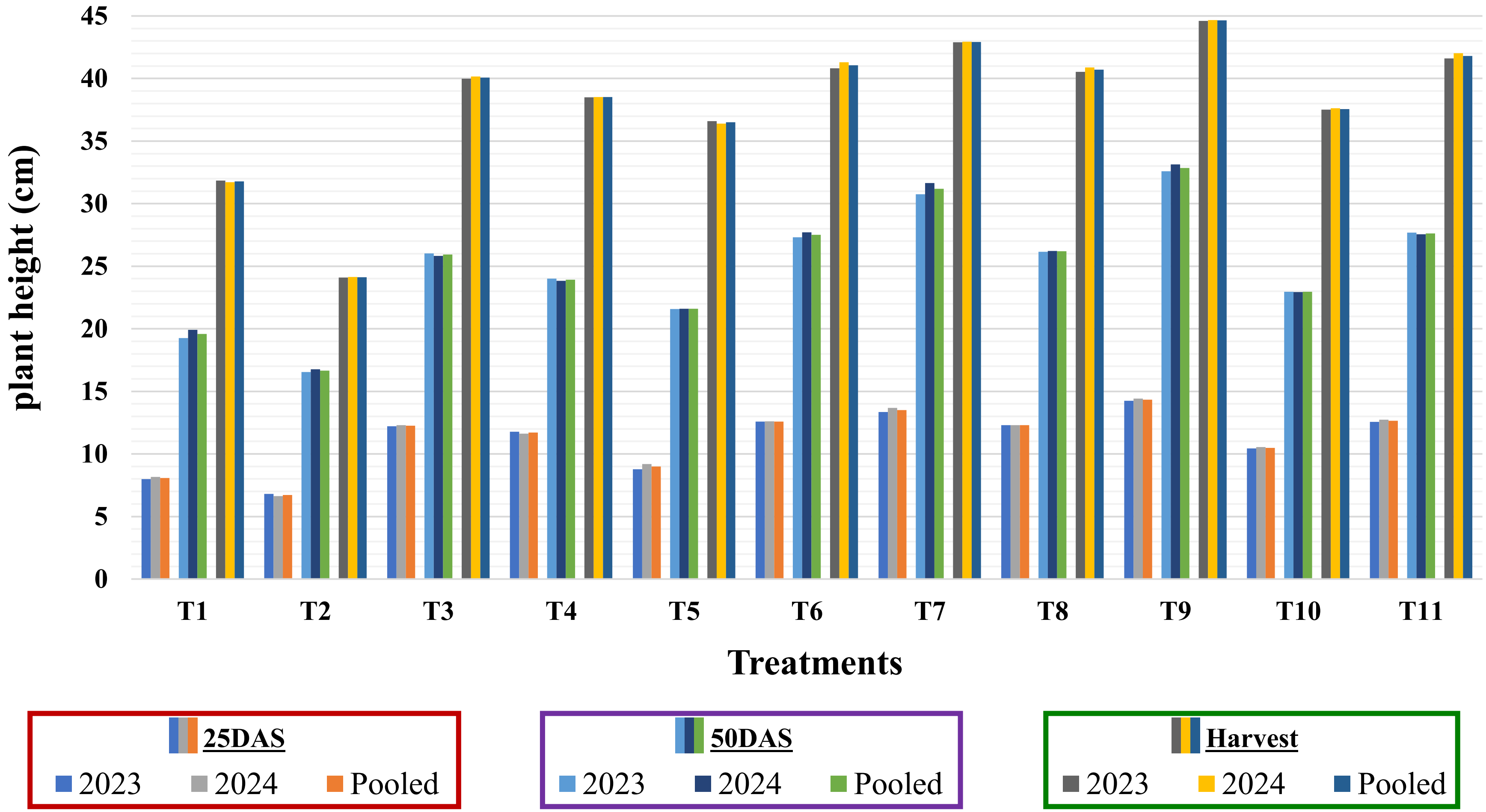

Fig. 4.1 Effect of different aluminium-alleviating organic materials on *plant height* of mungbean in acid soil

height (32.60 cm) while the lowest plant height (16.55 cm) was observed under treatment T_2 (absolute control). Among the single amendments, treatment T_6 recorded the highest plant height (27.32 cm). At harvest, the maximum plant height (44.61 cm) was again observed under treatment T_9 (wood ash + vermicompost) whereas the lowest plant height (24.09 cm) was recorded under treatment T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) recorded the highest plant height (40.81 cm).

Similarly, during the second trial (2024), a similar trend was observed at 25DAS, 50DAS and at harvest. Treatment T_9 (wood ash + vermicompost) recorded the highest plant height (14.42 cm, 33.13 cm, and 44.88 cm, respectively) and was found to be statistically at par with T_7 (wood ash + poultry manure) at 25DAS (13.67 cm), while the lowest plant height (cm) was observed under treatment T_2 (6.62 cm, 16.77 cm, and 24.14 cm, respectively). Among the single amendments, treatment T_6 recorded the maximum plant height (cm) at 25 DAS (12.60 cm), 50 DAS (27.71 cm), and at harvest (41.30 cm).

Pooled data for both trial (2023 and 2024) showed that maximum plant height (cm) was obtained in T_9 (wood ash + vermicompost) at 25 DAS (14.33 cm), 50DAS (32.86 cm) and at harvest (44.65 cm) whereas the lowest plant height (cm) was recorded under treatment T_2 (6.71 cm, 16.66 cm, and 24.12 cm, respectively). Among the single amendments, treatment T_6 recorded the maximum plant height (cm) at all growth stages (12.59 cm, 27.51 cm, and 41.05 cm, respectively).

The highest plant height recorded under treatment T_9 (wood ash + vermicompost) may be attributed to the combined beneficial effects of wood ash and vermicompost. Wood ash acts as a liming material that increases soil pH and reduces aluminium toxicity in acidic soils, while vermicompost supplies essential nutrients and beneficial microorganisms, thereby improving nutrient availability and plant growth. The beneficial role of wood ash in improving plant growth in acidic soils due to its liming effect and alleviation of aluminium toxicity has also been reported by An and Park (2021). In contrast, the lowest plant height observed under the control treatment could be due to the absence of nutrient supplementation and the persistence of aluminium toxicity. Among the single amendments, vermicompost recorded higher plant height, possibly due to improved soil fertility and microbial activity. Similar improvements in mungbean growth under organic nutrient management were also reported by Rambuatsaiha *et al*. (2017), Ezung *et al*. (2020) and Yadav *et al*. (2024).

4.1.1.2 Number of branches per plant

Data pertaining to number of branches per plant as influence by different organic materials are presented in Table 4.2 and graphically illustrated in Fig 4.2.

In the first trial (2024) at 25 DAS, the effect of different aluminium- alleviating organic materials was found to be non- significant. However, at 50DAS and at harvest, the treatments significantly influenced number of branches per plant, and the maximum number of branches per plant was recorded under treatment T_9 (wood ash + vermicompost) (4.22 and 4.66, respectively) which was statistically at par with T_7 (wood ash + poultry manure) (4.11 and 4.33) while the lowest number of branches per plant was observed under treatment T_2 (absolute control) (2.22, and 2.77, respectively). Among the single amendments, treatment T_6 (vermicompost) recorded the highest number of branches per plant at 50 DAS (3.11), and at harvest (3.89).

Similarly, during the second trial (2024), the effect of different organic materials on number of branches per plant at 25 DAS was non-significant. However, at 50DAS and at harvest number of branches per plant was significantly influenced by the application of different organic materials, and the maximum number of branches per plant was recorded under treatment T_9 (wood ash + vermicompost) (4.33 and 4.77, respectively) which was statistically at par with T_7 (4.22 and 4.44) whereas the lowest number of branches per plant was observed under treatment T_2 (2.33, and 2.78, respectively). Among the single amendments, the highest number of branches per plant was recorded under treatment T_6 at 50 DAS (3.22) and at harvest (4.00).

In the pooled analysis of both years (2023 and 2024), the application of different organic materials on number of branches per plant at 25 DAS was found to be non-significant. However, at 50 DAS and at harvest, number of branches per plant was significantly influenced by different organic materials, with the maximum number of branches per plant recorded under treatment T_9 (wood ash + vermicompost) (4.28 and

Table 4.2 Effect of different aluminium-alleviating organic materials on *number of branches per plant* of mungbean in acid soil

Treatments	Number of branches per plant								
	25DAS			50DAS			Harvest		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	1.55	1.55	1.55	2.44	2.55	2.50	2.89	3.00	2.94
T_2: Absolute control	1.55	1.55	1.55	**2.22**	**2.33**	**2.28**	**2.77**	**2.78**	**2.78**
T_3: WA @ 2t ha^{-1}	1.66	1.66	1.66	3.00	2.99	3.00	3.88	3.89	3.89
T_4: PM @ 2t ha^{-1}	1.66	1.66	1.66	2.88	2.88	2.88	3.66	3.77	3.72
T_5: RR @ 2t ha^{-1}	1.66	1.66	1.66	2.66	2.67	2.67	3.33	3.44	3.39
T_6: VC @ 2t ha^{-1}	1.66	2.00	1.83	**3.11**	**3.22**	**3.17**	**3.89**	**4.00**	**3.94**
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	2.00	2.00	2.00	**4.11**	**4.22**	**4.17**	**4.33**	**4.44**	**4.39**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	2.00	1.77	1.89	3.22	3.33	3.28	4.00	4.11	4.05
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	2.11	2.11	2.11	**4.22**	**4.33**	**4.28**	**4.66**	**4.77**	**4.72**
T_{10}: SR @ 2t ha^{-1}	1.66	1.66	1.66	2.77	2.77	2.77	3.44	3.55	3.50
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	2.00	2.00	2.00	3.44	3.44	3.44	4.22	4.22	4.22
SEm±	**0.19**	**0.17**	**0.13**	**0.14**	**0.22**	**0.13**	**0.19**	**0.18**	**0.13**
CD at 5%	**NS**	**NS**	**NS**	**0.42**	**0.64**	**0.37**	**0.57**	**0.54**	**0.38**

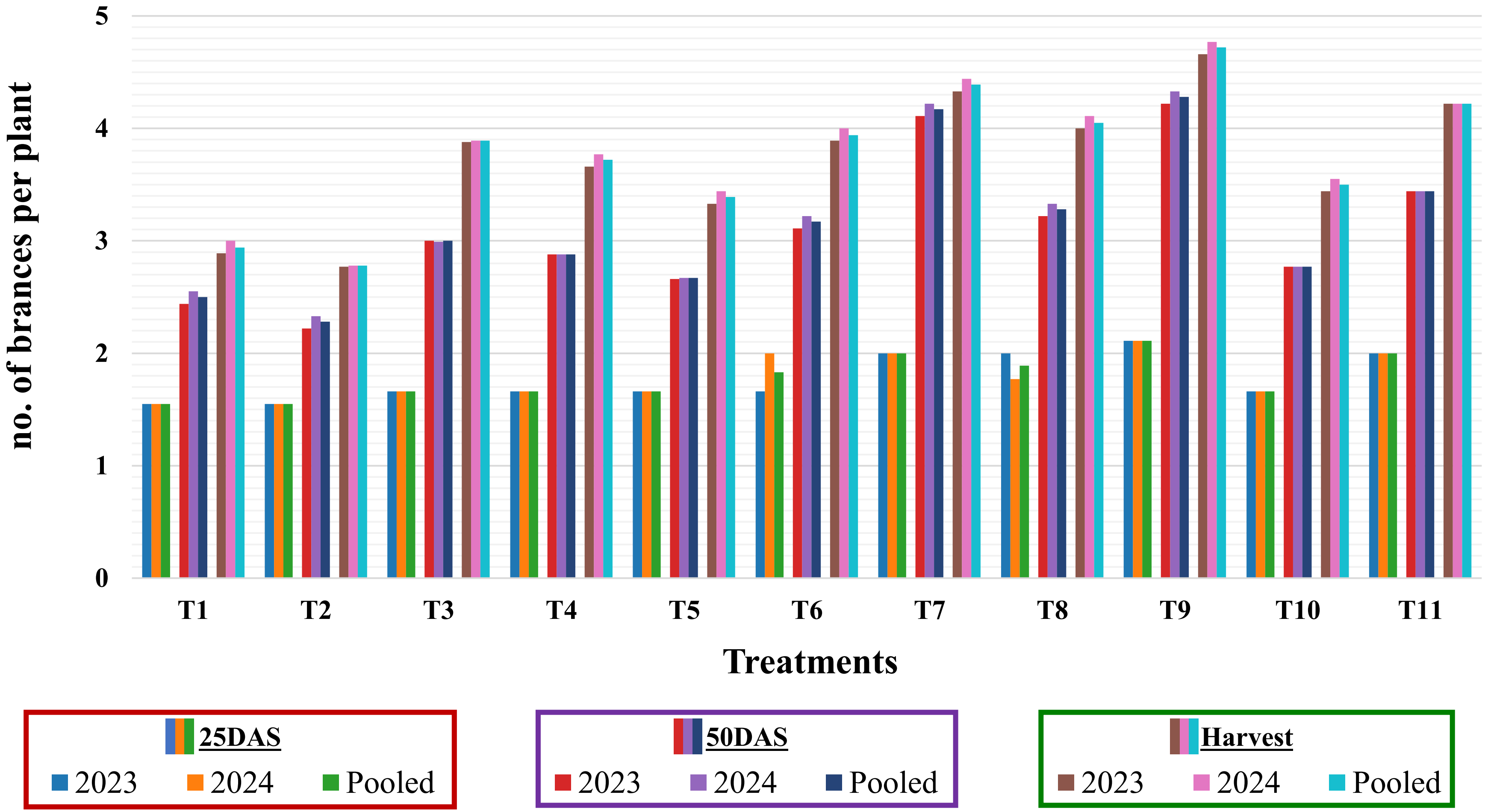

Fig. 4.2 Effect of different aluminium-alleviating organic materials on *number of branches per plant* of mungbean in acid soil

4.72, respectively), while the lowest number of branches per plant was observed under treatment T_2 (2.28 and 2.78, respectively). Among the single amendments, treatment T_6 recorded the highest number of branches per plant (4.17 and 4.39 at 50 DAS and at harvest, respectively).

The number of branches per plant was not significantly influenced at 25 DAS, which might be due to the early growth stage when the effect of organic amendments had not yet become evident. However, at later stages, the combined application of wood ash and vermicompost resulted in higher branching, which may be attributed to improved soil pH and reduced aluminium toxicity due to the liming effect of wood ash, along with enhanced nutrient availability from vermicompost. A similar beneficial effect of wood ash in acidic soils due to its liming action and alleviation of aluminium toxicity was reported by An and Park (2021). Improved nutrient availability, particularly nitrogen, may also have promoted vegetative growth and lateral branch development. In contrast, the lowest branching observed under the control treatment may be due to poor nutrient availability and continued aluminium toxicity. Among the single amendments, vermicompost resulted in higher branching due to improved soil fertility and microbial activity. Similar findings were also reported by Rambuatsaiha *et al*. (2017) and Yadav *et al*. (2024).

4.1.1.3 Number of leaves per plant

The data on number of leaves per plant as influenced by different organic materials are presented in Table 4.3 and graphically illustrated in Fig. 4.3. The treatments significantly influenced the number of leaves per plant during both the trials (2023 and 2024) and in the pooled analysis in all the growth stages.

In the initial trial conducted in 2023, the highest number of leaves per plant at 25DAS, 50DAS and at harvest was obtained under treatment T_9 (wood ash + vermicompost) (4.44, 8.44 and 7.44, respectively) which was statistically at par with T_7 (wood ash + poultry manure) (4.33, 8.22 and 7.11) whereas the lowest number of leaves per plant was observed under treatment T_2 (absolute control) (2.11, 4.11 and 3.77, respectively). Treatment T_6 (vermicompost) recorded the highest number of

Table 4.3 Effect of different aluminium-alleviating organic materials on *number of leaves per plant* of mungbean in acid soil

Treatments	Number of leaves per plant								
	25DAS			50DAS			Harvest		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	2.44	2.44	2.44	5.00	5.11	5.05	4.11	4.22	4.16
T_2: Absolute control	**2.11**	**2.22**	**2.17**	**4.11**	**4.22**	**4.16**	**3.77**	**3.89**	**3.83**
T_3: WA @ 2t ha^{-1}	3.33	3.44	3.39	6.77	6.89	6.83	5.77	5.89	5.83
T_4: PM @ 2t ha^{-1}	3.22	3.33	3.28	6.55	6.66	6.61	5.55	5.66	5.61
T_5: RR @ 2t ha^{-1}	3.00	3.00	3.00	6.22	6.22	6.22	5.11	4.99	5.05
T_6: VC @ 2t ha^{-1}	**3.44**	**3.44**	**3.44**	**7.00**	**7.11**	**7.05**	**6.11**	**6.22**	**6.16**
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	**4.33**	**4.33**	**4.33**	**8.22**	**8.33**	**8.28**	**7.11**	**7.22**	**7.17**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	3.88	3.89	3.89	7.22	7.33	7.28	6.44	6.44	6.44
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**4.44**	**4.55**	**4.50**	**8.44**	**8.55**	**8.50**	**7.44**	**7.55**	**7.50**
T_{10}: SR @ 2t ha^{-1}	3.11	3.11	3.11	6.22	6.33	6.28	5.22	5.11	5.16
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	4.00	4.11	4.05	7.55	7.66	7.61	6.66	6.77	6.72
SEm±	**0.15**	**0.12**	**0.10**	**0.15**	**0.17**	**0.12**	**0.18**	**0.21**	**0.14**
CD at 5%	**0.43**	**0.37**	**0.27**	**0.45**	**0.51**	**0.33**	**0.52**	**0.61**	**0.39**

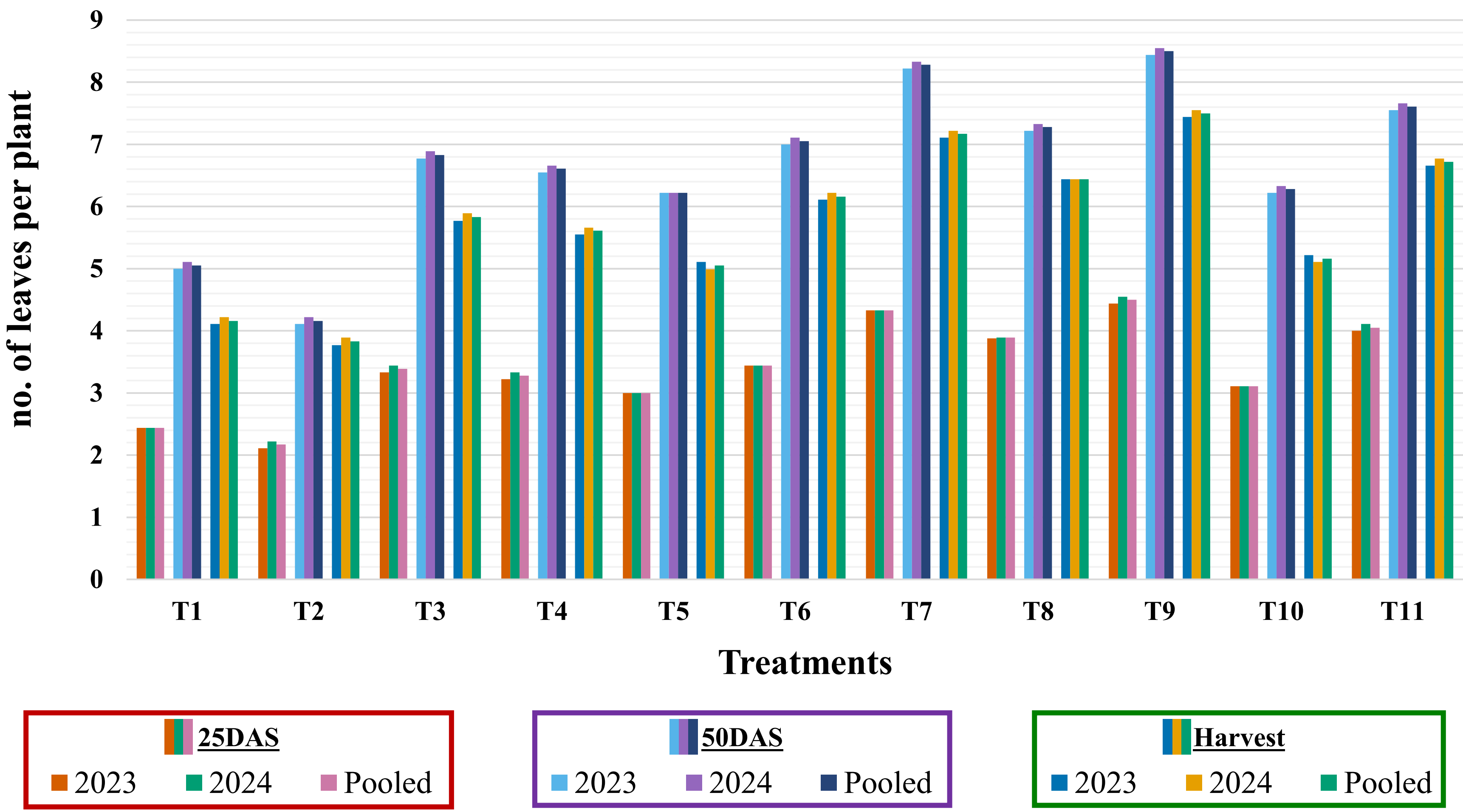

Fig. 4.3 Effect of different aluminium-alleviating organic materials on *number of leaves per plant* of mungbean in acid soil

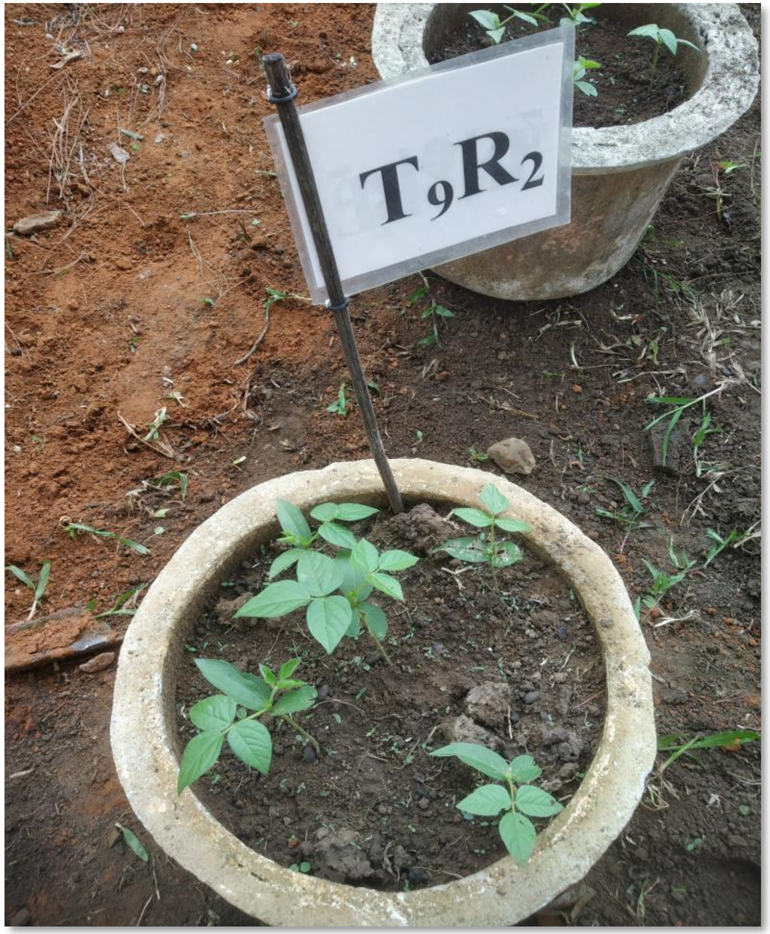

PLATE 4 Comparison of plant growth between treatment T_9 and absolute control (T_2) at the early growth stage

PLATE 5 Comparison of plant growth among treatment T_9, T_2 (absolute control) and T_1 (control) at the flowering and pod formation stage

leaves per plant at all growth stages (3.44, 7.00 and 6.11) among the single amendments.

Likewise, in the second trial (2024) the maximum number of leaves per plant was recorded under treatment T_9 (wood ash + vermicompost) (4.55, 8.55 and 7.55, respectively) at all crop growth stages which was statistically at par with T_7 (4.33, 8.33 and 7.22) while the lowest number of leaves per plant was observed under treatment T_2 (2.22, 4.22 and 3.89, respectively).). Among the single amendments, treatment T_6 recorded the maximum number of leaves per plant at 25 DAS (3.44), 50 DAS (7.11) , and at harvest (6.22). Pooled data for both trial (2023 and 2024) showed that maximum number of leaves per plant was obtained in T_9 (wood ash + vermicompost) at 25 DAS (4.50), 50DAS (8.50) and at harvest (7.50) which was statistically at par with T_7 (4.33, 8.28 and 7.17) whereas the lowest number of leaves per plant was recorded under treatment T_2 (2.17, 4.16, and 3.83, respectively). Among the single amendments, treatment T_6 recorded the maximum number of leaves per plant at all growth stages (3.44, 7.05, and 6.16, respectively).

Higher leaf production under the combined application of wood ash and vermicompost may be attributed to improved soil pH due to the liming effect of wood ash, which helps reduce aluminium toxicity in acidic soils, along with the supply of essential nutrients from vermicompost. Adequate availability of nutrients, particularly nitrogen, plays an important role in promoting vegetative growth and leaf development. In addition, vermicompost improves soil microbial activity and releases growth-promoting substances, which may have further stimulated leaf formation. In contrast, the lower number of leaves observed under the control treatment might be due to poor nutrient availability and the persistence of aluminium toxicity. Similar improvement in the number of leaves per plant in mungbean under organic and integrated nutrient management practices was also reported by Joshi *et al*. (2022) and Bhanupriya *et al*. (2020), who observed significantly higher leaf production with the application of organic nutrient sources compared to control treatments.

4.1.2 Yield parameters

The observations recorded on yield parameters, namely number of pods per plant, pod length, number of seeds per pod, seed yield, stover yield and harvest index, under different Al-alleviating organic materials are presented and discussed in the following sections.

4.1.2.1 Number of pods per plant

Observations on number of pods per plant under different organic material treatments are presented in Table 4.4 and illustrated in Fig. 4.4. A significant variation in number of pods per plant was observed due to the application of different organic materials, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first experimental trial (2023), treatment T_9 (wood ash + vermicompost) exhibited the highest number of pods per plant (18.22) whereas the lowest number of pods per plant (10.66) was observed under treatment T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) recorded the maximum number of pods per plant (15.22).

A similar trend was observed during the second trial (2024), where treatment T_9 (wood ash + vermicompost) exhibited the highest number of pods per plant (18.33), while the lowest number of pods per plant (10.77) was found under treatment T_2 (absolute control). Among the individual organic amendments, treatment T_6 (vermicompost) showed the maximum number of pods per plant (15.22).

The combined analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest number of pods per plant (18.27), while the lowest number of pods per plant (10.72) was obtained under treatment T_2 (absolute control). Among the individual amendments, the highest number of pods per plant (15.22) was recorded in treatment T_6 (vermicompost).

The higher number of pods per plant may be attributed to the combined application of wood ash and vermicompost, which improves soil pH, reduces aluminium toxicity, and enhances nutrient availability. Vermicompost further contributes essential nutrients and beneficial microorganisms that promote better growth and pod formation. In contrast, the lower number of pods under the absolute control may be due to poor nutrient availability and continued aluminium toxicity. Among the single amendments, vermicompost resulted in relatively higher pod formation due to its positive effect on soil fertility and microbial activity.

The results are in agreement with the findings of Bankoti *et al*. (2021), who reported a higher number of pods per plant in mungbean with the application of vermicompost along with recommended fertilizer dose. Similarly, Yadav *et al*. (2024) also observed maximum pods per plant under the combined application of FYM, vermicompost and vermiwash, highlighting the positive effect of organic nutrient sources on yield attributes. Comparable results were also reported by Olubode *et al*. (2018), who observed increased number of pods and grain yield in soybean following the application of wood ash in acid soil due to improvement in soil pH and microbial activity.

4.1.2.2 Pod length (cm)

Perusal of the data in Table 4.4 and Fig. 4.4 indicates that the pod length (cm)was significantly affected by the application of different organic materials, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the 2023 experiment, the maximum pod length (7.64 cm) was obtained under treatment T_9 (wood ash + vermicompost) whereas the shortest pod length (5.22 cm) was observed under treatment T_2 (absolute control). Treatment T_6 (vermicompost) registered the longest pod length (6.87 cm) among the individual amendments.

Similarly, in the 2024 experiment, the maximum pod length (7.67 cm) was recorded under treatment T_9 (wood ash + vermicompost), while the shortest pod length (5.27 cm) was observed under treatment T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) recorded the maximum pod length (6.85 cm).

The pooled results showed that treatment T_9 (wood ash + vermicompost) recorded the longest pod length (7.66 cm), in contrast the shortest pod length (5.25

cm) was observed under treatment T_2 (absolute control). Among the individual organic amendments, treatment T_6 (vermicompost) showed the longest pod length (6.86 cm).

The variation in pod length among treatments may be attributed to the influence of organic amendments on soil properties and nutrient availability. The combined application of wood ash and vermicompost may have improved soil pH and reduced aluminium toxicity in acidic soil, thereby enhancing nutrient uptake and reproductive growth, which resulted in greater pod length. In contrast, the lowest pod length under the absolute control may be due to poor nutrient availability and the persistence of aluminium toxicity. Similar results were reported by Rambuatsaiha *et al*. (2017), who observed greater pod length in mungbean under the combined application of *Rhizobium*, PSB and vermicompost compared to the control.

4.1.2.3 Number of seeds per pod

The number of seeds per pod as influenced by different organic materials is presented in Table 4.4 and graphically illustrated in Fig. 4.4. The application of different aluminium- alleviating organic materials significantly influenced number of seeds per pod, with all organic amendments performing better than T_1 (control) and T_2 (absolute control)**.**

In the first experimental trial (2023), among all the treatment T_9 (wood ash + vermicompost) exhibited the maximum number of seeds per pod (11.66) whereas the lowest number of seeds per pod (5.22) was found under treatment T_2 (absolute control). Among the individual amendments, treatment T_6 (vermicompost) recorded the maximum number of seeds per pod (9.66).

During the second trial (2024), the highest number of seeds per pod (11.77) was obtained from the treatment T_9 (wood ash + vermicompost). In contrast, the lowest number of seeds per pod (5.33) was observed under treatment T_2 (absolute control). Treatment T_6 (vermicompost) exhibited the maximum number of seeds per pod (9.89) among the single amendments. Based on pooled analysis, treatment T_9 (wood ash + vermicompost) registered the maximum number of seeds per pod (11.72); conversely, the lowest number of seeds per pod (5.27) was observed under treatment T_2 (absolute

Table 4.4 Effect of different aluminium-alleviating organic materials on *number of pods per plant, pod length, number of seeds per pod* of mungbean in acid soil

Treatments	No. of pods per plant			Pod length (cm)			No. of seeds per pod		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	11.33	11.44	11.39	5.71	5.73	5.72	6.44	6.55	6.50
T_2: Absolute control	10.66	10.77	10.72	5.22	5.27	5.25	5.22	5.33	5.27
T_3: WA @ 2t ha^{-1}	15.44	15.33	15.38	6.80	6.82	6.81	9.44	9.66	9.55
T_4: PM @ 2t ha^{-1}	14.55	14.66	14.61	6.72	6.74	6.73	8.77	8.89	8.83
T_5: RR @ 2t ha^{-1}	12.66	12.78	12.72	6.31	6.33	6.32	7.22	7.22	7.22
T_6: VC @ 2t ha^{-1}	15.22	15.22	15.22	6.87	6.85	6.86	9.66	9.89	9.78
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	17.33	17.44	17.38	7.30	7.34	7.32	10.77	10.77	10.77
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	16.00	16.11	16.05	6.93	6.96	6.94	9.77	10.00	9.89
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	18.22	18.33	18.27	7.64	7.67	7.66	11.66	11.77	11.72
T_{10}: SR @ 2t ha^{-1}	13.33	13.00	13.16	6.38	6.39	6.39	7.55	7.66	7.61
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	16.55	16.44	16.50	7.06	7.13	7.09	10.22	10.44	10.33
SEm±	**0.25**	**0.30**	**0.20**	**0.04**	**0.03**	**0.03**	**0.17**	**0.15**	**0.11**
CD at 5%	**0.74**	**0.89**	**0.56**	**0.11**	**0.10**	**0.07**	**0.51**	**0.43**	**0.32**

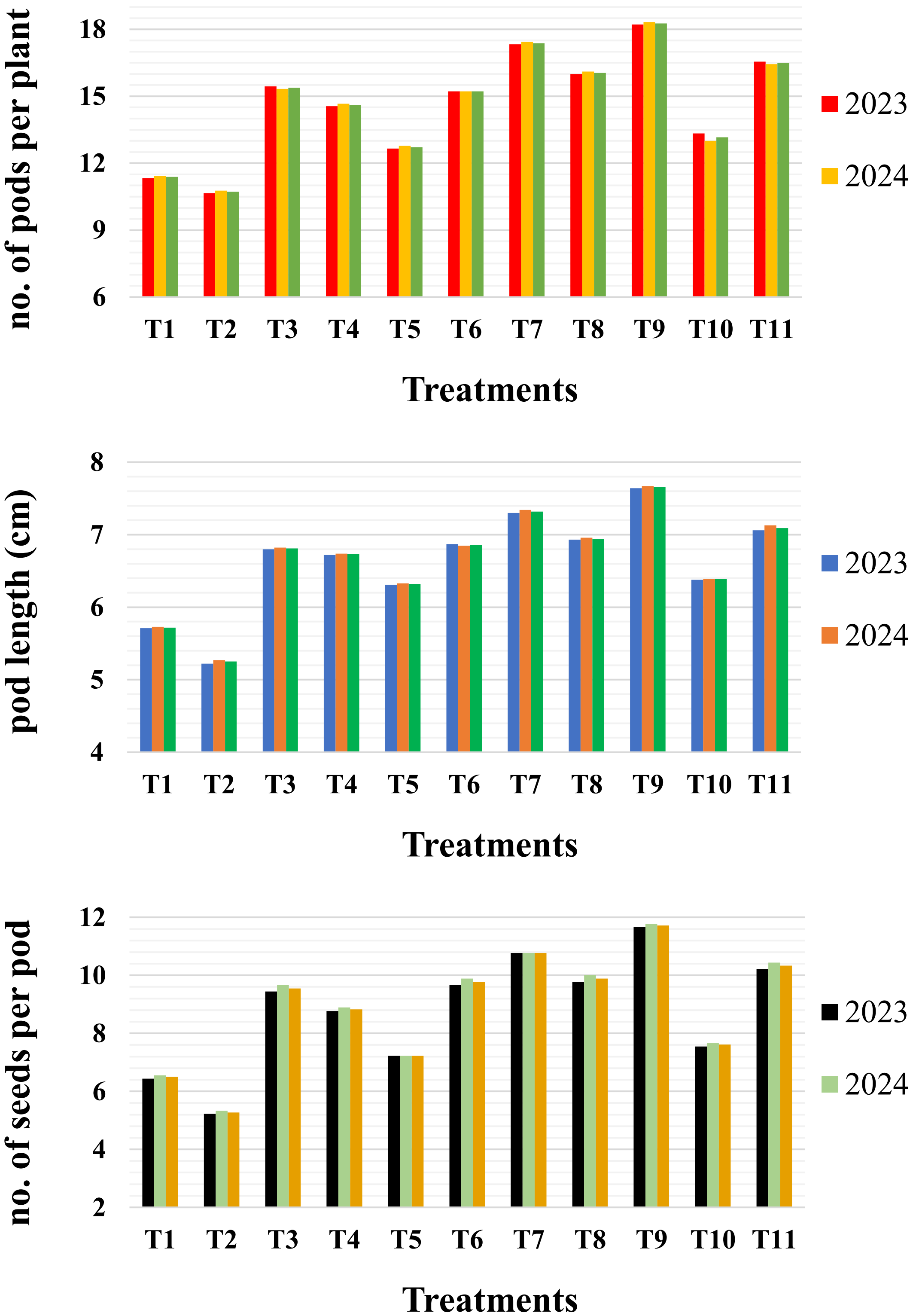

Fig. 4.4 Effect of different aluminium-alleviating organic materials on *number of pods per plant, pod length, number of seeds per pod* of mungbean in acid soil

control). Among the single amendments, treatment T_6 (vermicompost) recorded the maximum number of seeds per pod (9.78).

Higher seeds per pod under the combined application of wood ash and vermicompost may be attributed to improved soil conditions, reduced aluminium toxicity, and enhanced nutrient availability, which favour better reproductive development. The lowest number of seeds per pod under the absolute control may be due to inadequate nutrient supply and unfavourable soil conditions in acidic soils. Similar findings were reported by Rambuatsaiha *et al*. (2017), who observed higher seeds per pod in mungbean with the combined application of *Rhizobium*, PSB and vermicompost compared to the control. Likewise, Yadav *et al*. (2024) also reported increased seeds per pod under the combined application of FYM, vermicompost and vermiwash.

4.1.2.4 Seed yield (g/pot)

Seed yields as affected by different organic materials is presented in Table 4.5 and graphically shown in Fig. 4.5. A significant variation in seed yield was observed due to the application of different organic materials during both the trials and in pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The highest seed yield (26.21 g/pot) during the experimentation of 2023 was recorded under treatment T_9 (wood ash + vermicompost). By contrast**,** the lowest value (6.98 g/pot) was observed under treatment T_2 (absolute control). Treatment T_6 (vermicompost) registered the maximum seed yield (19.08 g/pot) among the single amendments.

A similar trend was observed during the second experimentation (2024 g/pot), where treatment T_9 (wood ash + vermicompost) exhibited the highest seed yield (26.37 g/pot), while the seed yield (7.05 g/pot) was found under treatment T_2 (absolute control). Among the individual organic amendments, treatment T_6 (vermicompost) showed the maximum seed yield (19.13 g/pot).

Table 4.5 Effect of different aluminium-alleviating organic materials on *seed yield, stover yield, and harvest index* of mungbean in acid soil

Treatments	Seed yield (g/pot)			Stover yield (g/pot)			Harvest index (%)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	9.97	9.99	9.98	12.15	12.23	12.19	45.09	44.97	45.03
T_2: Absolute control	**6.98**	**7.05**	**7.01**	**9.29**	**9.45**	**9.37**	**42.91**	**42.71**	**42.81**
T_3: WA @ 2t ha^{-1}	18.81	18.79	18.80	21.25	21.28	21.27	46.96	46.88	46.92
T_4: PM @ 2t ha^{-1}	16.77	16.89	16.83	19.80	19.78	19.79	45.86	46.07	45.97
T_5: RR @ 2t ha^{-1}	12.64	12.78	12.71	14.25	14.27	14.26	**47.01**	**47.24**	**47.13**
T_6: VC @ 2t ha^{-1}	**19.08**	**19.13**	**19.11**	**21.73**	**21.78**	**21.76**	46.75	46.76	46.76
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	24.11	24.06	24.09	27.14	27.17	27.16	47.04	46.97	47.01
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	21.23	21.25	21.24	22.91	22.87	22.89	48.09	48.17	48.13
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**26.21**	**26.37**	**26.29**	**29.29**	**29.31**	**29.30**	47.23	47.36	47.29
T_{10}: SR @ 2t ha^{-1}	13.45	13.43	13.44	14.81	14.85	14.83	47.60	47.49	47.55
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	22.26	22.23	22.24	23.07	23.03	23.05	**49.11**	**49.12**	**49.11**
SEm±	**0.21**	**0.14**	**0.12**	**0.20**	**0.14**	**0.12**	**0.36**	**0.29**	**0.23**
CD at 5%	**0.60**	**0.41**	**0.36**	**0.59**	**0.41**	**0.35**	**1.06**	**0.86**	**0.66**

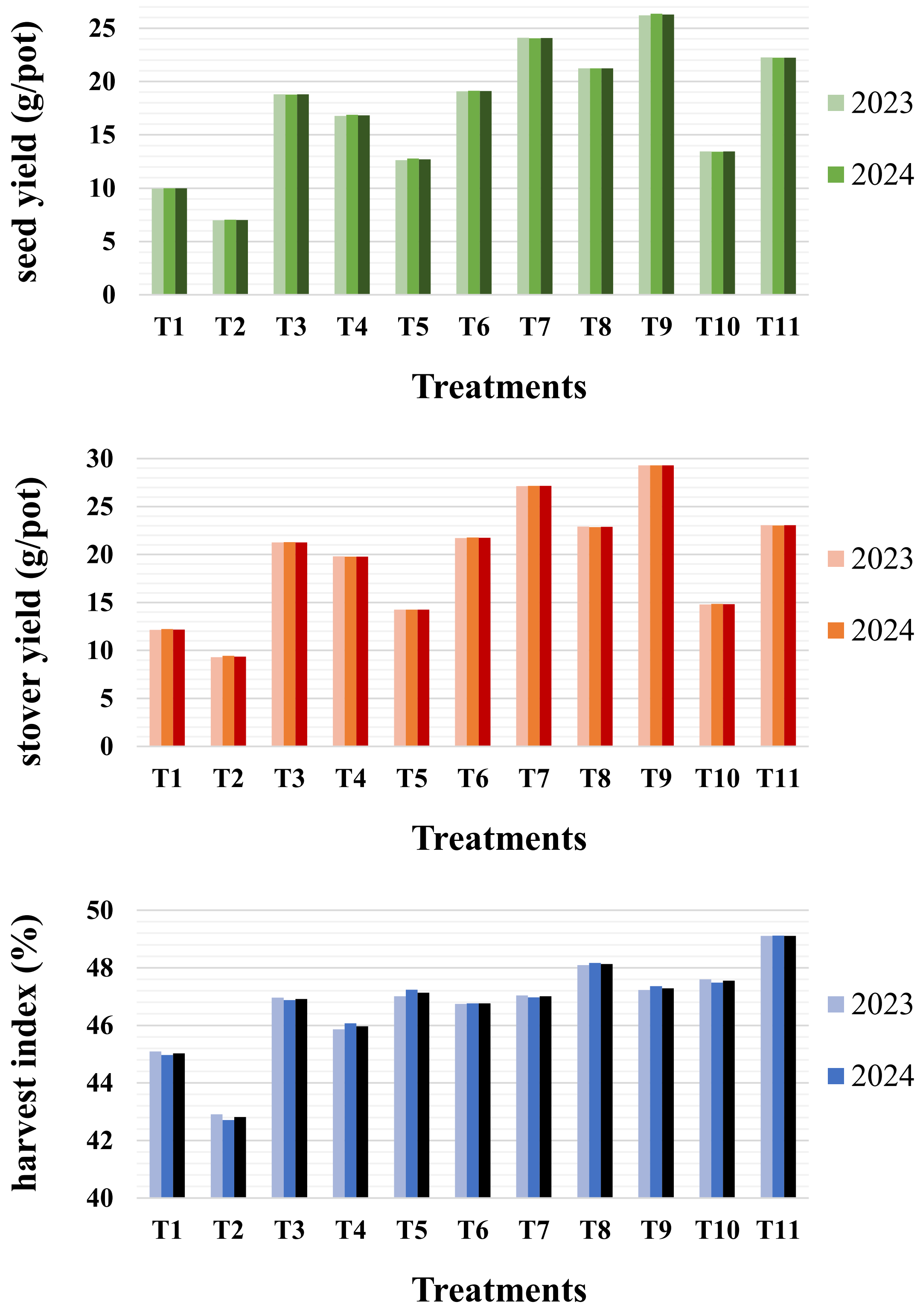

Fig. 4.5 Effect of different aluminium-alleviating organic materials on *seed yield, stover yield, and harvest index* of mungbean in acid soil

The pooled results showed that treatment T_9 (wood ash + vermicompost) recorded the maximum seed yield (26.29 g/pot) whereas the lowest seed yield (7.01 g/pot) was obtained under treatment T_2 (absolute control). Among the sole amendments, treatment T_6 (vermicompost) recorded the maximum number of pods per plant (19.11 g/pot).

Improvement in seed yield may be attributed to better nutrient availability and reduced aluminium toxicity in acidic soil due to the application of wood ash and vermicompost. The liming effect of wood ash helps in increasing soil pH and reducing aluminium toxicity, while vermicompost enhances nutrient supply and microbial activity, resulting in improved assimilate production and translocation towards seed development. Similar findings were reported by Yadav *et al*. (2024) in mungbean under combined application of FYM, vermicompost and vermiwash. Comparable results were also reported by Olubode *et al*. (2018), who observed increased grain yield of soybean following wood ash application in acid soil due to improvement in soil pH and microbial activity.

4.1.2.5 Stover yield (g/pot)

The effect of different organic materials on stover yield (g/pot) is presented in Table 4.5 and graphically shown in Fig. 4.5. The stover yield (g/pot) was significantly influenced by the application of different aluminium- alleviating organic materials during both the trials (2023 and 2024) as well as in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the initial trial conducted in 2023, treatment T_9 (wood ash + vermicompost) registered the maximum stover yield (29.29 g/pot). On the other hand, the lowest stover yield (9.29 g/pot) was obtained under treatment T_2 (absolute control). Treatment T_6 (vermicompost) exhibited the maximum seed yield (21.73 g/pot) among the single amendments.

During the second year of the study (2024), the maximum stover yield (29.31 g/pot) was obtained from the treatment T_9 (wood ash + vermicompost). In contrast, the minimum value (9.45 g/pot) was observed under treatment T_2 (absolute control).

Among the individual amendments, treatment T_6 (vermicompost) recorded the highest stover yield (21.78 g/pot).

Based on pooled analysis, treatment T_9 (wood ash + vermicompost) registered the maximum stover yield (29.30 g/pot) whereas the lowest stover yield (9.37 g/pot) was obtained under treatment T_2 (absolute control). Among the single application of organic materials, treatment T_6 (vermicompost) recorded the maximum stover yield (21.76 g/pot).

Enhanced stover yield may be associated with improved soil fertility and nutrient availability resulting from the application of organic amendments. Vermicompost contributes essential nutrients and beneficial microorganisms, while wood ash improves soil reaction and reduces aluminium toxicity, thereby promoting vigorous vegetative growth and greater biomass accumulation. Similar observations were reported by Rambuatsaiha *et al*. (2017), who recorded improved growth and biomass production in mungbean with the combined application of *Rhizobium*, PSB and vermicompost. Yadav *et al*. (2024) also reported increased stover yield under integrated use of organic nutrient sources.

4.1.2.6 Harvest index (%)

It is evident from the data presented in Table 4.5 and Fig 4.5 that harvest index (%) was significantly influenced with the application of different organic materials during both the trials and in pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The results revealed that the maximum harvest index (49.11%) among all the treatments was observed in T_{11} (wood ash + soybean residue) during the first season (2023), while the minimum value (42.91%) was recorded in absolute control (T_2). Among the individual organic amendments, treatment T_5 (rice residue) showed the highest harvest index (47.01%).

Similarly in the following season, similar pattern was observed where, T_{11} (wood ash + soybean residue) recorded the highest harvest index (49.12%), while the lowest

PLATE 6 Comparative view of pods and seeds under treatment T_9 and absolute control (T_2)

value (42.71%) was recorded in absolute control (T_2). Treatment T_5 (rice residue) exhibited the maximum harvest index (47.24%) among the single amendments.

The pooled results showed that treatment T_{11} (wood ash + soybean residue) recorded the maximum harvest index (49.11%) whereas the lowest value (42.81%) was found in absolute control (T_2). Among the sole amendments, treatment T_5 (rice residue) obtained the maximum harvest index (47.13%).

The improvement in harvest index may be attributed to more efficient partitioning of assimilates towards economic yield under better soil conditions created by the combined application of wood ash and soybean residue. Wood ash helps increase soil pH and reduce aluminium toxicity in acidic soils, while soybean residue contributes organic matter and nutrients through mineralization, thereby enhancing nutrient availability and overall crop performance. In addition, crop residues such as soybean residue have been reported to ameliorate soil acidity and reduce phytotoxic aluminium in acid soils, thereby improving crop growth and productivity (Panda *et al*., 2017). In contrast, the lower harvest index under the control condition may be due to poor soil fertility and the persistence of aluminium toxicity, which restricts nutrient uptake and reduces the efficiency of assimilate translocation to seeds.Similar findings were reported by Gill *et al*. (2015) and Demeyer *et al*. (2001), who observed that the application of wood ash improves soil chemical properties, enhances soil fertility and increases crop productivity in acidic soils.

4.1.3 Root parameters

Root parameters including root length, fresh root weight, dry root weight and relative root length were recorded at 48 hours after sowing, 30 DAS and at harvest, and the results as influenced by different aluminium-alleviating organic materials are presented and discussed in the following sections.

4.1.3.1 Root length (cm)

The data on root length (cm) as influenced by different organic materials are presented in Table 4.6 and graphically illustrated in Fig. 4.6. The treatments significantly influenced the root length (cm) during both the trials and in the pooled

Table 4.6 Effect of different aluminium-alleviating organic materials on *root length* of mungbean in acid soil

Treatments	Root length (cm)								
	48hrs			30DAS			Harvest		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	1.30	1.31	1.31	9.70	9.71	9.71	10.94	10.96	10.95
T_2: Absolute control	1.16	1.18	1.17	9.33	9.35	9.34	10.27	10.26	10.26
T_3: WA @ 2t ha^{-1}	2.10	2.11	2.10	11.76	11.77	11.76	16.56	16.58	16.57
T_4: PM @ 2t ha^{-1}	1.94	1.96	1.95	11.61	11.62	11.62	15.89	15.92	15.90
T_5: RR @ 2t ha^{-1}	1.51	1.52	1.52	10.33	10.32	10.33	13.73	13.72	13.73
T_6: VC @ 2t ha^{-1}	1.98	1.99	1.99	11.70	11.72	11.71	16.80	16.81	16.81
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	2.67	2.69	2.68	12.70	12.73	12.72	18.87	18.89	18.88
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	2.23	2.24	2.24	11.93	11.94	11.94	17.37	17.38	17.37
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	2.71	2.73	2.72	12.83	12.84	12.84	19.37	19.39	19.38
T_{10}: SR @ 2t ha^{-1}	1.70	1.71	1.71	10.70	10.73	10.72	14.57	14.56	14.56
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	2.34	2.34	2.34	12.27	12.28	12.27	17.79	17.81	17.80
SEm±	**0.02**	**0.01**	**0.01**	**0.02**	**0.01**	**0.01**	**0.03**	**0.02**	**0.02**
CD at 5%	**0.05**	**0.04**	**0.03**	**0.06**	**0.04**	**0.03**	**0.09**	**0.07**	**0.05**

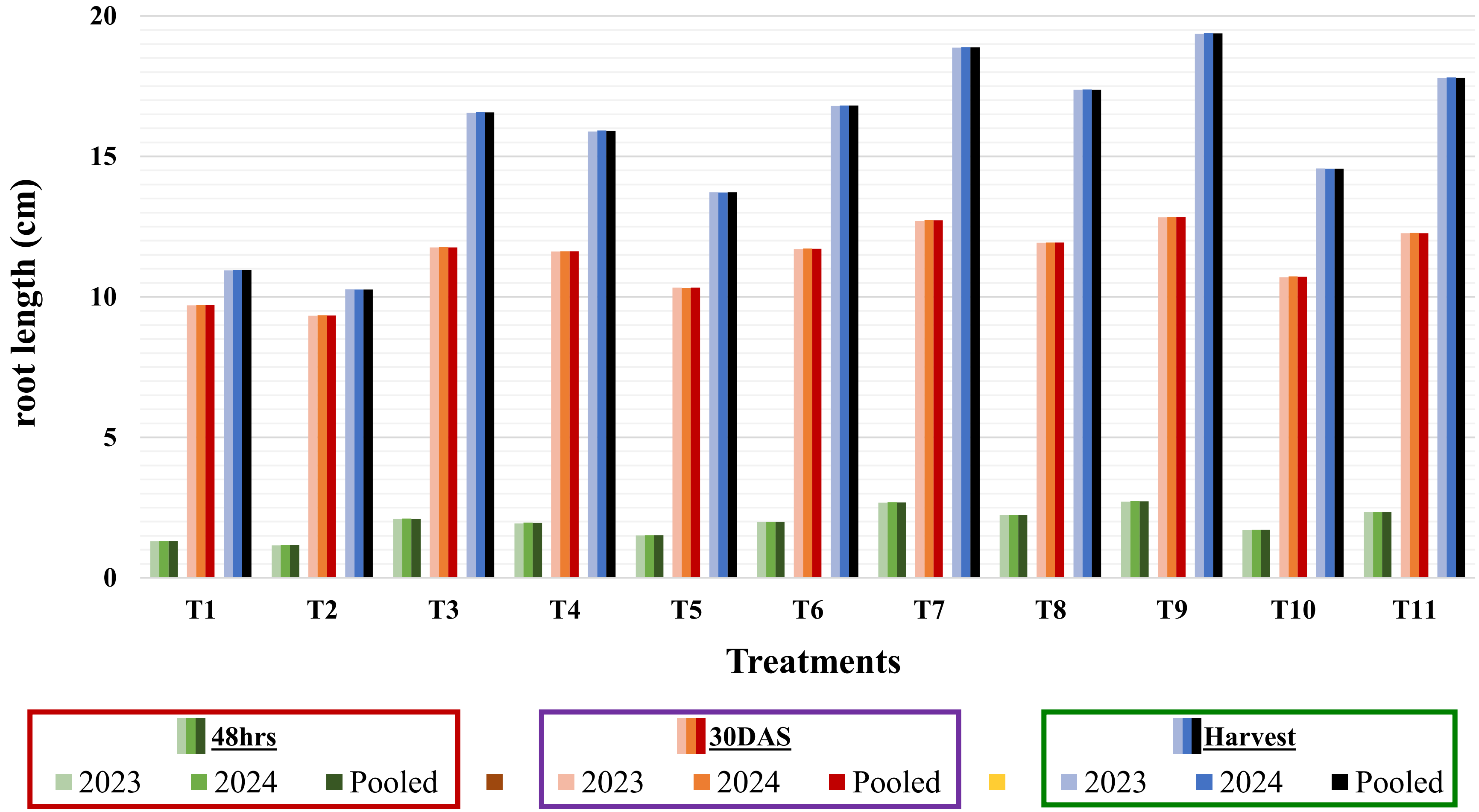

Fig. 4.6 Effect of different aluminium-alleviating organic materials on *root length* of mungbean in acid soil

analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the first season (2023), at 48 hrs after sowing, 30DAS and at harvest the longest root length (2.71 cm, 12.83 cm and 19.37 cm, respectively) was recorded under treatment T_9 (wood ash + vermicompost). At 48 hours after sowing, T_9 was statistically at par with treatment T_7 (wood ash + poultry manure) (2.67 cm). The shortest root length (1.16 cm, 9.33 cm and 10.27 cm, respectively) was observed under treatment T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) recorded the longest root length at 48 hours after sowing (2.10 cm) and 30 DAS (11.76 cm), whereas treatment T_6 (vermicompost) recorded the longest root length at harvest (16.80 cm).

In the second season (2024), the longest root length (2.73 cm, 12.84 cm and 19.39 cm, respectively) was registered under treatment T_9 (wood ash + vermicompost), while the shortest root length (1.18 cm, 9.35 cm, 10.26 cm, respectively) was observed under treatment T_2 (absolute control) at 48 hrs after sowing, 30DAS and at harvest. Among the individual amendments, treatment T_3 (wood ash) recorded the longest root length (2.11 cm and 11.77 cm, respectively) at 48 hours after sowing and 30 DAS, whereas treatment T_6 (vermicompost) recorded the longest root length (16.81cm) at harvest.

The pooled data of 2023 and 2024 revealed that treatment T_9 (wood ash + vermicompost) exhibited the longest root length (2.72 cm, 12.84 cm and 19.38 cm, respectively); conversely, the shortest root length (1.17 cm, 9.34 cm and 10.26 cm, respectively) was found under treatment T_2 (absolute control) at 48 hrs after sowing, 30DAS and at harvest. Among the individual amendments, the longest root length (2.10 cm and 11.76 cm, respectively) was recorded under treatment T_3 (wood ash) at 48 hours after sowing and 30 DAS, whereas treatment T_6 (vermicompost) recorded the longest root length (16.81cm) at harvest.

The longest root length was observed under the combined application of wood ash and vermicompost, which may be attributed to the synergistic effect of soil acidity amelioration and improved soil organic matter. Wood ash increases soil pH and supplies base cations such as calcium, magnesium and potassium, thereby reducing aluminium toxicity and creating favourable conditions for root growth. Vermicompost enhances soil organic matter, nutrient availability and microbial activity, which further promotes root elongation. Among the single amendments, wood ash resulted in comparatively longer roots due to its rapid liming effect, while vermicompost also improved root growth through gradual nutrient release and the presence of humic substances that stimulate root development. The shortest root length observed under the absolute control may be attributed to strongly acidic soil conditions where soluble aluminium inhibits root cell division and elongation, thereby restricting root growth. Similar findings were reported by Bessho and Bell (1992) and Muhrizal *et al*. (2003), who observed increased root length of mungbean with organic amendments due to the reduction of aluminium toxicity.

4.1.3.2 Fresh root weight (g)

Data pertaining to fresh root weight (g) as influenced by different organic materials are presented in Table 4.7 and graphically illustrated in Fig. 4.7. The effect of different organic materials on fresh root weight (g) at 48 hrs after sowing was found to be non-significant. However, at 30 DAS and at harvest, fresh root weight (g) was significantly influenced by the application of different organic materials during both the trials (2023 and 2024) as well as in the pooled analysis.

During the first year of experimentation (2023), among all the treatments, the maximum fresh root weight (1.36 g and 2.89 g, respectively) was recorded under treatment T_9 (wood ash + vermicompost) at 30 DAS and at harvest, while the lowest fresh root weight (0.44 g and 1.50 g, respectively) was observed under treatment T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) recorded the highest fresh root weight (1.13 g) at 30 DAS, whereas treatment T_6 (vermicompost) recorded the highest fresh root weight (2.42 g) at harvest.

A similar trend was observed during the second experimentation (2024), where treatment T_9 (wood ash + vermicompost) exhibited the highest fresh root weight (1.37 g and 2.91g, respectively) at 30 DAS and at harvest whereas the lowest fresh root

Table 4.7 Effect of different aluminium-alleviating organic materials on *fresh root weight* of mungbean in acid soil

Treatments	Fresh root weight (g)								
	48hrs			30DAS			Harvest		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	0.01	0.01	0.01	0.55	0.56	0.55	1.72	1.73	1.73
T_2: Absolute control	0.01	0.01	0.01	**0.44**	**0.46**	**0.45**	**1.50**	**1.52**	**1.51**
T_3: WA @ 2t ha^{-1}	0.02	0.02	0.02	**1.13**	**1.14**	**1.14**	2.35	2.36	2.36
T_4: PM @ 2t ha^{-1}	0.02	0.02	0.02	0.93	0.95	0.94	2.31	2.32	2.31
T_5: RR @ 2t ha^{-1}	0.01	0.01	0.01	0.62	0.63	0.63	1.83	1.81	1.82
T_6: VC @ 2t ha^{-1}	0.02	0.02	0.02	1.06	1.07	1.07	**2.42**	**2.43**	**2.43**
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	0.02	0.02	0.02	1.30	1.31	1.31	2.77	2.76	2.77
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	0.02	0.02	0.02	1.16	1.17	1.16	2.48	2.46	2.47
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	0.02	0.02	0.02	**1.36**	**1.37**	**1.36**	**2.89**	**2.91**	**2.90**
T_{10}: SR @ 2t ha^{-1}	0.02	0.02	0.02	0.69	0.68	0.69	1.92	1.93	1.93
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	0.02	0.02	0.02	1.23	1.21	1.22	2.57	2.58	2.57
SEm±	**0.00**	**0.00**	**0.00**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.00**
CD at 5%	**NS**	**NS**	**NS**	**0.03**	**0.04**	**0.02**	**0.02**	**0.02**	**0.01**

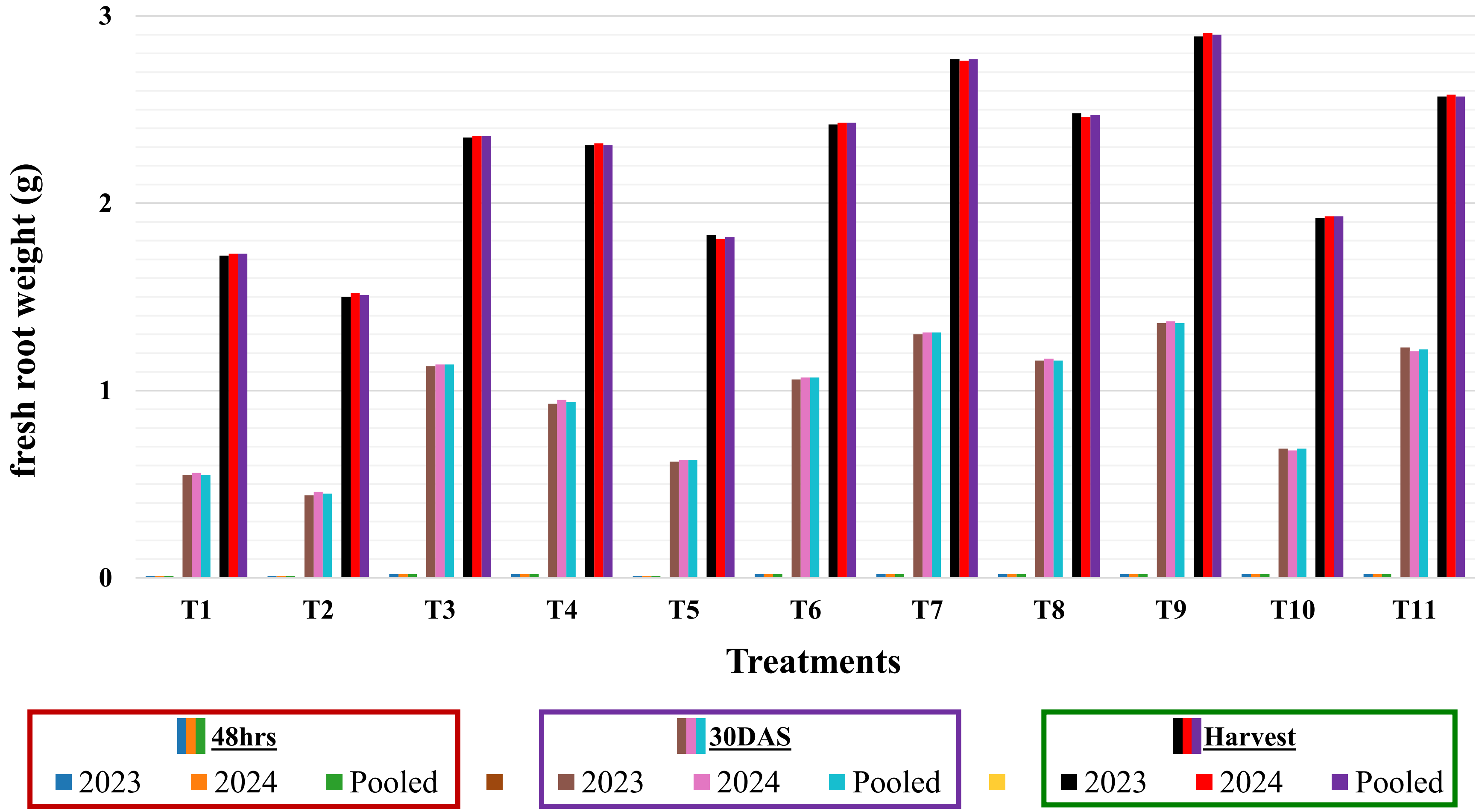

Fig. 4.7 Effect of different aluminium-alleviating organic materials on *fresh root weight* of mungbean in acid soil

weight (0.46 g and 1.52 g, respectively) was obtained under treatment T_2 (absolute control).

Among the individual amendments, the highest fresh root weight (1.14 g) was recorded under treatment T_3 (wood ash) at 30 DAS, whereas treatment T_6 (vermicompost) recorded the highest fresh root weight (2.43g) at harvest.

Based on pooled analysis of both years, treatment T_9 (wood ash + vermicompost) registered the maximum fresh root weight (1.36 g and 2.90 g, respectively) at 30 DAS and at harvest whereas the lowest fresh root weight (0.45 g and 1.51 g, respectively) was exhibited under treatment T_2 (absolute control). Among the single application of organic materials, the highest fresh root weight (1.14 g) was found under treatment T_3 (wood ash) at 30 DAS, whereas treatment T_6 (vermicompost) recorded the highest fresh root weight (2.43 g) at harvest.

The lowest fresh root weight observed under the absolute control may be attributed to the strongly acidic soil conditions where soluble Al^{3+} inhibits root cell division and elongation, reducing root biomass accumulation. Wang *et al*. (2016) reported that Al^{3+} stress significantly reduced root fresh weight in alfalfa by disrupting auxin transport in root tips, deforming cell structures in the meristematic zone, and impairing water and nutrient uptake. Among the single amendments, wood ash resulted in comparatively higher fresh root weight due to its liming effect, which elevated soil pH, reduced Al^{3+} solubility, and improved the availability of essential base cations critical for root cell development and biomass production (Demeyer *et al*., 2001). Vermicompost also produced higher fresh root weight owing to the stimulatory effect of its humic substances on root development, as Canellas *et al*. (2002) demonstrated that humic acids from vermicompost enhance root elongation and lateral root formation, directly contributing to greater root fresh weight. The highest fresh root weight was recorded under the combined application of wood ash and vermicompost, attributable to the synergistic effect of Al toxicity reduction by wood ash and the bio stimulant properties of vermicompost, which together promoted greater root development and fresh biomass accumulation (Haynes and Mokolobate, 2001).

4.1.3.3 Dry root weight (g)

Observations on dry root weight (g) under different organic material treatments are presented in Table 4.8 and illustrated in Fig. 4.8. The application of different organic materials on dry root weight at 48 hrs after sowing was found to be non-significant. However, a significant variation in dry root weight (g) was observed at 30 DAS and at harvest due to the application of different organic materials.

During the first season (2023), among all the treatments, the highest dry root weight (0.152 g and 0.62 g, respectively) was noted under treatment T_9 (wood ash + vermicompost) at 30 DAS and at harvest whereas the lowest dry root weight (0.013 g and 0.13 g, respectively) was observed under treatment T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) recorded the maximum dry root weight (0.40g) at 30 DAS, whereas treatment T_6 (vermicompost) recorded the maximum dry root weight at harvest.

The results obtained during the second season (2024) followed a similar trend, with treatment T_9 (wood ash + vermicompost) recording the highest dry root weight (0.153 g and 0.63 g, respectively) at 30 DAS and at harvest, while the lowest dry root weight (0.014 g and 0.12 g, respectively) was obtained under treatment T_2 (absolute control). Among the single application of organic materials, the highest dry root weight (0.096 g) was found under treatment T_3 (wood ash) at 30 DAS, whereas treatment T_6 (vermicompost) recorded the highest fresh root weight (0.41 g) at harvest.

The pooled results of both season (2023 and 2024) showed that treatment T_9 (wood ash + vermicompost) registered the maximum fresh root weight (0.153 g and 0.63 g, respectively) at 30 DAS and at harvest whereas the lowest fresh root weight (0.014 g and 0.13 g, respectively) was exhibited under treatment T_2 (absolute control). Among the individual amendments, the highest dry root weight (0.095 g) was obtained under treatment T_3 (wood ash) at 30 DAS, whereas treatment T_6 (vermicompost) recorded the highest dry root weight (0.40 g) at harvest.

The lowest dry root weight under the absolute control may be attributed to the adverse effects of soil acidity and Al^{3+} toxicity, which restrict root development and dry matter accumulation. Kochian *et al*. (2004) reported that Al^{3+} toxicity in acidic

Table 4.8 Effect of different aluminium-alleviating organic materials on *dry root weight* of mungbean in acid soil

Treatments	Dry root weight (g)								
	48hrs			30DAS			Harvest		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	0.0013	0.0013	0.0013	0.034	0.036	0.035	0.18	0.19	0.19
T_2: Absolute control	0.0013	0.0012	0.0013	**0.013**	**0.014**	**0.014**	**0.13**	**0.12**	**0.13**
T_3: WA @ 2t ha^{-1}	0.0013	0.0013	0.0013	**0.094**	**0.096**	**0.095**	0.37	0.38	0.38
T_4: PM @ 2t ha^{-1}	0.0013	0.0013	0.0013	0.070	0.071	0.071	0.31	0.32	0.32
T_5: RR @ 2t ha^{-1}	0.0013	0.0013	0.0013	0.047	0.046	0.046	0.23	0.22	0.23
T_6: VC @ 2t ha^{-1}	0.0013	0.0013	0.0013	0.082	0.084	0.083	**0.40**	**0.41**	**0.40**
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	0.0013	0.0013	0.0013	0.134	0.136	0.135	0.57	0.59	0.58
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	0.0013	0.0013	0.0013	0.113	0.114	0.114	0.44	0.44	0.44
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	0.0014	0.0013	0.0014	**0.152**	**0.153**	**0.153**	**0.62**	**0.63**	**0.63**
T_{10}: SR @ 2t ha^{-1}	0.0013	0.0013	0.0013	0.057	0.056	0.056	0.25	0.25	0.25
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	0.0013	0.0013	0.0013	0.123	0.124	0.124	0.50	0.51	0.50
SEm±	**0.00**	**0.00**	**0.00**	**0.002**	**0.001**	**0.001**	**0.00**	**0.00**	**0.00**
CD at 5%	**NS**	**NS**	**NS**	**0.006**	**0.004**	**0.004**	**0.01**	**0.01**	**0.01**

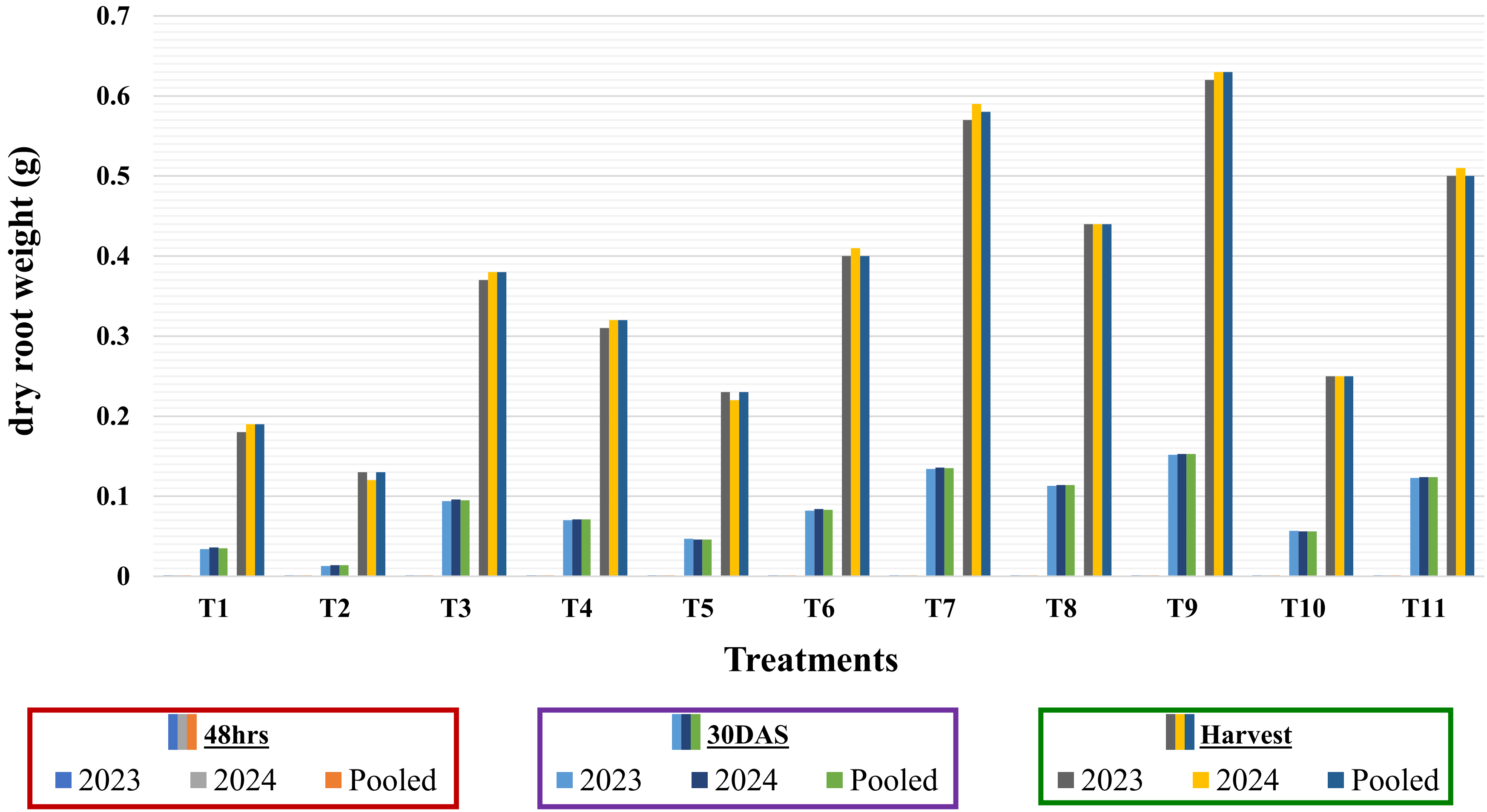

Fig. 4.8 Effect of different aluminium-alleviating organic materials on *dry root weight* of mungbean in acid soil

soils inhibits cell division and elongation at the root apex, resulting in stunted root systems with reduced biomass. Among the single amendments, wood ash resulted in comparatively higher dry root weight due to its liming effect, which increased soil pH and reduced phytotoxic Al^{3+}, creating more favourable conditions for root growth (Demeyer *et al*., 2001). Vermicompost also improved dry root biomass through gradual nutrient release and the presence of humic substances that stimulate root development (Canellas *et al*., 2002). The highest dry root weight was observed under the combined application of wood ash and vermicompost, which may be attributed to the combined effect of soil acidity neutralization and increased organic matter, resulting in reduced aluminium toxicity and improved nutrient availability. Similar findings were reported by Haynes and Mokolobate (2001), who observed enhanced root development with the combined application of organic and alkaline amendments due to reduced Al toxicity and improved soil fertility.

4.1.3.4 Relative root length (%)

Perusal of the data in Table 4.9 and Fig. 4.9 indicates that the relative root length was significantly affected by the application of different organic materials during both the trials and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the first year of study (2023), at 48 hrs after sowing, 30DAS and at harvest the maximum relative root length (234.11%, 137.51% and 188.63%, respectively) was observed under treatment T_9 (wood ash + vermicompost). At 48 hours after sowing, T_9 was statistically at par with treatment T_7 (wood ash + poultry manure) (230.37%). In contrast the minimum relative root length (100.00%, 100.00% and 100.00%, respectively) was recorded under treatment T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) recorded the highest relative root length (181.30% and 125.97%, respectively) at 48 hours after sowing and 30 DAS, whereas at harvest treatment T_6 (vermicompost) recorded the highest relative root length (163.64%).

A similar trend was observed during the second-year study (2024), where treatment T_9 (wood ash + vermicompost) exhibited the highest relative root length

Table 4.9 Effect of different aluminium-alleviating organic materials on *relative root length* of mungbean in acid soil

Treatments	Relative root length (%)								
	48hrs			30DAS			Harvest		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	112.44	111.97	112.20	103.93	103.82	103.87	106.59	106.83	106.71
T_2: Absolute control	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
T_3: WA @ 2t ha^{-1}	181.30	180.34	180.82	125.97	125.80	125.89	161.26	161.65	161.46
T_4: PM @ 2t ha^{-1}	167.89	167.24	167.57	124.39	124.23	124.31	154.74	155.22	154.98
T_5: RR @ 2t ha^{-1}	130.48	130.20	130.34	110.72	110.34	110.53	133.77	133.77	133.77
T_6: VC @ 2t ha^{-1}	171.06	170.09	170.58	125.36	125.30	125.33	163.64	163.92	163.78
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	230.37	229.92	230.14	136.08	136.10	136.09	183.77	184.17	183.97
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	192.93	191.74	192.34	127.86	127.69	127.78	169.16	169.45	169.30
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	234.11	233.62	233.86	137.51	137.31	137.41	188.63	189.05	188.84
T_{10}: SR @ 2t ha^{-1}	146.85	146.15	146.50	114.65	114.72	114.69	141.89	141.92	141.91
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	202.45	200.29	201.37	131.43	131.29	131.36	173.25	173.64	173.45
SEm±	1.59	1.23	1.01	0.48	0.30	0.28	0.40	0.35	0.26
CD at 5%	4.68	3.61	2.87	1.40	0.88	0.80	1.18	1.01	0.76

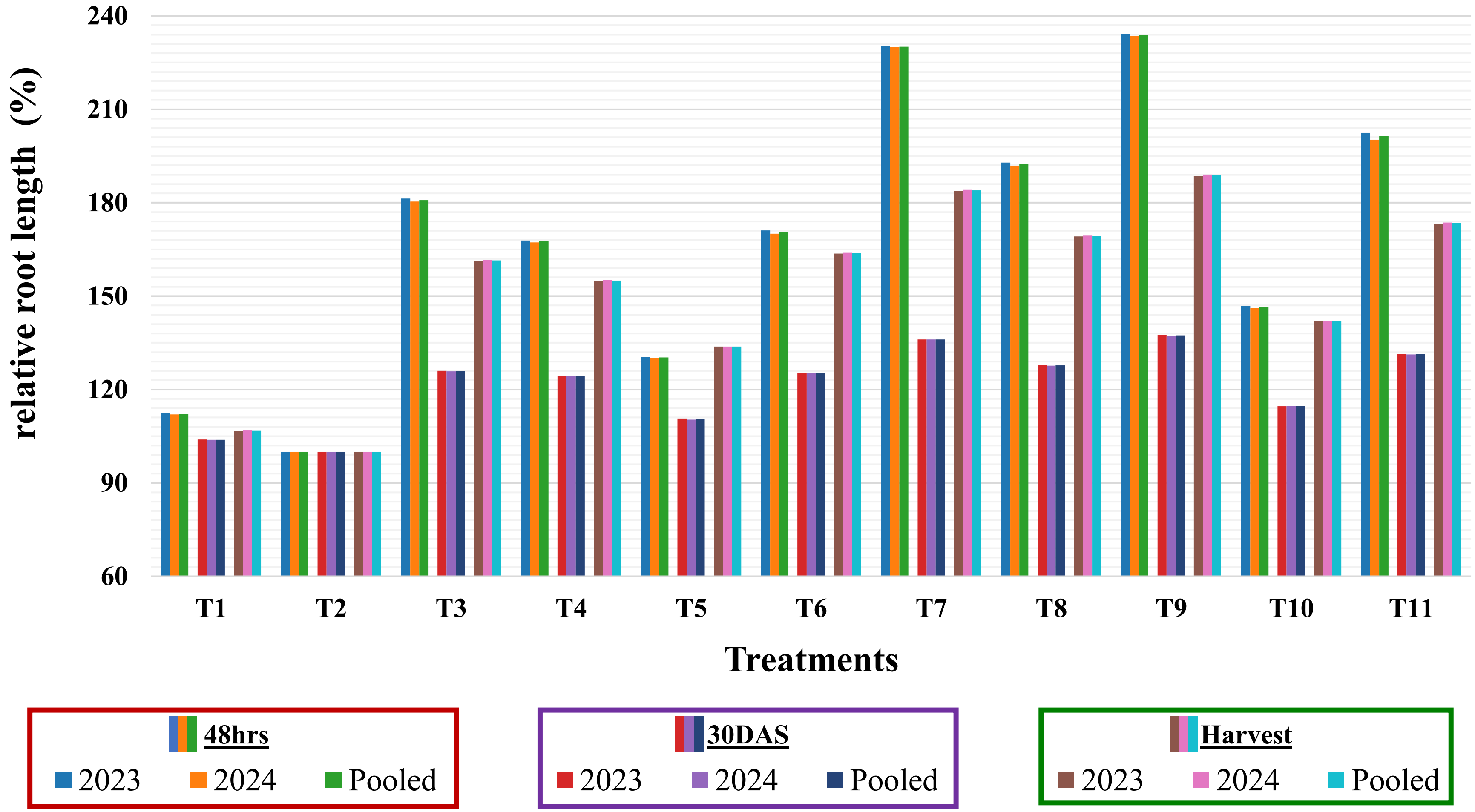

Fig. 4.9 Effect of different aluminium-alleviating organic materials on *relative root length* of mungbean in acid soil

PLATE 7 Comparison of root length between treatments T_2 and T_6; and T_2 and T_9

(233.62%, 137.31% and 189.05%, respectively), while the lowest relative root length (100.00%, 100.00% and 100.00%, respectively) was observed under treatment T_2 (absolute control) at 48 hrs after sowing, 30DAS and at harvest. Among the individual amendments, treatment T_3 (wood ash) recorded the maximum relative root length (180.34% and 180.82%, respectively) at 48 hours after sowing and 30 DAS, whereas treatment T_6 (vermicompost) recorded the highest relative root length (163.92%) at harvest.

The pooled data of 2023 and 2024 revealed that treatment T_9 (wood ash + vermicompost) exhibited the maximum relative root length (233.86%, 137.41% and 188.84%, respectively); conversely, the minimum relative root length (100.00%, 100.00% and 100.00%, respectively) was found under treatment T_2 (absolute control) at 48 hrs after sowing, 30DAS and at harvest. Among the individual amendments, the highest relative root length (180.82% and 125.89%, respectively) was recorded under treatment T_3 (wood ash) at 48 hours after sowing and 30 DAS, whereas treatment T_6 (vermicompost) recorded the maximum relative root length (163.78%) at harvest.

The highest relative root length was observed under the combined application of wood ash and vermicompost, which may be attributed to the synergistic effect of soil acidity amelioration and improved soil organic matter. Wood ash increases soil pH and supplies base cations, thereby reducing aluminium toxicity, while vermicompost enhances soil organic matter, nutrient availability and microbial activity, promoting better root growth. Among the single amendments, wood ash resulted in comparatively higher relative root length due to its rapid liming effect, while vermicompost also improved root growth through gradual nutrient release and the presence of humic substances. The lowest relative root length under the absolute control may be attributed to strongly acidic soil conditions where soluble aluminium restricts root cell division and elongation. Similar findings were reported by Bessho and Bell (1992) and Muhrizal *et al*. (2003), who observed improved root growth and relative root length of mungbean with organic amendments due to reduced aluminium toxicity.

4.2 Effect of different aluminium-alleviating organic materials on nutrient content and uptake of mungbean in acid soil

4.2.1 Nutrient content in seed and stover

The data on various nutrient contents in seed and stover, namely nitrogen, phosphorus, potassium, calcium, magnesium, aluminium and protein, as influenced by different Al-alleviating organic materials are presented and discussed in the following sections to highlight the variation in nutrient concentration under different treatments.

4.2.1.1 Nitrogen content in seed (%)

The data on the nitrogen content in seed as influenced by different organic materials are presented in Table 4.10 and graphically illustrated in Fig. 4.10. The treatments significantly influenced the nitrogen content in seed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest nitrogen content in seed (3.45%) under T_7 (wood ash + poultry manure), which was found to be statistically at par (3.42%) with T_9 (wood ash + vermicompost); whereas the lowest nitrogen content in seed (2.49%) was observed under T_2 (absolute control). Among the single amendments, treatment T_4 (poultry manure) exhibited the highest nitrogen content in seed (3.27%).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest nitrogen content in seed (3.47%), which was statistically at par (3.44%) with T_9 (wood ash + vermicompost). The lowest nitrogen content in seed (2.52%) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest nitrogen content in seed (3.28%).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the highest nitrogen content in seed (3.46%), while the lowest nitrogen content in seed (2.50%) was obtained under treatment T_2

(absolute control). Among the single amendments, the highest nitrogen content in seed (3.28%) was recorded in treatment T_4 (poultry manure).

The highest nitrogen content in mungbean seed may be attributed to the combined application of wood ash and poultry manure, which improved soil conditions and nutrient availability in the acidic soil. Wood ash reduced soil acidity and aluminium toxicity, while poultry manure supplied nutrients and organic matter, enhancing root growth, nutrient uptake and biological nitrogen fixation. In contrast, the lowest nitrogen content under the control condition may be due to poor nutrient availability and continued aluminium toxicity, which restrict root growth and nodulation. Among the individual organic amendments, poultry manure was the most effective due to its high nitrogen content and narrow C:N ratio that promotes rapid mineralization. Similar findings were reported by Kumawat (2006) and Choudhary *et al*. (2013). The beneficial effect of wood ash in acidic soils due to its liming action and alleviation of aluminium toxicity was also reported by An and Park (2021).

4.2.1.2 Phosphorus content in seed (%)

Data regarding phosphorus content in seed as influenced by different organic materials are presented in Table 4.10 and graphically illustrated in Fig. 4.10. The treatments significantly influenced the phosphorus content in seed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first trial (2023) the highest phosphorus content in seed (0.48%) was recorded under T_7 (wood ash + poultry manure); whereas the lowest phosphorus content in seed (0.17%) was observed under T_2 (absolute control). Among the single amendments, treatment T_4 (poultry manure) recorded the highest phosphorus content in seed (0.35%).

During the second trial (2024), a similar trend was noticed. Treatment T_7 (wood ash + poultry manure) recorded the highest phosphorus content in seed (0.48%), which was statistically at par (0.46%) with T_9 (wood ash + vermicompost). The lowest phosphorus content in seed (0.18%) was observed under treatment T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) obtained the highest phosphorus content in seed (0.36%).

The pooled data of both years (2023 and 2024) also revealed that treatment T_7 (wood ash + poultry manure) recorded the highest phosphorus content in seed (0.48%), whereas the lowest phosphorus content in seed (0.17%) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest phosphorus content in seed (0.36%) was recorded in treatment T_4 (poultry manure).

The increased phosphorus content in mungbean seed under the combined application of wood ash and poultry manure may be attributed to improved phosphorus availability in the acidic soil. Wood ash likely increased soil pH and reduced aluminium activity, thereby decreasing phosphorus fixation, while poultry manure supplied organic matter and phosphorus through mineralization, enhancing nutrient availability and uptake. Organic amendments also release organic acids during decomposition, which complex aluminium and iron and further reduce phosphorus fixation in acidic soils. In contrast, the lowest phosphorus content recorded under the control condition may be due to strong phosphorus fixation by aluminium and iron compounds, which limits its availability to plants. Among the individual organic amendments, poultry manure appeared to be more effective due to the mineralization of organic phosphorus and the release of organic acids during decomposition, which improve phosphorus availability and uptake in mungbean. Similar observations were also reported by Demeyer *et al*. (2001) and Haynes and Mokolobate (2001). Similar findings were also reported by Kumawat (2006), who observed higher phosphorus concentration in mungbean seed with the application of organic manures compared to the control.

4.2.1.3 Potassium content in seed (%)

Data pertaining to potassium content in seed as influenced by different organic materials are presented in Table 4.10 and graphically illustrated in Fig. 4.10. The treatments significantly improved potassium content in seed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the first trial conducted during 2023, the maximum potassium content in seed (1.22%) was observed under treatment T_7 (wood ash + poultry manure), which was statistically at par (1.21%) with T_9 (wood ash + vermicompost). On the other hand, the minimum potassium content in seed (0.78%) was recorded under treatment T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) registered the highest potassium content in seed (1.13%).

A comparable trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest potassium content in seed (1.23%), which was statistically at par (1.22%) with T_9 (wood ash + vermicompost). The lowest potassium content in seed (0.79%) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest potassium content in seed (1.12%).

The pooled analysis of both the years (2023 and 2024) revealed that treatment T_7 (wood ash + poultry manure) recorded the highest potassium content in seed (1.23%), while the lowest value (0.78%) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest potassium content in seed (1.13%) was recorded in treatment T_3 (wood ash).

Potassium content in mungbean seed was highest under the combined application of wood ash and poultry manure, due to improved potassium availability in the acidic soil and enhanced uptake by the crop. Wood ash supplied potassium and increased soil pH, reducing aluminium toxicity, while poultry manure provided potassium and organic matter, improving soil fertility and cation exchange capacity. The increased absorption of potassium under these amendments resulted in higher translocation and accumulation in the seeds. In contrast, the lowest seed potassium content under the control condition may be due to limited soil potassium availability and persistent aluminium toxicity, which restricted uptake and accumulation. Among the individual organic amendments, poultry manure was particularly effective due to its ability to supply potassium and improve soil chemical and biological properties. These findings are supported by Akinmutimi and Ukonu (2020), who reported increased soil pH and exchangeable potassium with wood ash and poultry manure

Table 4.10 Effect of different aluminium-alleviating organic materials on different nutrient contents (namely *nitrogen, phosphorus and potassium*) in seed of mungbean in acid soil

Treatments	Nutrient content in seed (%)								
	Nitrogen			Phosphorus			Potassium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	2.68	2.67	2.68	0.20	0.21	0.20	0.99	1.00	1.00
T_2: Absolute control	**2.49**	**2.52**	**2.50**	**0.17**	**0.18**	**0.17**	**0.78**	**0.79**	**0.78**
T_3: WA @ 2t ha^{-1}	3.19	3.20	3.20	0.25	0.25	0.25	**1.13**	**1.12**	**1.13**
T_4: PM @ 2t ha^{-1}	**3.27**	**3.28**	**3.28**	**0.35**	**0.36**	**0.36**	1.12	1.10	1.11
T_5: RR @ 2t ha^{-1}	3.13	3.12	3.13	0.27	0.26	0.27	1.04	1.03	1.04
T_6: VC @ 2t ha^{-1}	3.25	3.26	3.26	0.33	0.34	0.34	1.09	1.08	1.09
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	**3.45**	**3.47**	**3.46**	**0.48**	**0.48**	**0.48**	**1.22**	**1.23**	**1.23**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	3.29	3.30	3.30	0.37	0.38	0.37	1.15	1.15	1.15
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**3.42**	**3.44**	3.43	0.45	**0.46**	0.45	**1.21**	**1.22**	1.21
T_{10}: SR @ 2t ha^{-1}	3.17	3.18	3.18	0.29	0.30	0.30	1.06	1.05	1.06
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	3.33	3.34	3.34	0.40	0.41	0.41	1.18	1.18	1.18
SEm±	**0.01**	**0.02**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
CD at 5%	**0.04**	**0.05**	**0.03**	**0.03**	**0.03**	**0.02**	**0.04**	**0.03**	**0.02**

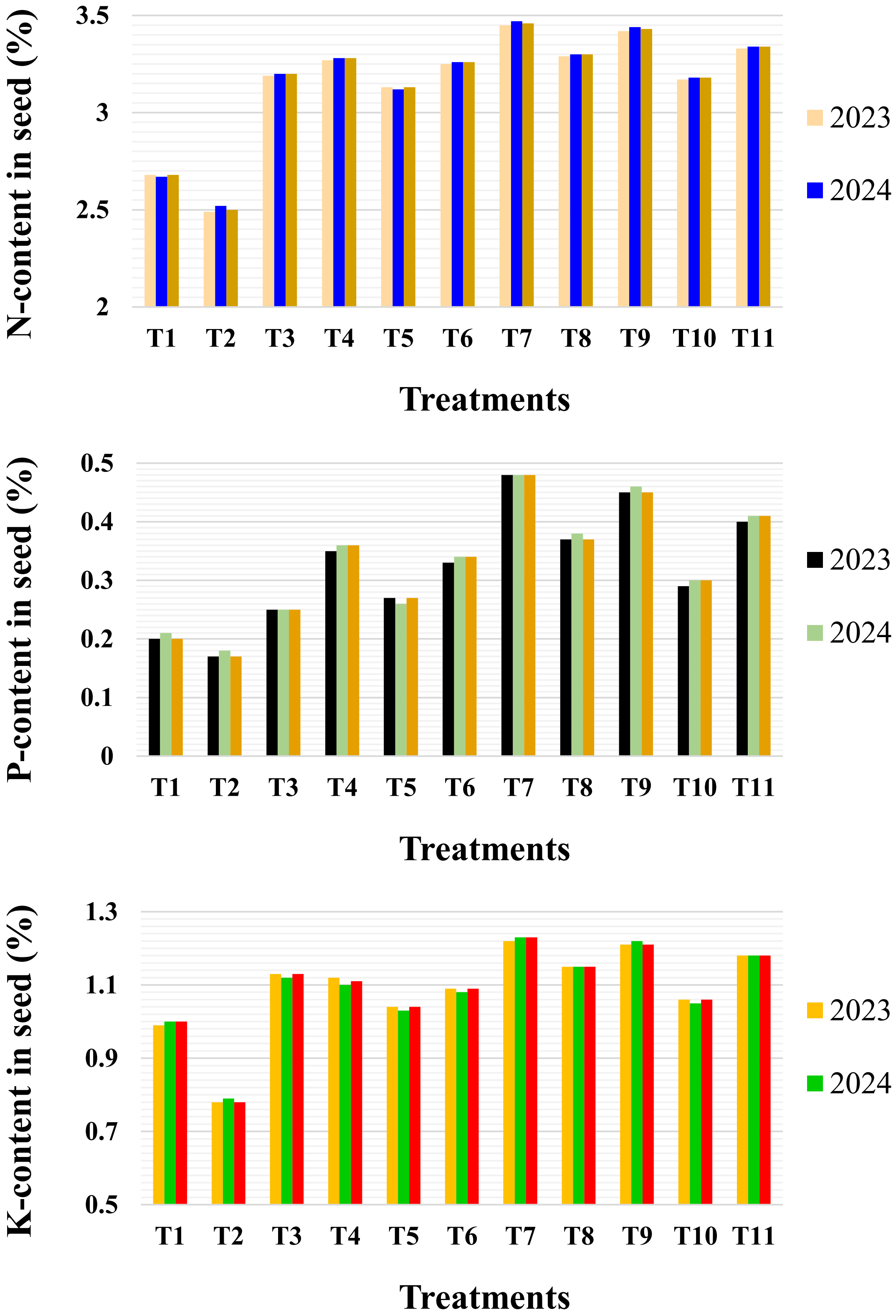

Fig. 4.10 Effect of different aluminium-alleviating organic materials on different nutrient contents (namely *nitrogen, phosphorus and potassium*) in seed of mungbean in acid soil

application, and by Paramisparam *et al*. (2021), who observed that animal manures enhance soil organic matter and cation exchange capacity, increasing exchangeable potassium and its uptake by crops.

4.2.1.4 Calcium content in seed (%)

Calcium content in seed under different organic materials is presented in Table 4.11 and graphically illustrated in Fig. 4.11. The treatments showed a significant effect on seed calcium content in both the years (2023 and 2024) and in the pooled results, where all organic amendments outperformed T_1 (control) and T_2 (absolute control).

During the 2023 experimental trial, the highest calcium content in seed (0.27%) was obtained under treatment T_7 (wood ash + poultry manure). In contrast, the lowest calcium content in seed (0.10%) was observed under T_2 (absolute control). Among the individual amendments, treatment T_4 (poultry manure) produced the highest calcium content in seed (0.18%).

The second trail conducted in 2024 also revealed a similar trend. Treatment T_7 (wood ash + poultry manure) recorded the highest calcium content in seed (0.26%). The lowest calcium content in seed (0.09%) was observed under treatment T_2 (absolute control). Among the single amendments, treatment T_4 (poultry manure) recorded the highest calcium content in seed (0.18%).

The pooled analysis of both experimental years (2023 and 2024) confirmed that treatment T_7 (wood ash + poultry manure) exhibited the highest calcium content in seed (0.27%), while the lowest calcium content in seed (0.10%) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest calcium content in seed (0.18%) was recorded in treatment T_4 (poultry manure).

Calcium content in mungbean seed was highest under the combined application of wood ash and poultry manure, due to increased calcium availability in the acidic soil and enhanced uptake by the crop. Wood ash supplied calcium and raised soil pH, reducing aluminium toxicity, while poultry manure provided calcium and improved soil organic matter and cation exchange capacity. The combined effect of these amendments promoted greater calcium uptake and accumulation in seeds. In contrast, the lowest seed calcium content under the control condition may be due to limited soil calcium availability and persistent aluminium toxicity. Among the individual organic amendments, poultry manure was particularly effective in supplying calcium and improving soil chemical and biological properties. These findings are supported by An and Park (2021) and Demeyer *et al*. (2001).

4.2.1.5 Magnesium content in seed (%)

The data on the magnesium content in seed as influenced by different organic materials are presented in Table 4.11 and graphically illustrated in Fig. 4.11. The treatments significantly influenced the magnesium content in seed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest magnesium content in seed (0.23%) under T_7 (wood ash + poultry manure); whereas the lowest magnesium content in seed (0.07%) was observed under T_2 (absolute control). Among the single amendments, treatment T_4 (poultry manure) exhibited the highest magnesium content in seed (0.15%).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest magnesium content in seed (0.22%). The lowest magnesium content in seed (0.07%) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest magnesium content in seed (0.15%).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the highest magnesium content in seed (0.22%), while the lowest magnesium content in seed (0.07%) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest magnesium content in seed (0.15%) was recorded in treatment T_4 (poultry manure).

Magnesium content in mungbean seed was highest under the combined application of wood ash and poultry manure, due to improved magnesium availability in the acidic soil and enhanced uptake by the crop. Wood ash supplied magnesium and increased soil pH, reducing aluminium toxicity and facilitating root nutrient absorption, while poultry manure contributed magnesium and organic matter, improving soil fertility, cation exchange capacity, and nutrient retention. The combined effect of these amendments promoted greater magnesium uptake and accumulation in seeds. In contrast, the lowest seed magnesium content under the control condition may be due to limited soil magnesium availability and persistent aluminium toxicity. Among the individual organic amendments, poultry manure was particularly effective in supplying magnesium and enhancing soil chemical and biological properties. These findings are supported by An and Park (2021) and Demeyer *et al*. (2001**)**, who reported that organic amendments and wood ash improve magnesium availability and plant uptake in acidic soils.

4.2.1.6 Aluminium content in seed (mg/kg)

The aluminium content in seed as affected by different organic materials are presented in Table 4.11 and graphically illustrated in Fig. 4.11. The treatments significantly influenced the aluminium content in seed during both the experimental trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the 2023 trial, treatment T_9 (wood ash + vermicompost) produced the lowest aluminium content in seed (6.79 mg/kg) under which was statistically at par (7.21 mg/kg) with T_7 (wood ash + poultry manure); whereas the highest aluminium content in seed (16.75%) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the lowest aluminium content in seed (10.18 mg/kg).

The results of the second trial in 2024 also indicated a comparable trend, where treatment T_9 (wood ash + vermicompost) recorded the lowest aluminium content in seed (6.57 mg/kg), which was statistically at par (7.00 mg/kg) with T_7 (wood ash + poultry manure). The highest aluminium content in seed (16.33 mg/kg) was observed under T_2 (absolute control). Among the individual applications, treatment T_3 (wood ash) exhibited the lowest aluminium content in seed (9.97 mg/kg).

Table 4.11 Effect of different aluminium-alleviating organic materials on different nutrient contents (namely *calcium, magnesium and aluminium*) in seed of mungbean in acid soil

Treatments	Nutrient content in seed								
	Calcium (%)			Magnesium (%)			Aluminium (mg/kg)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	0.11	0.10	0.10	0.08	0.09	0.09	14.63	14.42	14.52
T_2: Absolute control	**0.10**	**0.09**	**0.10**	**0.07**	**0.07**	**0.07**	**16.75**	**16.33**	**16.54**
T_3: WA @ 2t ha^{-1}	0.16	0.17	0.17	0.15	0.14	0.15	**10.18**	**9.97**	**10.07**
T_4: PM @ 2t ha^{-1}	**0.18**	**0.18**	**0.18**	**0.15**	**0.15**	**0.15**	11.45	11.24	11.34
T_5: RR @ 2t ha^{-1}	0.13	0.13	0.13	0.11	0.10	0.11	13.15	12.93	13.04
T_6: VC @ 2t ha^{-1}	0.15	0.15	0.15	0.14	0.13	0.14	11.02	10.81	10.92
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	**0.27**	**0.26**	**0.27**	**0.23**	**0.22**	**0.22**	**7.21**	**7.00**	**7.10**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	0.20	0.19	0.20	0.16	0.16	0.16	9.33	9.11	9.22
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	0.24	0.24	0.24	0.21	0.20	0.21	**6.79**	**6.57**	**6.68**
T_{10}: SR @ 2t ha^{-1}	0.14	0.14	0.14	0.11	0.11	0.11	12.51	12.29	12.40
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	0.21	0.20	0.21	0.18	0.18	0.18	8.70	8.50	8.60
SEm±	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.26**	**0.29**	**0.20**
CD at 5%	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.77**	**0.86**	**0.56**

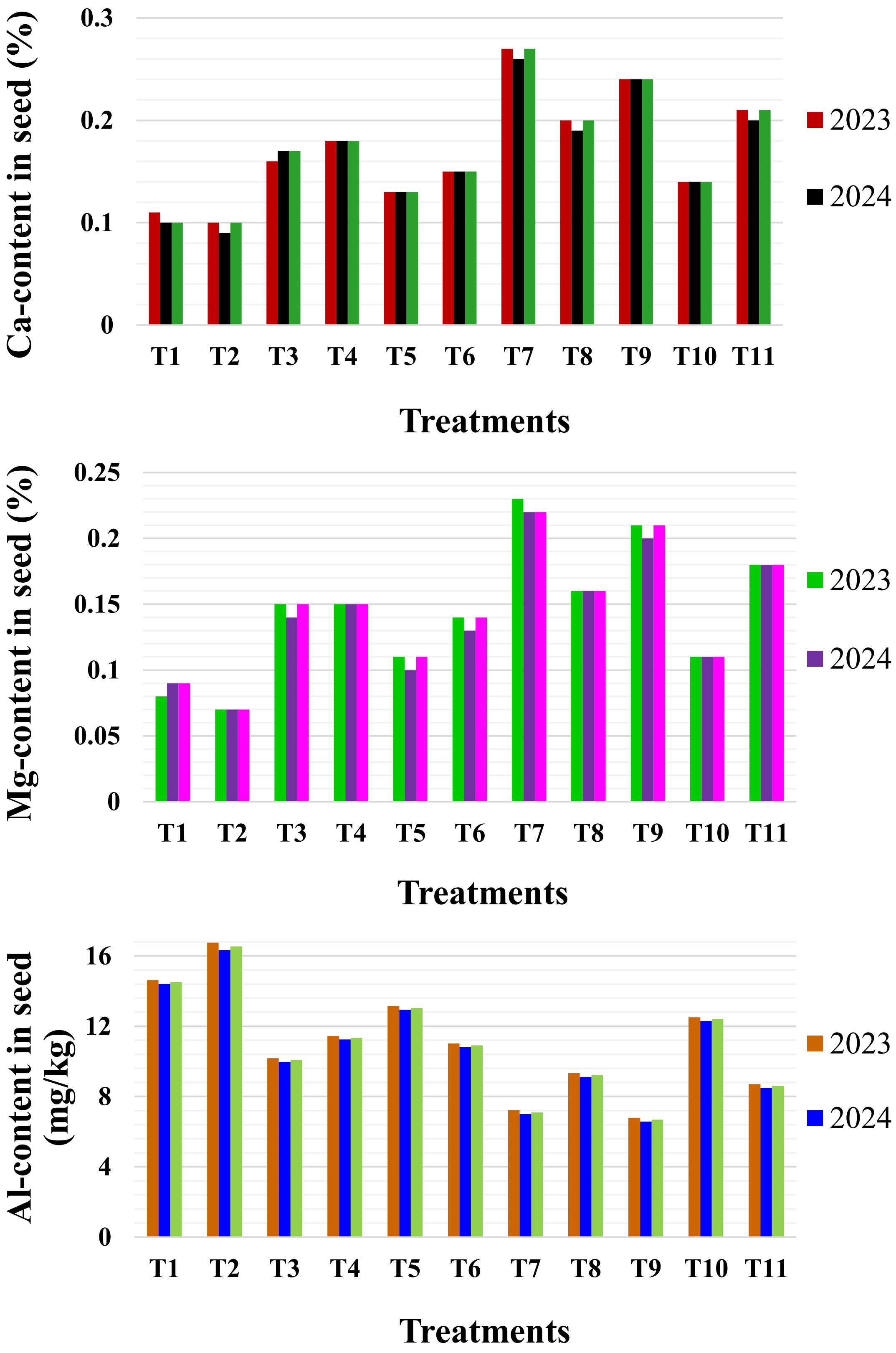

Fig. 4.11 Effect of different aluminium-alleviating organic materials on different nutrient contents (namely *calcium, magnesium and aluminium*) in seed of mungbean in acid soil

The pooled data of the two experimental years (2023 and 2024) revealed that treatment T_9 (wood ash + vermicompost) exhibited the lowest aluminium content in seed (6.68 mg/kg), which was statistically at par (7.10 mg/kg) with T_7 (wood ash + poultry manure); while the highest aluminium content in seed (16.54 mg/kg) was obtained under T_2 (absolute control). Among the single amendments, the lowest aluminium content in seed (10.07 mg/kg) was recorded in treatment T_3 (wood ash).

Aluminium content in mungbean seed was lowest under the combined application of wood ash and vermicompost, which can be attributed to the synergistic effect of soil acidity amelioration by wood ash and improved soil organic matter from vermicompost. Wood ash increases soil pH and supplies basic cations such as calcium, potassium, and magnesium, reducing aluminium solubility, while organic matter from vermicompost complexes aluminium ions, further decreasing its availability. Among the individual organic amendments, wood ash alone resulted in lower aluminium content in seeds due to its liming effect and the reduction of exchangeable aluminium in the soil. In contrast, the highest aluminium content was observed under the control condition, where persistent soil acidity and high soluble aluminium facilitated greater root uptake and accumulation in seeds. These findings are supported by Panda *et al.* (2017) and Demeyer *et al.* (2001)**,** who reported that organic amendments and crop residues reduce aluminium toxicity and its accumulation in plants grown in acidic soils.

4.2.1.7 Protein content in seed (%)

The protein content in seed as influenced by different organic materials is presented in Table 4.12 and graphically illustrated in Fig. 4.12. Significant variation among treatments was recorded during both the trials (2023 and 2024) and in the pooled analysis, with organic amendments showing higher performance compared to T_1 (control) and T_2 (absolute control).

During the first trial in 2023, the highest protein content in seed (21.56%) was observed under treatment T_7 (wood ash + poultry manure), which was statistically at par (21.37%) with T_9 (wood ash + vermicompost); whereas the lowest protein content in seed (15.56%) was observed under T_2 (absolute control). Among the single

Table 4.12 Effect of different aluminium-alleviating organic materials on *protein* content in seed of mungbean in acid soil

Treatments	Protein Content in Seed (%)		
	2023	2024	Pooled
T_1 : Control	16.77	16.71	16.74
T_2: Absolute control	15.56	15.73	15.65
T_3: WA @ 2t ha^{-1}	19.94	20.00	19.97
T_4: PM @ 2t ha^{-1}	20.44	20.50	20.47
T_5: RR @ 2t ha^{-1}	19.56	19.50	19.53
T_6: VC @ 2t ha^{-1}	20.31	20.38	20.35
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	21.56	21.69	21.63
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	20.57	20.63	20.60
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	21.37	21.50	21.44
T_{10}: SR @ 2t ha^{-1}	19.81	19.88	19.85
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	20.81	20.87	20.84
SEm±	**0.09**	**0.10**	**0.07**
CD at 5%	**0.26**	**0.30**	**0.19**

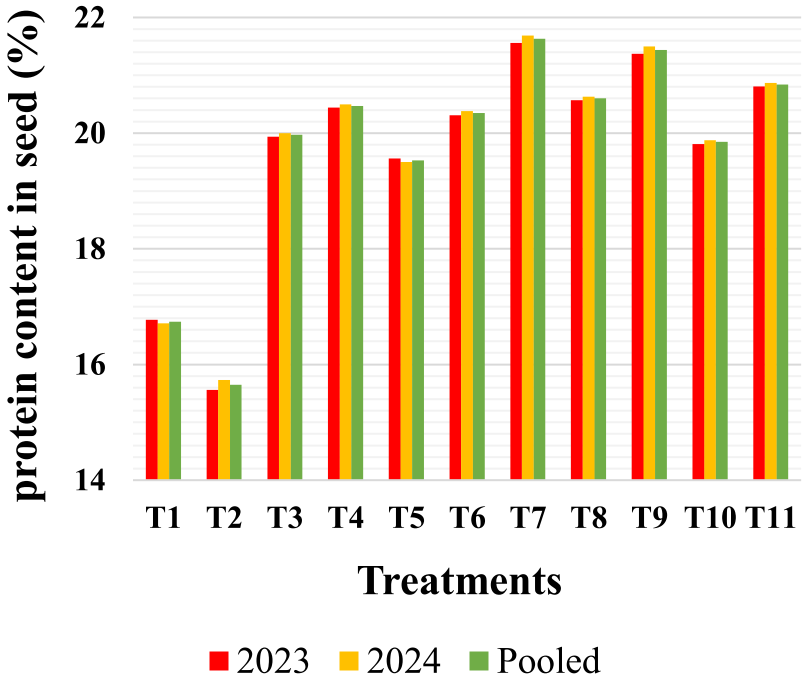

Fig. 4.12 Effect of different aluminium-alleviating organic materials on *protein* content in seed (%) of mungbean in acid soil

amendments, treatment T_4 (poultry manure) exhibited the highest protein content in seed (20.44%).

A comparable trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest protein content in seed (21.69%), which was statistically at par (21.50%) with T_9 (wood ash + vermicompost). The lowest protein content in seed (15.73%) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest protein content in seed (20.50%).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the highest protein content in seed (21.63%); while the lowest protein content in seed (15.65%) was obtained under T_2 (absolute control). Among the single amendments, the highest protein content in seed (20.47%) was recorded in T_4 (poultry manure).

Protein content in mungbean seed was highest under the combined application of wood ash and poultry manure due to improved soil conditions and greater nitrogen availability. Wood ash increased soil pH and reduced aluminium toxicity, while poultry manure supplied nutrients and enhanced nitrogen availability through mineralization. The combined effect promoted greater nitrogen uptake and assimilation, resulting in higher protein accumulation in seeds. In contrast, the lowest protein content was observed under the control condition, likely due to poor nutrient availability and persistent aluminium toxicity that restricted root growth, nodulation, and nitrogen fixation. Among the individual organic amendments, poultry manure resulted in relatively higher protein content in seeds due to its rich nutrient content and ability to improve soil fertility. Similar findings were reported by Kumawat (2006)**,** who observed higher protein content in mungbean seed with the application of organic manures compared to the control.

4.2.1.8 Nitrogen content in stover (%)

The effect of nitrogen content in stover as influenced by different organic materials is presented in Table 4.13 and graphically illustrated in Fig. 4.13. The treatments significantly affected the nitrogen content in stover during both the trials

(2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the initial trial in 2023, treatment T_9 (wood ash + vermicompost) recorded the highest nitrogen content in stover (2.49%), whereas the lowest nitrogen content in stover (2.14%) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) exhibited the highest nitrogen content in stover (2.34%).

A similar tendency was observed during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest nitrogen content in stover (2.50%), which was statistically at par (2.47%) with T_7 (wood ash + poultry manure). The lowest nitrogen content in stover (2.15%) was observed under T_2 (absolute control). Among the individual applications, treatment T_6 (vermicompost) exhibited the highest nitrogen content in stover (2.35%).

The pooled analysis of both years (2023 and 2024) further indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest nitrogen content in stover (2.50%); while the lowest nitrogen content in stover (2.15%) was obtained under T_2 (absolute control). Among the single amendments, the highest nitrogen content in stover (2.35%) was recorded in T_6 (vermicompost).

Nitrogen content in mungbean stover was highest under the combined application of wood ash and vermicompost due to improved soil conditions and enhanced nitrogen availability. Wood ash increased soil pH and reduced aluminium toxicity, while vermicompost improved soil organic matter and nutrient mineralization. The combined effect promoted better root growth and nitrogen uptake, resulting in greater nitrogen accumulation in the stover. In contrast, the lowest nitrogen content was observed under the control condition, which may be due to poor nutrient availability and persistent aluminium toxicity that restricted root growth, nodulation, and biological nitrogen fixation. Among the individual organic amendments, vermicompost resulted in relatively higher nitrogen content in stover due to its ability to improve soil fertility and gradually release nutrients. Similar findings were reported by Kumawat (2006) and Choudhary *et al*. (2013), who observed higher nitrogen content in mungbean with the application of organic manures compared to the control.

4.2.1.9 Phosphorus content in stover (%)

Data regarding phosphorus content in stover as influenced by different organic materials are presented in Table 4.13 and graphically illustrated in Fig. 4.13. The treatments significantly improved phosphorus content in stover during both experimental years (2023 and 2024) and in the pooled analysis compared to T_1 (control) and T_2 (absolute control).

The experimental results from the first trial in 2023 showed that the maximum phosphorus content in stover (0.35%) was recorded under T_9 (wood ash + vermicompost); whereas the minimum phosphorus content in stover (0.12%) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) exhibited the highest phosphorus content in stover (0.24%).

A similar trend was observed during the second trial in 2024. Treatment T_9 (wood ash + vermicompost) recorded the highest phosphorus content in stover (0.37%), whereas the lowest phosphorus content in stover (0.13%) was observed under T_2 (absolute control). Among the single applications, treatment T_6 (vermicompost) found the highest phosphorus content in stover (0.25%).

The pooled results of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) registered the highest phosphorus content in stover (0.36%); while the lowest phosphorus content in stover (0.12%) was obtained under T_2 (absolute control). Among the single amendments, the highest phosphorus content in stover (0.24%) was recorded in T_6 (vermicompost).

Phosphorus content in mungbean stover was highest under the combined application of wood ash and vermicompost due to improved phosphorus availability in the acidic soil. Wood ash increased soil pH and reduced aluminium activity, while vermicompost supplied organic matter and released organic acids that reduced phosphorus fixation. The combined effect enhanced phosphorus availability and uptake by the crop. In contrast, the lowest phosphorus content was observed under the control condition due to strong phosphorus fixation by aluminium and iron compounds in acidic soils. Among the individual organic amendments, vermicompost resulted in relatively higher phosphorus content in stover due to improved soil organic matter and nutrient mineralization**.** Similar findings were reported by Choudhary *et al*. (2013), while Haynes and Mokolobate (2001) reported that organic amendments reduce phosphorus fixation and improve phosphorus availability in acidic soils.

4.2.1.10 Potassium content in stover (%)

The data on the potassium content in stover as influenced by different organic materials are presented in Table 4.13 and graphically illustrated in Fig. 4.13. The treatments significantly influenced the potassium content in stover during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest potassium content in stover (1.40%) under T_7 (wood ash + poultry manure), which was statistically at par (1.39%) with T_9 (wood ash + vermicompost); whereas the lowest potassium content in stover (1.04%) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest potassium content in stover (1.24%).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest potassium content in stover (1.41%), which was statistically at par (1.40%) with T_9 (wood ash + vermicompost). The lowest potassium content in stover (1.05%) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest potassium content in stover (1.23%).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the highest potassium content in stover (1.41%), which was statistically at par (1.40%) with T_9 (wood ash + vermicompost); while the lowest potassium content in stover (1.04%) was obtained under T_2 (absolute control). Among the single amendments, the highest potassium content in stover (1.24%) was recorded in T_3 (wood ash).

Table 4.13 Effect of different aluminium-alleviating organic materials on different nutrient contents (namely *nitrogen, phosphorus and potassium*) in stover of mungbean in acid soil

Treatments	Nutrient content in stover (%)								
	Nitrogen			Phosphorus			Potassium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	2.20	2.21	2.21	0.14	0.15	0.14	1.09	1.10	1.10
T_2: Absolute control	**2.14**	**2.15**	**2.15**	**0.12**	**0.13**	**0.12**	**1.04**	**1.05**	**1.04**
T_3: WA @ 2t ha^{-1}	2.27	2.26	2.27	0.22	0.24	0.23	**1.24**	**1.23**	**1.24**
T_4: PM @ 2t ha^{-1}	2.31	2.33	2.32	0.20	0.21	0.21	1.20	1.21	1.20
T_5: RR @ 2t ha^{-1}	2.23	2.23	2.23	0.17	0.18	0.17	1.13	1.12	1.12
T_6: VC @ 2t ha^{-1}	**2.34**	**2.35**	**2.35**	**0.24**	**0.25**	**0.24**	1.18	1.19	1.19
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	2.45	**2.47**	2.46	0.32	0.31	0.32	**1.40**	**1.41**	**1.41**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	2.38	2.39	2.38	0.27	0.28	0.28	1.27	1.27	1.27
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**2.49**	**2.50**	**2.50**	**0.35**	**0.37**	**0.36**	**1.39**	**1.40**	**1.40**
T_{10}: SR @ 2t ha^{-1}	2.24	2.25	2.25	0.18	0.18	0.18	1.15	1.14	1.15
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	2.40	2.42	2.41	0.30	0.31	0.30	1.30	1.31	1.30
SEm±	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**
CD at 5%	**0.04**	**0.04**	**0.03**	**0.03**	**0.02**	**0.02**	**0.02**	**0.02**	**0.02**

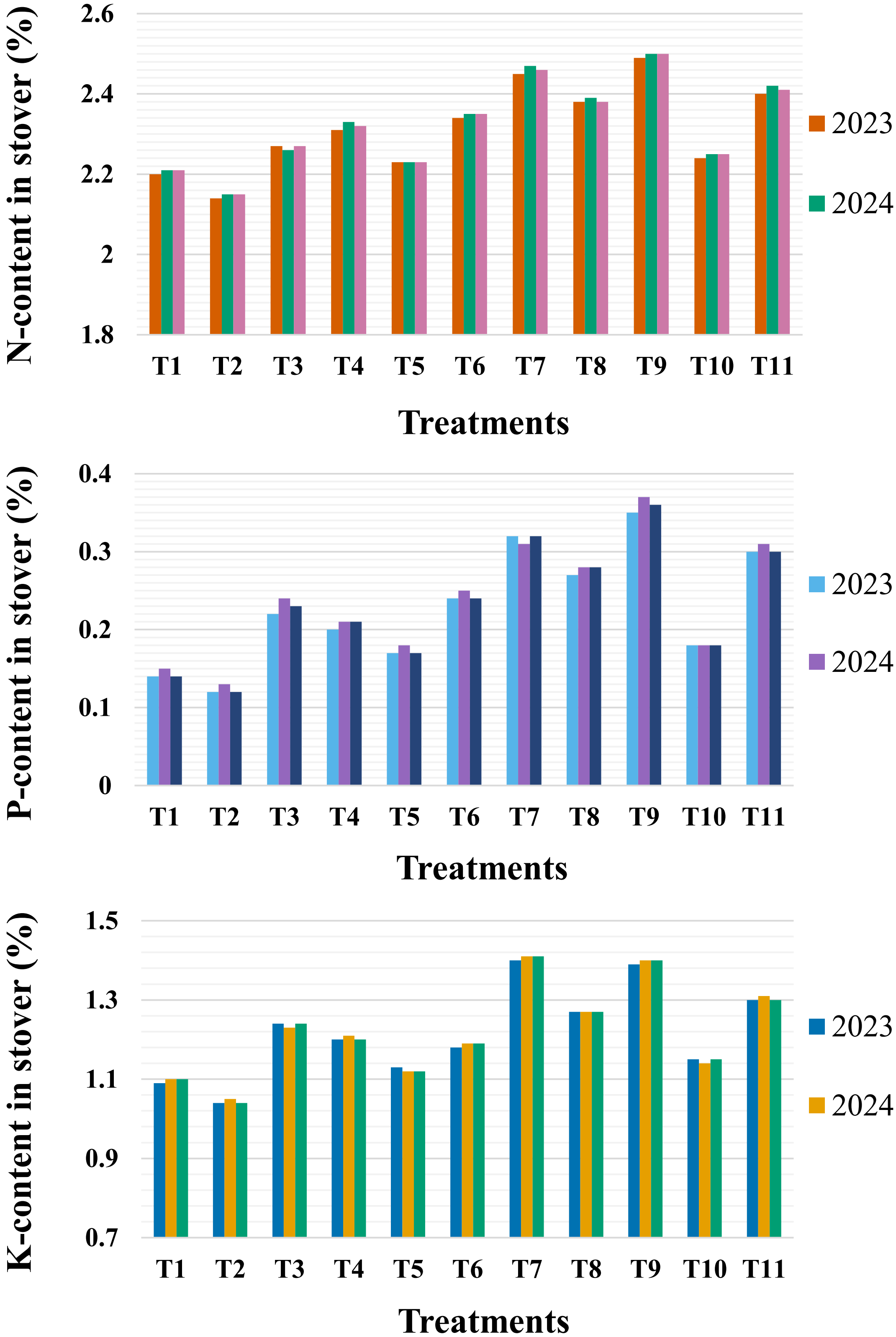

Fig. 4.13 Effect of different aluminium-alleviating organic materials on different nutrient contents (*nitrogen, phosphorus and potassium*) in stover of mungbean in acid soil

Potassium content in mungbean stover was highest under the combined application of wood ash and vermicompost due to improved potassium availability and uptake by the crop. Wood ash supplied potassium and increased soil pH, reducing aluminium toxicity, while vermicompost improved soil organic matter and nutrient retention. The combined effect enhanced potassium uptake and accumulation in the stover. In contrast, the lowest potassium content was observed under the control condition due to poor nutrient availability and restricted root growth under acidic soil conditions. Among the individual organic amendments, vermicompost resulted in relatively higher potassium content in stover due to its ability to improve soil fertility and nutrient availability. Similar findings were reported by Kumawat (2006), while Paramisparam *et al*. (2021) observed that animal manures enhance soil organic matter and cation exchange capacity, increasing exchangeable potassium and its uptake by crops.

4.2.1.11 Calcium content in stover (%)

Data pertaining to calcium content in stover as influenced by different organic materials are presented in Table 4.14 and graphically illustrated in Fig. 4.14. A significant variation in calcium content in stover was observed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the 2023 trial, treatment T_7 (wood ash + poultry manure) produced the highest calcium content in stover (0.73%); whereas the lowest calcium content in stover (0.22%) was observed under T_2 (absolute control). Among the individual amendments, treatment T_4 (poultry manure) recorded the highest calcium content in stover (0.60%).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest calcium content in stover (0.74%). The lowest calcium content in stover (0.21%) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest calcium content in stover (0.61%).

The pooled data of the two experimental years (2023 and 2024) revealed that treatment T_7 (wood ash + poultry manure) exhibited the highest calcium content in stover (0.74%); while the lowest calcium content in stover (0.22%) was obtained under T_2 (absolute control). Among the single amendments, the highest calcium content in stover (0.61%) was recorded in T_4 (poultry manure).

Calcium content in mungbean stover was highest under the combined application of wood ash and poultry manure due to improved calcium availability and better soil conditions. Wood ash supplied calcium and increased soil pH, thereby reducing aluminium toxicity, while poultry manure improved soil fertility and nutrient availability. The combined effect enhanced root growth and calcium uptake, resulting in greater accumulation in the stover. In contrast, the lowest calcium content was observed under the control condition, which may be due to poor nutrient availability and restricted root growth under acidic soil conditions affected by aluminium toxicity. Among the individual organic amendments, poultry manure resulted in relatively higher calcium content in stover due to its ability to supply nutrients and improve soil fertility. Similar findings were reported by Demeyer *et al*. (2001), who observed that application of wood ash increases the availability of basic cations such as Ca and improves nutrient uptake in crops grown on acidic soils.

4.2.1.12 Magnesium content in stover (%)

The effect of different organic materials on magnesium content in stover is summarized in Table 4.14 and graphically illustrated in Fig. 4.14. The treatments significantly influenced the magnesium content in stover during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first experimental season (2023) treatment T_7 (wood ash + poultry manure) recorded the highest magnesium content in stover (0.53%), while the lowest magnesium content in stover (0.17%) was observed under T_2 (absolute control). Among the single amendments, treatment T_4 (poultry manure) found the highest magnesium content in stover (0.42%).

A comparable trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) produced the highest magnesium content in stover (0.54%). The lowest magnesium content in stover (0.18%) was observed under T_2 (absolute control).

Among the single applications, treatment T_4 (poultry manure) exhibited the highest magnesium content in stover (0.42%).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the highest magnesium content in stover (0.54%); while the lowest magnesium content in stover (0.18%) was observed under T_2 (absolute control). Among the single amendments, the highest magnesium content in stover (0.42%) was recorded in T_4 (poultry manure).

Magnesium content in mungbean stover was highest under the combined application of wood ash and poultry manure due to improved magnesium availability and enhanced uptake by the crop. Wood ash supplied magnesium and ameliorated soil acidity by increasing soil pH, while poultry manure improved soil organic matter and microbial activity. The combined effect enhanced nutrient availability and promoted greater magnesium accumulation in the stover. In contrast, the lowest magnesium content was observed under the control condition due to limited nutrient availability and the adverse effects of aluminium toxicity on root growth. Among the individual organic amendments, poultry manure resulted in relatively higher magnesium content in stover due to its ability to improve soil fertility and nutrient availability. Similar observations were reported by Demeyer *et al*. (2001), who noted that wood ash application improves the availability of essential cations including Mg in acidic soils.

4.2.1.13 Aluminium content in stover (mg/kg)

The data on the aluminium content in stover as affected by different organic materials are presented in Table 4.14 and graphically illustrated in Fig. 4.14. The treatments significantly influenced the aluminium content in stover during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the lowest aluminium content in stover (86.72 mg/kg) under T_9 (wood ash + vermicompost); whereas the highest aluminium content in stover (166.03 mg/kg) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the lowest aluminium content in stover (107.50 mg/kg).

Table 4.14 Effect of different aluminium-alleviating organic materials on different nutrient contents (namely *calcium, magnesium and aluminium*) in stover of mungbean in acid soil

Treatments	Nutrient content in stover								
	Calcium (%)			Magnesium (%)			Aluminium (mg/kg)		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	0.26	0.26	0.26	0.21	0.22	0.21	162.64	162.42	162.53
T_2: Absolute control	0.22	0.21	0.22	0.17	0.18	0.18	166.03	165.82	165.92
T_3: WA @ 2t ha^{-1}	0.56	0.57	0.56	0.38	0.39	0.39	107.50	107.08	107.29
T_4: PM @ 2t ha^{-1}	0.60	0.61	0.61	0.42	0.42	0.42	114.71	114.50	114.61
T_5: RR @ 2t ha^{-1}	0.32	0.33	0.33	0.25	0.24	0.25	132.52	132.31	132.42
T_6: VC @ 2t ha^{-1}	0.52	0.53	0.52	0.33	0.34	0.34	109.84	109.62	109.73
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	0.73	0.74	0.74	0.53	0.54	0.54	89.05	88.63	88.84
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	0.64	0.65	0.65	0.45	0.46	0.45	104.11	103.90	104.01
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	0.71	0.70	0.70	0.52	0.51	0.52	86.72	86.51	86.62
T_{10}: SR @ 2t ha^{-1}	0.35	0.36	0.36	0.27	0.28	0.27	129.35	128.92	129.14
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	0.67	0.66	0.67	0.49	0.48	0.48	97.11	96.69	96.90
SEm±	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.36**	**0.34**	**0.25**
CD at 5%	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**0.01**	**1.06**	**0.99**	**0.71**

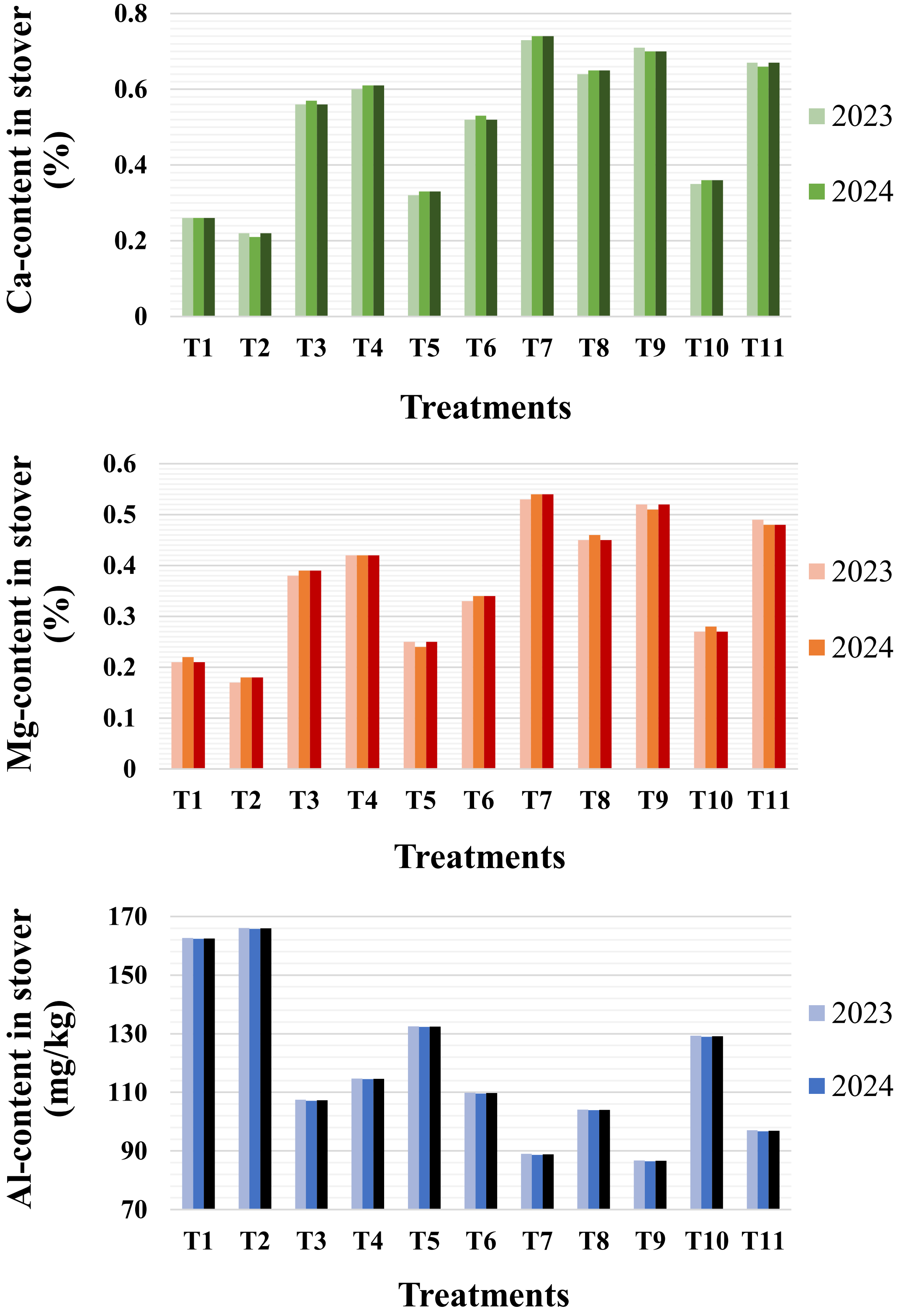

Fig. 4.14 Effect of different aluminium-alleviating organic materials on different nutrient contents (namely *calcium, magnesium and aluminium*) in stover of mungbean in acid soil

A similar trend was observed during the second trial (2024), where T_9 (wood ash + vermicompost) recorded the lowest aluminium content in stover (86.51 mg/kg). The highest aluminium content in stover (165.82 mg/kg) was observed under T_2 (absolute control). Among the sole applications, treatment T_3 (wood ash) registered the lowest aluminium content in stover (107.08 mg/kg).

The pooled results of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the lowest aluminium content in stover (86.62 mg/kg); while the highest aluminium content in stover (165.92 mg/kg) was obtained under T_2 (absolute control). Among the single amendments, the lowest aluminium content in stover (107.29 mg/kg) was recorded in T_3 (wood ash).

Aluminium content in mungbean stover was lowest under the combined application of wood ash and vermicompost, which may be attributed to improved soil chemical properties and reduced aluminium availability in the acidic soil. Wood ash increased soil pH and reduced aluminium solubility through its liming effect, while vermicompost added organic matter that can complex aluminium ions and decrease their availability. The combined effect of these amendments reduced aluminium uptake and accumulation in the stover. In contrast, the highest aluminium content was observed under the control condition, which may be due to the high availability of soluble aluminium in acidic soil and the absence of amendments to mitigate its toxicity. Among the individual organic amendments, wood ash resulted in relatively lower aluminium content in stover due to its ability to increase soil pH and reduce aluminium solubility. Similar observations were reported by Panda *et al*. (2017) and Demeyer *et al*. (2001), who noted that organic amendments and wood ash reduce aluminium toxicity and its availability in acidic soils.

4.2.1.14 Protein content in stover (%)

The Protein content in stover under various organic materials is given in Table 4.15 and graphically illustrated in Fig. 4.15. A significant influenced of treatments was observed in both the trials (2023 and 2024) and pooled data, where all organic amendments performed better than T_1 (control) and T_2 (absolute control).

Table 4.15 Effect of different aluminium-alleviating organic materials on *protein* content in stover of mungbean in acid soil

Treatments	Protein content in stover (%)		
	2023	2024	Pooled
T_1 : Control	13.75	13.81	13.78
T_2: Absolute control	13.38	13.44	13.41
T_3: WA @ 2t ha^{-1}	14.19	14.15	14.17
T_4: PM @ 2t ha^{-1}	14.44	14.56	14.50
T_5: RR @ 2t ha^{-1}	13.94	13.92	13.93
T_6: VC @ 2t ha^{-1}	14.63	14.69	14.66
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	15.32	15.44	15.38
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	14.86	14.92	14.89
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	15.56	15.62	15.59
T_{10}: SR @ 2t ha^{-1}	13.98	14.09	14.03
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	15.02	15.13	15.08
SEm±	0.08	0.08	0.06
CD at 5%	0.22	0.24	0.16

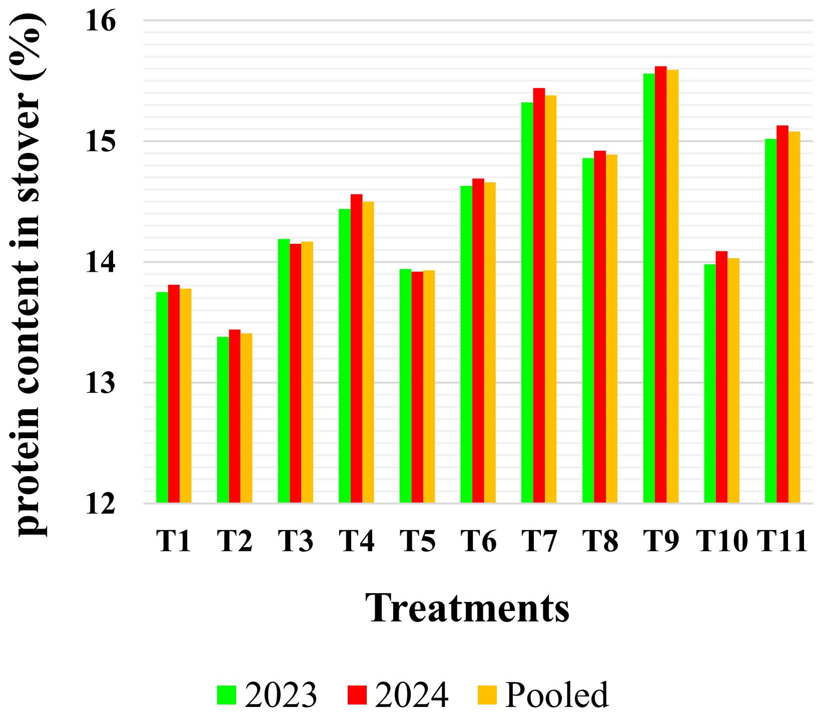

Fig. 4.15 Effect of different aluminium-alleviating organic materials on *protein* content in seed (%) of mungbean in acid soil

The experimental results from the first trial showed that treatment T_9 (wood ash + vermicompost) recorded the highest protein content in stover (15.56%). In contrast, the lowest protein content in stover (13.38%) was observed under T_2 (absolute control). Among the individual amendments, treatment T_6 (vermicompost) exhibited the highest protein content in stover (14.63%).

A similar trend was observed during the second trial (2024) where T_9 (wood ash + vermicompost) recorded the highest protein content in stover (15.62%), which was statistically at par (15.44%) with T_7 (wood ash + poultry manure). The lowest protein content in stover (13.44%) was observed under T_2 (absolute control). Among the single applications, treatment T_6 (vermicompost) obtained the highest protein content in stover (14.69%).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest protein content in stover (15.59%); while the lowest protein content in stover (13.41%) was obtained under T_2 (absolute control). Among the single amendments, the highest protein content in stover (14.46%) was recorded in T_6 (vermicompost).

Protein content in mungbean stover was highest under the combined application of wood ash and vermicompost, which may be attributed to improved soil conditions and enhanced nitrogen availability. Wood ash helped reduce soil acidity and aluminium toxicity by increasing soil pH, while vermicompost supplied organic matter and nutrients through mineralization, improving nitrogen uptake and assimilation. In contrast, the lowest protein content was observed under the control condition due to limited nutrient availability and restricted plant growth under acidic soil conditions. Among the individual organic amendments, vermicompost resulted in relatively higher protein content in stover due to improved soil fertility and nitrogen availability. Similar findings were reported by Kumawat (2006), who observed higher protein content in mungbean with the application of organic manures compared to the control.

4.2.2 Nutrient uptake in seed and stover (mg/pot)

Data related to the uptake of various nutrient in seed and stover under different Al-alleviating organic materials are presented and discussed in the following sections to indicate variations among treatments.

4.2.2.1 Nitrogen uptake in seed (mg/pot)

Data pertaining to nitrogen uptake in seed as influenced by different organic materials are presented in Table 4.16 and graphically illustrated in Fig. 4.16. The treatments significantly influenced the nitrogen uptake in seed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first year of study (2023), treatment T_9 (wood ash + vermicompost) produced the highest nitrogen uptake in seed (896.40 mg/pot). On the other hand, the lowest nitrogen uptake in seed (173.70 mg/pot) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) recorded the highest nitrogen uptake in seed (620.10 mg/pot).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest nitrogen uptake in seed (907.01mg/pot). The lowest nitrogen uptake in seed (177.35 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_6 (vermicompost) exhibited the highest nitrogen uptake in seed (623.72 mg/pot).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) recorded the highest nitrogen uptake in seed (901.70 mg/pot); while the lowest nitrogen uptake in seed (175.52 mg/pot) was obtained under T_2 (absolute control). Among the single amendments, the highest nitrogen uptake in seed (621.91 mg/pot) was recorded in T_6 (vermicompost).

Nitrogen uptake in mungbean seed was highest under the combined application of wood ash and vermicompost, which may be attributed to improved soil conditions and enhanced nitrogen availability. Wood ash reduced soil acidity and aluminium toxicity by increasing soil pH, while vermicompost supplied organic matter and nutrients through mineralization, improving nitrogen availability and uptake. In contrast, the lowest nitrogen uptake was observed under the control condition due to poor nutrient availability and the persistence of aluminium toxicity in acidic soil. Among the individual organic amendments, vermicompost resulted in relatively higher nitrogen uptake due to improved soil organic matter and nutrient mineralization. Similar findings were reported by Kumawat (2006), who observed improved nutrient uptake in mungbean with the application of organic manures.

4.2.2.2 Phosphorus uptake in seed (mg/pot)

Data related to phosphorus uptake in seed as influenced by different organic materials are presented in Table 4.16 and graphically illustrated in Fig. 4.16. The treatments significantly influenced the phosphorus uptake in seed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest phosphorus uptake in seed (117.04 mg/pot) under T_9 (wood ash + vermicompost), which was statistically at par (115.68 mg/pot) with T_7 (wood ash + poultry manure); whereas the lowest phosphorus uptake in seed (11.87 mg/pot) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) exhibited the highest phosphorus uptake in seed (62.95 mg/pot).

A similar trend was observed during the second trial in 2024. Treatment T_9 (wood ash + vermicompost) exhibited the highest phosphorus content in seed (120.41 mg/pot), which was statistically at par (116.30 mg/pot) with T_7 (wood ash + poultry manure). The lowest phosphorus content in seed (12.46 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_6 (vermicompost) exhibited the highest phosphorus content in seed (65.08 mg/pot).

The pooled analysis of both years (2023 and 2024) revealed that treatment T_9 (wood ash + vermicompost) exhibited the highest phosphorus uptake in seed (118.72 mg/pot), which was statistically at par (115.99 mg/pot) with T_7 (wood ash + poultry manure); while the lowest phosphorus uptake in seed (12.17 mg/pot) was obtained under T_2 (absolute control). Among the single amendments, the highest phosphorus uptake in seed (64.02 mg/pot) was recorded in T_6 (vermicompost).

Phosphorus uptake in mungbean seed was highest under the combined application of wood ash and vermicompost, which may be attributed to improved phosphorus availability in acidic soil. Wood ash increased soil pH and reduced aluminium activity, while vermicompost released organic acids during decomposition that reduced phosphorus fixation. In contrast, the lowest phosphorus uptake was recorded under the control condition due to strong phosphorus fixation by aluminium and iron compounds in acidic soils. Among the individual organic amendments, vermicompost improved phosphorus uptake through the addition of organic matter and enhanced microbial activity. Similar observations were reported by Haynes and Mokolobate (2001) and Choudhary *et al*. (2013), who noted that organic amendments improve phosphorus availability and uptake in acidic soils.

4.2.2.3 Potassium uptake in seed (mg/pot)

The potassium uptake in seed as affected by different organic materials is presented in Table 4.16 and graphically illustrated in Fig. 4.16. The treatments showed a significant effect on potassium uptake in seed in both the years (2023 and 2024) and in the pooled results, where all organic amendments performed better than T_1 (control) and T_2 (absolute control).

During the first trial (2023), the highest potassium uptake in seed (317.16 mg/pot) was recorded under treatment T_9 (wood ash + vermicompost); whereas the lowest potassium uptake in seed (54.28 mg/pot) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest potassium uptake in seed (212.61 mg/pot).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest potassium uptake in seed (320.80 mg/pot). The lowest potassium uptake in seed (54.28 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest potassium uptake in seed (212.61 mg/pot).

Table 4.16 Effect of different aluminium-alleviating organic materials on different nutrient uptakes (namely *nitrogen, phosphorus and potassium*) in seed of mungbean in acid soil

Treatments	Nutrient uptake in seed (mg/pot)								
	Nitrogen			Phosphorus			Potassium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	267.51	267.03	267.27	19.96	20.65	20.31	99.06	100.23	99.65
T_2: Absolute control	**173.70**	**177.35**	**175.52**	**11.87**	**12.46**	**12.17**	**54.28**	**55.39**	**54.84**
T_3: WA @ 2t ha^{-1}	600.14	601.21	600.68	47.01	47.59	47.30	**212.61**	**210.41**	**211.51**
T_4: PM @ 2t ha^{-1}	548.45	554.09	551.27	58.73	60.80	59.77	187.29	185.83	186.56
T_5: RR @ 2t ha^{-1}	395.67	398.64	397.15	34.58	33.64	34.11	131.86	132.04	131.95
T_6: VC @ 2t ha^{-1}	**620.10**	**623.72**	**621.91**	**62.95**	**65.08**	**64.02**	207.96	206.67	207.32
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	831.72	834.98	833.35	**115.68**	**116.30**	**115.99**	294.08	296.78	295.43
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	698.42	701.34	699.88	78.56	80.04	79.30	243.37	245.12	244.24
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**896.40**	**907.01**	**901.70**	**117.04**	**120.41**	**118.72**	**317.16**	**320.80**	**318.98**
T_{10}: SR @ 2t ha^{-1}	426.43	427.23	426.83	39.05	40.80	39.92	142.15	141.51	141.83
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	741.16	742.38	741.77	89.75	91.15	90.45	261.89	262.27	262.08
SEm±	**7.41**	**5.21**	**4.53**	**1.71**	**1.91**	**1.28**	**2.70**	**2.19**	**1.74**
CD at 5%	**21.74**	**15.27**	**12.91**	**5.00**	**5.61**	**3.65**	**7.91**	**6.42**	**4.95**

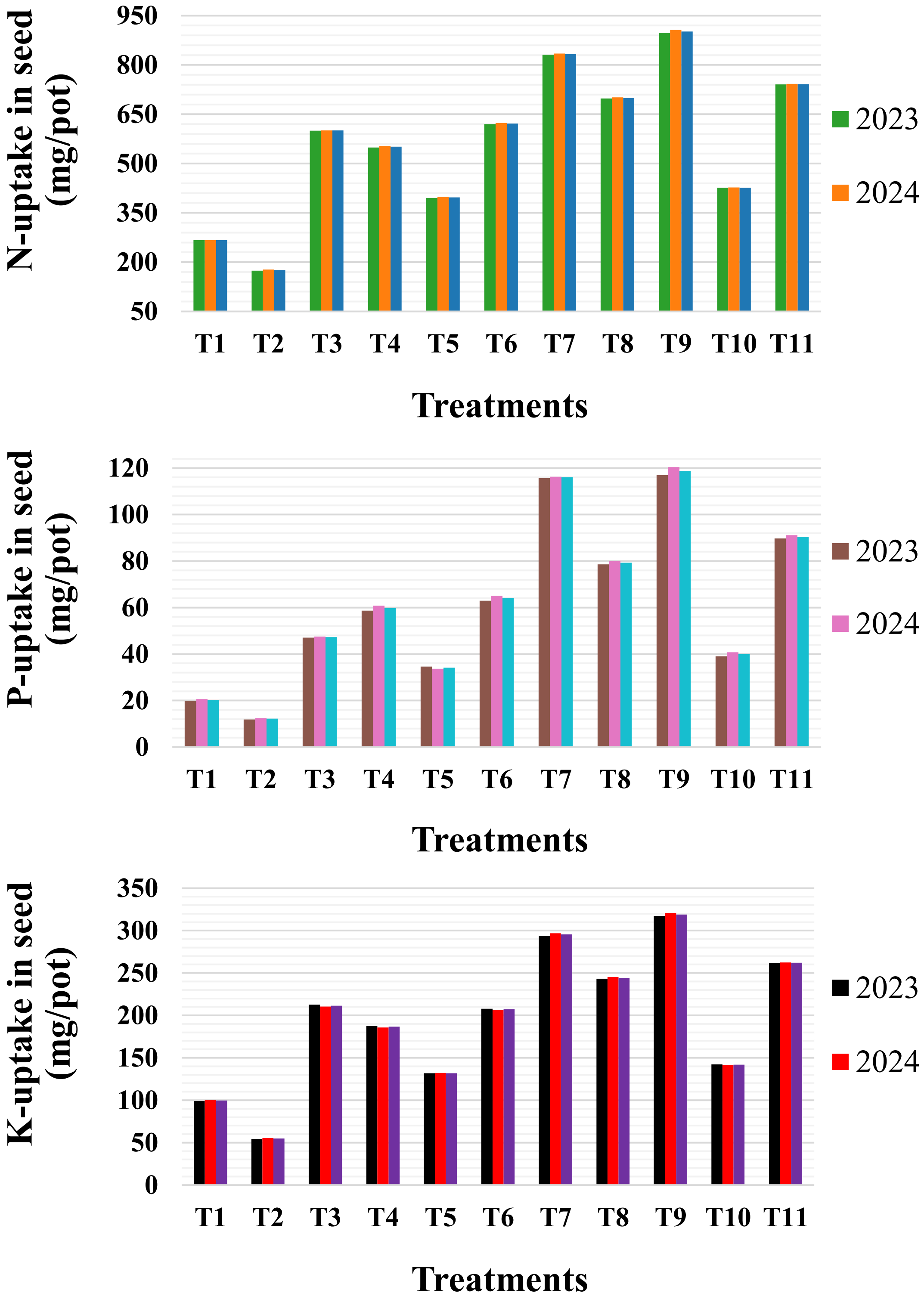

Fig. 4.16 Effect of different aluminium-alleviating organic materials on different nutrient uptakes (namely *nitrogen, phosphorus and potassium*) in seed of mungbean in acid soil

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest potassium uptake in seed (318.98 mg/pot); while the lowest potassium uptake in seed (54.84 mg/pot) was obtained under T_2 (absolute control). Among the single amendments, the highest potassium uptake in seed (211.51 mg/pot) was recorded in T_3 (wood ash).

Potassium uptake in mungbean seed was highest under the combined application of wood ash and vermicompost, which may be attributed to improved potassium availability and uptake by the crop. Wood ash supplied potassium and increased soil pH, while vermicompost improved soil fertility and nutrient retention through increased organic matter. In contrast, the lowest potassium uptake was observed under the control condition due to limited nutrient availability and restricted root growth under acidic soil conditions. Among the individual organic amendments, vermicompost resulted in relatively higher potassium uptake due to improved soil structure and nutrient mineralization. These findings are supported by Paramisparam *et al.* (2021) and Choudhary *et al.* (2013), who reported that organic amendments increase exchangeable potassium and enhance its uptake by crops

4.2.2.4 Calcium uptake in seed (mg/pot)

Calcium uptake in seed under different organic materials is presented in Table 4.17 and graphically illustrated in Fig. 4.17. The treatments significantly influenced the calcium uptake in seed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first experimental season (2023), treatment T_7 (wood ash + poultry manure) obtained the highest calcium uptake in seed (65.11 mg/pot), which was statistically at par (63.78 mg/pot) with T_9 (wood ash + vermicompost). The lowest calcium uptake in seed (6.75 mg/pot) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest calcium uptake in seed (30.73 mg/pot).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest calcium uptake in seed (63.37 mg/pot), which was statistically at par (63.28 mg/pot) with T_9 (wood ash + vermicompost). The lowest calcium uptake in seed (6.57 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest calcium uptake in seed (31.30 mg/pot).

The pooled data of both years (2023 and 2024) showed that treatment T_7 (wood ash + poultry manure) recorded the highest calcium uptake in seed (64.24 mg/pot), which was statistically at par (63.53 mg/pot) with T_9 (wood ash + vermicompost); while the lowest calcium uptake in seed (6.66 mg/pot) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest calcium uptake in seed (31.02 mg/pot) was recorded in treatment T_3 (wood ash).

Calcium uptake in mungbean seed was highest under the combined application of wood ash and poultry manure. This may be attributed to calcium supply from wood ash and improved soil fertility from poultry manure. Wood ash increased soil pH and reduced aluminium toxicity, while poultry manure improved nutrient availability, resulting in greater calcium uptake in the seeds. In contrast, the lowest calcium uptake was observed under the control condition due to poor nutrient availability and restricted root growth under acidic soil conditions. Among the individual organic amendments, wood ash resulted in relatively higher calcium uptake due to its richness in calcium and its ability to ameliorate soil acidity. Similar observations were reported by Demeyer *et al*. (2001) and An and Park (2021), who noted that organic amendments and ash materials improve soil pH and enhance the availability of basic cations such as calcium in acidic soils.

4.2.2.5 Magnesium uptake in seed (mg/pot)

Data regarding magnesium uptake in seed influenced by different organic materials are presented in Table 4.17 and graphically illustrated in Fig. 4.17. The treatments significantly improved the magnesium uptake in seed during both the trials (2023 and 2024) and in the pooled analysis, where all organic amendments outperformed T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest magnesium uptake in seed (54.64 mg/pot) under T_7 (wood ash + poultry manure), which was statistically at par (54.18

mg/pot) with T_9 (wood ash + vermicompost); whereas the lowest magnesium uptake in seed (5.11 mg/pot) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest magnesium uptake in seed (27.59 mg/pot).

However, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest magnesium uptake in seed (53.61 mg/pot), which was statistically at par (52.94 mg/pot) with T_7 (wood ash + poultry manure). The lowest magnesium uptake in seed (5.17 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest magnesium uptake in seed (26.92 mg/pot).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest magnesium uptake in seed (53.90 mg/pot), which was statistically at par (53.79 mg/pot) with T_7 (wood ash + poultry manure); while the lowest magnesium uptake in seed (5.14 mg/pot) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest magnesium uptake in seed (27.25 mg/pot) was recorded in treatment T_3 (wood ash).

Magnesium uptake in mungbean seed was highest under the combined application of wood ash and poultry manure. This may be attributed to magnesium supply from wood ash and improved soil fertility from poultry manure. Wood ash reduced soil acidity and increased magnesium availability, while poultry manure improved soil organic matter and nutrient uptake. In contrast, the lowest magnesium uptake was observed under the control condition due to limited nutrient availability and the adverse effects of aluminium toxicity on root growth. Among the individual organic amendments, wood ash resulted in relatively higher magnesium uptake due to its content of basic cations and its liming effect in acidic soils. Similar observations were reported by Demeyer *et al*. (2001), Haynes and Mokolobate (2001) and An and Park (2021), who reported that improvement of soil chemical properties through organic amendments enhances the availability and uptake of magnesium in acidic soils.

Table 4.17 Effect of different aluminium-alleviating organic materials on different nutrient uptakes (namely *calcium, magnesium and aluminium*) in seed of mungbean in acid soil

Treatments	Nutrient uptake in seed (mg/pot)								
	Calcium			Magnesium			Aluminium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	10.63	9.99	10.31	8.31	8.66	8.48	0.15	0.14	0.15
T_2: Absolute control	**6.75**	**6.57**	**6.66**	**5.11**	**5.17**	**5.14**	**0.11**	**0.11**	**0.11**
T_3: WA @ 2t ha^{-1}	**30.73**	**31.30**	**31.02**	**27.59**	**26.92**	**27.25**	0.19	0.19	0.19
T_4: PM @ 2t ha^{-1}	30.20	29.85	30.03	25.73	25.35	25.54	0.19	0.19	0.19
T_5: RR @ 2t ha^{-1}	16.44	16.19	16.32	13.50	13.21	13.36	0.17	0.16	0.17
T_6: VC @ 2t ha^{-1}	28.62	28.07	28.35	26.08	25.53	25.80	**0.21**	**0.21**	**0.21**
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	**65.11**	**63.37**	**64.24**	**54.64**	**52.94**	**53.79**	0.17	0.17	0.17
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	41.73	41.09	41.41	34.69	33.29	33.99	0.20	0.19	0.20
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**63.78**	**63.28**	**63.53**	**54.18**	**53.61**	**53.90**	0.18	0.17	0.18
T_{10}: SR @ 2t ha^{-1}	18.84	18.35	18.60	15.25	14.76	15.01	0.17	0.17	0.17
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	46.00	45.20	45.60	40.80	40.00	40.40	0.20	0.19	0.19
SEm±	**0.95**	**0.80**	**0.62**	**0.77**	**0.85**	**0.57**	**0.01**	**0.01**	**0.00**
CD at 5%	**2.79**	**2.34**	**1.77**	**2.26**	**2.49**	**1.63**	**0.02**	**0.01**	**0.01**

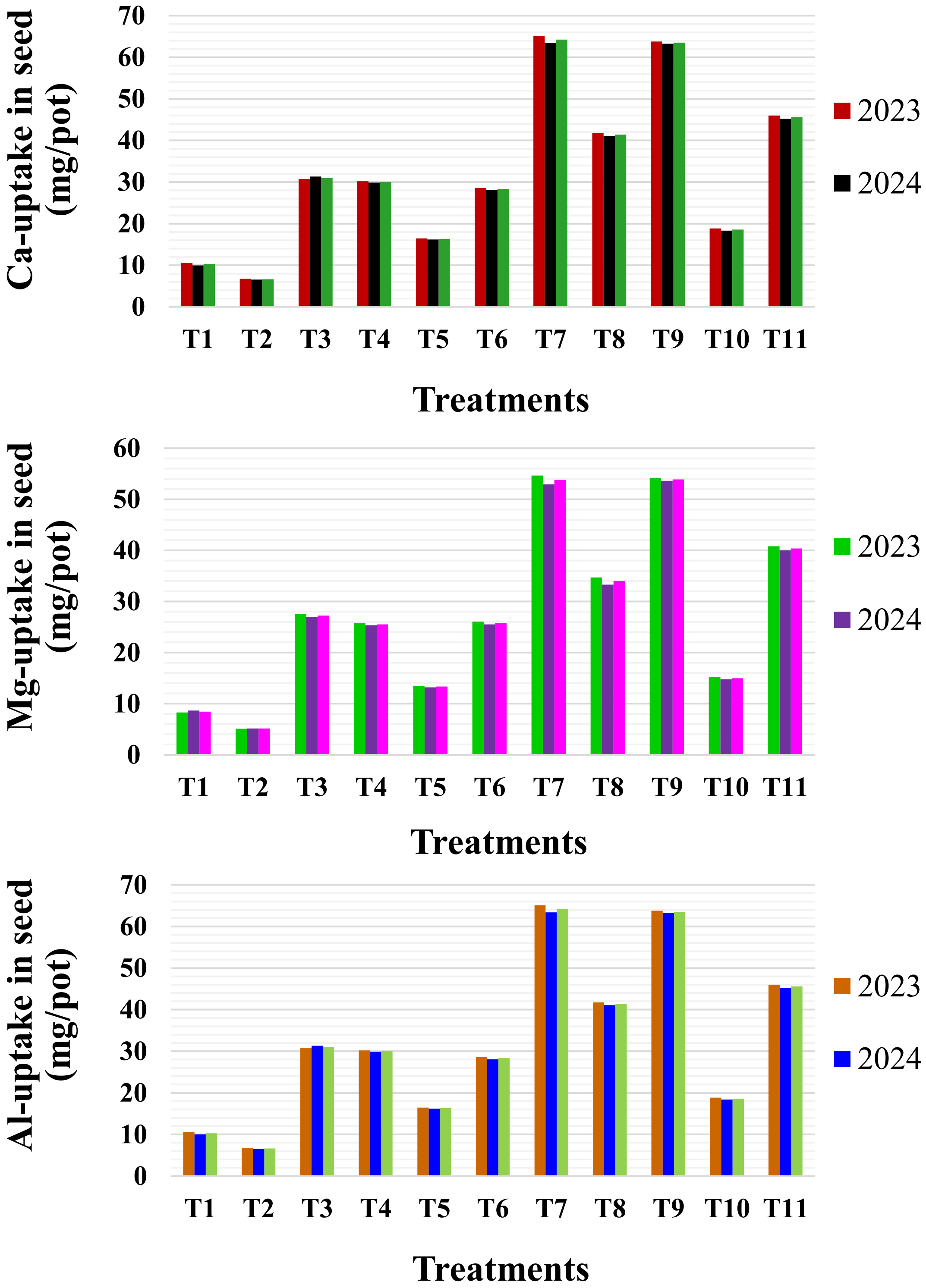

Fig. 4.17 Effect of different aluminium-alleviating organic materials on different nutrient uptakes (namely *calcium, magnesium and aluminium*) in seed of mungbean in acid soil

4.2.2.6 Aluminium uptake in seed (mg/pot)

The data on the aluminium uptake in seed as influenced by different organic materials are presented in Table 4.17 and graphically illustrated in Fig. 4.17. The treatments significantly influenced the aluminium uptake in seed during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first trial in 2023, T_6 (vermicompost) exhibited the highest aluminium uptake in seed (0.21 mg/pot) among all the treatments, while the lowest aluminium uptake in seed (0.11 mg/pot) was observed under T_2 (absolute control). Similar results were observed during the second trial in 2024 too, where T_6 (vermicompost) exhibited the highest aluminium uptake in seed (0.21 mg/pot) among all the treatments and T_2 (absolute control) recorded the lowest aluminium uptake in seed (0.11 mg/pot).

As a result, the pooled analysis of both years (2023 and 2024) indicated treatment T_6 (vermicompost) to exhibit the highest aluminium uptake in seed (0.21 mg/pot) and treatment T_2 (absolute control) to exhibit the lowest aluminium uptake in seed (0.11 mg/pot).

Aluminium uptake in mungbean seed was highest under the application of vermicompost. This may be attributed to improved plant growth and biomass production due to enhanced soil fertility and organic matter from vermicompost. Increased growth may result in greater absorption and translocation of aluminium present in the soil. In contrast, the lowest aluminium uptake was observed under the control condition due to poor plant growth and restricted root development under untreated acidic soil conditions affected by aluminium toxicity.Similar observations were reported by Demeyer *et al.* (2001) and An and Park (2021)**,** who noted that organic amendments improve soil properties and plant growth in acidic soils, which can influence aluminium dynamics and uptake in crops.

4.2.2.7 Nitrogen uptake in stover (mg/pot)

Observation recorded on the nitrogen uptake in stover as influenced by different organic materials are presented in Table 4.18 and graphically illustrated in Fig. 4.18.

The treatments showed a significant effect on nitrogen uptake in stover during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

Data from the 2023 experiment indicated that the highest nitrogen uptake in stover (729.35 mg/pot) was obtained with T_9 (wood ash + vermicompost); whereas the lowest nitrogen uptake in stover (198.78 mg/pot) was observed under T_2 (absolute control). Among the individual amendments, treatment T_6 (vermicompost) recorded the highest nitrogen uptake in stover (508.38 mg/pot).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest nitrogen uptake in stover (732.75 mg/pot). The lowest nitrogen uptake in stover (203.28 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_6 (vermicompost) exhibited the highest nitrogen uptake in stover (511.97 mg/pot).

The pooled results of both years (2023 and 2024) revealed that treatment T_9 (wood ash + vermicompost) exhibited the highest nitrogen uptake in stover (731.05 mg/pot); while the lowest nitrogen uptake in stover (201.03 mg/pot) was obtained under T_2 (absolute control). Among the single amendments, the highest nitrogen uptake in stover (510.17 mg/pot) was recorded in T_6 (vermicompost).

Nitrogen uptake in mungbean stover was highest under the combined application of wood ash and vermicompost due to improved soil conditions and nitrogen availability. Wood ash reduced soil acidity, while vermicompost enhanced soil fertility and nutrient mineralization, promoting better root growth and nitrogen uptake. In contrast, the lowest nitrogen uptake was observed under the control due to poor nutrient availability and aluminium toxicity. Among the individual amendments, vermicompost resulted in relatively higher nitrogen uptake because of improved soil organic matter and microbial activity. Similar observations were reported by Choudhary *et al*. (2013).

4.2.2.8 Phosphorus uptake in stover (mg/pot)

Data pertaining to phosphorus uptake in stover as influenced by different organic materials are presented in Table 4.18 and graphically illustrated in Fig. 4.18. The treatments significantly influenced the phosphorus uptake in stover during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

Results from the first trial (2023) revealed that the highest phosphorus uptake in stover (103.61 mg/pot) was obtained under treatment T_9 (wood ash + vermicompost), while the lowest phosphorus uptake in stover (11.13 mg/pot) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) registered the highest phosphorus uptake in stover (52.15 mg/pot).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest phosphorus content in stover (107.48 mg/pot). The lowest phosphorus content in stover (11.99 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_6 (vermicompost) exhibited the highest phosphorus content in stover (53.76 mg/pot).

The pooled analysis of both years (2023 and 2024) further revealed that treatment T_9 (wood ash + vermicompost) exhibited the highest phosphorus uptake in stover (105.54 mg/pot), while the lowest phosphorus uptake in stover (11.56 mg/pot) was obtained under T_2 (absolute control). Among the single amendments, the highest phosphorus uptake in stover (52.96 mg/pot) was recorded in T_6 (vermicompost).

Phosphorus uptake in mungbean stover was highest under the combined application of wood ash and vermicompost due to improved phosphorus availability in acidic soil. Wood ash increased soil pH and reduced aluminium activity, while vermicompost released organic acids that reduced phosphorus fixation. The lowest uptake occurred under the control due to strong phosphorus fixation by aluminium and iron compounds. Among the individual amendments, vermicompost resulted in relatively higher phosphorus uptake. Similar findings were reported by Haynes and Mokolobate (2001) and Kumawat (2006).

4.2.2.9 Potassium uptake in stover (mg/pot)

The data on the potassium uptake in stover as influenced by different organic materials are presented in Table 4.18 and graphically illustrated in Fig. 4.18. The treatments significantly influenced the potassium uptake in stover during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest potassium uptake in stover (408.19 mg/pot) under T_9 (wood ash + vermicompost); whereas the lowest potassium uptake in stover (96.30 mg/pot) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest potassium uptake in stover (262.83 mg/pot).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest potassium uptake in stover (409.36 mg/pot). The lowest potassium uptake in stover (99.28 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest potassium uptake in stover (262.49 mg/pot).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest potassium uptake in stover (408.77 mg/pot); while the lowest potassium uptake in stover (97.79 mg/pot) was obtained under T_2 (absolute control). Among the single amendments, the highest potassium uptake in stover (262.66 mg/pot) was recorded in T_3 (wood ash).

Potassium uptake in mungbean stover was highest under the combined application of wood ash and vermicompost due to improved potassium availability and soil fertility. Wood ash supplied potassium and increased soil pH, while vermicompost improved soil organic matter and nutrient retention. The lowest uptake was observed under the control due to limited nutrient availability and restricted root growth in acidic soil. Among the individual amendments, vermicompost resulted in relatively higher potassium uptake. Similar findings were reported by Paramisparam *et al*. (2021) and Choudhary *et al*. (2013).

Table 4.18 Effect of different aluminium-alleviating organic materials on different nutrient uptakes (namely *nitrogen, phosphorus and potassium*) in stover of mungbean in acid soil

Treatments	Nutrient uptake in stover (mg/pot)								
	Nitrogen			Phosphorus			Potassium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	267.27	270.20	268.74	17.03	17.94	17.49	132.79	134.09	133.44
T_2: Absolute control	**198.78**	**203.28**	**201.03**	**11.13**	**11.99**	**11.56**	**96.30**	**99.28**	**97.79**
T_3: WA @ 2t ha^{-1}	482.48	481.69	482.08	46.75	50.38	48.56	**262.83**	**262.49**	**262.66**
T_4: PM @ 2t ha^{-1}	457.32	460.78	459.05	39.58	42.19	40.88	236.90	239.30	238.10
T_5: RR @ 2t ha^{-1}	317.67	317.68	317.68	24.21	25.20	24.71	160.50	159.78	160.14
T_6: VC @ 2t ha^{-1}	**508.38**	**511.97**	**510.17**	**52.15**	**53.76**	**52.96**	257.09	259.92	258.51
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	665.00	671.03	668.02	86.87	85.11	85.99	380.93	383.93	382.43
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	544.43	545.81	545.12	62.63	63.28	62.96	291.68	291.22	291.45
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**729.35**	**732.75**	**731.05**	**103.61**	**107.48**	**105.54**	**408.19**	**409.36**	**408.77**
T_{10}: SR @ 2t ha^{-1}	331.22	334.62	332.92	26.15	26.24	26.20	170.76	169.79	170.27
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	554.42	557.22	555.82	69.23	70.64	69.93	299.12	300.89	300.01
SEm±	**5.22**	**4.09**	**3.32**	**2.42**	**1.77**	**1.50**	**3.35**	**2.29**	**2.03**
CD at 5%	**15.30**	**12.01**	**9.45**	**7.10**	**5.18**	**4.27**	**9.83**	**6.73**	**5.79**

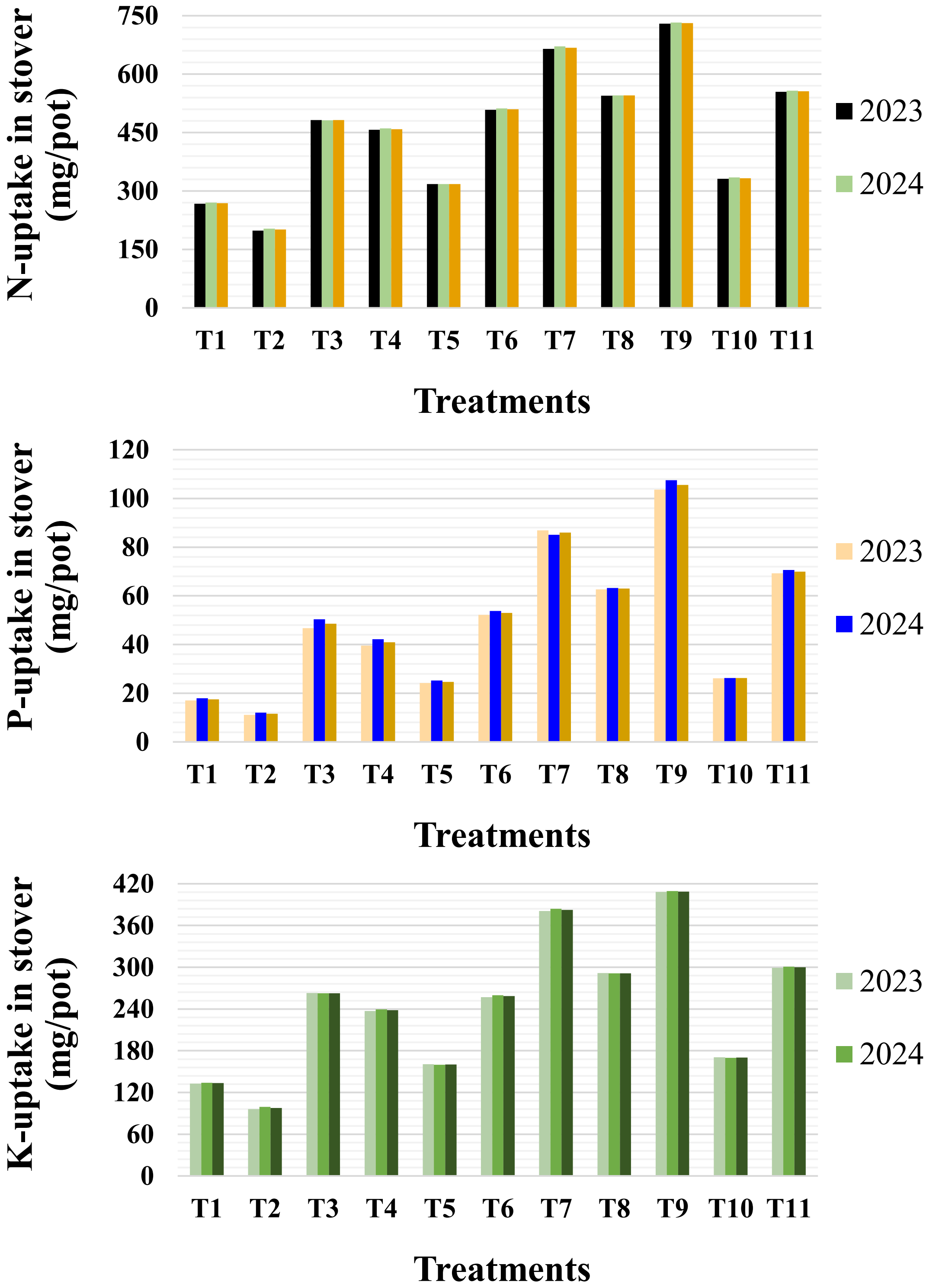

Fig. 4.18 Effect of different aluminium-alleviating organic materials on different nutrient uptakes (namely *nitrogen, phosphorus and potassium*) in stover of mungbean in acid soil

4.2.2.10 Calcium uptake in stover (mg/pot)

The effect of calcium uptake in stover as influenced by different organic materials is presented in Table 4.19 and graphically illustrated in Fig. 4.19. The treatments significantly improved calcium uptake in stover during both experimental years (2023 and 2024) and in the pooled results, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the first year of study, treatment T_9 (wood ash + vermicompost) recorded the highest calcium uptake in stover (207.01 mg/pot). In contrast, the lowest calcium uptake in stover (20.12 mg/pot) was observed under T_2 (absolute control). Among the individual amendments, treatment T_3 (wood ash) exhibited the highest calcium uptake in stover (119.04 mg/pot).

A similar trend was observed during the second trial (2024), where T_9 (wood ash + vermicompost) exhibited the highest calcium uptake in stover (204.19 mg/pot). The lowest calcium uptake in stover (20.15 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest calcium uptake in stover (121.29 mg/pot).

The pooled analysis of both experimental years (2023 and 2024) further confirmed that treatment T_9 (wood ash + vermicompost) obtained the highest calcium uptake in stover (205.60 mg/pot), while the lowest calcium uptake in stover (20.13 mg/pot) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest calcium uptake in stover (120.04 mg/pot) was recorded in treatment T_4 (poultry manure).

Calcium uptake in mungbean stover was highest under the combined application of wood ash and vermicompost due to improved calcium availability and soil conditions. Wood ash supplied calcium and reduced soil acidity, while vermicompost improved soil fertility. The lowest calcium uptake was observed under the control due to poor nutrient availability and aluminium toxicity. Among individual amendments, wood ash showed relatively higher calcium uptake due to its calcium content and liming effect. Similar findings were reported by Demeyer *et al*. (2001) and An and Park (2021).

4.2.2.11 Magnesium uptake in stover (mg/pot)

Data regarding magnesium uptake in stover as influenced by different organic materials are presented in Table 4.19 and graphically illustrated in Fig. 4.19. The results revealed significantly differences among treatments in both years (2023 and 2024) and in the pooled analysis, with organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest magnesium uptake in stover (151.37 mg/pot) under T_9 (wood ash + vermicompost), whereas the lowest magnesium uptake in stover (16.11 mg/pot) was observed under T_2 (absolute control). Among the single amendments, treatment T_4 (poultry manure) exhibited the highest magnesium uptake in stover (83.80 mg/pot).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest magnesium uptake in stover (150.45 mg/pot). The lowest magnesium uptake in stover (16.69 mg/pot) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest magnesium uptake in stover (83.72 mg/pot).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest magnesium uptake in stover (150.91 mg/pot), while the lowest magnesium uptake in stover (16.40 mg/pot) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest magnesium uptake in stover (83.76 mg/pot) was recorded in treatment T_4 (poultry manure).

Magnesium uptake in mungbean stover was highest under the combined application of wood ash and vermicompost due to improved magnesium availability and soil fertility. Wood ash increased soil pH and supplied basic cations, while vermicompost enhanced soil organic matter and microbial activity. The lowest uptake occurred under the control due to poor nutrient availability in acidic soil. Among individual amendments, wood ash resulted in relatively higher magnesium uptake. Similar observations were reported by Demeyer *et al*. (2001), Haynes and Mokolobate (2001) and An and Park (2021).

4.2.2.12 Aluminium uptake in stover (mg/pot)

The data on the aluminium uptake in stover as influenced by different organic materials are presented in Table 4.19 and graphically illustrated in Fig. 4.19. The treatments significantly influenced the aluminium uptake in stover during both the trials (2023 and 2024) and in the pooled analysis.

During the first trial in 2023, T_9 (wood ash + vermicompost) exhibited the highest aluminium uptake in stover (2.54 mg/pot) among all the treatments, while the lowest aluminium uptake in stover (1.54 mg/pot) was observed under T_2 (absolute control). Similar results were observed during the second trial in 2024 too, where T_9 (wood ash + vermicompost) exhibited the highest aluminium uptake in stover (2.54 mg/pot) among all the treatments and T_2 (absolute control) recorded the lowest aluminium uptake in stover (1.57 mg/pot).

As a result, the pooled analysis of both years (2023 and 2024) indicated treatment T_9 (wood ash + vermicompost) to exhibit the highest aluminium uptake in stover (2.54 mg/pot) and treatment T_2 (absolute control) to exhibit the lowest aluminium uptake in stover (1.56 mg/pot)

Aluminium uptake in mungbean stover was highest under the combined application of wood ash and vermicompost. This may be attributed to improved plant growth and biomass production under these treatments. Wood ash reduces soil acidity, while vermicompost improves soil fertility and microbial activity, leading to greater nutrient absorption and accumulation in plant biomass. In contrast, the lowest aluminium uptake was observed under the control condition due to restricted plant growth and lower biomass under untreated acidic soil conditions affected by aluminium toxicity. Similar observations were reported by Demeyer *et al*. (2001), who noted that wood ash and organic amendments improve soil properties and reduce aluminium toxicity in acidic soils.

Table 4.19 Effect of different aluminium-alleviating organic materials on different nutrient uptakes (namely *calcium, magnesium and aluminium*) in stover of mungbean in acid soil

Treatments	Nutrient uptake in stover (mg/pot)								
	Calcium			Magnesium			Aluminium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	31.17	32.20	31.69	25.10	26.49	25.79	1.97	1.98	1.98
T_2: Absolute control	20.12	20.15	20.13	16.11	16.69	16.40	1.54	1.57	1.56
T_3: WA @ 2t ha^{-1}	119.04	120.61	119.82	81.48	83.00	82.24	2.28	2.28	2.28
T_4: PM @ 2t ha^{-1}	118.79	121.29	120.04	83.80	83.72	83.76	2.27	2.26	2.27
T_5: RR @ 2t ha^{-1}	46.07	47.56	46.81	35.15	34.72	34.93	1.89	1.89	1.89
T_6: VC @ 2t ha^{-1}	112.23	114.73	113.48	72.55	73.34	72.95	2.39	2.39	2.39
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	199.04	200.12	199.58	144.77	147.61	146.19	2.42	2.41	2.41
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	147.36	147.88	147.62	102.31	104.45	103.38	2.38	2.38	2.38
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	207.01	204.19	205.60	151.37	150.45	150.91	2.54	2.54	2.54
T_{10}: SR @ 2t ha^{-1}	52.33	53.95	53.14	39.96	41.08	40.52	1.92	1.92	1.92
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	154.56	152.74	153.65	112.27	109.75	111.01	2.24	2.23	2.24
SEm±	**1.36**	**0.95**	**0.83**	**1.25**	**0.96**	**0.79**	**0.03**	**0.02**	**0.02**
CD at 5%	**3.98**	**2.78**	**2.36**	**3.65**	**2.81**	**2.24**	**0.08**	**0.05**	**0.05**

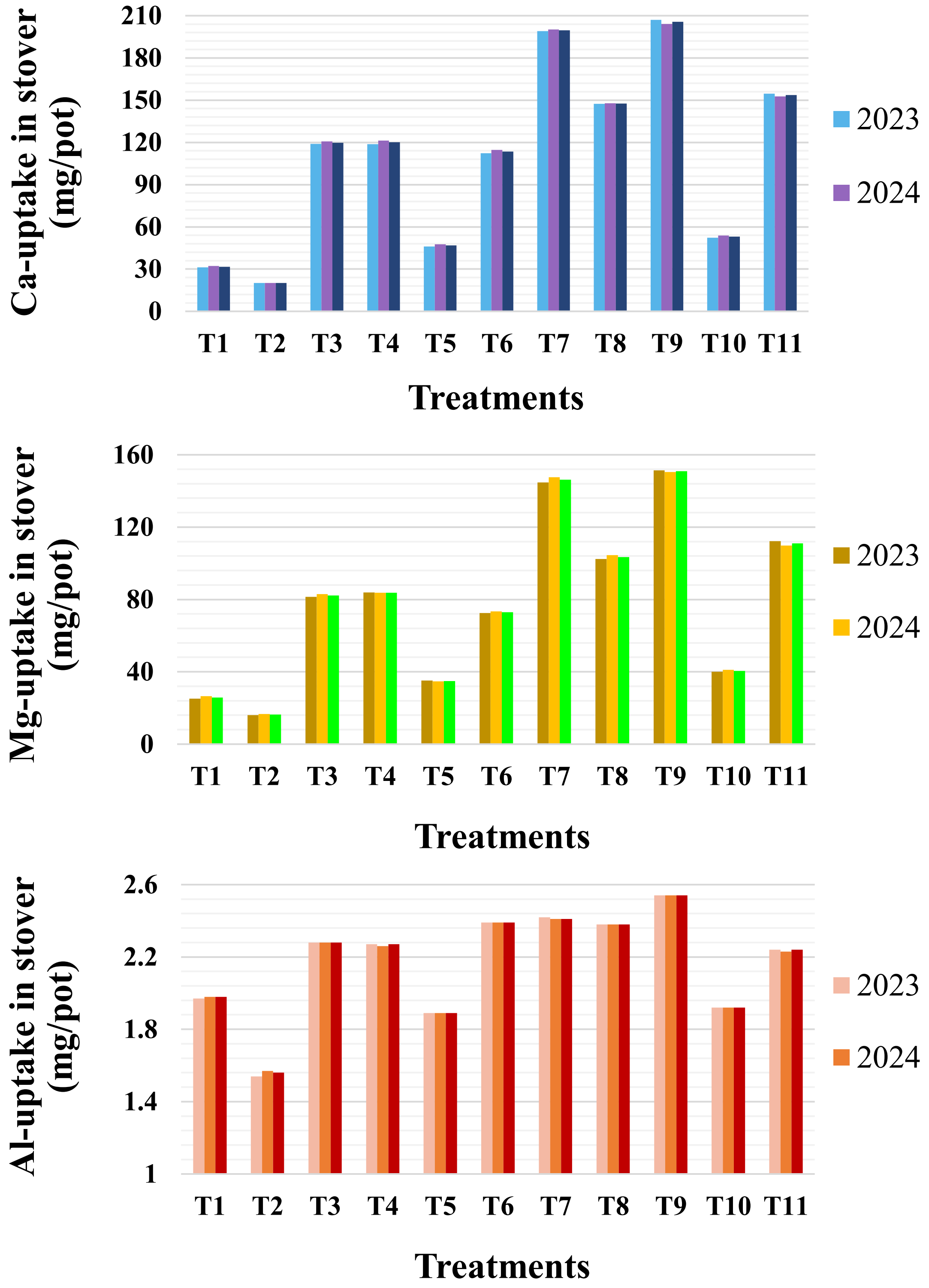

Fig. 4.19 Effect of different aluminium-alleviating organic materials on different nutrient uptakes (namely *calcium, magnesium and aluminium*) in stover of mungbean in acid soil

4.3 Effect of different aluminium-alleviating organic materials on the soil properties of an acid soil.

4.3.1 Soil solution analysis

The data on various soil solution properties, namely pH, calcium (ppm), magnesium (ppm), potassium (ppm), monomeric aluminium (ppm) and total aluminium (ppm), as influenced by different Al-alleviating organic materials are presented and discussed in the following sections to highlight the variation in soil solution properties under different treatments.

4.3.1.1 pH

Data pertaining to pH property as influenced by different organic materials are presented in Table 4.20 and graphically illustrated in Fig. 4.20. The treatments significantly influenced the pH property during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The results of the first trial (2023) showed that T_9 (wood ash + vermicompost) obtained the highest pH (5.79), which was statistically at par (5.78 pH) with T_7 (wood ash + poultry manure); whereas the lowest pH (4.66) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest pH (5.59).

A similar trend was observed during the second trial (2024), where T_9 (wood ash + vermicompost) exhibited the highest pH (5.81), which was statistically at par (5.80 pH) with T_7 (wood ash + poultry manure). The lowest pH (4.66) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest pH (5.60).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest pH (5.80), which was statistically at par (5.79 pH) with T_7 (wood ash + poultry manure); while the lowest pH (4.66) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest pH (5.59) was recorded in treatment T_3 (wood ash).

Table 4.20 Effect of different aluminium-alleviating organic materials on *soil solution pH* of an acid soil

Treatments	Soil solution pH		
	2023	2024	Pooled
T_1 : Control	4.74	4.76	4.75
T_2: Absolute control	**4.66**	**4.66**	**4.66**
T_3: WA @ 2t ha^{-1}	**5.59**	**5.60**	**5.59**
T_4: PM @ 2t ha^{-1}	5.55	5.55	5.55
T_5: RR @ 2t ha^{-1}	5.28	5.29	5.29
T_6: VC @ 2t ha^{-1}	5.56	5.57	5.56
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	**5.78**	**5.80**	**5.79**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	5.62	5.63	5.63
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**5.79**	**5.81**	**5.80**
T_{10}: SR @ 2t ha^{-1}	5.38	5.40	5.39
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	5.64	5.64	5.64
SEm±	**0.01**	**0.02**	**0.01**
CD at 5%	**0.04**	**0.05**	**0.03**

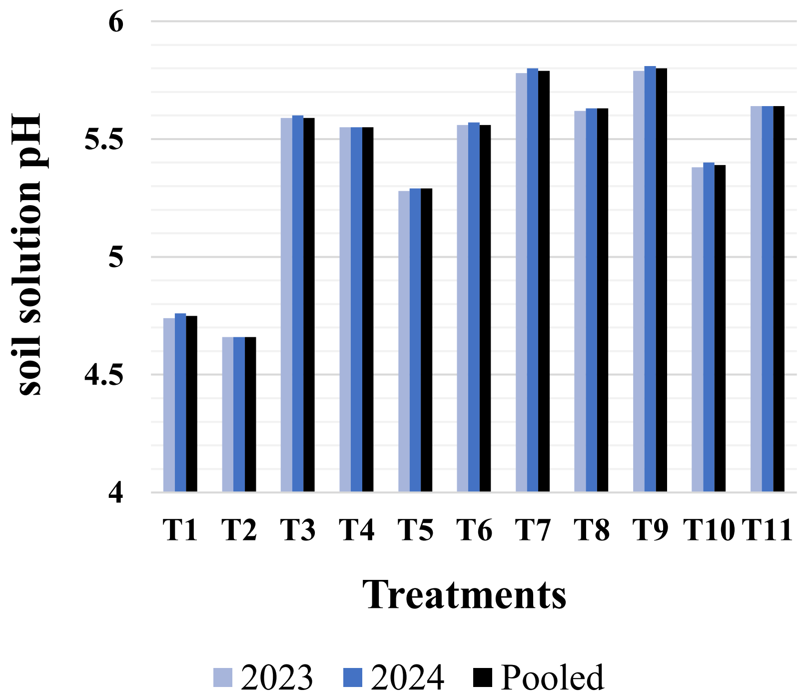

Fig. 4.20 Effect of different aluminium-alleviating organic materials on *soil solution pH* of an acid soil

Soil solution pH was lowest under the absolute control due to the inherent acidity of the soil and the absence of amendments to neutralize hydrogen and aluminium ions. Under such conditions, exchangeable aluminium remains active in the soil solution, maintaining a low pH environment. Among the individual amendments, wood ash increased soil solution pH due to its alkaline nature and the presence of basic cations such as calcium, magnesium, and potassium, which help neutralize soil acidity. The highest soil solution pH was observed under the combined application of wood ash and vermicompost. This may be attributed to the liming effect of wood ash along with the improvement of soil buffering capacity and microbial activity by vermicompost. Similar findings were reported by Muhrizal *et al*. (2003)**,** who observed that the application of organic materials increased soil pH and reduced aluminium toxicity in acidic soils.

4.3.1.2 Calcium (ppm)

Data regarding calcium (ppm) as affected by various organic materials are given in Table 4.21 and depicted in Fig. 4.21. The treatments significantly influenced the calcium during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the initial trial in 2023, treatment T_7 (wood ash + poultry manure) recorded the highest calcium (521.04 ppm); whereas the lowest calcium (93.52 ppm) was observed under T_2 (absolute control). Among the individual amendments, treatment T_4 (poultry manure) exhibited the highest calcium (327.32 ppm).

Similarly, during the second trial (2024), T_7 (wood ash + poultry manure) exhibited the highest calcium (527.72 ppm). The lowest calcium (100.20 ppm) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest calcium (334.00 ppm).

The pooled results of both years (2023 and 2024) revealed that treatment T_7 (wood ash + poultry manure) registered the highest calcium (524.38 ppm); while the lowest calcium (96.86 ppm) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest calcium (330.66 ppm) was recorded in treatment T_3 (wood ash).

Calcium concentration in the soil solution was lowest under the control due to low exchangeable calcium and the dominance of hydrogen and aluminium ions in acidic soil. Among the individual amendments, poultry manure increased calcium concentration through the addition of organic matter and nutrient mineralization. The highest calcium concentration was observed under the combined application of wood ash and poultry manure due to the supply of calcium from wood ash and improved soil fertility from poultry manure. Similar observations were reported by Bessho and Bell (1992) and Muhrizal *et al*. (2003)**,** who noted that organic materials increase the availability of basic cations such as calcium in acidic soils.

4.3.1.3 Magnesium (ppm)

The magnesium content (ppm) as influenced by different organic materials is presented in Table 4.21 and graphically illustrated in Fig. 4.21. The treatments exerted a significant effect on magnesium during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first experimental trial (2023), treatment T_7 (wood ash + poultry) recorded the highest magnesium (85.09 ppm), which was statistically at par (81.04 ppm) with T_9 (wood ash + vermicompost); whereas the lowest magnesium (28.36 ppm) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest magnesium (64.83 ppm).

A comparable trend was observed during the second trial (2024), where T_7 (wood ash + poultry) exhibited the highest magnesium (89.14 ppm), which was statistically at par (85.09) with T_9 (wood ash + vermicompost). The lowest magnesium (32.42 ppm) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest magnesium (68.88 ppm).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry) exhibited the highest magnesium (87.11 ppm), which was statistically at par (83.06 ppm) with T_9 (wood ash + vermicompost); while the lowest magnesium (30.39 ppm) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest magnesium (66.86 ppm) was recorded in treatment T_3 (wood ash).

Magnesium concentration in the soil solution was lowest under the control due to poor nutrient availability in acidic soil. Among the single amendments, wood ash increased magnesium concentration as it contains appreciable amounts of magnesium and improves soil pH. The highest magnesium concentration was recorded under the combined application of wood ash and poultry manure due to the combined effect of nutrient supply and improved soil fertility. Similar findings were reported by Bessho and Bell (1992) and Muhrizal *et al*. (2003)**,** who observed that organic amendments enhance magnesium availability in acidic soils.

4.3.1.4 Potassium (ppm)

The data on the potassium property as influenced by different organic materials are presented in Table 4.21 and graphically illustrated in Fig. 4.21. The treatments significantly influenced the potassium property during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest potassium (106.87 ppm) under T_7 (wood ash + poultry), which was statistically at par (101.66 ppm) with T_9 (wood ash + vermicompost); whereas the lowest potassium (24.76 ppm) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest potassium (74.29 ppm).

Similarly, during the second trial (2024), T_7 (wood ash + poultry) exhibited the highest potassium (108.18 ppm), which was statistically at par (104.27) with T_9 (wood ash + vermicompost). The lowest potassium (26.07 ppm) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest potassium (75.59 ppm).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry) exhibited the highest potassium (107.53 ppm), while the lowest potassium (25.42 ppm) was obtained under treatment T_2 (absolute control). Among

Table 4.21 Effect of different aluminium-alleviating organic materials on *soil solution calcium, magnesium and potassium* of an acid soil

Treatments	Soil solution properties (ppm)								
	Calcium			Magnesium			Potassium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	106.88	113.56	110.22	40.52	44.57	42.55	31.28	32.58	31.93
T_2: Absolute control	**93.52**	**100.20**	**96.86**	**28.36**	**32.42**	**30.39**	**24.76**	**26.07**	**25.42**
T_3: WA @ 2t ha^{-1}	313.96	320.64	317.30	**64.83**	**68.88**	**66.86**	**74.29**	**75.59**	**74.94**
T_4: PM @ 2t ha^{-1}	**327.32**	**334.00**	**330.66**	60.78	64.83	62.80	65.17	66.47	65.82
T_5: RR @ 2t ha^{-1}	146.96	153.64	150.30	48.62	52.67	50.65	39.10	37.80	38.45
T_6: VC @ 2t ha^{-1}	293.92	300.60	297.26	56.72	60.78	58.75	61.26	62.56	61.91
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	**521.04**	**527.72**	**524.38**	**85.09**	**89.14**	**87.11**	**106.87**	**108.18**	**107.53**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	340.68	347.36	344.02	68.88	72.93	70.91	80.81	80.81	80.81
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	454.24	460.92	457.58	**81.04**	**85.09**	**83.06**	**101.66**	**104.27**	102.96
T_{10}: SR @ 2t ha^{-1}	207.08	213.76	210.42	52.67	56.73	54.70	48.22	45.62	46.92
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	374.08	380.76	377.42	72.93	76.98	74.96	86.02	87.32	86.67
SEm±	**9.87**	**9.23**	**6.76**	**4.89**	**7.82**	**4.61**	**1.93**	**1.67**	**1.27**
CD at 5%	**28.94**	**27.07**	**19.25**	**14.33**	**22.94**	**13.14**	**5.65**	**4.89**	**3.63**

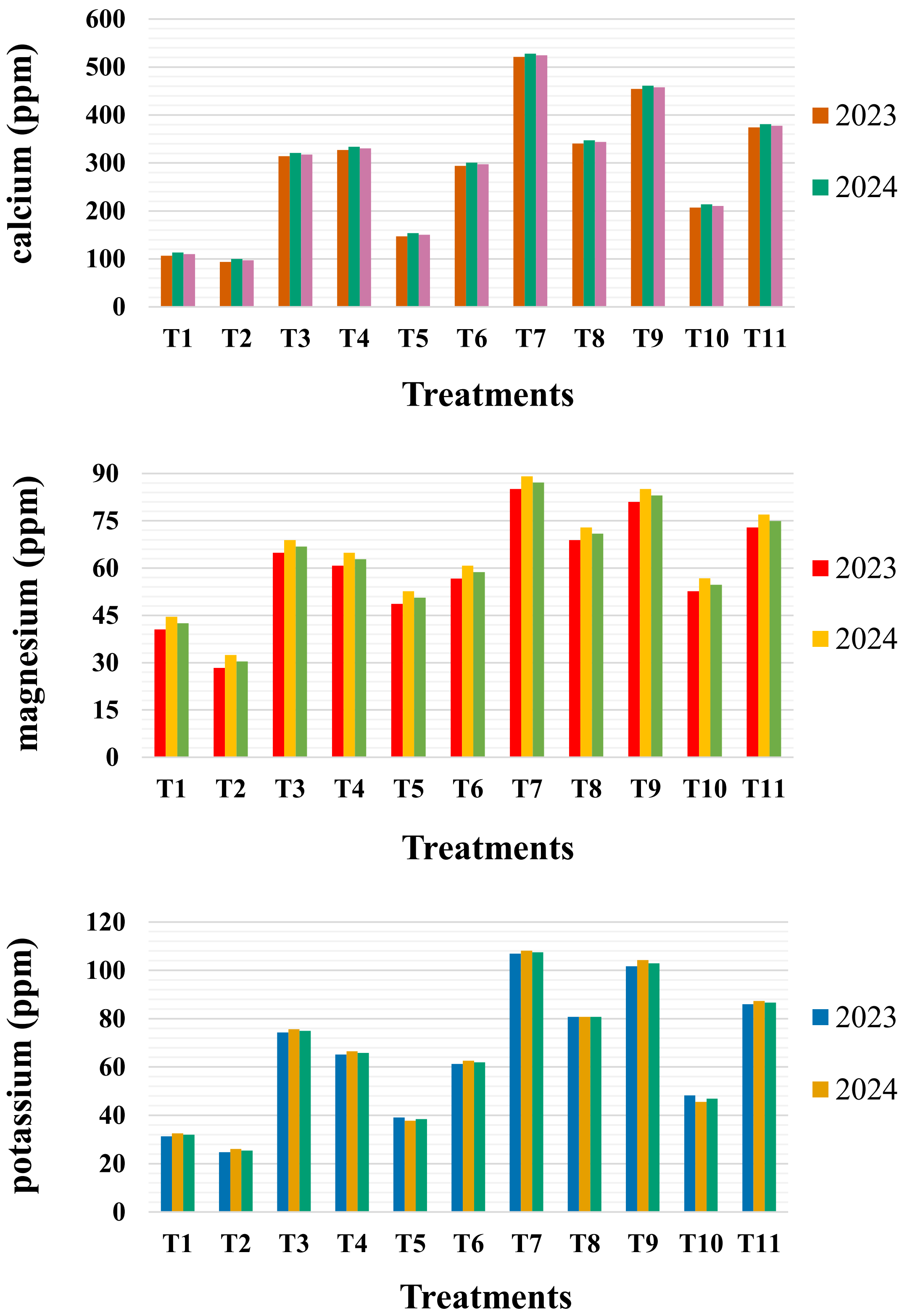

Fig. 4.21 Effect of different aluminium-alleviating organic materials on *soil solution calcium, magnesium and potassium* of an acid soil

the single amendments, the highest potassium (74.94 ppm) was recorded in treatment T_3 (wood ash).

Potassium concentration in the soil solution was lowest under the control due to limited nutrient availability in acidic soil. Among the individual amendments, wood ash increased potassium concentration because it is a direct source of potassium and improves soil pH. The highest potassium concentration was observed under the combined application of wood ash and poultry manure due to potassium supply from wood ash and improved soil fertility from poultry manure. Similar observations were reported by Bessho and Bell (1992) and Muhrizal *et al*. (2003), who reported that organic materials increase potassium availability in acidic soils.

4.3.1.5 Monomeric aluminium (ppm)

The data on the monomeric aluminium (ppm) as influenced by different organic materials are presented in Table 4.22 and graphically illustrated in Fig. 4.22. The treatments significantly affected the monomeric aluminium property during both experimental trials (2023 and 2024) and in the pooled analysis. All organic amendments performed better than T_1 (control) and T_2 (absolute control).

The results obtained during the first trial in 2023 showed that treatment T_9 (wood ash + vermicompost) recorded the lowest monomeric aluminium (0.29 ppm), which was statistically at par (0.33 ppm) with T_7 (wood ash + poultry); whereas the highest monomeric aluminium (2.14 ppm) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the lowest monomeric aluminium (0.57 ppm).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the lowest monomeric aluminium (0.29 ppm), which was statistically at par (0.32 ppm) with T_7 (wood ash + poultry). The highest monomeric aluminium (2.19 ppm) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest monomeric aluminium (0.57 ppm).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the lowest monomeric aluminium (0.29 ppm), which was statistically at par (0.33 ppm) with T_7 (wood ash + poultry); while the highest monomeric aluminium (2.17 ppm) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest monomeric aluminium (0.57 ppm) was recorded in treatment T_3 (wood ash).

Monomeric aluminium concentration was highest under the control due to the strong acidity of the soil, which increases the solubility of aluminium in the soil solution. In acidic soils, aluminium predominantly exists in soluble monomeric forms that are toxic to plants. Among the individual amendments, wood ash reduced monomeric aluminium concentration due to its alkaline nature and the presence of basic cations that increase soil pH and decrease aluminium solubility. The lowest monomeric aluminium concentration was observed under the combined application of wood ash and vermicompost. This reduction may be attributed to the liming effect of wood ash and the ability of organic matter from vermicompost to form stable complexes with aluminium ions. Similar results were reported by Bessho and Bell (1992) and Muhrizal *et al*. (2003), who found that organic materials reduce soluble aluminium in acidic soils.

4.3.1.6 Total aluminium (ppm)

The total aluminium content (ppm) as influenced by different organic materials is presented in Table 4.22 and graphically illustrated in Fig. 4.22. The treatments significantly influenced the total aluminium property during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial conducted during 2023 revealed that the treatment T_9 (wood ash + vermicompost) resulted in the lowest total aluminium (0.55 ppm), while the highest total aluminium (3.92 ppm) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) exhibited the lowest total aluminium (0.95 ppm).

The second trial conducted in 2024 exhibited a similar trend. Treatment T_9 (wood ash + vermicompost) recorded the lowest total aluminium (0.53 ppm), whereas the highest total aluminium (3.94 ppm) was observed under T_2 (absolute control).

Table 4.22 Effect of different aluminium-alleviating organic materials on *soil solution monomeric aluminium and total aluminium* of an acid soil

Treatments	Soil solution properties (ppm)					
	Monomeric aluminium			Total aluminium		
	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	1.97	1.92	1.95	3.64	3.62	3.63
T_2: Absolute control	**2.14**	**2.19**	**2.17**	**3.92**	**3.94**	**3.93**
T_3: WA @ 2t ha^{-1}	**0.57**	**0.57**	**0.57**	0.98	0.96	0.97
T_4: PM @ 2t ha^{-1}	0.65	0.64	0.65	1.25	1.23	1.24
T_5: RR @ 2t ha^{-1}	1.34	1.30	1.32	2.22	2.20	2.21
T_6: VC @ 2t ha^{-1}	0.63	0.63	0.63	**0.95**	**0.94**	**0.95**
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	**0.33**	**0.32**	**0.33**	0.71	0.71	0.71
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	0.49	0.49	0.49	0.85	0.85	0.85
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**0.29**	**0.29**	**0.29**	**0.55**	**0.53**	**0.54**
T_{10}: SR @ 2t ha^{-1}	1.03	1.07	1.05	1.75	1.75	1.75
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	0.45	0.46	0.45	0.83	0.85	0.84
SEm±	**0.04**	**0.03**	**0.03**	**0.03**	**0.02**	**0.02**
CD at 5%	**0.11**	**0.10**	**0.07**	**0.08**	**0.07**	**0.05**

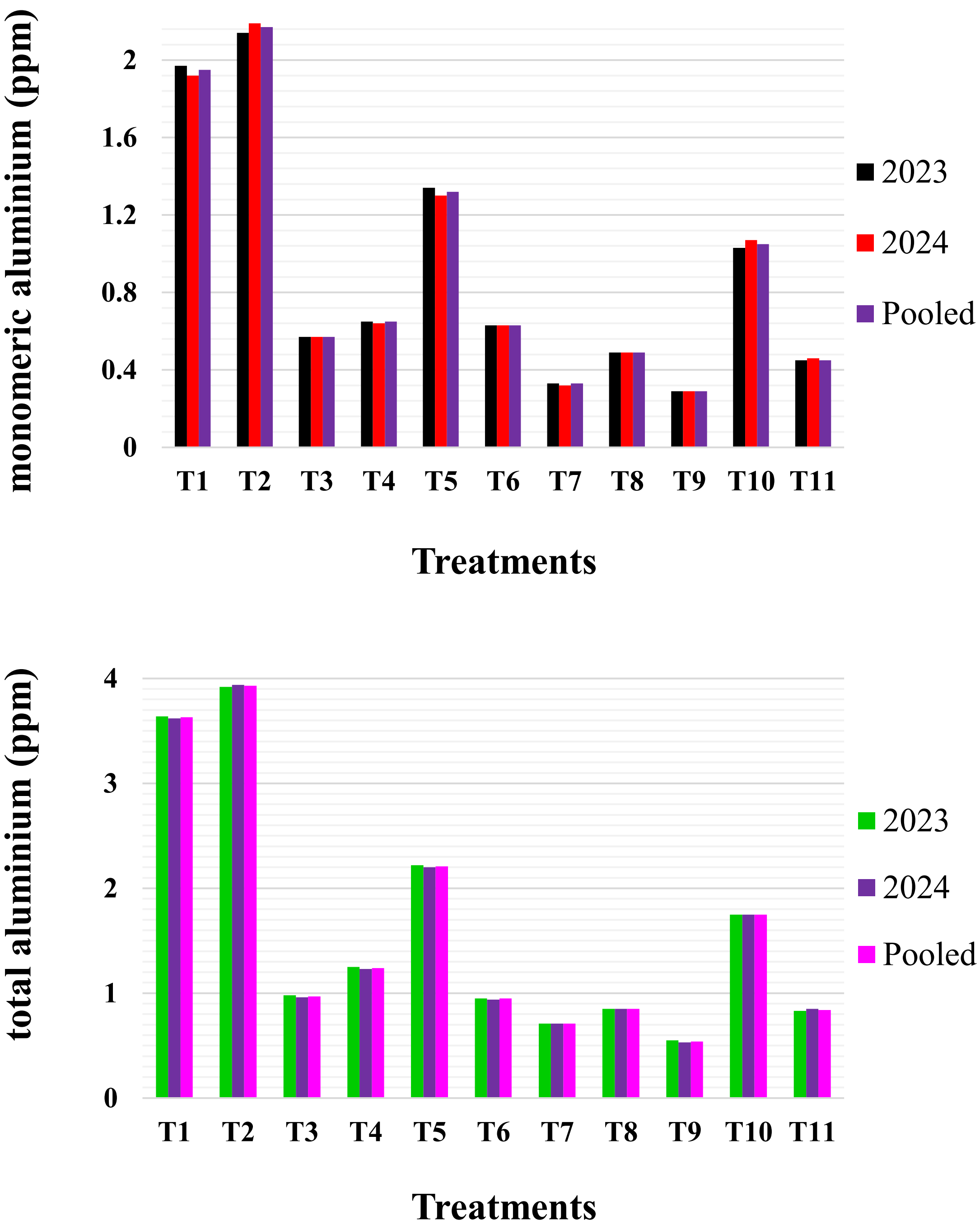

Fig. 4.22 Effect of different aluminium-alleviating organic materials on *soil solution monomeric aluminium and total aluminium* of an acid soil

Among the single applications, treatment T_6 (vermicompost) exhibited the lowest total aluminium (0.94 ppm).

The pooled analysis of the experimental data further indicated that treatment T_9 (wood ash + vermicompost) recorded the lowest total aluminium (0.54 ppm), while the highest total aluminium (3.93 ppm) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest total aluminium (0.95 ppm) was recorded in treatment T_6 (vermicompost).

Total aluminium concentration was highest under the control due to the strongly acidic nature of the soil, which promotes aluminium solubility in the soil solution. Among the individual amendments, vermicompost resulted in comparatively lower aluminium concentration because organic matter can form stable complexes with aluminium and reduce its activity in the soil solution. The lowest total aluminium concentration was recorded under the combined application of wood ash and vermicompost. This may be attributed to the combined effect of increased soil pH from wood ash and aluminium complexation by organic compounds from vermicompost. Similar findings were reported by Bessho and Bell (1992) and Muhrizal *et al*. (2003)**,** who observed that organic amendments reduce aluminium toxicity in acidic soils.

4.3.2 Soil solid phase analysis

The data on various soil solid phase properties, namely soil pH, electrical conductivity (dS/m), cation exchange capacity [cmol (p^+) kg^{-1}], organic carbon (%), exchangeable calcium [cmol (p^+) kg^{-1}], exchangeable magnesium [cmol (p^+) kg^{-1}], exchangeable potassium [cmol (p^+) kg^{-1}], exchangeable sodium [cmol (p^+) kg^{-1}], base saturation (%), exchangeable aluminium [cmol (p^+) kg^{-1}], exchangeable acidity [cmol (p^+) kg^{-1}], exchangeable hydrogen [cmol (p^+) kg^{-1}], total potential acidity [cmol (p^+) kg^{-1}], reserve acidity [cmol (p^+) kg^{-1}], effective cation exchange capacity [cmol (p^+) kg^{-1}], aluminium saturation [cmol (p^+) kg^{-1}], and different forms of aluminium (in mg/kg), as influenced by different Al-alleviating organic materials are presented and discussed in the following sections to highlight the variation in soil solid phase properties under different treatments.

4.3.2.1 Soil pH

The data pertaining to soil pH as affected by different organic materials are presented in Table 4.23 and graphically illustrated in Fig. 4.23. The treatments significantly influenced the soil pH during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first year of study (2023), treatment T_9 (wood ash + vermicompost) exhibited the highest soil pH (5.77), which was statistically at par (5.76 pH) with T_7 (wood ash + poultry manure); whereas the lowest soil pH (4.65) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest soil pH (5.57).

A similar trend was noticed in the second trial conducted during 2024. Treatment T_9 (wood ash + vermicompost) recorded the highest soil pH (5.80), while the lowest soil pH (4.65) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest soil pH (5.58).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest soil pH (5.79), which was statistically at par (5.77 pH) with T_7 (wood ash + poultry manure); while the lowest soil pH (4.65) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest soil pH (5.58) was recorded in treatment T_3 (wood ash).

The lowest soil pH under the absolute control may be attributed to the inherent acidity of the soil and the absence of amendments to neutralize hydrogen and aluminium ions. Under such conditions, the dominance of these ions maintains a low soil pH, which adversely affects nutrient availability and plant growth. Among the single amendments, wood ash increased soil pH due to its alkaline nature and the presence of basic cations such as calcium, potassium, and magnesium, which help neutralize soil acidity. The highest soil pH was observed under the combined application of wood ash and vermicompost. This improvement may be attributed to the liming effect of wood ash along with the addition of organic matter from vermicompost, which enhances soil buffering capacity and overall soil chemical

Table 4.23 Effect of different aluminium-alleviating organic materials on *soil pH* of post-harvest acid soil

Treatments	Soil pH		
	2023	2024	Pooled
T_1 : Control	4.73	4.75	4.74
T_2: Absolute control	4.65	4.65	4.65
T_3: WA @ 2t ha^{-1}	5.57	5.58	5.58
T_4: PM @ 2t ha^{-1}	5.53	5.54	5.54
T_5: RR @ 2t ha^{-1}	5.27	5.28	5.27
T_6: VC @ 2t ha^{-1}	5.54	5.56	5.55
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	5.76	5.78	5.77
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	5.61	5.62	5.62
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	5.77	5.80	5.79
T_{10}: SR @ 2t ha^{-1}	5.37	5.38	5.38
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	5.63	5.63	5.63
SEm±	**0.02**	**0.01**	**0.01**
CD at 5%	**0.05**	**0.04**	**0.03**
Initial value	**4.76**	**4.78**	—

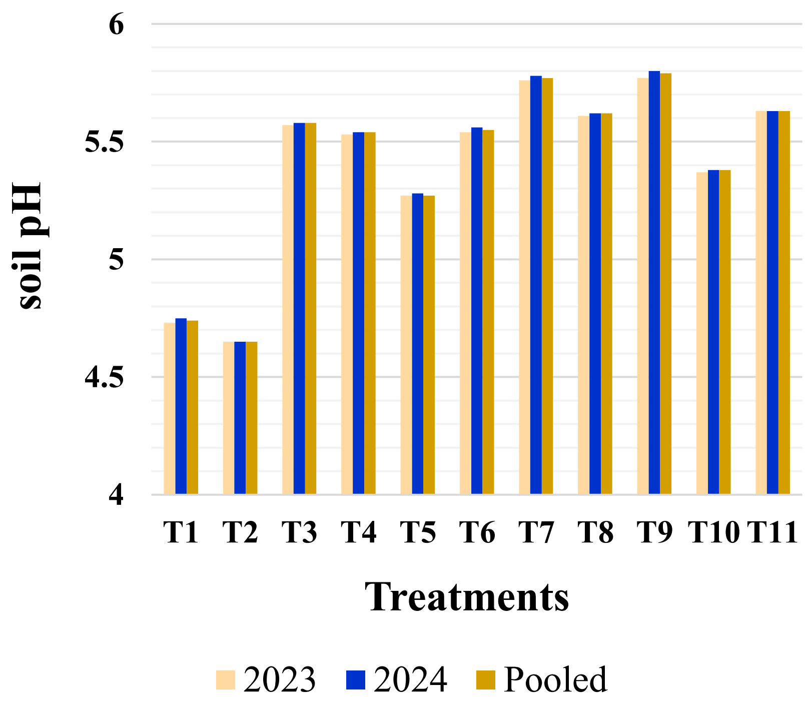

Fig. 4.23 Effect of different aluminium-alleviating organic materials on *soil pH* of post-harvest acid soil

properties. Similar observations have been reported by Muhrizal *et al*. (2003)**,** An and Park (2021)**,** and Lauricella *et al*. (2020)**,** who noted that organic amendments, including wood ash and various manures, effectively increase soil pH, base cation availability, and improve soil chemical conditions in acidic soils.

4.3.2.2 Electrical conductivity (dS/m)

Data regarding electrical conductivity as affected by various organic materials are presented in Table 4.24 and graphically illustrated in Fig. 4.24. The treatments had a significant effect on electrical conductivity during both trials conducted in 2023 and 2024 and also in the pooled results. All the organic amendments showed better performance compared to T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest electrical conductivity (0.17 dS/m) under T_7 (wood ash + poultry manure); whereas the lowest electrical conductivity (0.05 dS/m) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest electrical conductivity (0.12 dS/m).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest electrical conductivity (0.18 dS/m). The lowest electrical conductivity (0.05 dS/m) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest electrical conductivity (0.12 dS/m).

The pooled analysis of both experimental years (2023 and 2024) revealed that treatment T_7 (wood ash + poultry manure) exhibited the highest electrical conductivity (0.17 dS/m); while the lowest electrical conductivity (0.05 dS/m) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest electrical conductivity (0.12 dS/m) was recorded in treatment T_3 (wood ash).

The lowest EC under the absolute control may be due to the absence of nutrient additions and the limited concentration of soluble ions in the soil solution. Wood ash increased EC by supplying soluble salts and basic cations, improving the overall ionic content of the soil solution. The highest EC was observed with the combined application of wood ash and poultry manure, as poultry manure mineralization further

Table 4.24 Effect of different aluminium-alleviating organic materials on *electrical conductivity* of post-harvest acid soil

Treatments	Electrical conductivity (dS/m)		
	2023	2024	Pooled
T_1 : Control	0.07	0.08	0.08
T_2: Absolute control	0.05	0.05	0.05
T_3: WA @ 2t ha^{-1}	0.12	0.12	0.12
T_4: PM @ 2t ha^{-1}	0.11	0.10	0.10
T_5: RR @ 2t ha^{-1}	0.08	0.08	0.08
T_6: VC @ 2t ha^{-1}	0.09	0.09	0.09
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	0.17	0.18	0.17
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	0.13	0.13	0.13
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	0.16	0.17	0.16
T_{10}: SR @ 2t ha^{-1}	0.09	0.09	0.09
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	0.14	0.14	0.14
SEm±	**0.00**	**0.00**	**0.00**
CD at 5%	**0.01**	**0.01**	**0.01**
Initial value	**0.06**	**0.07**	—

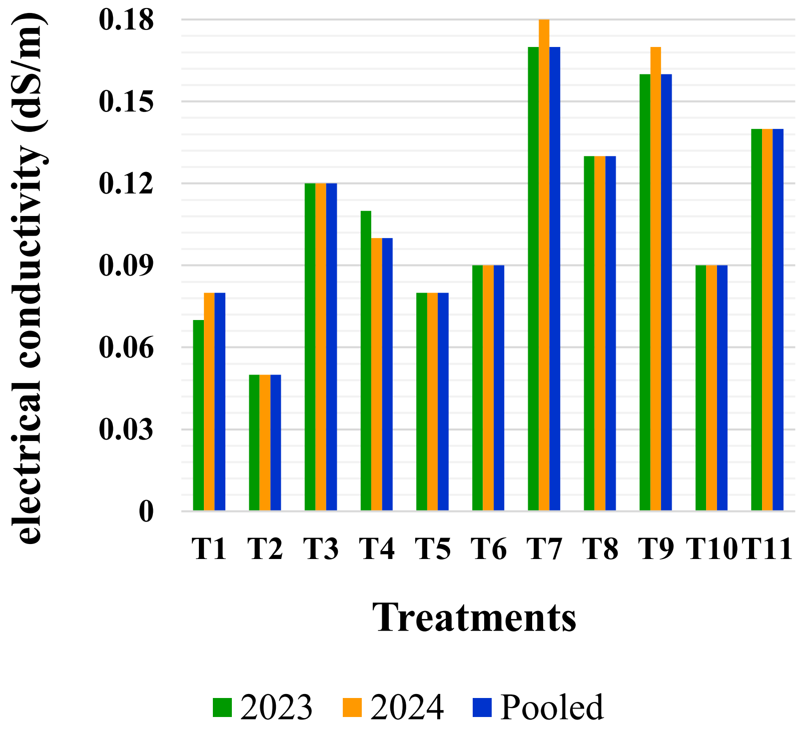

Fig. 4.24 Effect of different aluminium-alleviating organic materials on *electrical conductivity* of post-harvest acid soil

released soluble nutrients, enhancing the concentration of ions. This integrated effect of nutrient supply and improved soil chemical activity explains the higher electrical conductivity under combined organic amendments. Similar observations were reported by Bessho and Bell (1992), who noted that organic amendments can increase soluble ion concentration in acidic soils.

4.3.2.3 Organic carbon (%)

Organic carbon content in soil as influenced by different organic materials are presented in Table 4.25 and graphically illustrated in Fig. 4.25. A significant variation in organic carbon content was observed during both experimental years (2023 and 2024) and in pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the first year of experimentation (2023), treatment T_9 (wood ash + vermicompost) obtained the highest organic carbon (1.62%), which was statistically at par (1.60%) with T_7 (wood ash + poultry manure); whereas the lowest organic carbon (1.13%) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) exhibited the highest organic carbon (1.48%).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest organic carbon (1.63%), which was statistically at par (1.61%) with T_7 (wood ash + poultry manure). The lowest organic carbon (1.14%) was observed under T_2 (absolute control). Among the single applications, treatment T_6 (vermicompost) exhibited the highest organic carbon (1.49%).

The pooled results of both experimental years (2023 and 2024) confirmed that treatment T_9 (wood ash + vermicompost) exhibited the highest organic carbon (1.63%); while the lowest organic carbon (1.14%) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest organic carbon (1.49%) was recorded in treatment T_6 (vermicompost).

Table 4.25 Effect of different aluminium-alleviating organic materials on *organic carbon* of post-harvest acid soil

Treatments	Organic carbon (%)		
	2023	2024	Pooled
T_1 : Control	1.16	1.17	1.17
T_2: Absolute control	1.13	1.14	1.14
T_3: WA @ 2t ha^{-1}	1.22	1.23	1.23
T_4: PM @ 2t ha^{-1}	1.43	1.45	1.44
T_5: RR @ 2t ha^{-1}	1.35	1.36	1.36
T_6: VC @ 2t ha^{-1}	1.48	1.49	1.49
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	1.60	1.61	1.61
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	1.52	1.53	1.53
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	1.62	1.63	1.63
T_{10}: SR @ 2t ha^{-1}	1.37	1.38	1.38
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	1.54	1.54	1.54
SEm±	**0.01**	**0.01**	**0.01**
CD at 5%	**0.03**	**0.03**	**0.02**
Initial value	**1.17**	**1.20**	**—**

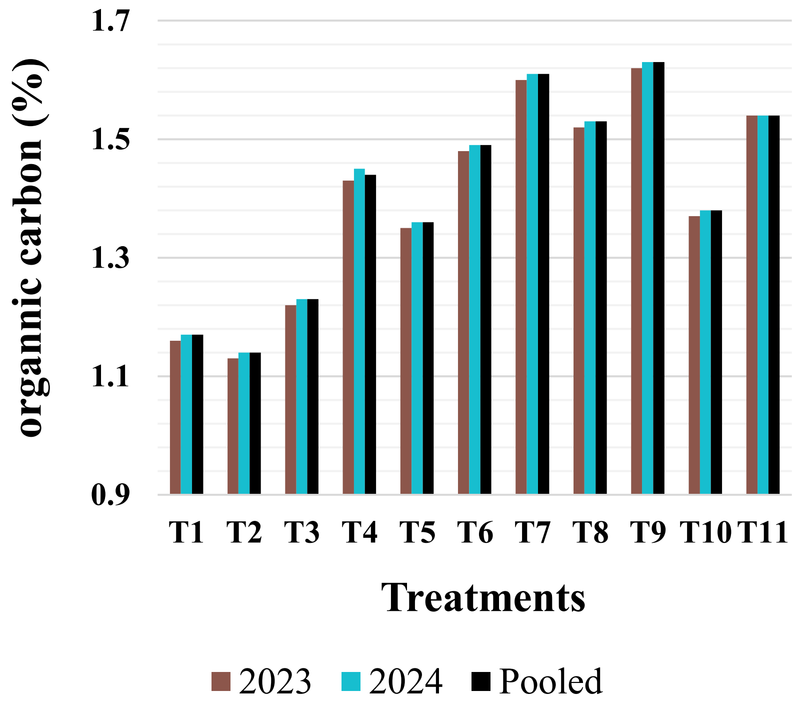

Fig. 4.25 Effect of different aluminium-alleviating organic materials on *organic carbon* of post-harvest acid soil

The lowest organic carbon under the absolute control may be due to the absence of organic inputs. Vermicompost increased soil organic carbon by adding stabilized organic matter and enhancing microbial activity, while the combined application of wood ash and vermicompost resulted in the highest organic carbon due to the synergistic effect of organic matter addition and improved soil conditions. Similar observations were reported by Kumawat (2026), who found that FYM remained at par with vermicompost in increasing soil organic carbon, and Terefe *et al*. (2024), who observed that vermicompost, especially with lime, significantly improved organic carbon and other soil properties in acidic soils. Olubode *et al*. (2018) also reported that wood ash application significantly increased soil pH and organic carbon in acid soil under soybean, further confirming the role of wood ash in improving soil organic matter in acidic conditions.

4.3.2.4 Cation exchange capacity [cmol (p^+) kg^{-1}]

The effect of different organic materials on cation exchange capacity of soil is presented in Table 4.26 and graphically illustrated in Fig. 4.26. The treatments significantly influenced the cation exchange capacity during both the years (2023 and 2024) and in the pooled analysis, with all organic amendments showing better performance than T_1 (control) and T_2 (absolute control).

During the 2023 trial, treatment T_9 (wood ash + vermicompost) recorded the highest cation exchange capacity (13.27 cmol (p^+) kg^{-1}), whereas the lowest cation exchange capacity (10.57 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) exhibited the highest cation exchange capacity (12.27 cmol (p^+) kg^{-1}).

Similarly, during the second trial (2024), T_9 (wood ash + vermicompost) exhibited the highest cation exchange capacity (13.30 cmol (p^+) kg^{-1}). The lowest cation exchange capacity (10.60 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the individual applications, treatment T_6 (vermicompost) exhibited the highest cation exchange capacity (12.30 cmol (p^+) kg^{-1}).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the highest cation exchange capacity (13.28

cmol (p^+) kg^{-1}); while the lowest cation exchange capacity (10.58 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest cation exchange capacity (12.28 cmol (p^+) kg^{-1}) was recorded in treatment T_6 (vermicompost).

The lowest CEC under the absolute control may be attributed to the absence of organic amendments and the low organic matter status of the acidic soil. Limited organic matter reduces the number of negatively charged sites for nutrient retention, resulting in lower cation exchange capacity. Among the single amendments, vermicompost enhanced CEC by adding organic matter, which increases exchange sites and improves the soil's ability to retain and supply essential nutrient cations. The highest CEC was observed under the combined application of wood ash and vermicompost. Wood ash supplied basic cations, while vermicompost contributed organic matter, creating a synergistic effect that improved soil chemical properties and markedly increased CEC. These results are supported by Sufardi *et al*. (2024), who reported that organic amendments improved CEC in acidic dryland soils by enhancing soil chemical properties and nutrient retention.

4.3.2.5 Exchangeable calcium [cmol (p^+) kg^{-1}]

The data on the exchangeable calcium as influenced by different organic materials are presented in Table 4.26 and graphically illustrated in Fig. 4.26. The treatments significantly influenced the exchangeable calcium during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest exchangeable calcium (3.30 cmol (p^+) kg^{-1}) under T_7 (wood ash + poultry manure); whereas the lowest exchangeable calcium (1.13 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_4 (poultry manure) exhibited the highest exchangeable calcium (2.33 cmol (p^+) kg^{-1}).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest exchangeable calcium (3.33 cmol (p^+) kg^{-1}). The lowest exchangeable calcium (1.17 cmol (p^+) kg^{-1}) was observed under T_2

(absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest exchangeable calcium (2.37 cmol (p^+) kg^{-1}).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the highest exchangeable calcium (3.32 cmol (p^+) kg^{-1}); while the lowest exchangeable calcium (1.15 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest exchangeable calcium (2.35 cmol (p^+) kg^{-1}) was recorded in treatment T_4 (poultry manure).

The lowest exchangeable calcium under the control may be attributed to the absence of amendments and the inherently low availability of basic cations in acidic soils. In such conditions, hydrogen and aluminium ions dominate the soil exchange complex, reducing the proportion of calcium on exchange sites. Among the single amendments, poultry manure recorded the highest exchangeable calcium, which may be attributed to its rich calcium content that neutralizes soil acidity and displaces hydrogen and aluminium ions from the exchange complex. The combined application of wood ash and poultry manure resulted in the highest exchangeable calcium, as poultry manure improved soil organic matter and nutrient retention, creating a favorable environment for calcium availability. These improvements in exchangeable calcium in acidic soils were also reported by Bessho and Bell (1992), Muhrizal *et al*. (2003), and An and Park (2021), who observed that organic amendments and ash materials increase soil pH and the availability of basic cations such as calcium.

4.3.2.6 Exchangeable magnesium [cmol (p^+) kg^{-1}]

The data pertaining to exchangeable magnesium as influenced by different organic materials are presented in Table 4.26 and graphically illustrated in Fig. 4.26. The treatments significantly influenced the exchangeable magnesium during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

Results from the first trial in 2023 exhibited the highest exchangeable magnesium (0.90 cmol (p^+) kg^{-1}) under T_7 (wood ash + poultry manure), which was statistically at par (0.87 cmol (p^+) kg^{-1}) with T_9 (wood ash + vermicompost); whereas the lowest exchangeable magnesium (0.43 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest exchangeable magnesium (0.70 cmol (p^+) kg^{-1}).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest exchangeable magnesium (0.93 cmol (p^+) kg^{-1}), which was statistically at par (0.90 cmol (p^+) kg^{-1}) with T_9 (wood ash + vermicompost). The lowest exchangeable magnesium (0.47 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest exchangeable magnesium (0.73 cmol (p^+) kg^{-1}).

The pooled results of both experimental years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) recorded the highest exchangeable magnesium (0.92 cmol (p^+) kg^{-1}), which was statistically at par (0.88 cmol (p^+) kg^{-1}) with T_9 (wood ash + vermicompost); while the lowest exchangeable magnesium (0.45 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest exchangeable magnesium (0.72 cmol (p^+) kg^{-1}) was recorded in treatment T_3 (wood ash).

The lowest exchangeable magnesium under the control reflects the limited availability of magnesium in acidic soils and the absence of nutrient amendments. Wood ash enhanced magnesium availability through its magnesium content and liming effect, which raises soil pH and reduces aluminium toxicity. The combined application of wood ash and poultry manure resulted in the highest magnesium content in the soil, as the addition of organic matter from poultry manure further improved soil structure, cation retention, and nutrient availability. These findings are consistent with Bessho and Bell (1992), Muhrizal *et al*. (2003), and An and Park (2021), who reported that the application of organic amendments and ash materials improves magnesium availability in acidic soils by enhancing soil chemical properties and base cation status.

Table 4.26 Effect of different aluminium-alleviating organic materials on *cation exchange capacity, exchangeable calcium and exchangeable magnesium* of post-harvest acid soil

Treatments	Soil solid-phase properties [cmol (p^+) kg^{-1}]								
	Cation exchange capacity			Exchangeable calcium			Exchangeable magnesium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	10.93	10.97	10.95	1.27	1.27	1.27	0.53	0.57	0.55
T_2: Absolute control	**10.57**	**10.60**	**10.58**	**1.13**	**1.17**	**1.15**	**0.43**	**0.47**	**0.45**
T_3: WA @ 2t ha^{-1}	11.03	11.07	11.05	2.27	2.30	2.28	**0.70**	**0.73**	**0.72**
T_4: PM @ 2t ha^{-1}	12.07	12.10	12.08	**2.33**	**2.37**	**2.35**	0.67	0.70	0.68
T_5: RR @ 2t ha^{-1}	11.40	11.43	11.42	1.43	1.47	1.45	0.60	0.63	0.62
T_6: VC @ 2t ha^{-1}	**12.27**	**12.30**	**12.28**	2.17	2.20	2.18	0.67	0.67	0.67
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	12.83	12.87	12.85	**3.30**	**3.33**	**3.32**	**0.90**	**0.93**	**0.92**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	12.50	12.53	12.52	2.40	2.43	2.42	0.73	0.77	0.75
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**13.27**	**13.30**	**13.28**	2.93	2.97	2.95	**0.87**	**0.90**	**0.88**
T_{10}: SR @ 2t ha^{-1}	12.00	12.03	12.02	1.77	1.80	1.78	0.63	0.63	0.63
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	12.77	12.80	12.78	2.57	2.60	2.58	0.80	0.80	0.80
SEm±	**0.07**	**0.06**	**0.05**	**0.05**	**0.05**	**0.03**	**0.04**	**0.08**	**0.04**
CD at 5%	**0.21**	**0.18**	**0.14**	**0.14**	**0.14**	**0.10**	**0.13**	**0.22**	**0.12**
Initial value	**10.80**	**10.90**	—	**1.30**	**1.40**	—	**0.50**	**0.60**	—

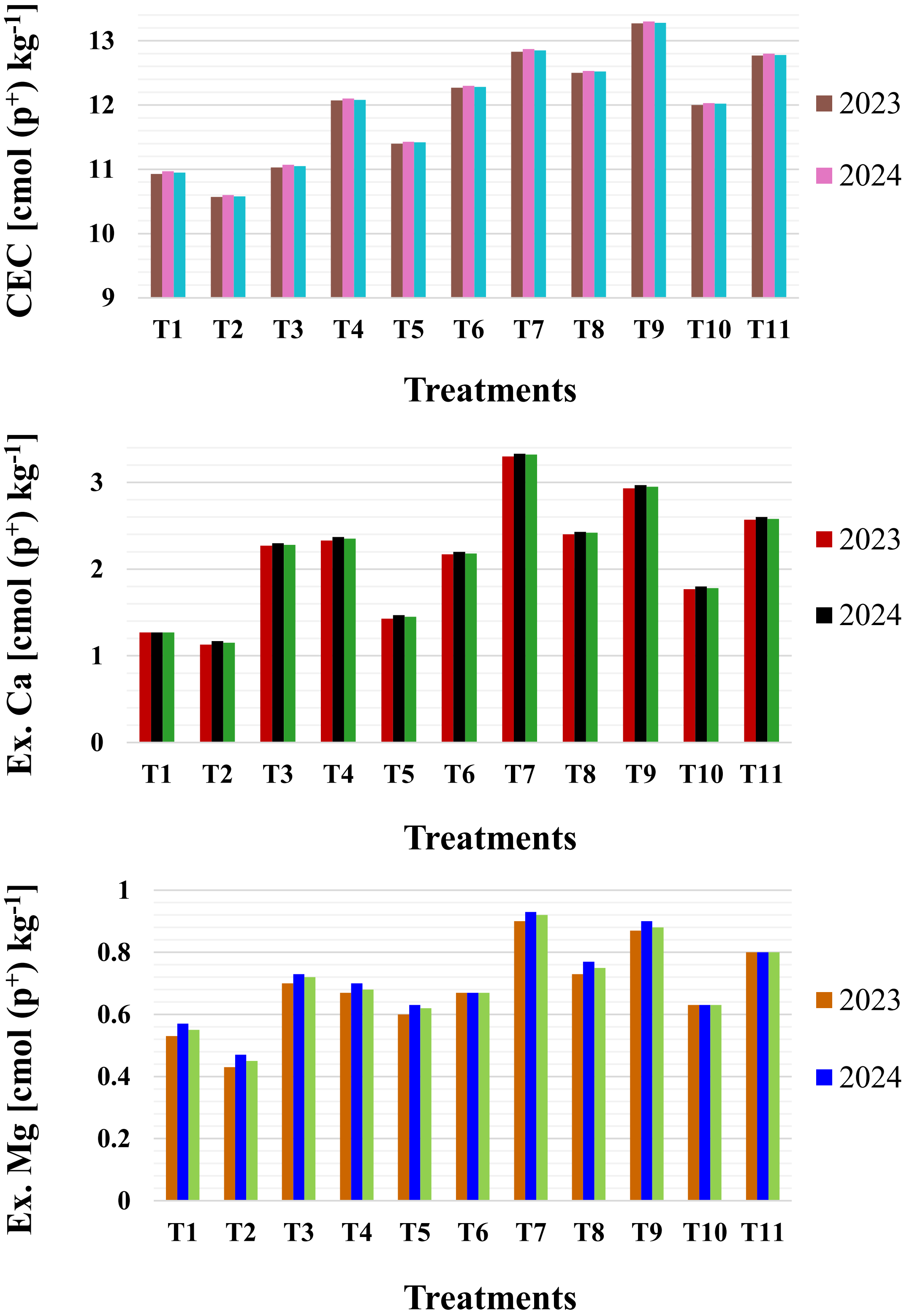

Fig. 4.26 Effect of different aluminium-alleviating organic materials on *cation exchange capacity, exchangeable calcium and exchangeable magnesium* of post-harvest acid soil

4.3.2.7 Exchangeable potassium [cmol (p^+) kg^{-1}]

Data regarding exchangeable potassium as affected by different organic materials are presented in Table 4.27 and graphically illustrated in Fig. 4.27. The treatments exerted a significant effect on exchangeable potassium during both the experimental years (2023 and 2024) as well as in the pooled analysis All organic amendments recorded superior value compared to T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the highest exchangeable potassium (0.30 cmol (p^+) kg^{-1}) under T_7 (wood ash + poultry manure); whereas the lowest exchangeable potassium (0.12 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the highest exchangeable potassium (0.23 cmol (p^+) kg^{-1}).

A comparable trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest exchangeable potassium (0.31 cmol (p^+) kg^{-1}). The lowest exchangeable potassium (0.13 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest exchangeable potassium (0.24 cmol (p^+) kg^{-1}).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the highest exchangeable potassium (0.31 cmol (p^+) kg^{-1}); while the lowest exchangeable potassium (0.13 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest exchangeable potassium (0.24 cmol (p^+) kg^{-1}) was recorded in treatment T_3 (wood ash).

The lowest exchangeable potassium under the control may be attributed to the lack of external potassium inputs and the naturally low availability of potassium in acidic soils. Among the single amendments, wood ash improved potassium availability both directly, by supplying K^+ ions, and indirectly, by increasing soil pH and reducing aluminium toxicity. The combined application of wood ash and poultry manure resulted in the highest exchangeable potassium, as poultry manure contributed organic matter and enhanced nutrient retention, promoting potassium availability. Similar observations were reported by Bessho and Bell (1992), Muhrizal *et al*. (2003), and An and Park (2021), who noted that organic amendments and ash materials increase soil potassium concentration and base cation availability in acidic soils.

4.3.2.8 Exchangeable sodium [cmol (p^+) kg^{-1}]

Data pertaining to exchangeable sodium as influenced by different organic materials are presented in Table 4.27 and graphically illustrated in Fig. 4.27. The effects of different organic materials on the exchangeable sodium during both the trials (2023 and 2024) as well as in the pooled analysis were found to be non-significant.

Table 4.27 Effect of different aluminium-alleviating organic materials on *exchangeable potassium and exchangeable sodium* of post-harvest acid soil

Treatments	Soil solid-phase properties [cmol (p^+) kg^{-1}]					
	Exchangeable potassium			Exchangeable sodium		
	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	0.14	0.14	0.14	0.09	0.09	0.09
T_2: Absolute control	0.12	0.13	0.13	0.08	0.09	0.09
T_3: WA @ 2t ha^{-1}	0.23	0.24	0.24	0.10	0.10	0.10
T_4: PM @ 2t ha^{-1}	0.22	0.22	0.22	0.10	0.10	0.10
T_5: RR @ 2t ha^{-1}	0.16	0.15	0.15	0.09	0.09	0.09
T_6: VC @ 2t ha^{-1}	0.20	0.20	0.20	0.09	0.09	0.09
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	0.30	0.31	0.31	0.11	0.11	0.11
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	0.25	0.25	0.25	0.10	0.10	0.10
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	0.28	0.29	0.29	0.10	0.11	0.10
T_{10}: SR @ 2t ha^{-1}	0.18	0.17	0.18	0.09	0.09	0.09
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	0.26	0.26	0.26	0.09	0.09	0.09
SEm±	**0.00**	**0.00**	**0.00**	**0.01**	**0.01**	**0.00**
CD at 5%	**0.01**	**0.01**	**0.01**	**NS**	**NS**	**NS**
Initial value	**0.13**	**0.13**	**—**	**0.08**	**0.09**	**—**

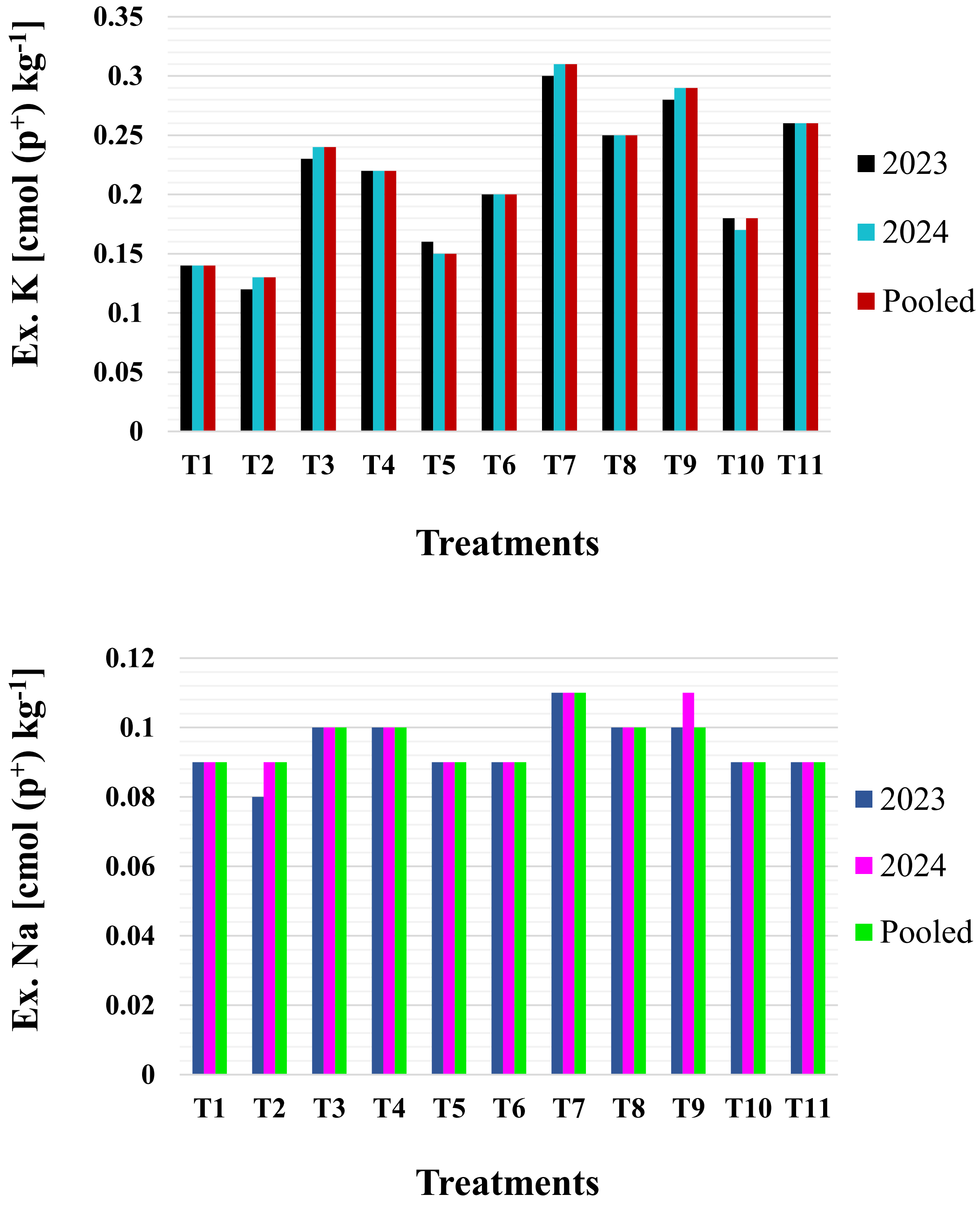

Fig. 4.27 Effect of different aluminium-alleviating organic materials on *exchangeable potassium and exchangeable sodium* of post-harvest acid soil

4.3.2.9 Base saturation (%)

The data related to base saturation as influenced by different organic materials are presented in Table 4.28 and graphically illustrated in Fig. 4.28. The treatments significantly influenced the base saturation during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first trial (2023), the highest base saturation (35.92%) was recorded under T_7 (wood ash + poultry manure); whereas the lowest base saturation (16.83%) was observed under T_2 (absolute control). Among the individual amendments, treatment T_3 (wood ash) exhibited the highest base saturation (29.94%).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest base saturation (36.48%). The lowest base saturation (17.42%) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the highest base saturation (30.48%).

The pooled analysis of the two experimental years (2023 and 2024) also revealed that treatment T_7 (wood ash + poultry manure) recorded the highest base saturation (36.20%); while the lowest base saturation (17.12%) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest base saturation (30.21%) was recorded in treatment T_3 (wood ash). treatment T_6 (vermicompost).

The lowest base saturation under the control may be attributed to the strongly acidic nature of the soil and the absence of amendments supplying basic cations. In untreated acidic soils, the exchange complex is dominated by hydrogen and aluminium ions, resulting in a lower proportion of base-forming cations. Wood ash increased base saturation due to its richness in basic cations, such as calcium, magnesium, and potassium, which replace acidic cations on the soil exchange complex. The combined application of wood ash and poultry manure resulted in the highest base saturation, as poultry manure improved soil fertility, organic matter content, and nutrient retention, further enhancing the proportion of exchangeable base cations. These observations are supported by Bessho and Bell (1992), who also reported that organic amendments can increase base saturation in acidic soils.

Table 4.28 Effect of different aluminium-alleviating organic materials on *base saturation* of post-harvest soil

Treatments	Base saturation (%)		
	2023	2024	Pooled
T_1 : Control	18.53	18.79	18.66
T_2: Absolute control	16.83	17.42	17.12
T_3: WA @ 2t ha^{-1}	29.94	30.48	30.21
T_4: PM @ 2t ha^{-1}	27.47	27.94	27.70
T_5: RR @ 2t ha^{-1}	20.03	20.47	20.25
T_6: VC @ 2t ha^{-1}	25.43	25.64	25.54
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	35.92	36.48	36.20
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	27.81	28.32	28.07
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	31.53	32.03	31.78
T_{10}: SR @ 2t ha^{-1}	22.25	22.44	22.34
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	29.14	29.33	29.23
SEm±	**0.55**	**0.48**	**0.36**
CD at 5%	**1.61**	**1.39**	**1.04**
Initial value	**18.61**	**20.37**	—

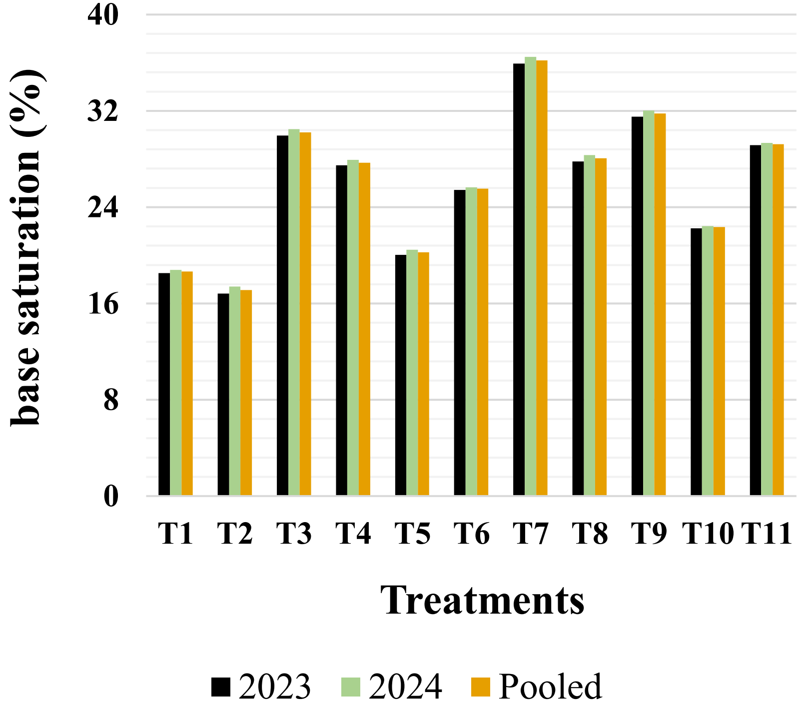

Fig. 4.28 Effect of different aluminium-alleviating organic materials on *base saturation* of post-harvest soil

4.3.2.10 Exchangeable aluminium [cmol (p^+) kg^{-1}]

The influence of different organic materials on exchangeable aluminium in soil as influenced is shown in Table 4.29 and graphically illustrated in Fig. 4.29. A significant variation in exchangeable aluminium was observed during both experimental years (2023 and 2024) and in pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The results of the first trial conducted in 2023 indicated that treatment T_9 (wood ash + vermicompost) obtained the lowest exchangeable aluminium (1.21 cmol (p^+) kg^{-1}), which was statistically at par (1.25 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure); whereas the highest exchangeable aluminium (2.29 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the lowest exchangeable aluminium (1.50 cmol (p^+) kg^{-1}).

A similar trend was observed during the second trial (2024), where T_9 (wood ash + vermicompost) exhibited the lowest exchangeable aluminium (1.17 cmol (p^+) kg^{-1}), which was statistically at par (1.21 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure). The highest exchangeable aluminium (2.21 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest exchangeable aluminium (1.46 cmol (p^+) kg^{-1}).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the lowest exchangeable aluminium (1.19 cmol (p^+) kg^{-1}), which was statistically at par (1.23 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure); while the highest exchangeable aluminium (2.25 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest exchangeable aluminium (1.48 cmol (p^+) kg^{-1}) was recorded in treatment T_3 (wood ash).

The highest exchangeable aluminium was recorded under the absolute control, where strongly acidic soil conditions and the absence of amendments allowed Al^{3+} to remain highly soluble and dominate the cation exchange complex, inhibiting root growth and nutrient uptake. Single application of wood ash reduced exchangeable aluminium by elevating soil pH through its base cation content (Ca^{2+}, Mg^{2+}, K^+), which displaced Al^{3+} from exchange sites and promoted its precipitation as insoluble hydroxide forms (Demeyer *et al*., 2001). The lowest exchangeable aluminium was observed under the combined application of wood ash and vermicompost, reflecting a synergistic effect: wood ash raised soil pH while vermicompost contributed soluble organic compounds that complexed Al^{3+} ions, reducing their availability (Alter and Mitchell, 1992; Thomas, 1975). These results are consistent with Bessho and Bell (1992) and Muhrizal *et al*. (2003), who reported that combined organic and liming amendments more effectively reduce exchangeable aluminium than applied alone, underscoring the value of integrated amendment strategies in managing aluminium toxicity in acidic soils.

4.3.2.11 Exchangeable acidity [cmol (p^+) kg^{-1}]

The data on the exchangeable acidity as influenced by different organic materials are presented in Table 4.29 and graphically illustrated in Fig. 4.29. The treatments significantly influenced the exchangeable acidity during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the lowest exchangeable acidity (1.50 cmol (p^+) kg^{-1}) under T_9 (wood ash + vermicompost), which was statistically at par (1.59 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure); whereas the highest exchangeable acidity (2.96 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the individual amendments, treatment T_3 (wood ash) exhibited the lowest exchangeable acidity (1.96 cmol (p^+) kg^{-1}).

A comparable trend was observed during the second trial (2024), where T_9 (wood ash + vermicompost) exhibited the lowest exchangeable acidity (1.46 cmol (p^+) kg^{-1}), which was statistically at par (1.54 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure). The highest exchangeable acidity (2.88 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest exchangeable acidity (1.88 cmol (p^+) kg^{-1}).

The pooled results of both years (2023 and 2024) found that treatment T_9 (wood ash + vermicompost) recorded the lowest exchangeable acidity (1.48), which was statistically at par (1.57 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure); while the highest exchangeable acidity (2.92 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest exchangeable acidity (1.92 cmol (p^+) kg^{-1}) was recorded in treatment T_3 (wood ash).

The highest exchangeable acidity under the absolute control may be due to the dominance of hydrogen and aluminium ions on the soil exchange complex in untreated acidic soil. Among the single amendments, wood ash resulted in lower exchangeable acidity. The alkaline nature of wood ash neutralizes soil acidity and replaces acidic cations from the exchange complex with basic cations such as Ca^{2+}, Mg^{2+}, and K^+, thereby reducing exchangeable acidity (Demeyer *et al.*, 2001). The lowest exchangeable acidity was recorded under the combined application of wood ash and vermicompost. The combined effect of liming by wood ash and organic matter addition from vermicompost improves soil chemical properties and reduces the concentration of acidic cations in the soil.

4.3.2.12 Exchangeable hydrogen [cmol (p^+) kg^{-1}]

The data pertaining to exchangeable hydrogen as affected by different organic materials are presented in Table 4.29 and graphically illustrated in Fig. 4.29. The treatments significantly influenced the exchangeable hydrogen during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the 2023 trial, treatment T_9 (wood ash + vermicompost) observed the lowest exchangeable hydrogen (0.29 cmol (p^+) kg^{-1}), which was statistically at par (0.34 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure); whereas the highest exchangeable hydrogen (0.67 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the lowest exchangeable hydrogen (0.46 cmol (p^+) kg^{-1}).

A similar pattern was observed during the second trial (2024), where T_9 (wood ash + vermicompost) exhibited the lowest exchangeable hydrogen (0.29 cmol (p^+) kg^{-1}), which was statistically at par (0.33 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure). The highest exchangeable hydrogen (0.67 cmol (p^+) kg^{-1}) was observed

Table 4.29 Effect of different aluminium-alleviating organic materials on *exchangeable aluminium, exchangeable acidity and exchangeable hydrogen* of post-harvest acid soil

Treatments	Soil solid-phase properties [cmol (p^+) kg^{-1}]								
	Exchangeable aluminium			Exchangeable acidity			Exchangeable hydrogen		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	2.08	2.04	2.06	2.71	2.71	2.71	0.63	0.67	0.65
T_2: Absolute control	2.29	2.21	2.25	2.96	2.88	2.92	0.67	0.67	0.67
T_3: WA @ 2t ha^{-1}	1.50	1.46	1.48	1.96	1.88	1.92	0.46	0.42	0.44
T_4: PM @ 2t ha^{-1}	1.55	1.54	1.55	2.09	2.04	2.07	0.54	0.50	0.52
T_5: RR @ 2t ha^{-1}	1.88	1.84	1.86	2.46	2.46	2.46	0.62	0.59	0.61
T_6: VC @ 2t ha^{-1}	1.54	1.50	1.52	2.04	1.96	2.00	0.50	0.46	0.48
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	1.25	1.21	1.23	1.59	1.54	1.57	0.34	0.33	0.34
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	1.46	1.42	1.44	1.84	1.79	1.82	0.38	0.37	0.38
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	1.21	1.17	1.19	1.50	1.46	1.48	0.29	0.29	0.29
T_{10}: SR @ 2t ha^{-1}	1.71	1.71	1.71	2.29	2.29	2.29	0.58	0.58	0.58
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	1.34	1.34	1.34	1.71	1.71	1.71	0.37	0.37	0.37
SEm±	**0.06**	**0.08**	**0.05**	**0.06**	**0.05**	**0.04**	**0.04**	**0.09**	**0.05**
CD at 5%	**0.16**	**0.24**	**0.14**	**0.16**	**0.14**	**0.10**	**0.13**	**0.25**	**0.14**
Initial value	**2.13**	**2.20**	—	**2.75**	**2.63**	—	**0.62**	**0.63**	—

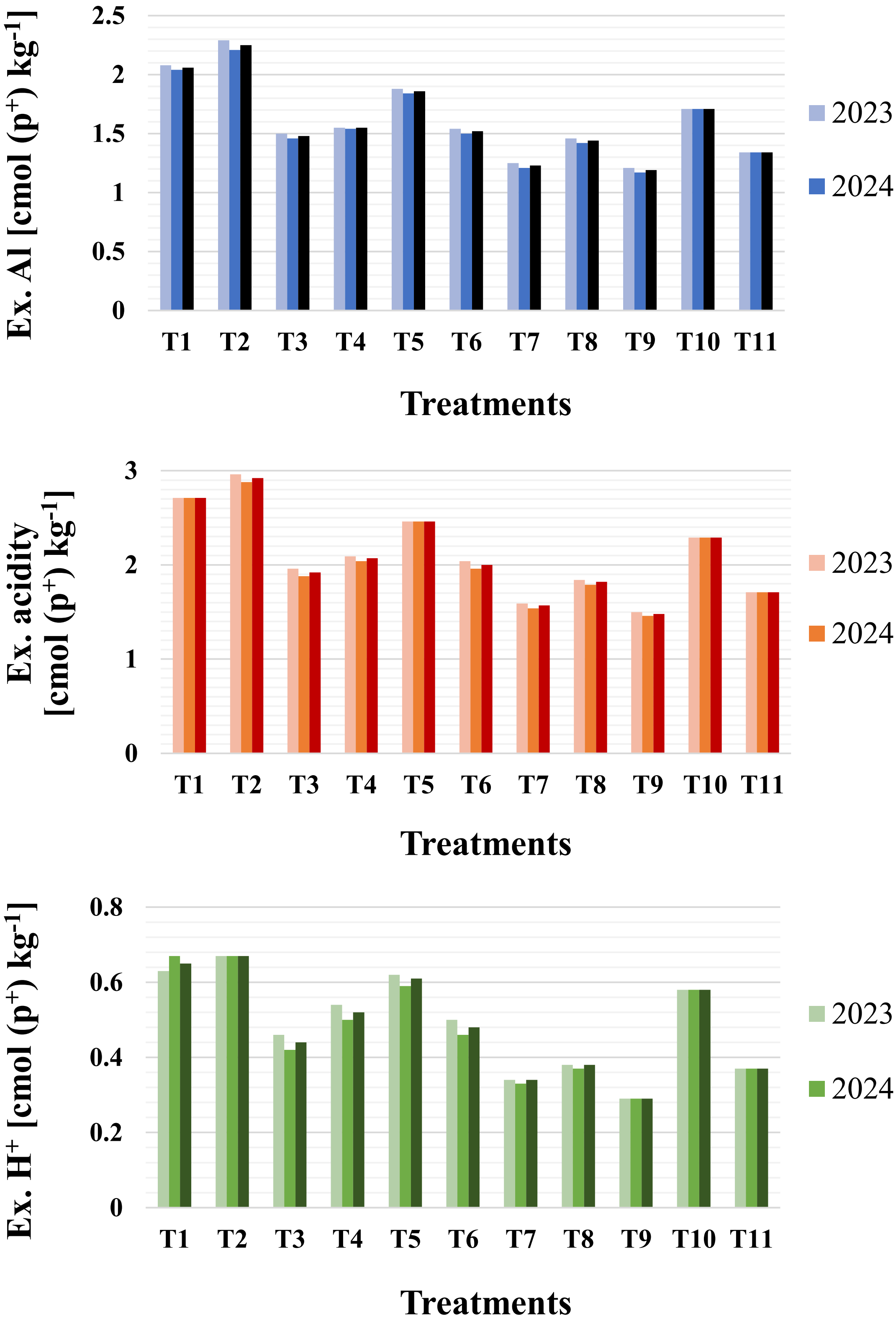

Fig. 4.29 Effect of different aluminium-alleviating organic materials on *exchangeable aluminium, exchangeable acidity and exchangeable hydrogen* of post-harvest acid soil

under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest exchangeable hydrogen (0.42 cmol (p^+) kg^{-1}).

The pooled data of both years (2023 and 2024) revealed that treatment T_9 (wood ash + vermicompost) exhibited the lowest exchangeable hydrogen (0.29 cmol (p^+) kg^{-1}), which was statistically at par (0.34 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure); while the highest exchangeable hydrogen (0.67 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest exchangeable hydrogen (0.44 cmol (p^+) kg^{-1}) was recorded in treatment T_3 (wood ash).

The highest exchangeable hydrogen under the absolute control may be attributed to the strongly acidic soil environment where hydrogen ions dominate the soil exchange complex. Among the single amendments, wood ash reduced exchangeable hydrogen by neutralizing hydrogen ions and supplying basic cations to replace them on the exchange sites. The lowest exchangeable hydrogen was observed under the combined application of wood ash and vermicompost, where soil acidity neutralization and improved organic matter enhanced soil buffering capacity and reduced hydrogen ion dominance on the exchange complex (Demeyer *et al*., 2001; Wong, 1981).

4.3.2.13 Total potential acidity [cmol (p^+) kg^{-1}]

The data on the total potential acidity as influenced by different organic materials are presented in Table 4.30 and graphically illustrated in Fig. 4.30. The treatments significantly influenced the total potential acidity during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the lowest total potential acidity (10.27 cmol (p^+) kg^{-1}) under T_9 (wood ash + vermicompost), which was statistically at par (10.33 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure); whereas the highest total potential acidity (14.80 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the lowest total potential acidity (11.27 cmol (p^+) kg^{-1}).

A similar trend was observed during the second trial (2024), where T_9 (wood ash + vermicompost) exhibited the lowest total potential acidity (10.20 cmol (p^+) kg^{-1}), which was statistically at par (10.27 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure). The highest total potential acidity (14.73 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest total potential acidity (11.20 cmol (p^+) kg^{-1}).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the lowest total potential acidity (10.23 cmol (p^+) kg^{-1}), which was statistically at par (10.30 cmol (p^+) kg^{-1}) with T_7 (wood ash + poultry manure); while the highest total potential acidity (14.77 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest total potential acidity (11.23 cmol (p^+) kg^{-1}) was recorded in treatment T_3 (wood ash).

The highest total potential acidity under the absolute control may be attributed to the strongly acidic nature of the soil and the absence of amendments to neutralize hydrogen and aluminium ions. Among the single amendments, wood ash lowered TPA through its liming effect and supply of base cations (Demeyer *et al*., 2001). The lowest TPA was recorded under the combined application of wood ash and vermicompost. Wood ash increases soil pH and reduces aluminium activity, while vermicompost enhances soil buffering capacity and contributes organic matter, which forms complexes with aluminium and stabilizes soil chemical properties (Wong, 1981).

4.3.2.14 Reserve acidity [cmol (p^+) kg^{-1}]

The data on the reserve acidity as influenced by different organic materials are presented in Table 4.30 and graphically illustrated in Fig. 4.30. The treatments significantly influenced the reserve acidity during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the lowest reserve acidity (8.75 cmol (p^+) kg^{-1}) under T_7 (wood ash + poultry manure), which was statistically at par (8.77 cmol (p^+) kg^{-1}) with T_9 (wood ash + vermicompost); whereas the highest reserve acidity (11.84

cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) exhibited the lowest reserve acidity (9.29 cmol (p^+) kg^{-1}).

The results of the second trial in 2024 also indicated a comparable trend, where T_7 (wood ash + poultry manure) exhibited the lowest reserve acidity (8.72 cmol (p^+) kg^{-1}), which was statistically at par (8.74 cmol (p^+) kg^{-1}) with T_9 (wood ash + vermicompost). The highest reserve acidity (11.86 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the lowest reserve acidity (9.29 cmol (p^+) kg^{-1}).

The pooled results of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) recorded the lowest reserve acidity (8.74 cmol (p^+) kg^{-1}), which was statistically at par (8.75 cmol (p^+) kg^{-1}) with T_9 (wood ash + vermicompost); while the highest reserve acidity (11.85 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the individual amendments, the lowest reserve acidity (9.30 cmol (p^+) kg^{-1}) was recorded in treatment T_6 (vermicompost) and poultry manure respectively.

The highest reserve acidity under the absolute control may be due to the accumulation of acidic cations, particularly aluminium and hydrogen, on the soil exchange complex. Among the single amendments, vermicompost lowered reserve acidity by increasing organic matter content and promoting microbial activity, which can complex Al^{3+} ions (Wong, 1981). The lowest reserve acidity was observed under the combined application of wood ash and poultry manure, where the liming action of wood ash neutralizes acidic cations and poultry manure improves soil chemical balance through organic matter addition, collectively reducing reserve acidity.

4.3.2.15 Effective cation exchange capacity [cmol (p^+) kg^{-1}]

Data regarding effective cation exchange capacity as influenced by different organic materials are presented in Table 4.58 and graphically illustrated in Fig. 4.58. The treatments significantly affected the effective cation exchange capacity during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

During the first trial in 2023, treatment T_7 (wood ash + poultry manure) recorded the highest effective cation exchange capacity (6.20 cmol (p^+) kg^{-1}), whereas the lowest effective cation exchange capacity (4.73 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single amendments, treatment T_4 (poultry manure) exhibited the highest effective cation exchange capacity (5.40 cmol (p^+) kg^{-1}).

A comparable trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the highest effective cation exchange capacity (6.24 cmol (p^+) kg^{-1}). The lowest effective cation exchange capacity (4.72 cmol (p^+) kg^{-1}) was observed under T_2 (absolute control). Among the single applications, treatment T_4 (poultry manure) exhibited the highest effective cation exchange capacity (5.42 cmol (p^+) kg^{-1}).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the highest effective cation exchange capacity (6.22 cmol (p^+) kg^{-1}), while the lowest effective cation exchange capacity (4.73 cmol (p^+) kg^{-1}) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest effective cation exchange capacity (5.41 cmol (p^+) kg^{-1}) was recorded in treatment T_4 (poultry manure).

The lowest effective cation exchange capacity under the absolute control may be attributed to the absence of organic amendments and the low availability of exchangeable base cations in the acidic soil, resulting in a soil exchange complex dominated by acidic cations and reduced nutrient retention. Application of poultry manure increased ECEC by adding organic matter and essential nutrients, which enhanced exchange sites and the soil's capacity to retain cations. The highest ECEC was observed under the combined application of wood ash and poultry manure, as wood ash supplied basic cations (Ca, Mg, K) while poultry manure contributed organic matter. The synergistic effect of these amendments improved soil fertility, nutrient retention, and the soil's ability to supply essential cations. These results are supported by Bessho and Bell (1992), who reported that organic matter treatments increase ECEC through the addition of exchangeable cations and by enhancing soil pH and EC,

Table 4.30 Effect of different aluminium-alleviating organic materials on *total potential acidity, reserve acidity and effective cation exchange capacity (effective CEC)* of post-harvest acid soil

Treatments	Soil solid-phase properties [cmol (p^+) kg^{-1}]								
	Total potential acidity			Reserve acidity			Effective CEC		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	14.33	14.13	14.23	11.62	11.42	11.52	4.74	4.77	4.75
T_2: Absolute control	**14.80**	**14.73**	**14.77**	**11.84**	**11.86**	**11.85**	**4.73**	**4.72**	**4.73**
T_3: WA @ 2t ha^{-1}	**11.27**	**11.20**	**11.23**	9.30	9.32	9.31	5.27	5.25	5.26
T_4: PM @ 2t ha^{-1}	11.40	11.33	11.37	9.31	**9.29**	**9.30**	**5.40**	**5.42**	**5.41**
T_5: RR @ 2t ha^{-1}	13.27	13.27	13.27	10.81	10.81	10.81	4.78	4.76	4.77
T_6: VC @ 2t ha^{-1}	11.33	11.27	11.30	**9.29**	9.31	**9.30**	5.16	5.11	5.14
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	**10.33**	**10.27**	**10.30**	**8.75**	**8.72**	**8.74**	**6.20**	**6.24**	**6.22**
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	11.13	11.07	11.10	9.30	9.27	9.29	5.31	5.34	5.33
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**10.27**	**10.20**	**10.23**	**8.77**	**8.74**	**8.75**	5.68	5.72	5.70
T_{10}: SR @ 2t ha^{-1}	13.13	13.00	13.07	10.84	10.71	10.77	4.96	4.99	4.98
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	10.93	10.87	10.90	9.22	9.16	9.19	5.43	5.46	5.45
SEm±	**0.09**	**0.11**	**0.07**	**0.10**	**0.11**	**0.07**	**0.09**	**0.06**	**0.05**
CD at 5%	**0.25**	**0.33**	**0.20**	**0.30**	**0.32**	**0.21**	**0.26**	**0.18**	**0.15**
Initial value	**14.2**	**14**	—	**11.57**	**11.37**	—	**4.76**	**4.85**	—

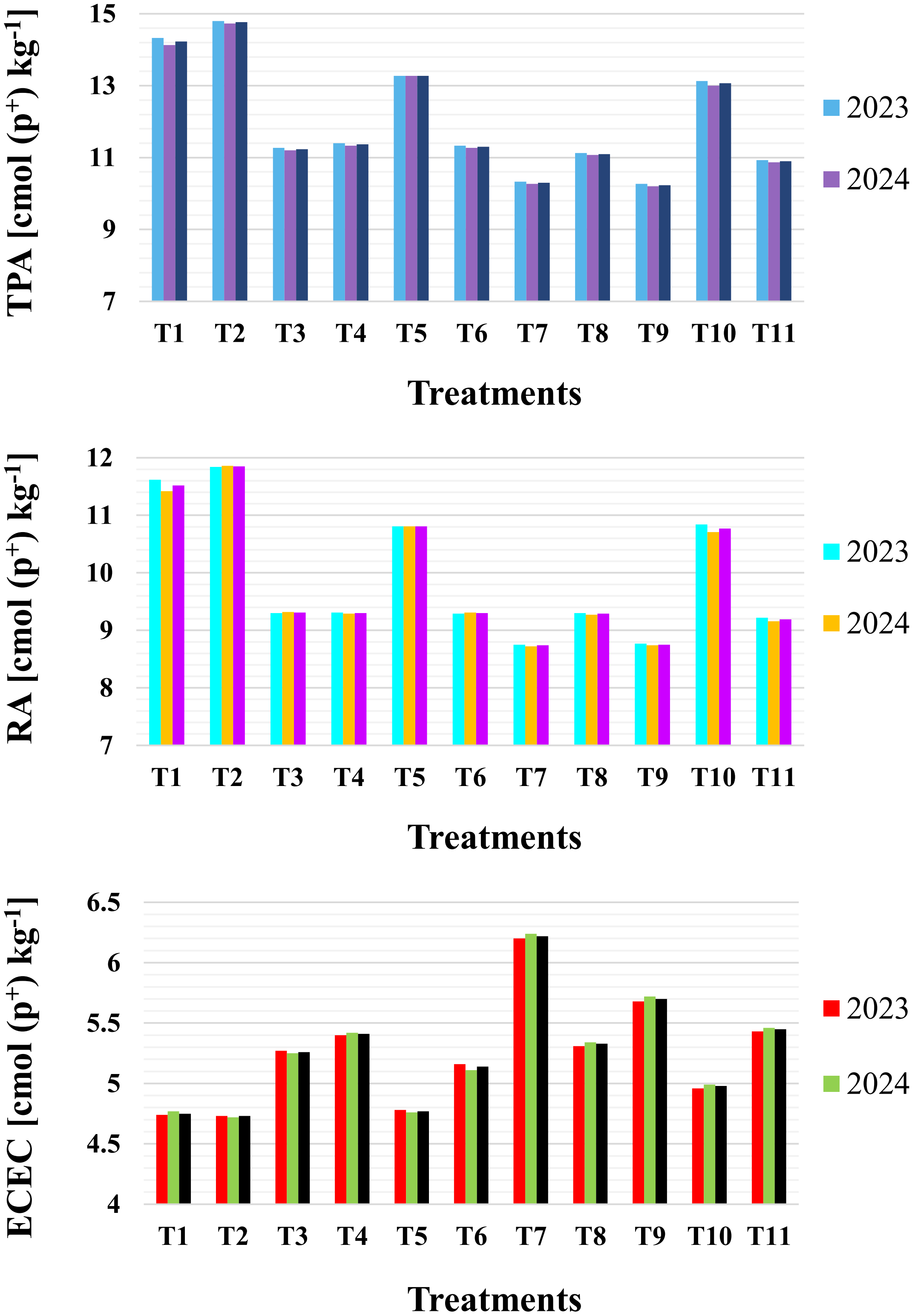

Fig. 4.30 Effect of different aluminium-alleviating organic materials on *total potential acidity (TPA), reserve acidity (RA) and effective cation exchange capacity* (ECEC) of post-harvest acid soil

and by Voundi Nkana *et al*. (1998), who observed that wood ash application increased ECEC, supplied Ca and K, and reduced aluminium toxicity in acidic tropical soils.

4.3.2.16 Aluminium saturation (%)

The data on the aluminium saturation as influenced by various organic materials are presented in Table 4.31 and graphically illustrated in Fig. 4.31. The treatments significantly influenced the aluminium saturation during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the lowest aluminium saturation (20.17%) under T_7 (wood ash + poultry manure), which was statistically at par (21.31%) with T_9 (wood ash + vermicompost); whereas the highest aluminium saturation (48.49%) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the lowest aluminium saturation (28.55%).

A similar trend was observed during the second trial (2024), where T_7 (wood ash + poultry manure) exhibited the lowest aluminium saturation (19.39%), which was statistically at par (20.45%) with T_9 (wood ash + vermicompost). The highest aluminium saturation (46.74%) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest aluminium saturation (27.81%).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_7 (wood ash + poultry manure) exhibited the lowest aluminium saturation (19.78%), which was statistically at par (20.88%) with T_9 (wood ash + vermicompost); while the highest aluminium saturation (47.62%) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest aluminium saturation (28.18%) was recorded in treatment T_3 (wood ash). vermicompost).

The highest aluminium saturation under the absolute control may be attributed to the strongly acidic soil conditions where aluminium dominates the soil exchange complex in the absence of amendments. Under such conditions, a greater proportion of exchange sites are occupied by Al^{3+} ions, resulting in higher aluminium saturation.

Table 4.31 Effect of different aluminium-alleviating organic materials on *aluminium saturation* of post-harvest acid soil

Treatments	Aluminium saturation (%)		
	2023	2024	Pooled
T_1 : Control	43.95	42.95	43.45
T_2: Absolute control	48.49	46.74	47.62
T_3: WA @ 2t ha^{-1}	28.55	27.81	28.18
T_4: PM @ 2t ha^{-1}	28.63	28.45	28.54
T_5: RR @ 2t ha^{-1}	39.21	38.90	39.06
T_6: VC @ 2t ha^{-1}	29.88	29.38	29.63
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	20.17	19.39	19.78
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	27.54	26.58	27.06
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	21.31	20.45	20.88
T_{10}: SR @ 2t ha^{-1}	34.47	34.24	34.36
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	24.61	24.47	24.54
SEm±	1.00	1.65	0.97
CD at 5%	2.94	4.85	2.75
Initial value	44.7	41.2	—

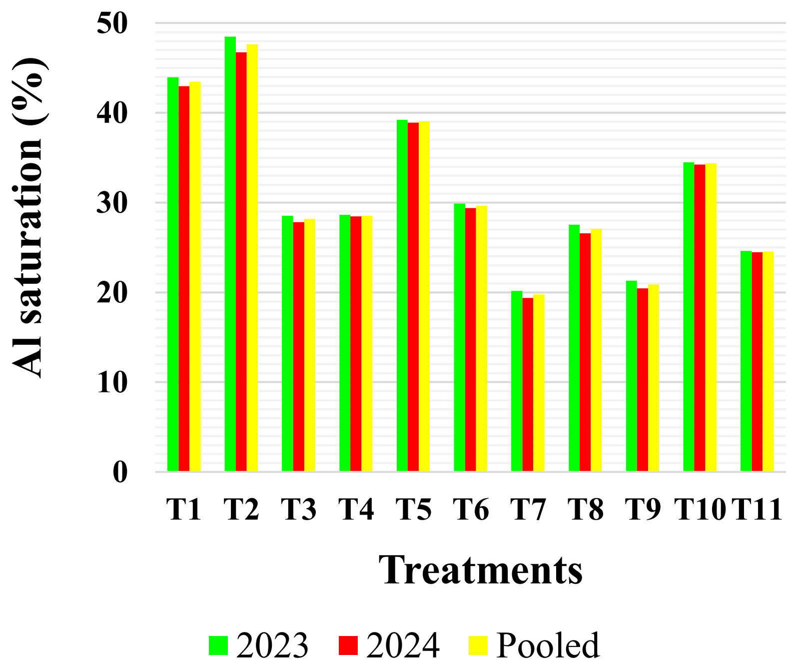

Fig. 4.31 Effect of different aluminium-alleviating organic materials on *aluminium saturation* of post-harvest acid soil

Among the single amendments, wood ash reduced aluminium saturation due to its liming effect and the supply of base cations such as Ca, Mg and K, which replace aluminium on the exchange sites and increase soil pH. The lowest aluminium saturation was observed under the combined application of wood ash and poultry manure, which may be attributed to the neutralization of soil acidity by wood ash along with the addition of organic matter from poultry manure that improves soil buffering capacity and enhances the retention of base-forming cations. Similar trends were reported by Bessho and Bell (1992), who observed that the addition of organic materials and lime increased soil pH and effective cation exchange capacity while markedly decreasing exchangeable aluminium and aluminium saturation in acid soils. Likewise, Muhrizal *et al*. (2003) reported that the incorporation of organic materials such as green manure, rice straw and poultry-based amendments significantly increased soil pH and exchangeable Ca and Mg while reducing exchangeable aluminium and aluminium saturation, thereby improving the chemical environment of acidic soils.

4.3.2.17 Forms of aluminium

The following sections demonstrate the effect and significance of different Al-alleviating organic materials, applied under different treatments, on different forms of aluminium, namely exchangeable aluminium (mg/kg), organic bound aluminium (mg/kg), amorphous aluminium (mg/kg), cumulative amorphous and crystalline aluminium (mg/kg), and crystalline aluminium (mg/kg).

4.3.2.17.1 Exchangeable aluminium (mg/kg)

Exchangeable aluminium (KCl extractable Al) in soil as influenced by various organic materials are presented in Table 4.32 and graphically illustrated in Fig. 4.32. The treatments significantly influenced the exchangeable aluminium during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The findings of the first trial conducted in 2023 revealed that treatment T_9 (wood ash + vermicompost) resulted in the lowest exchangeable aluminium (92.20 mg/kg) under, which was statistically at par (94.73 mg/kg) with T_7 (wood ash + poultry manure); whereas the highest exchangeable aluminium (159.25 mg/kg) was observed under T_2 (absolute control). Among the individual amendments, treatment T_3 (wood ash) exhibited the lowest exchangeable aluminium (117.55 mg/kg).

A similar pattern was noticed during the second trial (2024), where T_9 (wood ash + vermicompost) exhibited the lowest exchangeable aluminium (90.93 mg/kg), which was statistically at par (93.47 mg/kg) with T_7 (wood ash + poultry manure). The highest exchangeable aluminium (157.84 mg/kg) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest exchangeable aluminium (116.28 mg/kg).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the lowest exchangeable aluminium (91.57 mg/kg), which was statistically at par (94.10 mg/kg) with T_7 (wood ash + poultry manure); while the highest exchangeable aluminium (158.55 mg/kg) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest exchangeable aluminium (116.92 mg/kg) was recorded in treatment T_3 (wood ash).

The highest exchangeable aluminium under the absolute control may be attributed to the strongly acidic soil conditions where Al^{3+} remains highly soluble and dominates the cation exchange complex in the absence of corrective amendments, inhibiting root growth and nutrient uptake (Thomas, 1975). Among single amendments, wood ash reduced exchangeable aluminium by elevating soil pH through its base cation content (Ca^{2+}, Mg^{2+}, K^{+}), which displaced Al^{3+} from exchange sites and promoted its precipitation as insoluble hydroxide forms (Demeyer *et al*., 2001). The lowest exchangeable aluminium was recorded under the combined application of wood ash and vermicompost, reflecting the synergistic effect of liming and organo-aluminium complexation by vermicompost-derived humic substances (Alter and Mitchell, 1992; Thomas, 1975). This is consistent with Bessho and Bell (1992) and Haynes and Mokolobate (2001), who reported that combined organic and liming amendments more effectively reduce exchangeable Al than either material applied alone, a finding further supported by Haile *et al*. (2025), who recorded up to 88%

reduction in exchangeable acidity under integrated vermicompost and lime application.

4.3.2.17.2 Organic bound aluminium (mg/kg)

Data pertaining to organic bound aluminium (pyrophosphate extractable Al) as influenced by different organic materials are presented in Table 4.32 and graphically illustrated in Fig. 4.32. The treatments significantly affected the organic bound aluminium during both experimental years (2023 and 2024) as well as in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The experimental results from the first trial in 2023 showed that treatment T_9 (wood ash + vermicompost) recorded the highest organic bound aluminium (260.98 mg/kg), whereas the lowest organic bound aluminium (185.27 mg/kg) was observed under T_2 (absolute control). Among the single amendments, treatment T_6 (vermicompost) exhibited the highest organic bound aluminium (225.12 mg/kg).

A similar trend was observed during the second trial (2024), where T_9 (wood ash + vermicompost) exhibited the highest organic bound aluminium (262.31 mg/kg). The lowest organic bound aluminium (186.60 mg/kg) was observed under T_2 (absolute control). Among the single applications, treatment T_6 (vermicompost) exhibited the highest organic bound aluminium (226.45 mg/kg).

The pooled analysis of the experimental data further revealed that treatment T_9 (wood ash + vermicompost) recorded the highest organic bound aluminium (261.65 mg/kg), while the lowest organic bound aluminium (185.94 mg/kg) was obtained under treatment T_2 (absolute control). Among the single amendments, the highest organic bound aluminium (225.79 mg/kg) was recorded in treatment T_6 (vermicompost).

The lowest organic bound aluminium under the absolute control may be attributed to the limited organic matter content of the untreated soil, which restricts the formation of stable Al-organic complexes (Driscoll and Schecher, 1990). Among single amendments, vermicompost produced higher organic bound aluminium by supplying abundant humic and fulvic acids with carboxyl and hydroxyl functional groups capable of complexing Al^{3+} and converting it into stable organic-bound forms (Alter and Mitchell, 1992). The highest organic bound aluminium was observed under the combined application of wood ash and vermicompost, where elevated soil pH from wood ash stabilized Al-organic complexes while vermicompost provided the reactive organic ligands necessary for complexation. This is supported by Haynes and Mokolobate (2001), who demonstrated that increasing organic matter input progressively raises the organic-bound Al fraction through enhanced organo-aluminium complexation in acidic soils.

4.3.2.17.3 Amorphous aluminium (mg/kg)

The data on the amorphous aluminium (acid ammonium oxalate extractable Al) as influenced by different organic materials are presented in Table 4.32 and graphically illustrated in Fig. 4.32. The treatments significantly influenced the amorphous aluminium during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

The first trial in 2023 exhibited the lowest amorphous aluminium (1904.86 mg/kg) under T_9 (wood ash + vermicompost), which was statistically at par (1993.98 mg/kg) with T_7 (wood ash + poultry manure); whereas the highest amorphous aluminium (3420.01 mg/kg) was observed under T_2 (absolute control). Among the single amendments, treatment T_3 (wood ash) exhibited the lowest amorphous aluminium (2395.05 mg/kg).

During the second trial (2024), T_9 (wood ash + vermicompost) exhibited the lowest amorphous aluminium (1882.57 mg/kg). The highest amorphous aluminium (3397.73 mg/kg) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest amorphous aluminium (2372.77 mg/kg).

The pooled analysis of both years (2023 and 2024) indicated that treatment T_9 (wood ash + vermicompost) exhibited the lowest amorphous aluminium (1893.72 mg/kg); while the highest amorphous aluminium (3408.87 mg/kg) was obtained under

Table 4.32 Effect of different aluminium-alleviating organic materials on the *exchangeable aluminium, organic bound aluminium and amorphous aluminium* of post-harvest acid soil

Treatments	Forms of Aluminium (in mg/kg)								
	Exchangeable aluminium			Organic bound aluminium			Amorphous aluminium		
	2023	2024	Pooled	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	152.91	151.77	152.34	197.23	198.55	197.89	3197.19	3174.91	3186.05
T_2: Absolute control	159.25	157.84	158.55	185.27	186.60	185.94	3420.01	3397.73	3408.87
T_3: WA @ 2t ha^{-1}	117.55	116.28	116.92	217.15	219.81	218.48	2395.05	2372.77	2383.91
T_4: PM @ 2t ha^{-1}	122.62	120.09	121.36	223.80	225.12	224.46	2573.31	2551.02	2562.17
T_5: RR @ 2t ha^{-1}	146.71	145.44	146.07	206.53	207.85	207.19	2996.65	2974.37	2985.51
T_6: VC @ 2t ha^{-1}	121.35	120.09	120.72	225.12	226.45	225.79	2506.46	2484.18	2495.32
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	94.73	93.47	94.10	259.66	260.98	260.32	1993.98	1971.70	1982.84
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	109.88	108.65	109.27	231.77	233.09	232.43	2239.08	2216.80	2227.94
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	92.20	90.93	91.57	260.98	262.31	261.65	1904.86	1882.57	1893.72
T_{10}: SR @ 2t ha^{-1}	141.63	140.36	141.00	209.18	210.51	209.85	2929.81	2907.53	2918.67
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	103.61	104.88	104.24	237.07	238.40	237.74	2149.96	2127.68	2138.82
SEm±	1.75	1.22	1.06	1.44	1.92	1.20	30.79	26.02	20.15
CD at 5%	5.12	3.57	3.03	4.23	5.63	3.42	90.29	76.31	57.44
Initial value	149.24	149.24	—	182.62	186.6	—	3197.19	3130.35	—

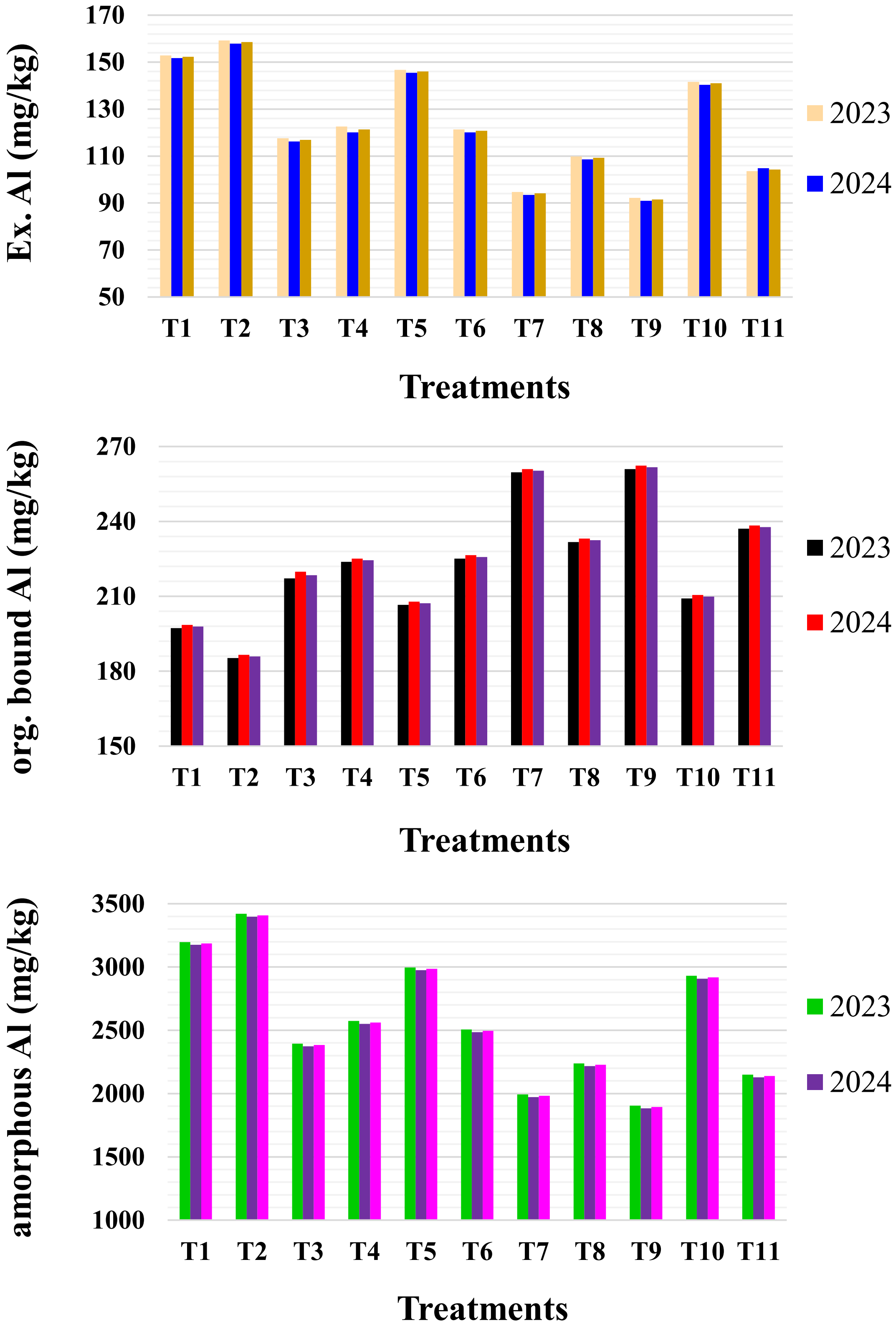

Fig. 4.32 Effect of different aluminium-alleviating organic materials on the *exchangeable aluminium, organic bound aluminium and amorphous aluminium* of post-harvest acid soil

treatment T_2 (absolute control). Among the single amendments, the lowest amorphous aluminium (2383.91 mg/kg) was recorded in treatment T_3 (wood ash).

The highest amorphous aluminium under the absolute control may be attributed to the strongly acidic conditions that maintain Al^{3+} in highly reactive and soluble forms, sustaining a large pool of amorphous Al hydroxides through continuous dissolution of aluminosilicate minerals (Driscoll and Schecher, 1990). Among single amendments, wood ash reduced amorphous aluminium as the increase in soil pH following its application reduces aluminium solubility and promotes the transformation of reactive Al into less soluble forms (Demeyer *et al*., 2001). The lowest amorphous aluminium was recorded under the combined application of wood ash and vermicompost, where the increase in soil pH from wood ash reduced Al solubility while organic compounds from vermicompost further immobilized reactive Al through complexation, collectively reducing the amorphous Al pool (Haynes and Mokolobate, 2001).

4.3.2.17.4 Cumulative Amorphous and Crystalline aluminium (mg/kg)

Data regarding cumulative amorphous and crystalline aluminium (dithionate citrate bicarbonate extractable Al) as influenced by different organic materials are presented in Table 4.33 and graphically illustrated in Fig. 4.33. The treatments significantly influenced the amorphous aluminium during both the trials (2023 and 2024) and in the pooled analysis, with all organic amendments performing better than T_1 (control) and T_2 (absolute control).

In the first trial carried out during 2023, treatment T_9 (wood ash + vermicompost) obtained the lowest cumulative amorphous and crystalline aluminium (3232.15 mg/kg), whereas the highest cumulative amorphous and crystalline aluminium (4707.93 mg/kg) was observed under T_2 (absolute control). Among the individual amendments, treatment T_3 (wood ash) exhibited the lowest cumulative amorphous and crystalline aluminium (3727.02 mg/kg).

A similar tendency was observed during the second trial (2024), where T_9 (wood ash + vermicompost) registered the lowest cumulative amorphous and crystalline aluminium (3223.32 mg/kg). The highest cumulative amorphous and crystalline aluminium (4699.09 mg/kg) was observed under T_2 (absolute control). Among the single applications, treatment T_3 (wood ash) exhibited the lowest cumulative amorphous and crystalline aluminium (3718.19 mg/kg).

The pooled analysis of both years (2023 and 2024) further indicated that treatment T_9 (wood ash + vermicompost) recorded the lowest cumulative amorphous and crystalline aluminium (3227.74 mg/kg); while the highest cumulative amorphous and crystalline aluminium (4703.51 mg/kg) was obtained under treatment T_2 (absolute control). Among the single amendments, the lowest cumulative amorphous and crystalline aluminium (3722.61 mg/kg) was recorded in treatment T_3 (wood ash).

The highest cumulative amorphous and crystalline aluminium under the absolute control may be attributed to the strongly acidic conditions, where the absence of ameliorating amendments sustains continuous mineral dissolution and accumulation of reactive Al species in both amorphous and poorly crystalline forms (Driscoll and Schecher, 1990). Among single amendments, wood ash reduced cumulative aluminium as its alkaline nature elevated soil pH, reducing the solubility of reactive Al and promoting its transformation into more stable, less toxic mineral forms (Demeyer *et al*., 2001). The lowest cumulative amorphous and crystalline aluminium was observed under the combined application of wood ash and vermicompost, where concurrent pH elevation and organic complexation reduced reactive Al pools across multiple fractions. The increase in soil pH reduces Al solubility while organic matter from vermicompost sequesters Al^{3+} ions, together reducing the accumulation of both amorphous and crystalline reactive Al forms in the soil (Haynes and Mokolobate, 2001).

4.3.2.17.5 Crystalline aluminium (mg/kg)

Data pertaining to crystalline aluminium (amorphous aluminium minus dithionate citrate bicarbonate extractable Al) as influenced by different organic materials are presented in Table 4.33 and graphically illustrated in Fig. 4.33. The effects of different organic materials on the crystalline aluminium during both the trials (2023 and 2024) as well as in the pooled analysis were found to be non-significant.

Table 4.33 Effect of different aluminium-alleviating organic materials on the *cumulative amorphous and crystalline aluminium, and crystalline aluminium* of post-harvest acid soil

Treatments	Forms of Aluminium (in mg/kg)					
	Cumulative amorphous and crystalline aluminium			Crystalline aluminium		
	2023	2024	Pooled	2023	2024	Pooled
T_1 : Control	4504.68	4522.36	4513.52	1307.49	1347.45	1327.47
T_2: Absolute control	**4707.93**	**4699.09**	**4703.51**	1287.92	1301.36	1294.64
T_3: WA @ 2t ha^{-1}	**3727.02**	**3718.19**	**3722.61**	1331.97	1345.42	1338.70
T_4: PM @ 2t ha^{-1}	3903.77	3894.93	3899.35	1330.46	1343.90	1337.18
T_5: RR @ 2t ha^{-1}	4266.08	4266.08	4266.08	1269.43	1300.55	1284.99
T_6: VC @ 2t ha^{-1}	3859.58	3841.90	3850.74	1353.12	1357.72	1355.42
T_7: WA @2t ha^{-1} + PM @ 2t ha^{-1}	3302.84	3294.00	3298.42	1308.86	1322.30	1315.58
T_8: WA @ 2t ha^{-1} + RR @ 2t ha^{-1}	3612.14	3603.30	3607.72	1373.06	1386.50	1379.78
T_9: WA @ 2t ha^{-1} + VC @ 2t ha^{-1}	**3232.15**	**3223.32**	**3227.74**	1327.30	1340.74	1334.02
T_{10}: SR @ 2t ha^{-1}	4213.06	4204.23	4208.65	1283.25	1296.70	1289.98
T_{11}: WA @ 2t ha^{-1} + SR @ 2t ha^{-1}	3514.93	3506.09	3510.51	1364.97	1378.42	1371.70
SEm±	**13.84**	**20.29**	**12.28**	**28.27**	**31.27**	**21.08**
CD at 5%	**40.61**	**59.52**	**35.01**	**NS**	**NS**	**NS**
Initial value	**4513.52**	**4487.01**	—	**1316.33**	**1356.66**	—

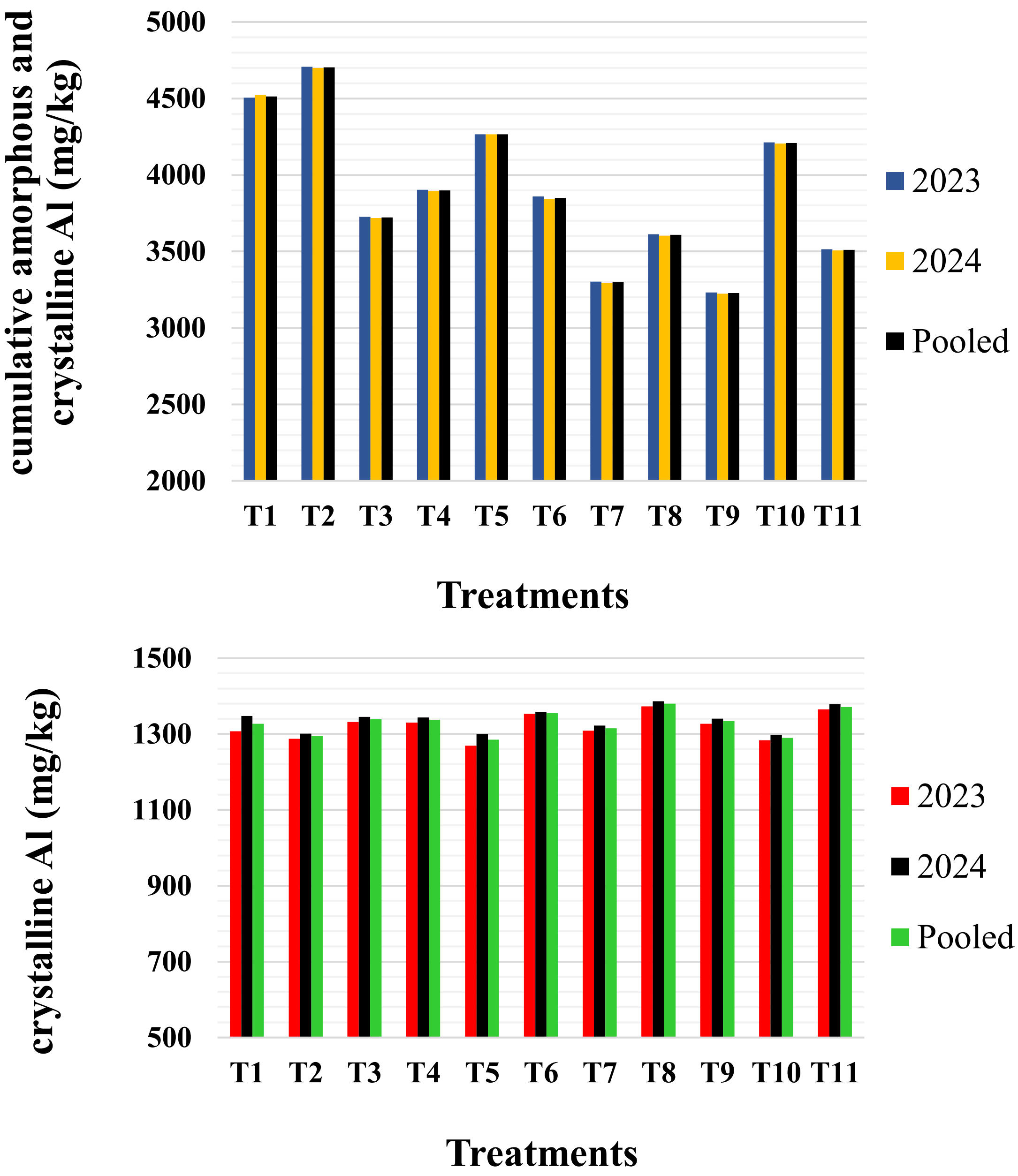

Fig. 4.33 Effect of different aluminium-alleviating organic materials on the *cumulative amorphous and crystalline aluminium, and crystalline aluminium* of post-harvest acid soil

PLATE 8 Overview of lab work

PLATE 8 (contd.) **Overview of lab work**

CHAPTER - V

SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

The presented investigation entitled "**Alleviation of Aluminium toxicity of Mungbean in acid soil of Nagaland using organic materials**" was conducted during the summer seasons of 2023 and 2024 at the Experimental farm of the Department of Soil Science, School of Agricultural Sciences (SAS), Nagaland University, Medziphema campus, Nagaland. The experiment consisted of 11 treatments including RDF (control), absolute control, and different organic amendments such as wood ash, poultry manure, rice residue, vermicompost and soybean residue applied individually as well as in combination with wood ash. The experiment was laid out in a Completely Randomized Design (CRD) with three replications. The main findings of the investigation are summarized below:

5.1 Effect of different aluminium alleviating organic materials on growth and yield of mungbean in acid soil.

The application of different aluminium-alleviating organic materials significantly influenced the growth, root development, yield attributes, seed yield (g/pot), stover yield (g/pot), and harvest index (%) of mungbean in acid soil during both years of experimentation (2023 and 2024) as well as in the pooled analysis.

With respect to growth parameters, plant height (cm), number of branches per plant, and number of leaves per plant recorded at 25 days after sowing (DAS), 50 DAS, and at harvest were significantly superior under organic material treatments compared to the absolute control. The combined application of wood ash + vermicompost (T_9) consistently recorded the highest values for all growth parameters across both years and in the pooled mean. The absolute control (T_2) registered the lowest growth performance, reflecting the severe growth-inhibiting effect of aluminium toxicity in unamended acid soil. Among single amendment treatments, vermicompost (T_6) exhibited the best growth parameters, indicating its effectiveness in alleviating Al stress individually.

Root parameters assessed at 48 hours after sowing, 30 DAS, and at harvest revealed that T_9 produced the longest root length (cm), highest fresh root weight (g), highest dry root weight (g), and the greatest relative root length (%) among all treatments at all stages of observation. The absolute control (T_2) consistently recorded the lowest root growth across all sampling stages, confirming the detrimental effect of Al toxicity on root elongation and development. Among single amendments, wood ash (T_3) promoted maximum root length (cm) and relative root length (%) at early growth stages, while vermicompost (T_6) was most effective in sustaining root development at later stages of crop growth.

Regarding yield attributes, the number of pods per plant, pod length (cm), and number of seeds per pod were all significantly improved by the application of organic amendments. Treatment T_9 recorded the highest values for all yield attributes, while T_2 recorded the lowest, further corroborating the negative impact of unmitigated Al toxicity on reproductive development. Among single amendment treatments, vermicompost (T_6) performed best for yield attributing characters.

In terms of yield, both seed yield (g/pot) and stover yield (g/pot) were maximized under T_9, demonstrating the superiority of the combined wood ash + vermicompost treatment in improving the overall productivity of mungbean in acid soil. Harvest index (%) was highest under T_{11} (wood ash + soybean residue), suggesting a more efficient partitioning of dry matter to economic yield under that treatment. The absolute control (T_2) recorded the lowest seed yield (g/pot), stover yield (g/pot), and harvest index (%). Among single amendments, wood ash (T_3) recorded the highest harvest index (%).

Overall, the results pertaining to growth, root development, yield attributes, and yield clearly established that combined applications of aluminium-alleviating organic materials — particularly wood ash + vermicompost (T_9) — are most effective in overcoming Al-induced toxicity and enhancing the productivity of mungbean in acid soil. Single amendments also conferred moderate but significant improvements in growth and yield over the absolute control, with vermicompost (T_6) being the most promising among individual treatments.

5.2 Effect of different aluminium-alleviating organic materials on nutrient content and uptake of Mungbean in Acid Soil

The application of different aluminium-alleviating organic materials significantly influenced the nutrient content and nutrient uptake in both seed and stover of mungbean during 2023, 2024, and in the pooled analysis.

With regard to nutrient content in seed, the highest nitrogen (%), phosphorus (%), potassium (%), calcium (%), and magnesium (%) contents were recorded under the combined application of wood ash + poultry manure (T_7), which remained statistically at par with wood ash + vermicompost (T_9) for nitrogen content (%) during both years, phosphorus content (%) during 2024, and potassium content (%) during both years of experimentation. The absolute control (T_2) recorded the lowest contents of all major nutrients in seed, reflecting the adverse effect of unmitigated aluminium toxicity on nutrient accumulation in the grain. Among single amendment treatments, poultry manure (T_4) recorded the highest nitrogen (%), phosphorus (%), calcium (%), and magnesium (%) contents in seed, whereas wood ash (T_3) recorded the highest potassium content (%).

Aluminium concentration in seed (mg/kg) was lowest under T_9, which remained statistically at par with T_7, while the absolute control (T_2) recorded the highest aluminium concentration (mg/kg), indicating greater accumulation of toxic Al in plant tissue under unamended acid soil conditions. Among single amendments, wood ash (T_3) was most effective in reducing aluminium concentration (mg/kg) in seed. Protein content (%) in seed followed a trend similar to nitrogen, being highest under T_7, which remained at par with T_9 during both years of study. The absolute control (T_2) recorded the lowest protein content (%), while among single amendment treatments, poultry manure (T_4) recorded the highest protein content (%) in seed.

In respect of nutrient content in stover, nitrogen (%) and phosphorus (%) contents were highest under T_9, whereas potassium content (%) was highest under T_7, which remained statistically at par with T_9. The absolute control (T_2) recorded the lowest values for all nutrients in stover. Among single amendment treatments, vermicompost (T_6) recorded the highest nitrogen (%) and phosphorus (%) contents in stover, while wood ash (T_3) recorded the highest potassium content (%). Calcium (%) and magnesium (%) contents in stover were highest under T_7 and lowest under T_2, and among single amendments, poultry manure (T_4) recorded the highest values for both these nutrients. Aluminium content in stover (mg/kg) was lowest under T_9 and highest under T_2, while among single amendments, wood ash (T_3) recorded the lowest aluminium concentration (mg/kg) in stover. Protein content (%) in stover was highest under T_9, which remained statistically at par with T_7 during 2023, whereas T_2 recorded the lowest values.

Concerning nutrient uptake by seed, the uptake of nitrogen (mg/pot), phosphorus (mg/pot), and potassium (mg/pot) was highest under T_9, with phosphorus uptake (mg/pot) remaining statistically at par with T_7 during both years and in the pooled analysis. The absolute control (T_2) recorded the lowest uptake of all nutrients. Among single amendment treatments, vermicompost (T_6) recorded the highest uptake of nitrogen (mg/pot) and phosphorus (mg/pot), whereas wood ash (T_3) recorded the highest potassium uptake (mg/pot) by seed. Calcium (mg/pot) and magnesium uptake (mg/pot) by seed were highest under T_7, remaining statistically at par with T_9, and lowest under T_2. Among single amendments, wood ash (T_3) recorded the highest uptake of both calcium (mg/pot) and magnesium (mg/pot). Aluminium uptake (mg/pot) in seed was lowest under T_2 and highest under T_6 among single amendment treatments, reflecting differences in dry matter accumulation and tissue Al concentration across treatments.

Nutrient uptake by stover followed a comparable trend to that observed in seed. Uptake of nitrogen (mg/pot), phosphorus (mg/pot), and potassium (mg/pot) by stover was highest under T_9 and lowest under T_2. Among single amendments, vermicompost (T_6) recorded the highest nitrogen (mg/pot) and phosphorus uptake (mg/pot), while wood ash (T_3) recorded the highest potassium uptake (mg/pot) by stover. Uptake of calcium (mg/pot) and magnesium (mg/pot) by stover was highest under T_9 and lowest under T_2, and among single amendment treatments, wood ash (T_3) and poultry manure (T_4) recorded higher calcium (mg/pot) and magnesium uptake (mg/pot), respectively. Aluminium uptake (mg/pot) by stover was lowest under T_2 and highest under T_9, which may be attributed to the substantially greater biomass production under T_9 despite its lower tissue Al concentration (mg/kg).

Overall, the results clearly demonstrated that combined application of aluminium-alleviating organic materials — particularly wood ash + poultry manure (T_7) and wood ash + vermicompost (T_9) — significantly improved nutrient concentration (%) and uptake (mg/pot) in both seed and stover of mungbean while simultaneously reducing aluminium accumulation (mg/kg) in plant tissues under acid soil conditions. Among single amendment treatments, vermicompost (T_6) and poultry manure (T_4) were most effective in improving nitrogen and phosphorus nutrition, while wood ash (T_3) was most efficient in enhancing potassium, calcium, and magnesium status and in reducing Al concentration (mg/kg) in mungbean tissues.

5.3 Effect of different aluminium alleviating organic materials on the soil properties of an acid soil.

The application of different aluminium-alleviating organic materials markedly influenced the chemical properties of acid soil in both the soil solution phase and soil solid phase during 2023, 2024, and in the pooled analysis.

With regard to soil solution properties, soil solution pH was highest under the combined application of wood ash + vermicompost (T_9), which remained statistically at par with wood ash + poultry manure (T_7), while the lowest soil solution pH was recorded under the absolute control (T_2). Among single amendment treatments, wood ash (T_3) recorded the highest soil solution pH. Calcium concentration (ppm) in the soil solution was highest under T_7 and lowest under T_2, whereas among single amendments, poultry manure (T_4) recorded the highest value. Magnesium concentration (ppm) in the soil solution was highest under T_7, which remained statistically at par with T_9, while T_2 recorded the lowest value; among single amendments, wood ash (T_3) recorded the highest magnesium concentration (ppm). Potassium concentration (ppm) in the soil solution was highest under T_7, which remained at par with T_9 during both years of study, whereas T_2 recorded the lowest values; among single amendments, T_3 recorded the highest potassium concentration (ppm).

Monomeric aluminium concentration (ppm) in the soil solution was lowest under T_9, which remained statistically at par with T_7, while the highest concentration was observed under the absolute control (T_2), indicating the most severe Al toxicity in the unamended acid soil. Among single amendment treatments, wood ash (T_3) recorded the lowest monomeric aluminium concentration (ppm). Similarly, total aluminium (ppm) in the soil solution was lowest under T_9 and highest under T_2, whereas among single amendments, vermicompost (T_6) recorded the lowest total aluminium concentration (ppm), reflecting its effectiveness in immobilizing Al through organic complexation.

In respect of soil solid phase properties, soil pH was highest under T_9, which remained statistically at par with T_7 during 2023 and in the pooled analysis, while T_2 recorded the lowest soil pH values. Among single amendment treatments, wood ash (T_3) recorded the highest soil pH. Electrical conductivity (EC, dS/m) was highest under T_7 and lowest under T_2, while among single amendments, wood ash (T_3) recorded the highest EC (dS/m). Cation exchange capacity [CEC, cmol (p^+) kg^{-1}] and soil organic carbon (OC, %) were both highest under T_9, with organic carbon (%) remaining statistically at par with T_7 during both years, while T_2 recorded the lowest values for both parameters. Among single amendments, vermicompost (T_6) recorded the highest CEC [cmol (p^+) kg^{-1}] and organic carbon content (%), attributable to its high humified organic matter contribution to the soil.

Exchangeable calcium [cmol (p^+) kg^{-1}], magnesium [cmol (p^+) kg^{-1}], and potassium [cmol (p^+) kg^{-1}] were highest under T_7, with exchangeable magnesium remaining statistically at par with T_9, whereas T_2 recorded the lowest exchangeable base cation values. Among single amendment treatments, wood ash (T_3) recorded the highest exchangeable base cations. Exchangeable sodium [cmol (p^+) kg^{-1}] was non-significant across all treatments. Base saturation (%) was highest under T_7 and lowest under T_2, while among single amendments, wood ash (T_3) recorded the highest base saturation (%), reflecting its greater capacity to supply basic cations to the soil exchange complex.

Acidity-related soil parameters were markedly reduced with the application of organic amendments. Exchangeable aluminium [cmol (p^+) kg^{-1}], exchangeable acidity [cmol (p^+) kg^{-1}], and exchangeable hydrogen [cmol (p^+) kg^{-1}] were all lowest under T_9, which remained statistically at par with T_7, while the highest values for all acidity parameters were recorded under the absolute control (T_2). Among single amendment treatments, wood ash (T_3) recorded the lowest values for exchangeable aluminium [cmol (p^+) kg^{-1}], exchangeable acidity [cmol (p^+) kg^{-1}], and exchangeable hydrogen [cmol (p^+) kg^{-1}]. Total potential acidity [TPA, cmol (p^+) kg^{-1}] followed a similar trend, being lowest under T_9 and highest under T_2, with wood ash (T_3) recording the lowest value among single amendments. Reserve acidity [cmol (p^+) kg^{-1}] was lowest under T_7, which remained statistically at par with T_9, and highest under T_2, whereas among single amendments, vermicompost (T_6) recorded the lowest reserve acidity [cmol (p^+) kg^{-1}]. Effective cation exchange capacity [ECEC, cmol (p^+) kg^{-1}] was highest under T_7 and lowest under T_2, while among single amendments, poultry manure (T_4) recorded the highest ECEC [cmol (p^+) kg^{-1}]. Aluminium saturation (%) was lowest under T_7, which remained at par with T_9, and highest under T_2, whereas among single amendments, wood ash (T_3) recorded the lowest aluminium saturation (%), further confirming its liming effect in raising soil pH and precipitating Al ions.

With respect to the different forms of aluminium in soil, exchangeable aluminium (KCl extractable Al, mg/kg) was lowest under T_9, which remained statistically at par with T_7, and highest under T_2, while among single amendments, wood ash (T_3) recorded the lowest exchangeable aluminium (mg/kg). Organic-bound aluminium (pyrophosphate extractable Al, mg/kg) was highest under T_9 and lowest under T_2, indicating that the organic amendments promoted greater complexation and immobilization of Al in organic-bound fractions, thereby reducing its bioavailability. Among single amendment treatments, vermicompost (T_6) recorded the highest organic-bound aluminium (mg/kg). Amorphous aluminium (acid ammonium oxalate extractable Al, mg/kg) and cumulative amorphous and crystalline aluminium (dithionite-citrate-bicarbonate extractable Al, mg/kg) were lowest under T_9 and highest under T_2, whereas among single amendments, wood ash (T_3) recorded the lowest values. Crystalline aluminium (mg/kg) remained non-significant across all treatments.

Overall, the results clearly established that the combined application of aluminium-alleviating organic materials — particularly wood ash + vermicompost (T_9) and wood ash + poultry manure (T_7) — effectively improved the chemical properties of acid soil by increasing soil pH, soil organic carbon (%), cation exchange capacity [cmol (p^+) kg^{-1}], and exchangeable base cations [cmol (p^+) kg^{-1}], while simultaneously and substantially reducing aluminium toxicity, exchangeable acidity [cmol (p^+) kg^{-1}], and total potential acidity [cmol (p^+) kg^{-1}]. Among single amendment treatments, wood ash (T_3) was most effective in ameliorating soil acidity and reducing Al toxicity, while vermicompost (T_6) was most prominent in improving soil organic carbon (%) and CEC [cmol (p^+) kg^{-1}] under acid soil conditions.

CONCLUSION

Based on the findings of the present investigation conducted during 2023 and 2024, the following conclusions are drawn:

The application of different organic materials showed significant potential for alleviating aluminium toxicity in acid soil. The combined application of wood ash + vermicompost (T_9) was the most effective in reducing Al availability, promoting Al immobilization, and improving soil conditions. Among single amendments, wood ash (T_3) was most effective in correcting soil acidity and reducing Al toxicity.

The combined application of wood ash + vermicompost (T_9) significantly improved growth, root development, yield attributes, seed yield and stover yield of mungbean grown in acid soil, whereas wood ash + soybean residue (T_{11}) recorded the highest harvest index. Among single amendments, vermicompost (T_6) was the most promising for improving growth and yield.

Organic amendments enhanced nutrient concentration and uptake and reduced aluminium accumulation in mungbean tissues. Wood ash + poultry manure (T_7) was most effective in improving nutrient concentration, whereas wood ash + vermicompost (T_9) resulted in higher nutrient uptake by seed and stover. Among single amendments, poultry manure (T_4) improved nutrient content, while vermicompost (T_6) enhanced nutrient uptake.

The application of organic amendments improved soil properties by increasing soil pH, organic carbon, CEC, exchangeable bases, base saturation and ECEC, while reducing soil acidity and toxic aluminium forms. The combined application of wood ash + vermicompost (T_9) was most effective in reducing exchangeable, amorphous and cumulative aluminium fractions and increasing organic-bound aluminium, indicating Al immobilization and reduced bioavailability. T_9 also reduced exchangeable acidity, total potential acidity, monomeric Al and total Al in soil solution. Wood ash + poultry manure (T_7) was superior in improving exchangeable bases, base saturation and ECEC. Among single amendments, wood ash (T_3) was most effective in reducing soil acidity and Al toxicity, whereas vermicompost (T_6) improved organic carbon and CEC.

Overall, the combined application of wood ash + vermicompost (T_9) is recommended as an effective, eco-friendly and sustainable strategy for ameliorating aluminium toxicity and improving mungbean productivity in acid soils of Nagaland. Further studies under field conditions are suggested to evaluate the long-term residual effects of these organic amendments and their integration with lime or mineral fertilizers for sustainable acid soil management.

REFERENCES

REFERENCES

Abraham, A. 1984. Release of soluble aluminium in soils under submerged conditions and its effect on rice. Ph.D. (Ag.) Thesis, Kerala Agricultural University, Thrissur, India, 189 p.

Adams, F. 1981. Nutritional imbalances and constraints to plant growth on acid soils. *Journal of Plant Nutrition*. **4**: 81–87.

Adeleke, K. A. and Akinrinde, E. A. 2011. Use of organic-based amendments to ameliorate aluminium toxicity in legume production on a typic paleudalf of South-Western Nigeria. *Journal of Agronomy*. **10**(2): 56-61.

Agegnehu, G., Nelson, P.N. and Bird, M.I. (2016). The effects of biochar, compost and manure on soil fertility and crop productivity: A review. *Agriculture, Ecosystems & Environment*. **222**: 118–134.

Agriculture Canada. 1984. Analytical Methods Manual (B. H. Sheldrick, ed.). Land Resource Institute, Ottawa, ON, LLRI Contribution: 84–90.

Ahmad, F. and Tan, K. H.1986. Effects lime and organic matter on soybean seeding grown in aluminium toxic soil. *Soil Science Society of America Journal.* **50**: 656-661.

Akinmutimi, A. L. and Ukonu, A. 2020. Comparative effects of wood ash and poultry manure on soil pH and potassium release from an acid Ultisol in Umudike, Abia State, Nigeria. *Current Investigations in Agriculture and Current Research* 8(2): Article 000283.

Alter, D. and Mitchell, A. 1992. Use of vermicompost extract as an aluminium inhibitor in aqueous solutions. *Communications in Soil Science and Plant Analysis*. 23: 231–240.

Alva, A. K., Blamey, F. P. C., Edwards, D. G. and Asher, C. J. 1986. An evaluation of aluminium indices to predict aluminium toxicity to plants grown in nutrient solutions. *Communications in Soil Science and Plant Analysis*. **17**(12): 1271-1280.

An J. Y. and Park, B. B. 2021. Effects of wood ash and N fertilization on soil chemical properties and growth of *Zelkova serrata* across soil types. *Scientific Reports*. **11**: 14489.

Asghar, M. and Kanehiro, Y. 1980. Effects of sugarcane trash and pineapple residue on soil pH, redox potential, extractable Al, Fe and Mn. *Tropical Agriculture*. **57**: 245–258.

Bandyopadhyay, S., Ray, P., Padua, S., Ramachandran, S., Jena, R. K., Deb Roy, P., Dutta, D. P., Baruah, U., Sah, K. D., Singh, S. K., Nayak, D. C. and Ray, S. K.

2018. Forms of acidity in soils developed on different landforms along an altitudinal sequence in Nagaland, India. *Journal of the Indian Society of Soil Science*. **66**(2): 125–135.

Bankoti, P., Paarthiban, K. and Nautiyal, M. (2021). Performance of summer mung bean (*Vigna radiata* L.) at different organic sources of nutrients. *International Journal of Current Microbiology and Applied Sciences*. **10**(3): 8-13.

Bartlett, R. J. and Riego, D. C. 1972. Effect of chelation on the toxicity of aluminium. *Plant Soil.* **37**: 419-423.

Baruah, T. C. and Barthakur, H. P. 1997. A textbook of soil analysis. Vikas Publishing House Pvt. Ltd., New Delhi.

Behera, R. D., Pattanayak, S. and Mohanty, P. 2016. Incubation study of calcium silicate as an acid soil amendment with and without FYM. *Advances in Life Sciences*. **5**(1): 139–143.

Bekele, A., Kibret, K., Bedadi, B., Yli-Halla, M. and Balemi, T. 2018. Effects of lime, vermicompost and chemical P fertilizer on selected properties of acid soils of Ebantu District, Western Highlands of Ethiopia. *Applied and Environmental Soil Science*. **2018**(1): 8178305.

Berek, A. K., Radjagukguk, B. and Maas, A. 1995. The effect of different organic materials on the alleviation of Al toxicity in soybean on a red-yellow podzolic soil. In *Plant-soil interactions at low pH: Principles and Management* (pp. 579-584). Springer, Dordrecht.

Bessho, T. and Bell, L. C. 1992. Soil solid and solution phase changes and mung bean response during amelioration of aluminium toxicity with organic matter. *Plant and Soil*. **140**(2): 183-196.

Bhanupriya, P., Meena, R. S., Singh, S. P., Singh, A., Kumar, S., and Gurjar, D. S. 2020. Effect of integrated nutrient management on mungbean (Vigna radiata) under custard apple based agri-horti system in Vindhyan region of Uttar Pradesh. *Indian Journal of Agricultural Sciences.* **90**.

Black, C. A. 1965. Methods of soil analysis. American Society of Agronomy, Inc, Publisher, Madison, Wisconsin, USA. pp.171-175.

Blamey, F. P. C., Edwards, D. G. and Asher, C. J. 1983. Effects of aluminium, OH:Al and P:Al molar ratios, and ionic strength on soybean root elongation in solution culture. *Soil Science*. **136**: 197–207.

Bloom, P. R., McBride, M. B. and Weaver, R. M. 1979. Aluminium organic matter in acid soils: buffering and solution aluminium activity. *Soil Science Society of America Journal*. **43**(3): 488-493.

Bougnom, B. P., Mair, J., Etoa, F. X. and Insam, H. 2009. Composts with wood ash addition: A risk or a chance for ameliorating acid tropical soils? *Geoderma*. **153**(3–4): 402–407.

Brogan, J. C. 1967. The effect of humic acid on aluminium toxicity. Transaction International Congress Soil Science, 7th. **3**: 227-234.

Bruce, R. C., Warrell, L. A., Edwards, D. G. and Bell, L. C. 1988. Effects of aluminium and calcium in the soil solution of acid soils on root elongation of Glycine max cv. Forrest. *Australian Journal of Agricultural Research*. **39**(3): 319-338.

Cabrera, F. and Talibudeen, O. 1977. Effect of soil pH and organic matter on labile aluminium in soils under permanent grass. *Journal of Soil Science.* **28**: 259-270.

Canada Soil Survey Committee, Subcommittee on Methods of Analysis. 1978. Manual on soil sampling and methods of analysis. In J. A. McKeague, ed. Canadian Society of Soil Science, Ottawa, Canada: 98–106.

Canellas, L. P., Olivares, F. L., Okorokova-Façanha, A. and Façanha, A. R. 2002. Humic acids isolated from earthworm compost enhance root elongation, lateral root emergence, and plasma membrane H^+-ATPase activity in maize roots. *Plant Physiology*. **130**: 1951–1957.

Chapman, H. D. and Pratt, P. F. 1961. Methods of Analysis for Soils, Plants and Water. University of California, Agriculture Division, California, USA.

Chapman, H. D. 1965. Cation exchange capacity by ammonium saturation. *American Journal of Agronomy.* **9**: 891- 901.

Chen and He. 1985. Chemical distinction of oxide mineral in soil colloids. In : Methods for soil colloid research (in Chinese, Hseung, Y. *et al*., eds.). Science press, Beijing. 241-303.

Ching, H. Y., Ahmed, O. H. and Majid, N. M. A. 2014. Improving phosphorus availability in an acid soil using organic amendments produced from agroindustrial wastes. *The Scientific World Journal*. Pp 1–6.

Choudhary, H. R., Sharma, O. P., Singh, R. K., Singh, K., Kumar, R. and Yadav, L. 2013. Influence of organic manures and chemical fertilizer on nutrient uptake, yield and profitability of mungbean (Vigna radiata L. Wilczek). *Madras Agricultural Journal*. **100**: 339–341.

Clapham, W. M. and Zibilske, L. M. 1992. Wood ash as a liming amendment. *Communications in Soil Science and Plant Analysis*. **23**: 1209–1227.

Cochran, W. G. and Cox, G. M. 1957. *Experimental Designs*. Asia Publishing House, New Delhi.

Das, S. and Ganesan, M. 2022. Aluminium induced malate transporter (ALMT1) is regulating the aluminium stress tolerance responses of mungbean seedlings. *Plant Gene*. **32**: 100388.

Demeyer, A., Voundi Nkana, J. C. and Verloo, M. G. 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: an overview. *Bioresource Technology*. **77**: 287–295.

Driscoll, C. T. and Schecher, W. D. 1990. The chemistry of aluminium in the environment. *Environmental Geochemistry and Health*. **12**: 28–49.

Evans, C. E. and Kamprath, E. T. 1970. Lime responses as related to percent Al saturation, solution Al and organic matter content. *Soil Science Society of America Proceedings.* **34**: 893-896.

Ezung, N. K., Yanthan, M. B., Rajkhowa, D. J. and Jamir, T. (2020). Performance of mungbean as influenced by organic practice and plant geometry on growth, yield and economics under NEH region of India. Journal of Food Legumes, **33**(1), 36–40.

Fageria, N.K., Baligar, V.C. and Jones, C.A. 2002. Growth and Mineral Nutrition of Field Crops (3rd ed.). Marcel Dekker Inc., New York, USA.

Foy, C. D. 1988. Plant adaptation to acid, aluminium-toxic soils. *Communication in Soil Science and Plant Analysis.* **19**: 959-987.

Gill, K. S., Malhi, S. S. and Lupwayi, N. Z. 2015. Wood ash improved soil properties and crop yield for nine years and saved fertilizer. *Journal of Agricultural Science*. **7**(12): 1–13.

Ginting, S., Johnson, B. B. and Wilkens, S. 1998. Alleviation of aluminium phytotoxicity on soybean growth by organic anions in nutrient solutions. *Functional Plant Biology*. **25**(8): 901-908.

Gupta, P. K. 1999. Soil, Plant, Water and Fertilizer Analysis. Agrobios (India), Jodhpur, India

Haile, T. T., Tilahun, A., Tulu, T. and Mekonen, T. 2025. Effects of lime and vermicompost application on soil physicochemical properties and phosphorus availability in acidic soils. *Scientific Reports*. **15**: 24671.

Harper, S. M., Edwards, D. G., Kerven, G. L. and Asher, C. J .1995. Effects of organic acid fractions extracted from *Eucalyptus camaldulensis* leaves on root elongation of maize (*Zea mays*) in the presence and absence of aluminium. *Plant Soil*. **171**: 189-192.

Haynes, R. J. 1984. Lime and phosphate in the soil–plant system. *Advances in Agronomy*. **37**: 249–315.

Haynes, R. J. and Naidu, R. 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems*. **51**(1): 123–137.

Haynes, R. J. and Mokolobate, M. S. 2001. Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. *Nutrient Cycling in Agroecosystems*. **59**(1): 47-63.

Hester, J. B. 1935. The amphoteric nature of three Coastal Plain soils. I. In relation to plant growth. *Soil Science.* **39**: 237-243.

Hoyt, P. B. and Turner, R. C. 1975. Effects of organic materials added to very acid soils on pH, aluminium, exchangeable NH_4 and crop yields. *Soil Science.* **119**: 227-237.

Huang, J. W., Grunes, D. L. and Kochian, L. V. 1992. Aluminium effects on the kinetics of calcium uptake into cells of the wheat root apex. *Planta.* **188**: 414-421.

Hue, N. V., Craddock, G. R. and Adams, F. 1986. Effect of organic acids on aluminium toxicity in subsoils. *Soil Science Society of America Journal*. **50**: 28–34.

Hue, N. V. and Amien, I. 1989. Aluminium detoxification with green manures. *Communications in Soil Science and Plant Analysis*. **20**(15-16): 1499-1511.

Hue N.V. 1992. Correcting soil acidity if lightly weathered ultisol with chicken manure and sewage sludge. *Communications in Soil Science Plant Analysis.* **23**: 241-264.

Hue, N. V. and Licudine, D. L. 1999. Amelioration of subsoil acidity through surface application of organic manures. *American Society of Agronomy, Crop Science Society of America and Soil Science Society of America*. **2**: 623–632.

IBSRAM, 1989. Soil Management and small holder development in the pacific islands. Thailand IBSRAM proceeding No 8.

Islam, M. A., Islam, S., Akter, A., Rahman, M. H. and Nandwani, D. 2021. Effect of organic amendments on soil acidity and nutrient availability: A review. *Journal of Soil Science and Plant Nutrition*. **21**: 254–268.

Iyamuremye, F., Dick, R. P. and Baham, J. 1996. Organic amendments and phosphorus dynamics: 1. Phosphorus chemistry and sorption. *Soil Science.* **161**: 426-435.

Jackson, M. L. 1973. Soil chemical analysis. Prentice Hall of India Pvt. Ltd., New Delhi, India.

Jaiswal, S. K., Naamala, J. and Dakora, F. D. 2018. Nature and mechanisms of aluminium toxicity, tolerance and amelioration in symbiotic legumes and rhizobia. *Biology and Fertility of Soils*. **54**(3): 309-318.

Jalal, F., Akhtar, K., Saeed, S., Said, F., Khan, Z. H., Hussain, S., Imtiaz, M., Khan, M. A., Liu, K., Harrison, M. T., Saud, S., Hassan, S., El-Kahtany, K. and Fahad, S. 2024. Biochar as sustainable input for nodulation, yield and quality of mung bean. *Journal of Umm Al-Qura University for Applied Sciences*. **10**: 510–517.

Joshi, N., Joshi, S., Singh, S., Sharma, J. K., Shekhawat, H. S. and Sutaliya, R. 2022. Impact of organic nutrient management practices on growth and yield of mungbean. *International Journal of Bio-Resource and Stress Management*. **13**.

Judge, A. 2001. The effects of surface-applied poultry manure on top and subsoil acidity and selected soil fertility characteristics. M.Sc. (Ag.) Thesis, University of Natal, Pietermaritzburg, South Africa, 113 p.

Kerven, G. L., Edwards, D. G., Asher, C. J., Hallman, P. S. and Kokot, S. 1989. Aluminium determination in soil solution. II. Short-term colorimetric procedures for the measurement of inorganic monomeric aluminium in the presence of organic acid ligands. Australian Journal of Soil Research. **27**: 91–102.

Kidanemariam, W., Agegnehu, G. and Molla, E. 2020. The ameliorative effects of lime and vermicompost on yield and yield components of barley (*Hordeum vulgare* L.) and soil properties in acidic soil of northwestern Ethiopia. *International Journal of Plant and Soil Science*. **37**(2): 318–334.

Kochian, L. V.1995. Cellular mechanism of aluminium toxicity and resistance on plant. Ann. Rev. *Plant Physiology and Plant Molecular Biology.* **46**: 237-260.

Kochian, L.V., Hoekenga, O.A. and Piñeros, M.A. 2004. How do crop plants tolerate acid soils? Mechanisms of aluminium tolerance and phosphorus efficiency. *Annual Review of Plant Biology*. **55** (1): 459–493.

Kretzschmar, R. M., Hafner, H., Bationo, A. and Marschner, H. 1991. Long- and short-term effects of crop residues on aluminium toxicity, phosphorus availability and growth of pearl millet in an acid sandy soil. *Plant and Soil*. **136**: 215–223.

Kumari, M. S. S. and Kumari, K. U. 2002. Effect of vermicompost enriched with rock phosphate on growth and yield of cowpea. *Journal of the Indian Society of Soil Science*. **50**(2): 223–224.

Kumawat, N. 2006. Effect of organic manures, PSB and phosphorus fertilization on growth, yield and quality of mungbean (*Vigna radiata* L. Wilczek). M.Sc. (Ag.) Thesis, Rajasthan Agricultural University, Bikaner, India.

Lauricella, D., Butterly, C. R., Clark, G. J., Sale, P. W., Li, G. and Tang, C. 2020. Effectiveness of innovative organic amendments in acid soils depends on their ability to supply P and alleviate Al and Mn toxicity in plants. *Journal of Soils and Sediments*. **20**: 3951–3962.

Liu, J. and Hue, N. V. 2001. Amending subsoil acidity by surface applications of gypsum, lime and composts. *Communications in Soil Science and Plant Analysis*. **32**(14): 2117–2132.

Liu, J., Khan, S., Hu, Y., Yin, L. and Huang, J. 2023. Physiological mechanisms of exogenous organic acids to alleviate aluminium toxicity in seedlings of mungbean, buckwheat, and rice. *Plant Physiology and Biochemistry*. **203**: 108031.

Lungu, O. I., Temba, J., Chirwa, B. and Lungu C. 1993. Effects of lime and farmyard manure on soil acidity and maize growth on an acid Alfisol from Zambia. *Tropical Agriculture.* **70**: 309-314.

Mattson and Hester. 1933. The laws of colloidal behavior: XII. The amphoteric nature of soils in relation to aluminium toxicity. *Soil Science.* **36**:229-244.

Mortenson, J. L. 1963. Complexing of metals by soil organic matter. *Soil Science Society of America Proceedings*. **27**:179-186.

Mugwira, L. M. 1980. Growth and Ca, Mg, K and P uptake by triticale, wheat and rye at four Al levels. *Journal of Plant Nutrition.* **2**: 591-606.

Muhrizal, S., Shamshuddin, J. M. H. A., Husni, M. H. A. and Fauziah, I. 2003. Alleviation of aluminium toxicity in an acid sulfate soil in Malaysia using organic materials. *Communications in Soil Science and Plant Analysis*. **34**(19-20): 2993-3011.

Naramabuye, F. X. and Haynes, R. J. 2006. Effect of organic amendments on soil pH and Al solubility and use of laboratory indices to predict their liming effect. *Soil Science*. **171**(10): 754–763.

Naramabuye, F. X. and Haynes, R. J. 2007. The liming effect of five organic manures when incubated with an acid soil. *Journal of Plant Nutrition and Soil Science*. **170**: 615–622.

Neogy, M., Datta, J., Roy, A.K. and Mukherji, S. 2002. Studies on phytotoxic effect of aluminium on growth and some morphological parameters of *Vigna radiata* L. Wilczek. *Journal of Environmental Biology*. **23**(4): 411–416.

Netwal, L. C. 2003. Effect of FYM and vermicompost on nutrient uptake and quality of cowpea (*Vigna unguiculata* L. Walp.) grown under saline condition. M.Sc. (Ag.) Thesis, Rajasthan Agricultural University, Bikaner, India.

Nkana, J. C. V., Demeyer, A. and Verloo, M. G. 1998. Chemical effects of wood ash on plant growth in tropical acid soils. *Bioresource Technology*. **63(**3): 251–260.

Noble, A. D., Zenneck, I. and Randall, P. J. 1996. Leaf litter ash alkalinity and neutralisation of soil acidity. *Plant Soil*. **179**: 293-302.

Ohno, T. and Erich, M. S. 1990. Effect of wood ash application on soil pH and soil test nutrient levels. *Agriculture, Ecosystems & Environment*. **32**: 223–239.

Olubode, A. A., Soretire, A. and Adeyemi, N. O. 2018. Influence of organic manure and wood ash on the abundance of soil microorganisms, organic carbon and grain yield of soybean (*Glycine max* L. Merrill) in acid soil. *Journal of Agricultural Science and Environment*. **18**(1): 1–9.

Oluwaseun, J. A. and Akinrinde, E. A. 2013. Ameliorating Aluminium toxicity in soybean production with combinations of fertilizer materials on an alfisol in southwestern Nigeria. In *Joint Proceedings of the 27th Soil Science Society of East Africa and the 6th African Soil Science Society Conference*.

Oluwatoyinbo, F. I., Akande M. O. and Adediran, J. A. 2005. Response of okra (*Abelmoschus esculentus*) to lime and phosphorus fertilization in acid soil. *World Journal of Agricultural Sciences.* **1**: 178-183.

Otieno, F. A. and Zingore, S. 2018. Effect of farmyard manure and lime on nutrient uptake and yield of legumes in acid soils. *Soil Use and Management*. **34**(1): 50–60.

Page, A. L., Miller, R. H. and Keeney, D. R. 1982. Methods of soil analysis. Part 2. 2nd Ed. Agronomy No. 9. American Society of Agronomy/Soil Science Society of America, Madison, Wisconsin, USA.

Panda, A., Jha, P., Kumar, A. and Bajpai, R. K. 2017**.** Impact of organic residues application as a soil amendment on response in soil acidity. *International Journal of Chemical Studies*. **5**(1): 105–109.

Paramisparam, P., Ahmed, O. H., Omar, L., Ch'ng, H. Y., Johan, P. D. and Hamidi, N. H. 2021. Co-application of charcoal and wood ash to improve potassium availability in tropical mineral acid soils. *Agronomy* **11**(10): 2081.

Pavan, M. A. and Bingham, F. T. 1982. Toxicity of aluminium to coffee seedlings grown in nutrient solutions. *Soil Science Society of America Journal*. **46**: 993–997.

Pavan, M. A. 1983. The relationship of non-exchangeable, exchangeable and soluble Al with pH, CEC, Al saturation percentage and organic matter in acid soils of Parana State, Brazil. *Revista Brasileira de Ciencia do Solo*. **7**: 39–46.

Qin, R. J. and Chen, F. X. 1998. The effect of organic matter on high active aluminium of soil. *Chinese Journal of Soil Science*. **29**: 111–112.

Qin, R. and Chen, F. 2005. Amelioration of aluminium toxicity in red soil through use of barnyard and green manure. *Communications in Soil Science and Plant Analysis*. **36**(13-14): 1875-1889.

Raghawendra, S. and Kedar, P. 2008. Effect of vermicompost, rhizobium and DAP on growth, yield and nutrient uptake by chickpea. *Journal of Food Legumes*. **21**(2): 112–114.

Rahman, M. A., Lee, S. H., Ji, H. C., Kabir, A. H., Jones, C. S. and Lee, K. W. 2018. Importance of mineral nutrition for mitigating aluminium toxicity in plants on acidic soils: current status and opportunities. *International Journal of Molecular Sciences*. **19**: 3073.

Rambuatsaiha, T., Gohain, T. and Kikon, N. 2017. Optimization of organic nutrient sources for green gram (Vigna radiata L. Welczek) under rainfed conditions. Indian Journal of Agricultural Research. **51**(5): 443–447.

Ramesh, P., Singh, M., Panwar, N. R., Singh, A. B. and Ramana, S. 2006. Response of pigeonpea (*Cajanus cajan*) varieties to organic manures and their influence on fertility and enzyme activity of soil. *Indian Journal of Agricultural Sciences*. **76**(4): 252–254.

R'bia, O., Horchani, F., Smida, I., Mejri, M. and Aschi-Smiti, S. 2011. Aluminium phytotoxicity and plant acclimation to acidic soils. *International Journal of Agricultural Research.* **6**: 194-208.

Richards, L. A. 1954. Diagnosis and improvement of saline soil and alkali soils. Handbook No. 60, United States Department of Agriculture.

Ritchie, G. S. P. 1989. The chemical behavior of aluminium, hydrogen and manganese in acid soils. In: *Soil Acidity and Plant Growth*, ed. A. D. Robson, Academic Press, Sydney, pp. 1–60.

Rout, G., Samantaray, S. and Das, P. 2001. Aluminium toxicity in plants: a review. *Agronomie*. **21**(1): 3-21.

Ryan, P. R., Ditomaso, J. M. and Kochian, L. V. 1993. Aluminium toxicity in roots: an investigation of spatial sensitivity and the role of the root cap. *Journal of Experimental Botany*. **44**(2): 437–446.

Senkiw, K. A. 2004. Alkaline humic substances and the amelioration of an acid sulphate soil and copper-contaminated mine tailings. *M.Sc. (Ag.) Thesis*, University of Manitoba, Winnipeg, Manitoba, Canada. 132 p.

Shamshuddin, J., Muhrizal, S., Fauziah, I. and Husni, M. H. A. 2004. Effects of adding organic materials to an acid sulfate soil on the growth of cocoa (*Theobroma cacao* L.) seedlings. *Science of the Total Environment*. **323**(1–3): 33–45.

Shen, Z. G. and Shen, Q. R. 2001. Effects of organic materials on the alleviation of aluminium toxicity in acid red soil. *Plant and Soil*. **230**: 195–202.

Stevenson, F. J. and Vance, G. F. 1989. Naturally occurring aluminium – organic complexes. In: Sposito G (ed) The Environmental Chemistry of Aluminium, pp 117-146. CRC Press, Boca Raton.

Sufardi, S., Yakob, R. B., Khalil, M., Arabia, T. and Khairullah, K. 2024. Amelioration's effects on soil chemical properties in maize cultivation in dryland Aceh, Indonesia. *Indian Journal of Agricultural Research* 58: 835–841.

Sultana, B. S., Mian, M. H., Jahiruddin, M., Rahman, M. M., Siddique, M. N. E. A. and Sultana, J. 2019. Amendment of acidic soil with lime and manure for enhancing fertility, nutrient uptake and yield of wheat–mungbean–monsoon rice in the Old Himalayan Piedmont Plain. *Asian Journal of Soil Science and Plant Nutrition*. **4**(2): 1–26.

Suthipradit, S., Edwards, D. G. and Asher, C. J. 1990. Effects of aluminium on tap-root elongation of soybean (*Glycine max*), cowpea (*Vigna unguiculata)* and green gram (*Vigna radiata*) grown in the presence of organic acids. *Plant Soil.* **124**: 233-237.

Tang, C., Nuruzzaman, M., Rengel, Z. and McGowan, B. 2007. The effect of poultry litter and feedlot manure on soil aluminium availability and growth of wheat in an acid soil. *Soil Research*. **45**: 342–350.

Terefe, Z., Feyisa, T., Molla, E. and Ejigu, W. 2024. Effects of vermicompost and lime on acidic soil properties and malt barley (*Hordeum distichum* L.) productivity in Mecha district, northwest Ethiopia. *PLOS ONE*. **19**(12): e0311914.

Thomas, G. 1975. The relationship between organic matter and exchangeable aluminium in acid soil. *Soil Science Society of America Proceedings*. **39**: 591.

Vasanthi, D. and Subramanian, S. 2004. Effect of vermicompost on nutrient uptake and protein content in blackgram. *Legume Research*. **27**(4): 293–295.

Vieira, F. C. B., He, Z. L., Wilson, C. and Bayer, C. 2008. Transformation of aluminium in an acidic sandy soil amended with organic composts. *Communications in Soil Science and Plant Analysis*. **39**: 139–155.

Vieira, F. C. B., He, Z. L., Wilson, C. and Bayer, C. 2009**.** Speciation of aluminium in solution of an acidic sandy soil amended with organic composts. *Communications in Soil Science and Plant Analysis*. **40**(13–14): 2094–2110.

Wahab, A. and Lugo-López, M. A. 1980. An approach to minimize Al toxicity in Ultisols through organic matter additions. *The Journal of Agriculture of the University of Puerto Rico*. **64**(1): 1–8.

Walkley, A. J. and Black, I. A. 1934. Estimation of soil organic carbon by the chromic acid titration method. Soil Science. **37**: 29–38.

Wang, S., Ren, X., Huang, B., Wang, G., Zhou, P. and An, Y. 2016. Aluminium-induced reduction of plant growth in alfalfa (Medicago sativa) is mediated by interrupting auxin transport and accumulation in roots. *Scientific Reports* **6**: 30079.

Whalen, J. K., Chang, C., Clayton, G. W. and Carefoot, J. P. 2000. Cattle manure amendments can increase the pH of acid soils. *Soil Science Society of America Journal*. **64**(3): 962–966.

Wild, A .1988. Soil acidity and alkalinity. In: Wild A (ed) Russell's Soil Conditions and Plant Growth, pp 844-889. Longman, Harlow.

Wong, M. T. F. 1981. The humic acids and amino acids of mushroom compost. M.Sc. Dissertation, University of Reading, Reading, United Kingdom, 167 p.

Wong, M. T. F. and Swift, R. S. 1995. Amelioration of aluminium phytotoxicity with organic matter. In *Plant-soil interactions at low pH: Principles and Management*. 41-45.

Wright, R. J., Hern, J. L., Baligar, V. C. and Bennett, O. L. 1985. The effect of surface applied soil amendments on barley root growth in an acid subsoil. *Communications in Soil Science and Plant Analysis*. **16**(2): 179–192.

Wright, R. J. 1989. Soil aluminium toxicity and plant growth. *Communications in Soil Science and Plant Analysis.* **20**: 1479-1497.

Yadav, O.S. 2001. Effect of nitrogen sources and biofertilizer on growth and quality of cowpea. M.Sc. (Ag.) Thesis, RAU, Bikaner.

Yadav, R. K., Saini, Y., Meena, B. S., Kumar, R., Yadav, V. K. and Bijarnia, A. 2024. Influence of organic sources of nutrient on mungbean performance in south-eastern Rajasthan. *Indian Journal of Agronomy*. **69**(4).

Zhang, H., He, C. and Zhang, X. 2023**.** Mechanism of Al toxicity alleviation in acidic red soil by rice-straw hydrochar application and comparison with pyrochar. *Science of the Total Environment*. **877**: 162849.

Zheng, S. J. 2010. Crop production on acidic soils: overcoming aluminium toxicity and phosphorus deficiency. *Annals of Botany*. **106**(1): 183–184.

APPENDICES

Appendix I: Effect of different aluminium-alleviating organic materials on *plant height (cm)* of mungbean in acid soil, at *25DAS.*

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	169.07	16.91	347.31	2.30	***S***
	Error	22	1.07	0.05			
	Total	32	170.14				
ANOVA TABLE **2024**	Treatment	10	173.66	17.37	75.02	2.30	***S***
	Error	22	5.09	0.23			
	Total	32	178.75				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.19	0.19	1.35	4.06	***NS***
	Treatment (T)	12	342.22	28.52	203.60	1.98	***S***
	Y x T	12	0.50	0.04	0.30	1.98	***NS***
	Error	44	6.16	0.14			
	Total	69	349.08				

Appendix II: Effect of different aluminium-alleviating organic materials on *plant height (cm)* of mungbean in acid soil, at *50DAS.*

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	680.53	68.05	105.84	2.30	***S***
	Error	22	14.15	0.64			
	Total	32	694.67				
ANOVA TABLE **2024**	Treatment	10	709.68	70.97	163.77	2.30	***S***
	Error	22	9.53	0.43			
	Total	32	719.21				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.65	0.65	1.21	4.06	***NS***
	Treatment (T)	12	1388.19	115.68	214.95	1.98	***S***
	Y x T	12	2.02	0.17	0.31	1.98	***NS***
	Error	44	23.68	0.54			
	Total	69	1414.54				

Appendix III: Effect of different aluminium-alleviating organic materials on *plant height (cm)* of mungbean in acid soil, at *Harvest.*

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	998.06	99.81	382.04	2.30	***S***
	Error	22	5.75	0.26			
	Total	32	1003.81				
ANOVA TABLE **2024**	Treatment	10	1029.83	102.98	124.40	2.30	***S***
	Error	22	18.21	0.83			
	Total	32	1048.04				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.27	0.27	0.49	4.06	***NS***
	Treatment (T)	12	2027.18	168.93	310.23	1.98	***S***
	Y x T	12	0.71	0.06	0.11	1.98	***NS***
	Error	44	23.96	0.54			
	Total	69	2052.12				

Appendix IV: Effect of different aluminium-alleviating organic materials on *number of branches per plant* of mungbean in acid soil, at *25DAS.*

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	1.26	0.13	1.12	2.30	***NS***
	Error	22	2.47	0.11			
	Total	32	3.73				
ANOVA TABLE **2024**	Treatment	10	1.23	0.12	1.46	2.30	***NS***
	Error	22	1.86	0.08			
	Total	32	3.09				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.01	4.06	***NS***
	Treatment (T)	12	2.25	0.19	1.91	1.98	***NS***
	Y x T	12	0.24	0.02	0.20	1.98	***NS***
	Error	44	4.33	0.10			
	Total	69	6.82				

Appendix V: Effect of different aluminium-alleviating organic materials on *number of branches per plant* of mungbean in acid soil, at *50DAS.*

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	11.91	1.19	19.65	2.30	***S***
	Error	22	1.33	0.06			
	Total	32	13.24				
ANOVA TABLE **2024**	Treatment	10	12.48	1.25	8.83	2.30	***S***
	Error	22	3.11	0.14			
	Total	32	15.59				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.06	0.06	0.60	4.06	***NS***
	Treatment (T)	12	24.34	2.03	20.09	1.98	***S***
	Y x T	12	0.05	0.00	0.04	1.98	***NS***
	Error	44	4.44	0.10			
	Total	69	28.89				

Appendix VI: Effect of different aluminium-alleviating organic materials on *number of branches per plant* of mungbean in acid soil, at *Harvest.*

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	10.38	1.04	9.28	2.30	***S***
	Error	22	2.46	0.11			
	Total	32	12.84				
ANOVA TABLE **2024**	Treatment	10	10.66	1.07	10.46	2.30	***S***
	Error	22	2.24	0.10			
	Total	32	12.90				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.11	0.11	1.00	4.06	***NS***
	Treatment (T)	12	21.00	1.75	16.37	1.98	***S***
	Y x T	12	0.04	0.00	0.03	1.98	***NS***
	Error	44	4.70	0.11			
	Total	69	25.85				

Appendix VII: Effect of different aluminium-alleviating organic materials on *number of leaves per plant* of mungbean in acid soil, at *25DAS*

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	16.22	1.62	25.46	2.30	***S***
	Error	22	1.40	0.06			
	Total	32	17.62				
ANOVA TABLE **2024**	Treatment	10	16.44	1.64	35.19	2.30	***S***
	Error	22	1.03	0.05			
	Total	32	17.46				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.04	0.04	0.77	4.06	***NS***
	Treatment (T)	12	32.61	2.72	49.22	1.98	***S***
	Y x T	12	0.05	0.00	0.07	1.98	***NS***
	Error	44	2.43	0.06			
	Total	69	35.13				

Appendix VIII: Effect of different aluminium-alleviating organic materials on *number of leaves per plant* of mungbean in acid soil, at *50DAS*

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	49.56	4.96	70.28	2.30	***S***
	Error	22	1.55	0.07			
	Total	32	51.11				
ANOVA TABLE **2024**	Treatment	10	49.85	4.99	54.96	2.30	***S***
	Error	22	2.00	0.09			
	Total	32	51.85				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.17	0.17	2.12	4.06	***NS***
	Treatment (T)	12	99.39	8.28	102.75	1.98	***S***
	Y x T	12	0.02	0.00	0.02	1.98	***NS***
	Error	44	3.55	0.08			
	Total	69	103.13				

Appendix IX: Effect of different aluminium-alleviating organic materials on *number of leaves per plant* of mungbean in acid soil, at *Harvest*

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	40.45	4.05	42.71	2.30	***S***
	Error	22	2.08	0.09			
	Total	32	42.54				
ANOVA TABLE **2024**	Treatment	10	41.77	4.18	31.91	2.30	***S***
	Error	22	2.88	0.13			
	Total	32	44.65				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.06	0.06	0.54	4.06	***NS***
	Treatment (T)	12	82.10	6.84	60.64	1.98	***S***
	Y x T	12	0.13	0.01	0.09	1.98	***NS***
	Error	44	4.96	0.11			
	Total	69	87.25				

Appendix X: Effect of different aluminium-alleviating organic materials on *number of pods per plant* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	176.63	17.66	93.64	2.30	***S***
	Error	22	4.15	0.19			
	Total	32	180.78				
ANOVA TABLE **2024**	Treatment	10	177.00	17.70	64.10	2.30	***S***
	Error	22	6.07	0.28			
	Total	32	183.07				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.01	0.01	0.03	4.06	***NS***
	Treatment (T)	12	353.30	29.44	126.70	1.98	***S***
	Y x T	12	0.32	0.03	0.12	1.98	***NS***
	Error	44	10.22	0.23			
	Total	69	363.86				

Appendix XI: Effect of different aluminium-alleviating organic materials on *pod length (cm)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	14.54	1.45	316.20	2.30	***S***
	Error	22	0.10	0.00			
	Total	32	14.64				
ANOVA TABLE **2024**	Treatment	10	14.50	1.45	423.05	2.30	***S***
	Error	22	0.08	0.00			
	Total	32	14.57				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.01	0.01	3.27	4.06	***NS***
	Treatment (T)	12	29.03	2.42	602.90	1.98	***S***
	Y x T	12	0.01	0.00	0.17	1.98	***NS***
	Error	44	0.18	0.00			
	Total	69	29.22				

Appendix XII: Effect of different aluminium-alleviating organic materials on *number of seeds per pod* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	116.04	11.60	127.35	2.30	***S***
	Error	22	2.00	0.09			
	Total	32	118.05				
ANOVA TABLE **2024**	Treatment	10	118.52	11.85	183.98	2.30	***S***
	Error	22	1.42	0.06			
	Total	32	119.94				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.29	0.29	3.69	4.06	***NS***
	Treatment (T)	12	234.46	19.54	251.23	1.98	***S***
	Y x T	12	0.10	0.01	0.11	1.98	***NS***
	Error	44	3.42	0.08			
	Total	69	238.27				

Appendix XIII: Effect of different aluminium-alleviating organic materials on *seed yield (g/pot)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	1104.37	110.44	872.87	2.30	***S***
	Error	22	2.78	0.13			
	Total	32	1107.15				
ANOVA TABLE **2024**	Treatment	10	1101.93	110.19	1843.16	2.30	***S***
	Error	22	1.32	0.06			
	Total	32	1103.24				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.03	0.03	0.31	4.06	***NS***
	Treatment (T)	12	2206.22	183.85	1973.65	1.98	***S***
	Y x T	12	0.08	0.01	0.07	1.98	***NS***
	Error	44	4.10	0.09			
	Total	69	2210.42				

Appendix XIV: Effect of different aluminium-alleviating organic materials on *stover yield (g/pot)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	1184.05	118.40	971.52	2.30	***S***
	Error	22	2.68	0.12			
	Total	32	1186.73				
ANOVA TABLE **2024**	Treatment	10	1169.75	116.98	2025.49	2.30	***S***
	Error	22	1.27	0.06			
	Total	32	1171.02				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.02	0.02	0.17	4.06	***NS***
	Treatment (T)	12	2353.75	196.15	2183.92	1.98	***S***
	Y x T	12	0.05	0.00	0.05	1.98	***NS***
	Error	44	3.95	0.09			
	Total	69	2357.77				

Appendix XV: Effect of different aluminium-alleviating organic materials on *harvest index (%)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	80.36	8.04	20.66	2.30	***S***
	Error	22	8.56	0.39			
	Total	32	88.92				
ANOVA TABLE **2024**	Treatment	10	86.33	8.63	33.71	2.30	***S***
	Error	22	5.63	0.26			
	Total	32	91.97				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.00	4.06	***NS***
	Treatment (T)	12	166.40	13.87	43.00	1.98	***S***
	Y x T	12	0.29	0.02	0.08	1.98	***NS***
	Error	44	14.19	0.32			
	Total	69	180.89				

Appendix XVI: Effect of different aluminium-alleviating organic materials on *root length (cm)* of mungbean in acid soil, at *48hrs*.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	7.95	0.80	910.49	2.30	***S***
	Error	22	0.02	0.00			
	Total	32	7.97				
ANOVA TABLE **2024**	Treatment	10	8.03	0.80	1286.50	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	8.04				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.37	4.06	***NS***
	Treatment (T)	12	15.98	1.33	1778.62	1.98	***S***
	Y x T	12	0.00	0.00	0.07	1.98	***NS***
	Error	44	0.03	0.00			
	Total	69	16.02				

Appendix XVII: Effect of different aluminium-alleviating organic materials on *root length (cm)* of mungbean in acid soil, at 30DAS.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	41.41	4.14	3586.95	2.30	***S***
	Error	22	0.03	0.00			
	Total	32	41.44				
ANOVA TABLE **2024**	Treatment	10	41.56	4.16	7218.59	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	41.57				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.55	4.06	***NS***
	Treatment (T)	12	82.97	6.91	7992.09	1.98	***S***
	Y x T	12	0.00	0.00	0.20	1.98	***NS***
	Error	44	0.04	0.00			
	Total	69	83.02				

Appendix XVIII: Effect of different aluminium-alleviating organic materials on *root length (cm)* of mungbean in acid soil, at *Harvest*.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	269.56	26.96	9679.55	2.30	***S***
	Error	22	0.06	0.00			
	Total	32	269.62				
ANOVA TABLE **2024**	Treatment	10	271.41	27.14	17323.88	2.30	***S***
	Error	22	0.03	0.00			
	Total	32	271.44				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	1.11	4.06	***NS***
	Treatment (T)	12	540.96	45.08	20719.39	1.98	***S***
	Y x T	12	0.00	0.00	0.15	1.98	***NS***
	Error	44	0.10	0.00			
	Total	69	541.07				

Appendix XIX: Effect of different aluminium-alleviating organic materials on *fresh root weight (g)* of mungbean in acid soil, at *48hrs*.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.00	0.00	1.33	2.30	***NS***
	Error	22	0.00	0.00			
	Total	32	0.00				
ANOVA TABLE **2024**	Treatment	10	0.00	0.00	1.05	2.30	***NS***
	Error	22	0.00	0.00			
	Total	32	0.00				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.06	4.06	***NS***
	Treatment (T)	12	0.00	0.00	1.95	1.98	***NS***
	Y x T	12	0.00	0.00	0.05	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.00				

Appendix XX: Effect of different aluminium-alleviating organic materials on *fresh root weight (g)* of mungbean in acid soil, at 30DAS.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	3.16	0.32	854.15	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	3.17				
ANOVA TABLE **2024**	Treatment	10	3.12	0.31	588.55	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	3.13				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.86	4.06	***NS***
	Treatment (T)	12	6.28	0.52	1162.35	1.98	***S***
	Y x T	12	0.00	0.00	0.40	1.98	***NS***
	Error	44	0.02	0.00			
	Total	69	6.30				

Appendix XXI: Effect of different aluminium-alleviating organic materials on *fresh root weight (g)* of mungbean in acid soil, at *Harvest*.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	5.99	0.60	4396.06	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	6.00				
ANOVA TABLE **2024**	Treatment	10	6.00	0.60	4607.83	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	6.01				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.92	4.06	***NS***
	Treatment (T)	12	12.00	1.00	7498.29	1.98	***S***
	Y x T	12	0.00	0.00	0.93	1.98	***NS***
	Error	44	0.01	0.00			
	Total	69	12.00				

Appendix XXII: Effect of different aluminium-alleviating organic materials on *dry root weight (g)* of mungbean in acid soil, at *48hrs*.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.00	0.00	1.36	2.30	***NS***
	Error	22	0.00	0.00			
	Total	32	0.00				
ANOVA TABLE **2024**	Treatment	10	0.00	0.00	1.34	2.30	***NS***
	Error	22	0.00	0.00			
	Total	32	0.00				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.22	4.06	***NS***
	Treatment (T)	12	0.00	0.00	1.97	1.98	***NS***
	Y x T	12	0.00	0.00	0.29	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.00				

Appendix XXIII: Effect of different aluminium-alleviating organic materials on *dry root weight (g)* of mungbean in acid soil, at 30DAS.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.06	0.01	468.97	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.06				
ANOVA TABLE **2024**	Treatment	10	0.06	0.01	1031.02	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.06				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	1.21	4.06	***NS***
	Treatment (T)	12	0.12	0.01	1077.14	1.98	***S***
	Y x T	12	0.00	0.00	0.12	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.12				

Appendix XXIV: Effect of different aluminium-alleviating organic materials on *dry root weight (g)* of mungbean in acid soil, at *Harvest*.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.77	0.08	1491.39	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.77				
ANOVA TABLE **2024**	Treatment	10	0.81	0.08	1266.40	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.81				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.18	4.06	***NS***
	Treatment (T)	12	1.57	0.13	2277.31	1.98	***S***
	Y x T	12	0.00	0.00	1.11	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	1.58				

Appendix XXV: Effect of different aluminium-alleviating organic materials on *relative root length (%)* of mungbean in acid soil, at *48hrs*.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	59331.78	5933.18	778.01	2.30	***S***
	Error	22	167.77	7.63			
	Total	32	59499.55				
ANOVA TABLE **2024**	Treatment	10	58667.06	5866.71	1287.21	2.30	***S***
	Error	22	100.27	4.56			
	Total	32	58767.33				
ANOVA Table of **Pooled Final**	Years (Y)	1	9.48	9.48	1.56	4.06	***NS***
	Treatment (T)	12	117993.86	9832.82	1614.09	1.98	***S***
	Y x T	12	4.98	0.41	0.07	1.98	***NS***
	Error	44	268.04	6.09			
	Total	69	118276.36				

Appendix XXVI: Effect of different aluminium-alleviating organic materials on *relative root length (%)* of mungbean in acid soil, at 30DAS.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	4755.40	475.54	695.86	2.30	***S***
	Error	22	15.03	0.68			
	Total	32	4770.44				
ANOVA TABLE **2024**	Treatment	10	4750.32	475.03	1748.10	2.30	***S***
	Error	22	5.98	0.27			
	Total	32	4756.30				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.22	0.22	0.47	4.06	***NS***
	Treatment (T)	12	9505.48	792.12	1658.68	1.98	***S***
	Y x T	12	0.24	0.02	0.04	1.98	***NS***
	Error	44	21.01	0.48			
	Total	69	9526.96				

Appendix XXVII: Effect of different aluminium-alleviating organic materials on *relative root length (%)* of mungbean in acid soil, at *Harvest*.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	25573.46	2557.35	5285.89	2.30	***S***
	Error	22	10.64	0.48			
	Total	32	25584.10				
ANOVA TABLE **2024**	Treatment	10	25799.95	2579.99	7189.64	2.30	***S***
	Error	22	7.89	0.36			
	Total	32	25807.84				
ANOVA Table of **Pooled Final**	Years (Y)	1	1.17	1.17	2.77	4.06	***NS***
	Treatment (T)	12	51372.94	4281.08	10160.93	1.98	***S***
	Y x T	12	0.47	0.04	0.09	1.98	***NS***
	Error	44	18.54	0.42			
	Total	69	51393.11				

Appendix XXVIII: Effect of different aluminium-alleviating organic materials on *nitrogen content in seed (%)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	2.69	0.27	445.27	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	2.70				
ANOVA TABLE **2024**	Treatment	10	2.72	0.27	348.69	2.30	***S***
	Error	22	0.02	0.00			
	Total	32	2.73				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	2.25	4.06	***NS***
	Treatment (T)	12	5.40	0.45	651.16	1.98	***S***
	Y x T	12	0.00	0.00	0.23	1.98	***NS***
	Error	44	0.03	0.00			
	Total	69	5.43				

Appendix XXIX: Effect of different aluminium-alleviating organic materials on *phosphorus content in seed (%)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.29	0.03	114.08	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.30				
ANOVA TABLE **2024**	Treatment	10	0.30	0.03	99.90	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.30				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	2.20	4.06	***NS***
	Treatment (T)	12	0.59	0.05	177.24	1.98	***S***
	Y x T	12	0.00	0.00	0.17	1.98	***NS***
	Error	44	0.01	0.00			
	Total	69	0.60				

Appendix XXX: Effect of different aluminium-alleviating organic materials on *potassium content in seed (%)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.47	0.05	82.09	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.48				
ANOVA TABLE **2024**	Treatment	10	0.46	0.05	139.69	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.47				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.00	4.06	***NS***
	Treatment (T)	12	0.92	0.08	171.87	1.98	***S***
	Y x T	12	0.00	0.00	0.30	1.98	***NS***
	Error	44	0.02	0.00			
	Total	69	0.95				

Appendix XXXI: Effect of different aluminium-alleviating organic materials on *calcium content in seed (%)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.09	0.01	164.18	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.09				
ANOVA TABLE **2024**	Treatment	10	0.09	0.01	195.25	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.09				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.67	4.06	***NS***
	Treatment (T)	12	0.18	0.01	297.01	1.98	***S***
	Y x T	12	0.00	0.00	0.17	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.18				

Appendix XXXII: Effect of different aluminium-alleviating organic materials on *magneisum content in seed (%)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.07	0.01	214.47	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.07				
ANOVA TABLE **2024**	Treatment	10	0.07	0.01	114.33	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.07				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.33	4.06	***NS***
	Treatment (T)	12	0.14	0.01	251.53	1.98	***S***
	Y x T	12	0.00	0.00	0.21	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.14				

Appendix XXXIII: Effect of different aluminium-alleviating organic materials on *aluminium content in seed (%)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	282.47	28.25	136.08	2.30	***S***
	Error	22	4.57	0.21			
	Total	32	287.04				
ANOVA TABLE **2024**	Treatment	10	275.23	27.52	107.40	2.30	***S***
	Error	22	5.64	0.26			
	Total	32	280.87				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.88	0.88	3.77	4.06	***NS***
	Treatment (T)	12	557.64	46.47	200.37	1.98	***S***
	Y x T	12	0.06	0.01	0.02	1.98	***NS***
	Error	44	10.20	0.23			
	Total	69	568.78				

Appendix XXXIV: Effect of different aluminium-alleviating organic materials on *protein content in seed (%)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	104.86	10.49	444.49	2.30	***S***
	Error	22	0.52	0.02			
	Total	32	105.38				
ANOVA TABLE **2024**	Treatment	10	106.08	10.61	344.01	2.30	***S***
	Error	22	0.68	0.03			
	Total	32	106.76				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.06	0.06	2.23	4.06	***NS***
	Treatment (T)	12	210.86	17.57	645.70	1.98	***S***
	Y x T	12	0.08	0.01	0.23	1.98	***NS***
	Error	44	1.20	0.03			
	Total	69	212.20				

Appendix XXXV: Effect of different aluminium-alleviating organic materials on *nitrogen content in stover (%)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.36	0.04	81.03	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.37				
ANOVA TABLE **2024**	Treatment	10	0.38	0.04	74.73	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.39				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.66	4.06	***NS***
	Treatment (T)	12	0.74	0.06	129.24	1.98	***S***
	Y x T	12	0.00	0.00	0.19	1.98	***NS***
	Error	44	0.02	0.00			
	Total	69	0.77				

Appendix XXXVI: Effect of different aluminium-alleviating organic materials on *phosphorus content in stover (%)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.17	0.02	73.37	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.18				
ANOVA TABLE **2024**	Treatment	10	0.17	0.02	101.29	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.18				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.61	4.06	***NS***
	Treatment (T)	12	0.34	0.03	141.47	1.98	***S***
	Y x T	12	0.00	0.00	0.26	1.98	***NS***
	Error	44	0.01	0.00			
	Total	69	0.35				

Appendix XXXVII: Effect of different aluminium-alleviating organic materials on *potassium content in stover (%)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.41	0.04	209.10	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.42				
ANOVA TABLE **2024**	Treatment	10	0.42	0.04	261.32	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.42				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	1.43	4.06	***NS***
	Treatment (T)	12	0.83	0.07	387.13	1.98	***S***
	Y x T	12	-3.59	-0.30	-1671.04	1.98	***NS***
	Error	44	0.01	0.00			
	Total	69	-2.75				

Appendix XXXVIII: Effect of different aluminium-alleviating organic materials on *calcium content in stover (%)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	1.06	0.11	1515.59	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	1.06				
ANOVA TABLE **2024**	Treatment	10	1.03	0.10	1481.30	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	1.03				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.67	4.06	***NS***
	Treatment (T)	12	2.09	0.17	2496.38	1.98	***S***
	Y x T	12	0.00	0.00	1.03	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	2.09				

Appendix XXXIX: Effect of different aluminium-alleviating organic materials on *magnesium content in stover (%)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.49	0.05	1004.75	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.49				
ANOVA TABLE **2024**	Treatment	10	0.48	0.05	1214.29	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.48				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.45	4.06	***NS***
	Treatment (T)	12	0.96	0.08	1829.91	1.98	***S***
	Y x T	12	0.00	0.00	1.23	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.97				

Appendix XXXX: Effect of different aluminium-alleviating organic materials on *aluminium content in stover (%)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	21814.54	2181.45	5554.37	2.30	***S***
	Error	22	8.64	0.39			
	Total	32	21823.18				
ANOVA TABLE **2024**	Treatment	10	21876.92	2187.69	6361.92	2.30	***S***
	Error	22	7.57	0.34			
	Total	32	21884.49				
ANOVA Table of **Pooled Final**	Years (Y)	1	1.38	1.38	3.74	4.06	***NS***
	Treatment (T)	12	43691.29	3640.94	9885.56	1.98	***S***
	Y x T	12	0.17	0.01	0.04	1.98	***NS***
	Error	44	16.21	0.37			
	Total	69	43709.05				

Appendix XXXXI: Effect of different aluminium-alleviating organic materials on *protein content in stover (%)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	14.13	1.41	81.46	2.30	***S***
	Error	22	0.38	0.02			
	Total	32	14.51				
ANOVA TABLE **2024**	Treatment	10	14.94	1.49	73.97	2.30	***S***
	Error	22	0.44	0.02			
	Total	32	15.38				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.07	0.07	3.66	4.06	***NS***
	Treatment (T)	12	29.02	2.42	128.86	1.98	***S***
	Y x T	12	0.04	0.00	0.20	1.98	***NS***
	Error	44	0.83	0.02			
	Total	69	29.96				

Appendix XXXXII: Effect of different aluminium-alleviating organic materials on *nitrogen uptake in seed (mg/pot)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	1571446.97	157144.70	952.98	2.30	***S***
	Error	22	3627.76	164.90			
	Total	32	1575074.73				
ANOVA TABLE **2024**	Treatment	10	1591423.95	159142.39	1957.06	2.30	***S***
	Error	22	1788.97	81.32			
	Total	32	1593212.92				
ANOVA Table of **Pooled Final**	Years (Y)	1	169.81	169.81	1.38	4.06	***NS***
	Treatment (T)	12	3162737.02	263561.42	2140.90	1.98	***S***
	Y x T	12	133.90	11.16	0.09	1.98	***NS***
	Error	44	5416.73	123.11			
	Total	69	3168457.46				

Appendix XXXXIII: Effect of different aluminium-alleviating organic materials on *phosphorus uptake in seed (mg/pot)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	38238.91	3823.89	437.77	2.30	***S***
	Error	22	192.17	8.73			
	Total	32	38431.08				
ANOVA TABLE **2024**	Treatment	10	39499.21	3949.92	359.92	2.30	***S***
	Error	22	241.44	10.97			
	Total	32	39740.65				
ANOVA Table of **Pooled Final**	Years (Y)	1	25.69	25.69	2.61	4.06	***NS***
	Treatment (T)	12	77719.19	6476.60	657.21	1.98	***S***
	Y x T	12	18.94	1.58	0.16	1.98	***NS***
	Error	44	433.61	9.85			
	Total	69	78197.43				

Appendix XXXXIV: Effect of different aluminium-alleviating organic materials on *potassium uptake in seed (mg/pot)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	203620.55	20362.05	933.81	2.30	***S***
	Error	22	479.72	21.81			
	Total	32	204100.27				
ANOVA TABLE **2024**	Treatment	10	206892.94	20689.29	1437.14	2.30	***S***
	Error	22	316.72	14.40			
	Total	32	207209.66				
ANOVA Table of **Pooled Final**	Years (Y)	1	3.85	3.85	0.21	4.06	***NS***
	Treatment (T)	12	410464.15	34205.35	1889.72	1.98	***S***
	Y x T	12	49.34	4.11	0.23	1.98	***NS***
	Error	44	796.43	18.10			
	Total	69	411313.77				

Appendix XXXXV: Effect of different aluminium-alleviating organic materials on *calcium uptake in seed (mg/pot)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	11755.65	1175.57	433.73	2.30	***S***
	Error	22	59.63	2.71			
	Total	32	11815.28				
ANOVA TABLE **2024**	Treatment	10	11422.23	1142.22	596.31	2.30	***S***
	Error	22	42.14	1.92			
	Total	32	11464.38				
ANOVA Table of **Pooled Final**	Years (Y)	1	4.23	4.23	1.83	4.06	***NS***
	Treatment (T)	12	23173.42	1931.12	834.93	1.98	***S***
	Y x T	12	4.46	0.37	0.16	1.98	***NS***
	Error	44	101.77	2.31			
	Total	69	23283.88				

Appendix XXXXVI: Effect of different aluminium-alleviating organic materials on *magnesium uptake in seed (mg/pot)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	8689.85	868.98	488.53	2.30	***S***
	Error	22	39.13	1.78			
	Total	32	8728.98				
ANOVA TABLE **2024**	Treatment	10	8239.83	823.98	380.05	2.30	***S***
	Error	22	47.70	2.17			
	Total	32	8287.53				
ANOVA Table of **Pooled Final**	Years (Y)	1	5.63	5.63	2.85	4.06	***NS***
	Treatment (T)	12	16924.60	1410.38	714.68	1.98	***S***
	Y x T	12	5.08	0.42	0.21	1.98	***NS***
	Error	44	86.83	1.97			
	Total	69	17022.14				

Appendix XXXXVII: Effect of different aluminium-alleviating organic materials on *aluminium uptake in seed (mg/pot)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.02	0.00	29.77	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.03				
ANOVA TABLE **2024**	Treatment	10	0.02	0.00	26.96	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.02				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.84	4.06	***NS***
	Treatment (T)	12	0.04	0.00	47.17	1.98	***S***
	Y x T	12	0.00	0.00	0.15	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.05				

Appendix XXXXVIII: Effect of different aluminium-alleviating organic materials on *nitrogen uptake in stover (mg/pot)* of mungbean in acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	827076.70	82707.67	1012.51	2.30	***S***
	Error	22	1797.09	81.69			
	Total	32	828873.79				
ANOVA TABLE **2024**	Treatment	10	830250.55	83025.05	1651.28	2.30	***S***
	Error	22	1106.14	50.28			
	Total	32	831356.69				
ANOVA Table of **Pooled Final**	Years (Y)	1	128.58	128.58	1.95	4.06	***NS***
	Treatment (T)	12	1657270.49	138105.87	2093.07	1.98	***S***
	Y x T	12	56.75	4.73	0.07	1.98	***NS***
	Error	44	2903.23	65.98			
	Total	69	1660359.05				

Appendix XXXXIX: Effect of different aluminium-alleviating organic materials on *phosphorus uptake in stover (mg/pot)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	26122.19	2612.22	148.42	2.30	***S***
	Error	22	387.20	17.60			
	Total	32	26509.39				
ANOVA TABLE **2024**	Treatment	10	26593.74	2659.37	284.02	2.30	***S***
	Error	22	206.00	9.36			
	Total	32	26799.73				
ANOVA Table of **Pooled Final**	Years (Y)	1	30.14	30.14	2.24	4.06	***NS***
	Treatment (T)	12	52677.72	4389.81	325.61	1.98	***S***
	Y x T	12	38.21	3.18	0.24	1.98	***NS***
	Error	44	593.20	13.48			
	Total	69	53339.27				

Appendix XXXXX: Effect of different aluminium-alleviating organic materials on *potassium uptake in stover (mg/pot)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	294295.80	29429.58	872.39	2.30	***S***
	Error	22	742.16	33.73			
	Total	32	295037.96				
ANOVA TABLE **2024**	Treatment	10	295706.49	29570.65	1872.45	2.30	***S***
	Error	22	347.44	15.79			
	Total	32	296053.93				
ANOVA Table of **Pooled Final**	Years (Y)	1	22.91	22.91	0.93	4.06	***NS***
	Treatment (T)	12	589965.69	49163.81	1985.34	1.98	***S***
	Y x T	12	36.60	3.05	0.12	1.98	***NS***
	Error	44	1089.59	24.76			
	Total	69	591114.80				

Appendix XXXXXI: Effect of different aluminium-alleviating organic materials on *calcium uptake in stover (mg/pot)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	127766.73	12776.67	2307.12	2.30	***S***
	Error	22	121.83	5.54			
	Total	32	127888.57				
ANOVA TABLE **2024**	Treatment	10	125047.54	12504.75	4649.99	2.30	***S***
	Error	22	59.16	2.69			
	Total	32	125106.70				
ANOVA Table of **Pooled Final**	Years (Y)	1	8.08	8.08	1.97	4.06	***NS***
	Treatment (T)	12	252772.01	21064.33	5120.69	1.98	***S***
	Y x T	12	42.26	3.52	0.86	1.98	***NS***
	Error	44	181.00	4.11			
	Total	69	253003.35				

Appendix XXXXXII: Effect of different aluminium-alleviating organic materials on *magnesium uptake in stover (mg/pot)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	64771.05	6477.11	1392.10	2.30	***S***
	Error	22	102.36	4.65			
	Total	32	64873.41				
ANOVA TABLE **2024**	Treatment	10	64545.17	6454.52	2350.94	2.30	***S***
	Error	22	60.40	2.75			
	Total	32	64605.57				
ANOVA Table of **Pooled Final**	Years (Y)	1	5.64	5.64	1.52	4.06	***NS***
	Treatment (T)	12	129282.18	10773.52	2912.44	1.98	***S***
	Y x T	12	34.04	2.84	0.77	1.98	***NS***
	Error	44	162.76	3.70			
	Total	69	129484.62				

Appendix XXXXXIII: Effect of different aluminium-alleviating organic materials on *aluminium uptake in stover (mg/pot)* of mungbean in acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	2.70	0.27	117.42	2.30	***S***
	Error	22	0.05	0.00			
	Total	32	2.75				
ANOVA TABLE **2024**	Treatment	10	2.53	0.25	349.99	2.30	***S***
	Error	22	0.02	0.00			
	Total	32	2.55				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.01	4.06	***NS***
	Treatment (T)	12	5.23	0.44	288.49	1.98	***S***
	Y x T	12	0.00	0.00	0.12	1.98	***NS***
	Error	44	0.07	0.00			
	Total	69	5.30				

Appendix XXXXXIV: Effect of different aluminium-alleviating organic materials on *soil solution pH* of an acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	4.46	0.45	672.57	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	4.48				
ANOVA TABLE **2024**	Treatment	10	4.48	0.45	623.39	2.30	***S***
	Error	22	0.02	0.00			
	Total	32	4.49				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.51	4.06	***NS***
	Treatment (T)	12	8.94	0.74	1078.26	1.98	***S***
	Y x T	12	0.00	0.00	0.09	1.98	***NS***
	Error	44	0.03	0.00			
	Total	69	8.97				

Appendix XXXXXV: Effect of different aluminium-alleviating organic materials on *soil solution calcium (ppm)* of an acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	574314.63	57431.46	196.63	2.30	***S***
	Error	22	6425.63	292.07			
	Total	32	580740.25				
ANOVA TABLE **2024**	Treatment	10	574314.63	57431.46	224.72	2.30	***S***
	Error	22	5622.42	255.56			
	Total	32	579937.05				
ANOVA Table of **Pooled Final**	Years (Y)	1	736.27	736.27	2.69	4.06	***NS***
	Treatment (T)	12	1148629.25	95719.10	349.57	1.98	***S***
	Y x T	12	0.00	0.00	0.00	1.98	***NS***
	Error	44	12048.05	273.82			
	Total	69	1161413.57				

Appendix XXXXXVI: Effect of different aluminium-alleviating organic materials on *soil solution magnesium (ppm)* of an acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	8748.32	874.83	12.21	2.30	***S***
	Error	22	1575.94	71.63			
	Total	32	10324.25				
ANOVA TABLE **2024**	Treatment	10	8747.33	874.73	4.77	2.30	***S***
	Error	22	4038.34	183.56			
	Total	32	12785.67				
ANOVA Table of **Pooled Final**	Years (Y)	1	271.05	271.05	2.12	4.06	***NS***
	Treatment (T)	12	17495.65	1457.97	11.43	1.98	***S***
	Y x T	12	0.00	0.00	0.00	1.98	***NS***
	Error	44	5614.27	127.60			
	Total	69	23380.97				

Appendix XXXXXVII: Effect of different aluminium-alleviating organic materials on *soil solution potassium (ppm)* of an acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	22787.61	2278.76	204.95	2.30	***S***
	Error	22	244.61	11.12			
	Total	32	23032.22				
ANOVA TABLE **2024**	Treatment	10	23829.98	2383.00	285.77	2.30	***S***
	Error	22	183.46	8.34			
	Total	32	24013.44				
ANOVA Table of **Pooled Final**	Years (Y)	1	8.34	8.34	0.86	4.06	***NS***
	Treatment (T)	12	46585.16	3882.10	399.03	1.98	***S***
	Y x T	12	32.43	2.70	0.28	1.98	***NS***
	Error	44	428.07	9.73			
	Total	69	47053.99				

Appendix XXXXXVIII: Effect of different aluminium-alleviating organic materials on *soil solution monomeric aluminium (ppm)* of an acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	12.62	1.26	296.28	2.30	***S***
	Error	22	0.09	0.00			
	Total	32	12.72				
ANOVA TABLE **2024**	Treatment	10	12.65	1.27	378.57	2.30	***S***
	Error	22	0.07	0.00			
	Total	32	12.73				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.03	4.06	***NS***
	Treatment (T)	12	25.26	2.11	553.84	1.98	***S***
	Y x T	12	0.01	0.00	0.26	1.98	***NS***
	Error	44	0.17	0.00			
	Total	69	25.44				

Appendix XXXXXIX: Effect of different aluminium-alleviating organic materials on *soil solution total aluminium (ppm)* of an acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	41.67	4.17	2013.44	2.30	***S***
	Error	22	0.05	0.00			
	Total	32	41.72				
ANOVA TABLE **2024**	Treatment	10	41.92	4.19	2828.71	2.30	***S***
	Error	22	0.03	0.00			
	Total	32	41.95				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.53	4.06	***NS***
	Treatment (T)	12	83.59	6.97	3922.53	1.98	***S***
	Y x T	12	0.00	0.00	0.13	1.98	***NS***
	Error	44	0.08	0.00			
	Total	69	83.67				

Appendix XXXXXX: Effect of different aluminium-alleviating organic materials on *soil pH* of post-harvest acid soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	4.42	0.44	605.49	2.30	***S***
	Error	22	0.02	0.00			
	Total	32	4.44				
ANOVA TABLE **2024**	Treatment	10	4.44	0.44	708.24	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	4.46				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	3.22	4.06	***NS***
	Treatment (T)	12	8.86	0.74	1088.15	1.98	***S***
	Y x T	12	0.00	0.00	0.13	1.98	***NS***
	Error	44	0.03	0.00			
	Total	69	8.90				

Appendix XXXXXXI: Effect of different aluminium-alleviating organic materials on *electrical conductivity (dS/m)* of post-harvest acid soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.04	0.00	80.08	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.04				
ANOVA TABLE **2024**	Treatment	10	0.04	0.00	77.61	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.05				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	2.25	4.06	***NS***
	Treatment (T)	12	0.09	0.01	130.69	1.98	***S***
	Y x T	12	0.00	0.00	0.60	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.09				

Appendix XXXXXXII: Effect of different aluminium-alleviating organic materials on *organic carbon (%)* of post-harvest soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	0.89	0.09	217.04	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.90				
ANOVA TABLE **2024**	Treatment	10	0.88	0.09	215.57	2.30	***S***
	Error	22	0.01	0.00			
	Total	32	0.89				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	4.03	4.06	***NS***
	Treatment (T)	12	1.77	0.15	360.45	1.98	***S***
	Y x T	12	0.00	0.00	0.06	1.98	***NS***
	Error	44	0.02	0.00			
	Total	69	1.79				

Appendix XXXXXXIII: Effect of different aluminium-alleviating organic materials on *cation exchange capacity [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	23.06	2.31	143.58	2.30	***S***
	Error	22	0.35	0.02			
	Total	32	23.41				
ANOVA TABLE **2024**	Treatment	10	23.06	2.31	211.38	2.30	***S***
	Error	22	0.24	0.01			
	Total	32	23.30				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.02	0.02	1.36	4.06	***NS***
	Treatment (T)	12	46.12	3.84	285.01	1.98	***S***
	Y x T	12	0.00	0.00	0.00	1.98	***NS***
	Error	44	0.59	0.01			
	Total	69	46.73				

Appendix XXXXXXIV: Effect of different aluminium-alleviating organic materials on *exchangeable calcium [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	14.08	1.41	193.61	2.30	***S***
	Error	22	0.16	0.01			
	Total	32	14.24				
ANOVA TABLE **2024**	Treatment	10	14.26	1.43	213.88	2.30	***S***
	Error	22	0.15	0.01			
	Total	32	14.41				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.02	0.02	2.17	4.06	***NS***
	Treatment (T)	12	28.34	2.36	338.82	1.98	***S***
	Y x T	12	0.00	0.00	0.02	1.98	***NS***
	Error	44	0.31	0.01			
	Total	69	28.66				

Appendix XXXXXXV: Effect of different aluminium-alleviating organic materials on *exchangeable magnesium [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.58	0.06	10.00	2.30	***S***
	Error	22	0.13	0.01			
	Total	32	0.70				
ANOVA TABLE **2024**	Treatment	10	0.57	0.06	3.38	2.30	***S***
	Error	22	0.37	0.02			
	Total	32	0.95				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.01	0.01	0.85	4.06	***NS***
	Treatment (T)	12	1.15	0.10	8.40	1.98	***S***
	Y x T	12	0.00	0.00	0.03	1.98	***NS***
	Error	44	0.50	0.01			
	Total	69	1.66				

Appendix XXXXXXVI: Effect of different aluminium-alleviating organic materials on *exchangeable potassium [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.11	0.01	253.33	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.11				
ANOVA TABLE **2024**	Treatment	10	0.12	0.01	297.68	2.30	***S***
	Error	22	0.00	0.00			
	Total	32	0.12				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.33	4.06	***NS***
	Treatment (T)	12	0.22	0.02	457.12	1.98	***S***
	Y x T	12	0.00	0.00	0.69	1.98	***NS***
	Error	44	0.00	0.00			
	Total	69	0.23				

Appendix XXXXXXVII: Effect of different aluminium-alleviating organic materials on *exchangeable sodium [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.00	0.00	1.04	2.30	***NS***
	Error	22	0.00	0.00			
	Total	32	0.00				
ANOVA TABLE **2024**	Treatment	10	0.00	0.00	1.19	2.30	***NS***
	Error	22	0.00	0.00			
	Total	32	0.00				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.11	4.06	***NS***
	Treatment (T)	12	0.00	0.00	1.81	1.98	***NS***
	Y x T	12	0.00	0.00	0.05	1.98	***NS***
	Error	44	0.01	0.00			
	Total	69	0.01				

Appendix XXXXXXVIII: Effect of different aluminium-alleviating organic materials on *base saturation (%)* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	1049.37	104.94	115.46	2.30	***S***
	Error	22	19.99	0.91			
	Total	32	1069.37				
ANOVA TABLE **2024**	Treatment	10	1063.37	106.34	156.85	2.30	***S***
	Error	22	14.92	0.68			
	Total	32	1078.29				
ANOVA Table of **Pooled Final**	Years (Y)	1	2.69	2.69	3.39	4.06	***NS***
	Treatment (T)	12	2112.36	176.03	221.87	1.98	***S***
	Y x T	12	0.38	0.03	0.04	1.98	***NS***
	Error	44	34.91	0.79			
	Total	69	2150.34				

Appendix XXXXXXIX: Effect of different aluminium-alleviating organic materials on *exchangeable aluminium [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	3.53	0.35	37.29	2.30	***S***
	Error	22	0.21	0.01			
	Total	32	3.74				
ANOVA TABLE **2024**	Treatment	10	3.32	0.33	16.43	2.30	***S***
	Error	22	0.44	0.02			
	Total	32	3.76				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.02	0.02	1.26	4.06	***NS***
	Treatment (T)	12	6.84	0.57	38.45	1.98	***S***
	Y x T	12	0.01	0.00	0.05	1.98	***NS***
	Error	44	0.65	0.01			
	Total	69	7.52				

Appendix XXXXXXX: Effect of different aluminium-alleviating organic materials on *exchangeable acidity [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	6.44	0.64	70.31	2.30	***S***
	Error	22	0.20	0.01			
	Total	32	6.64				
ANOVA TABLE **2024**	Treatment	10	6.50	0.65	91.96	2.30	***S***
	Error	22	0.16	0.01			
	Total	32	6.66				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.02	0.02	3.01	4.06	***NS***
	Treatment (T)	12	12.92	1.08	132.72	1.98	***S***
	Y x T	12	0.02	0.00	0.19	1.98	***NS***
	Error	44	0.36	0.01			
	Total	69	13.32				

Appendix XXXXXXXI: Effect of different aluminium-alleviating organic materials on *exchangeable hydrogen [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	0.51	0.05	9.06	2.30	***S***
	Error	22	0.12	0.01			
	Total	32	0.63				
ANOVA TABLE **2024**	Treatment	10	0.53	0.05	2.43	2.30	***S***
	Error	22	0.48	0.02			
	Total	32	1.01				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.17	4.06	***NS***
	Treatment (T)	12	1.03	0.09	6.25	1.98	***S***
	Y x T	12	0.01	0.00	0.06	1.98	***NS***
	Error	44	0.60	0.01			
	Total	69	1.65				

Appendix XXXXXXXII: Effect of different aluminium-alleviating organic materials on *total potential acidity [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	75.55	7.55	346.27	2.30	***S***
	Error	22	0.48	0.02			
	Total	32	76.03				
ANOVA TABLE **2024**	Treatment	10	73.83	7.38	190.33	2.30	***S***
	Error	22	0.85	0.04			
	Total	32	74.68				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.10	0.10	3.38	4.06	***NS***
	Treatment (T)	12	149.34	12.44	410.68	1.98	***S***
	Y x T	12	0.04	0.00	0.10	1.98	***NS***
	Error	44	1.33	0.03			
	Total	69	150.81				

Appendix XXXXXXXIII: Effect of different aluminium-alleviating organic materials on *reserve acidity [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	38.84	3.88	125.15	2.30	***S***
	Error	22	0.68	0.03			
	Total	32	39.52				
ANOVA TABLE **2024**	Treatment	10	37.04	3.70	102.94	2.30	***S***
	Error	22	0.79	0.04			
	Total	32	37.83				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.03	0.03	0.80	4.06	***NS***
	Treatment (T)	12	75.80	6.32	188.53	1.98	***S***
	Y x T	12	0.07	0.01	0.18	1.98	***NS***
	Error	44	1.47	0.03			
	Total	69	77.38				

Appendix XXXXXXXIV: Effect of different aluminium-alleviating organic materials on *effective cation exchange capacity [cmol (p^+) kg^{-1}]* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	5.94	0.59	26.08	2.30	***S***
	Error	22	0.50	0.02			
	Total	32	6.44				
ANOVA TABLE **2024**	Treatment	10	6.32	0.63	56.24	2.30	***S***
	Error	22	0.25	0.01			
	Total	32	6.57				
ANOVA Table of **Pooled Final**	Years (Y)	1	0.00	0.00	0.14	4.06	***NS***
	Treatment (T)	12	12.25	1.02	60.01	1.98	***S***
	Y x T	12	0.01	0.00	0.07	1.98	***NS***
	Error	44	0.75	0.02			
	Total	69	13.02				

Appendix XXXXXXXV: Effect of different aluminium-alleviating organic materials on *aluminium saturation (%)* of post-harvest soil.

	SoV	*DF*	*SS*	*MSS*	*F Cal*	*F Tab at 5%*	*S/NS*
ANOVA TABLE **2023**	Treatment	10	2480.58	248.06	82.23	2.30	***S***
	Error	22	66.36	3.02			
	Total	32	2546.94				
ANOVA TABLE **2024**	Treatment	10	2372.30	237.23	28.95	2.30	***S***
	Error	22	180.26	8.19			
	Total	32	2552.56				
ANOVA Table of **Pooled Final**	Years (Y)	1	7.53	7.53	1.34	4.06	***NS***
	Treatment (T)	12	4849.43	404.12	72.10	1.98	***S***
	Y x T	12	3.46	0.29	0.05	1.98	***NS***
	Error	44	246.62	5.61			
	Total	69	5107.04				

Appendix XXXXXXXVI: Effect of different aluminium-alleviating organic materials on *exchangeable aluminium (mg/kg)* of post-harvest soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	16313.04	1631.30	178.33	2.30	***S***
	Error	22	201.24	9.15			
	Total	32	16514.28				
ANOVA TABLE **2024**	Treatment	10	16029.49	1602.95	359.64	2.30	***S***
	Error	22	98.06	4.46			
	Total	32	16127.55				
ANOVA Table of **Pooled Final**	Years (Y)	1	21.81	21.81	3.21	4.06	***NS***
	Treatment (T)	12	32330.63	2694.22	396.08	1.98	***S***
	Y x T	12	11.90	0.99	0.15	1.98	***NS***
	Error	44	299.30	6.80			
	Total	69	32663.64				

Appendix XXXXXXXVII: Effect of different aluminium-alleviating organic materials on *organic bound aluminium (mg/kg)* of post-harvest soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	16951.66	1695.17	271.33	2.30	***S***
	Error	22	137.45	6.25			
	Total	32	17089.10				
ANOVA TABLE **2024**	Treatment	10	16909.67	1690.97	152.75	2.30	***S***
	Error	22	243.55	11.07			
	Total	32	17153.22				
ANOVA Table of **Pooled Final**	Years (Y)	1	34.63	34.63	4.00	4.06	***NS***
	Treatment (T)	12	33858.92	2821.58	325.85	1.98	***S***
	Y x T	12	2.41	0.20	0.02	1.98	***NS***
	Error	44	381.00	8.66			
	Total	69	34276.95				

Appendix XXXXXXXVIII: Effect of different aluminium-alleviating organic materials on *amorphous aluminium (mg/kg)* of post-harvest soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	7566206.05	756620.60	266.10	2.30	***S***
	Error	22	62553.33	2843.33			
	Total	32	7628759.38				
ANOVA TABLE **2024**	Treatment	10	7566217.64	756621.76	372.54	2.30	***S***
	Error	22	44681.20	2030.96			
	Total	32	7610898.84				
ANOVA Table of **Pooled Final**	Years (Y)	1	8192.13	8192.13	3.36	4.06	***NS***
	Treatment (T)	12	15132423.69	1261035.31	517.42	1.98	***S***
	Y x T	12	0.00	0.00	0.00	1.98	***NS***
	Error	44	107234.53	2437.15			
	Total	69	15247850.35				

Appendix XXXXXXXXIX: Effect of different aluminium-alleviating organic materials on *cumulative amorphous and crystalline aluminium (mg/kg)* of post-harvest soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	6946391.91	694639.19	1207.96	2.30	***S***
	Error	22	12651.14	575.05			
	Total	32	6959043.05				
ANOVA TABLE **2024**	Treatment	10	7067307.77	706730.78	572.08	2.30	***S***
	Error	22	27178.05	1235.37			
	Total	32	7094485.83				
ANOVA Table of **Pooled Final**	Years (Y)	1	681.66	681.66	0.75	4.06	***NS***
	Treatment (T)	12	14012507.02	1167708.92	1289.99	1.98	***S***
	Y x T	12	1192.66	99.39	0.11	1.98	***NS***
	Error	44	39829.19	905.21			
	Total	69	14054210.54				

Appendix XXXXXXXXX: Effect of different aluminium-alleviating organic materials on *crystalline aluminium (mg/kg)* of post-harvest soil.

	SoV	***DF***	***SS***	***MSS***	***F Cal***	***F Tab at 5%***	***S/NS***
ANOVA TABLE **2023**	Treatment	10	34287.42	3428.74	1.43	2.30	***NS***
	Error	22	52759.04	2398.14			
	Total	32	87046.45				
ANOVA TABLE **2024**	Treatment	10	27774.01	2777.40	0.95	2.30	***NS***
	Error	22	64527.74	2933.08			
	Total	32	92301.75				
ANOVA Table of **Pooled Final**	Years (Y)	1	4578.50	4578.50	1.72	4.06	***NS***
	Treatment (T)	12	60591.93	5049.33	1.89	1.98	***NS***
	Y x T	12	1469.50	122.46	0.05	1.98	***NS***
	Error	44	117286.78	2665.61			
	Total	69	183926.71				