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Liming Materials in Combination with Co-Composted Biochar for Subsoil Acidity Amelioration in Southern Laterites of Kerala

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: To assess the capacity of co-composted biochar liming material combinations to alleviate surface, subsoil acidity and aluminium saturation.

Study Design: A field experiment was laid out in randomized block design (RBD) replicated thrice with seven treatments *viz.,* ½ LR as Burnt lime (BL) + ½ as Phosphogypsum (PG) + Co-composted biochar (CCB) (5t ha^{-1}), ½ LR as Dolomite (DL) + ½ as PG + CCB (5t ha^{-1}) and ½ LR as BL + ½ as PG & Magnesium sulphate (MS) (3:2) + CCB (5t ha^{-1}) each @ 100 per cent lime requirement (LR) and @ 75 per cent LR including an absolute control.

Place and Duration of the Study: Instructional Farm, College of Agriculture, Vellayani, Thiruvananthapuram, Kerala, between June 2023 and September 2023.

Methodology: A field experiment was laid out and soil samples from four depths *viz.,* 0-15, 15-30, 30-60 and 60-90 cm were analysed for soil pH, exchangeable acidity and Al saturation at the beginning of the experiment and at crop harvest. Plant biometric observations and yield attributes were also assessed at crop harvest stage.

Results: The application of ½ LR as BL + ½ as PG + CCB (5t ha^{-1}) @ 100 per cent LR exhibited higher values of soil pH (5.74, 5.53, 5.45 and 5.28) up to 90 cm depth, effective alleviation of exchangeable acidity (0.377 meq $100g^{-1}$, 0.877 meq $100g^{-1}$, 1.057 meq $100g^{-1}$), potential acidity (24.0 meq $100g^{-1}$, 30.0 meq $100g^{-1}$, 32.0 meq $100g^{-1}$) and pH dependent acidity (23.623 meq $100g^{-1}$, 29.123 meq $100g^{-1}$, 30.943 meq $100g^{-1}$) in the subsoil (15-90 cm) and higher reduction in Al saturation (3.66 %, 8.36 %, 21.5 %, 22.3 %) up to 90cm depth, higher rate of crop growth and yield at the harvest stage.

Conclusion: The combined application of liming materials and co-composted biochar could achieve effective moderation of soil acidity and Al toxicity.

Keywords: Subsoil acidity; aluminium toxicity; laterite soils; co-composted biochar; fodder sorghum; liming materials; phosphogypsum; burnt lime.

1. INTRODUCTION

The tropics and subtropics account for 60 per cent of the acid soils in the world. Soils of the humid tropics are naturally acidic, low in plant nutrients, and contain an abundance of Al and Fe oxides. The origin and intensification of soil acidity is due to high rainfall, leaching of bases, mineralization of organic matter, external inputs of acid-forming chemical fertilizers and inappropriate agricultural practices. The most notable effect of soil acidity is the drastic reduction in crop yield as a result of decrease in nutrient uptake especially calcium, magnesium and potassium, and direct injury to plant roots caused by aluminum toxicity at soil pH below 5.5 (Adams, 1984). Laterite soils fall under the soil order Ultisols covering about 18 per cent of the land area in tropics (Eswaran et al., 1992). Red and lateritic soils are the third most important soils of the world occupying 13 per cent of land area globally. These soils are spread across the semi-arid to humid tropics (Sehgal, 1998).

About 70 to 75 per cent of the total geographic area of Kerala are covered by laterite soils. More than 90 per cent of Kerala soils are acidic in reaction with about 54 per cent being extremely to strongly acid (pH 3.5 to 5.5), rich in iron and aluminium oxides leading to toxicity of these elements when pH falls below 5.5 Though acidic and infertile, these soils can become productive with proper liming and fertilization (KSPB, 2013). The soils of southern laterites of Kerala experiencing tropical moist sub humid monsoon climate with low rainfall compared to other areas are acidic with higher concentration of low-activity lateritic clay, weak retention of the bases, abundant Al, Fe, Mn and Cu, but very limited N, P, S, Mo and B which constrain crop production.

Surface soil acidity and its effect on crop production has been a research subject for several centuries. Recognition of subsoil acidity and its consequences, however, is quite recent (Sumner, 1970; Reeve & Sumner, 2006). Subsoil acidity, as characterized by low Ca and high Al at depths below the plough layer, is restricting crop growth and production in many parts of the world, especially in the humid tropics where most soils are highly weathered (Adams, 1984; Cahn et al., 1993). Aluminium toxicity interferes with the plant availability, uptake, transport and utilization of essential nutrients such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), molybdenum (Mo) and boron (B). and inhibits physiological and biological activities of plants, root development and uptake of water (Clark, 1984; Singh et al., 2017).

The alleviation of subsoil acidity by applying amendments on the soil surface is determined by the transportation of basic cations into deeper layers and their reaction with the acidity present in the subsoil horizons. This transportation process is affected by factors such as water availability and the concentration of cations in the leaching water. Surface application of amendments containing mobile anions, such as sulphate, nitrate, or chloride can mitigate subsoil acidity. These anions facilitate the leaching of bases into the subsoil (Pleysier & Juo, 1981; Pavan et al., 1984).

Conventional surface applied lime such as limestone, burnt lime or dolomite does not ameliorate the adverse effects of subsoil acidity, and subsoil incorporation of lime by deep ploughing or using specialized equipments is not a feasible option. The effectiveness of liming in improving subsoil acidity is often limited due to the slow downward movement of lime within the soil profiles, consumption of OH^- ions released from lime by exchangeable H^+ and Al^{3+}, reactions of OH^- ions with Fe and Al oxides abundant in the highly weathered soils etc. Phosphogypsum, a by-product of wet-acid production of phosphoric acid from rock phosphate contains more soluble Ca compared to burnt lime and it can be used for enhancing root growth in subsoil and complementing liming of acid soils. Application of gypsum as an amendment alone or in combination with burnt lime and dolomite lowers surface and subsoil acidity and improves the nutrient availability in soil layers (Aloka, 2016). When phosphogypsum is applied to the surface soil, it moves down with percolating water and alleviates subsoil acidity and aluminium toxicity below the plough layer (Caires et al., 2002).

Lime incorporation into the soil was found to be more competent in decreasing soil acidity and increasing the availability of calcium and magnesium at the soil surface while the application of phosphogypsum improved the availability of sulphur and calcium in the subsoil layers. Therefore, a combination of lime and phosphogypsum was found to be appropriate for the simultaneous amelioration of surface and subsoil acidity (Besen et al., 2021).

Magnesium sulphate with higher solubility and mobility in soils compared to conventional lime can readily move down the soil profile and break the Al-created chemical barrier. The net pH change depends upon the two conflicting reactions namely replacement of H^+ and Al^{3+} by Mg^{2+} through the reaction between magnesium sulphate and soil colloid and the replacement of OH^- by SO_4^{2-} through ligand exchange. Incorporation of lime and magnesium sulphate alone or in combination decreases exchangeable acidity and improves base saturation of soils (Bandyopadhyay, 2003).

The largescale application of organic amendments like biochar, composts and animal manures substantially improves soil pH (Lund & Doss, 1980; Hern et al., 1988; Wright et al., 1985; Sharpley et al., 1993; Sweeten, 1998). Biochar compost mixtures are also identified as potential agents to ameliorate soil acidity. Co-composting of biochar with organic wastes forms an organic coating on biochar molecules reducing its hydrophobicity and enhances its nutrient retention (Joseph et al., 2017). The organic coating also facilitates swift downward movement of biochar along with percolating water and achieves better alleviation of subsoil acidity and aluminium toxicity.

The combined application of inorganic and organic amendments can enhance the increment in soil pH through better alleviation of soil acidity. Integrated application of biochar and lime in combination with soil test-based fertilizer dose + FYM + $ZnSO_4$ was found to raise soil pH to near neutrality from an initial value of 5.20 in a two season field experiment with *kharif* rice and *summer* cowpea in the acid soils of Karnataka. The improvement in pH could be ascribed to CaO in lime which reacts with water leading to the production of OH- ions which forms $Al(OH)_3$ and H_2O, and the release of basic cations from biochar into the soil which exchange with exchangeable Al^{3+} and H^+ ions on the soil exchange complex, thereby raising the soil pH and reducing exchangeable acidity (Meena & Prakasha, 2020).Therefore, an integrated approach involving inorganic and organic ameliorants is essential to mitigate the ill effects of surface and subsoil acidity and enhance crop productivity.

2. MATERIALS AND METHODS

2.1 Study Area

The experiment was carried out during the period from June 2023 to September 2023 at the

Instructional Farm, COA, Vellayani which lies at 8°25'47.61"N latitude and 76°59'13.93"E longitude at an altitude of 29 m above mean sea level. Fodder sorghum variety Co 31 was used for the field experiment. The seeds required for planting were obtained from Tamil Nadu Agricultural University.

2.2 Experimental Details

The experiment was laid out in Randomised Block Design (RBD) with seven treatments and three replications.

T_1: Absolute control
T_2: 1/2 LR (Lime requirement) as burnt lime (BL) + 1/2 LR as Phosphogypsum (PG) + co-composted biochar (CCB) (5 t/ha) @ 100% LR
T_3: 1/2 LR as dolomite (DL)+ 1/2 LR as PG + CCB (5 t/ha) @ 100% LR
T_4: 1/2 LR as BL + 1/2 LR as PG and Magnesium sulphate (MS)(3:2) + CCB (5 t/ha) @ 100% LR
T_5: 1/2 LR as BL + 1/2 LR as PG + CCB (5 t/ha) @ 75% LR
T_6: 1/2 LR as DL + 1/2 LR as PG + CCB (5 t/ha) @ 75% LR
T_7: 1/2 LR as BL + 1/2 LR as PG and MS (3:2) + CCB (5 t/ha) @ 75% LR

2.3 Production of Co-composted Biochar

Biochar was produced by the slow pyrolysis method with coconut husk as the feedstock. Coconut husk was selected mainly because of its higher alkalinity (pH>9.0) and liming potential. 50 kg coconut husk was pyrolyzed slowly to obtain 19.25 kg biochar with a recovery of 38.5 per cent. Biochar obtained was cooled, shade dried, powdered and sieved through 2mm sieves and co-composted aerobically with banana psuedostem in 1:1 ratio. The co-compost was ready within 2-3 months and was shade dried and sieved through 2 mm sieves.

2.4 Preparation and Analysis of Soil Samples

Soil samples from four depths *viz.,* 0-15, 15-30, 30-60 and 60-90 cm were collected before and after the field investigation and analysed for soil pH, exchangeable acidity and potential acidity by following standard procedures (Table 1). Aluminium saturation was computed using the equation given below.

$$Al\ Saturation\ (\%) = \frac{ExAl}{ECEC}\ x\ 100$$

ExAl -Exchangeable Al^{3+}, ECEC- Effective cation exchange capacity

The soil properties at the beginning of the field experiment are presented in Table 2.

2.5 Plant Biometric Observations and Yield Attributes

Plant biometric observations (plant height (m), root volume (cm^3), root length (cm), fresh and dry weight of shoot and root (grams $plant^{-1}$)) and yield attributes (Green fodder yield (t ha^{-1}) and dry matter yield (t ha^{-1})) were also assessed. The height of the observation plants from all the treatments and replications were measured from the ground level to the uppermost leaf and the average height was recorded in metre. The green fodder yield was calculated based on the shoot fresh weight per plant and the dry matter yield was calculated based on the total dry weight per plant. The length of the roots of all the observation plants from all the treatments and replications were measured from the base of the plant to the tip of the root and the average root length was recorded in cm. The Archimedes principle of water displacement was employed for estimating the root volume. The roots of the observation plants from all the treatments and replications were immersed in a predetermined volume of water taken in a measuring cylinder. The displacement of water was recorded as the root volume in cm^3.

2.6 Field Preparation, Layout and Application of Treatments

The experimental site was cleared and plots of 3m x 2m dimensions were prepared. The lime requirement of the surface soil in the experimental site was estimated following the SMP buffer method (Shoemaker et al*.,* 1961). The treatments were applied as per the lime requirement 15 days prior to the application of fertilizers as per KAU POP (Kerala Agricultural University, Package of Practices) recommendations. The fertilizer recommendation for fodder sorghum is 60:40:20 kg ha^{-1} NPK (KAU, 2015). The entire quantity of P and K was supplied as basal dose whereas N was applied in two splits *ie.,* half as basal and the rest at 30 days after sowing.

2.7 Planting and After Cultivation

Fodder sorghum seeds were dibbled @ 2-3 seeds per hole at a spacing of 45 cm x 15 cm. The seed rate was 12-15 kg ha^{-1}. Thinning was carried out at the 20^{th} day after sowing and the crop was irrigated on alternate days. Weeding was carried out as and when required.

Table 1. Analytical methods followed for soil analysis

Sl. No.	Parameter	Method	Reference
1	pH	pH meter (1:2.5 soil water/CaCl2/KCl ratio)	Jackson (1973)
2	Exchangeable acidity	1N KCl extraction and standard alkali titration	Yuan (1959)
3	Potential acidity	$BaCl_2$ extraction and titration	Page et al. (1982)

Table 2. Soil properties at the beginning of the field experiment

Sl. No.	Soil attributes	0-15 cm	15-30 cm	30-60 cm	60-90 cm
1.	Soil pH	4.77	4.52	4.63	4.50
4.	Exchangeable acidity (meq 100 g^{-1})	1.17	1.45	1.52	1.66
3.	Potential acidity (meq 100 g^{-1})	36.0	38.0	38.0	42.0
4.	pH dependent acidity (meq 100 g^{-1})	32.83	36.55	36.48	40.34
5.	Aluminium saturation (%)	33.8	44.0	53.7	57.0
6.	Lime requirement (surface soil) (kg)	1350	-	-	-

2.8 Harvesting

The crop was harvested by cutting at the base. After harvest the observation plants were uprooted and dried to record the dry matter content.

3. RESULTS AND DISCUSSION

3.1 Soil Reaction

Soil pH varied significantly among treatments for all the depths considered (Table 3), with ½ LR as BL + ½ as PG + CCB (5t ha^{-1}) @ 100 per cent LR recording the highest value of 5.74, 5.53, 5.45 and 5.28 at 0-15, 15-30, 30-60 and 60-90 cm respectively. At 0-15 cm, ½ LR as BL + ½ as PG + CCB (5t ha^{-1}) @ 100 per cent LR was on par with 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t ha^{-1})) @ 75 per cent LR (5.62) while soil pH at all the other depths differed significantly from other treatments. The higher increment in soil pH for ½ LR as BL + ½ as PG + CCB (5t ha^{-1}) @ 100 per cent LR might be due to the combined effect of burnt lime, phosphogypsum and CCB wherein phosphogypsum supplies soluble Ca and CCB facilitates the swift transport of Ca from the liming materials into the subsoil. The high alkalinity, basic cation content and Al adsorption properties of CCB also contribute substantially to the rise in pH.

3.2 Exchangeable Acidity

Exchangeable acidity (Table 4) at 0-15 cm depth was the lowest under 1/2 LR as BL + 1/2 LR as PG + CCB (5 t ha^{-1})) @ 100 per cent LR (0.207 meq 100 g^{-1}) which was on par with 1/2 LR as BL + ½ LR as PG + CCB (5 t ha^{-1}) @ 100 per cent LR (0.207 meq 100g^{-1}). At 15-30 and 60-90 cm depths, 1/2 LR as BL + ½ LR as PG + CCB (5 t ha^{-1}) @ 100 per cent LR recorded the lowest exchangeable acidity values of 0.377 meq 100g^{-1} and 1.057 meq 100g^{-1} respectively. At 15-30 cm depth, 1/2 LR as BL + ½ LR as PG + CCB (5 t ha^{-1}) @ 100 per cent LR showcased prominent variation from the other treatments and was followed by 1/2 LR as BL + 1/2 LR as PG + CCB (5 t ha^{-1})) @ 100 per cent LR (0.520 meq 100g^{-1}). At 60-90 cm depth, 1/2 LR as BL + 1/2 LR as PG + CCB (5 t ha^{-1})) @ 100 per cent LR was comparable with 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR (1.130 meq 100g^{-1}) and 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (1.180 meq 100g^{-1}). At 30-60 cm depth, 1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR displayed the lowest exchangeable acidity (0.877 meq 100g^{-1}) which was on par with 1/2 LR as BL + 1/2 LR as PG + CCB (5 t ha^{-1})) @ 100 per cent LR (0.877 meq 100g^{-1}), 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (0.883 meq 100g^{-1}) and 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR (0.920 meq 100g^{-1}) respectively. The effective alleviation of exchangeable acidity by these treatments might be due to the supply of higher concentration of labile Ca or Mg coupled with the presence of CCB with higher alkalinity, basic cation content and Al adsorption properties. CCB can increase the rate of transport of Ca or Mg ions into the subsoil by forming organo-Ca or organo-Mg complexes.

Table 3. Effect of treatments on soil pH at the end of the field experiment

Treatments	0-15 cm	15-30 cm	30-60 cm	60-90 cm
T_1: Absolute control	4.63	4.47	4.67	4.39
T_2:1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	5.74	5.53	5.45	5.28
T_3:1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	5.53	5.37	5.29	5.15
T_4:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR	5.31	5.35	5.37	5.21
T_5:1/2 LR as BL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	5.35	5.27	5.13	4.89
T_6:1/2 LR as DL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	5.25	5.21	5.19	4.79
T_7:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR	5.62	5.35	5.25	5.14
SEm±	0.06	0.04	0.03	0.05
CD (0.05)	0.20	0.11	0.10	0.15

Table 4. Effect of treatments on soil exchangeable acidity (meq 100g^{-1}) at the end of the field experiment

Treatments	0-15 cm	15-30 cm	30-60 cm	60-90 cm
T_1: Absolute control	1.207	1.537	1.540	1.620
T_2:1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	0.207	0.377	0.877	1.057
T_3:1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	0.330	0.520	0.877	1.130
T_4:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR	0.207	0.590	0.883	1.180
T_5:1/2 LR as BL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	0.487	0.780	1.030	1.387
T_6:1/2 LR as DL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	0.523	0.950	1.110	1.467
T_7:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR	0.280	0.693	0.920	1.263
SEm±	0.022	0.021	0.026	0.034
CD (0.05)	0.069	0.065	0.092	0.105

Table 5. Effect of treatments on potential acidity (meq $100g^{-1}$) of the soil at the end of the field experiment

Treatments	0-15 cm	15-30 cm	30-60 cm	60-90 cm
T_1: Absolute control	38.7	40.0	40.0	41.3
T_2:1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	22.7	24.0	30.0	32.0
T_3:1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	28.7	30.7	28.0	33.3
T_4:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR	19.3	32.0	34.0	36.0
T_5:1/2 LR as BL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	26.0	34.0	38.0	37.3
T_6:1/2 LR as DL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	31.3	34.0	38.0	38.0
T_7:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR	16.0	26.0	29.3	34.0
SEm±	0.98	1.41	1.61	1.23
CD (0.05)	3.02	4.36	4.97	3.80

Table 6. Effect of treatments on pH dependent acidity (meq $100g^{-1}$) of the soil at the end of the field experiment

Treatments	0-15 cm	15-30 cm	30-60 cm	60-90 cm
T_1: Absolute control	37.460	38.463	38.460	39.713
T_2:1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	22.460	23.623	29.123	30.943
T_3:1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	28.337	30.147	27.123	32.203
T_4:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR	19.127	31.410	33.117	34.820
T_5:1/2 LR as BL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	25.513	33.220	36.970	35.947
T_6:1/2 LR as DL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	30.810	33.050	36.890	36.533
T_7:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR	15.720	25.307	28.413	32.737
SEm±	0.988	1.407	1.381	1.230
CD (0.05)	3.045	4.335	4.913	3.791

Table 7. Effect of treatments on Al saturation (%) of the soil at the end of the field experiment

Treatments	0-15 cm	15-30 cm	30-60 cm	60-90 cm
T_1: Absolute control	45.0	43.9	54.9	53.5
T_2:1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	3.66	8.36	21.5	22.3
T_3:1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	6.80	12.5	22.4	23.3
T_4:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR	3.82	16.2	22.0	22.8
T_5:1/2 LR as BL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	9.67	18.9	28.4	29.8
T_6:1/2 LR as DL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	12.1	23.0	30.5	32.1
T_7:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR	5.57	17.3	24.4	25.4
SEm±	0.63	0.52	1.16	1.23
CD (0.05)	1.94	1.60	3.57	3.80

Table 8. Effect of treatments on plant biometric observations at the end of the field experiment

Treatments	Plant height (m)	Root length (cm)	Root volume (cm^3)	Fresh weight (g $plant^{-1}$)		Dry matter production (g $plant^{-1}$)	
				Shoot	Root	Shoot	Root
T_1: Absolute control	1.13	30.5	25.2	112	39.7	36.0	7.67
T_2:1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	3.50	60.1	31.5	588	274	339	109
T_3:1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	2.76	45.2	32.4	350	275	186	108
T_4:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR	3.06	51.3	36.8	476	288	227	116
T_5:1/2 LR as BL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	2.05	38.7	31.2	437	277	218	122
T_6:1/2 LR as DL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	2.55	40.0	29.8	445	208	207	91.0
T_7:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR	2.91	44.5	42.3	442	221	197	108
SEm±	0.15	2.05	1.82	35.4	16.3	7.04	5.92
CD (0.05)	0.46	6.30	5.60	109	50.3	21.7	18.2

Table 9. Effect of treatments on yield attributes

Treatments	Green fodder yield (t ha^{-1})	Dry matter yield (t ha^{-1})		
		Shoot	Root	Total
T_1: Absolute control	16.5	5.31	1.13	6.44
T_2:1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	86.7	50.1	16.1	66.2
T_3:1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR	51.7	27.4	15.9	43.3
T_4:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR	70.2	33.5	17.2	50.6
T_5:1/2 LR as BL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	64.5	32.2	18.0	50.2
T_6:1/2 LR as DL + 1/2 as PG + CCB (5t/ha) @ 75 per cent LR	65.6	30.4	13.4	43.9
T_7:1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR	65.1	29.1	15.9	45.0
SEm±	5.22	1.04	0.87	1.53
CD (0.05)	16.1	3.20	2.69	4.70

3.3 Potential and pH Dependent Acidity

Potential and pH dependent acidities (Tables 5 & 6) at 0-15 cm depth projected the lowest value of 16.0 meq 100g^{-1} and 15.720 meq 100g^{-1} for 1/2 LR as BL + ½ as PG & MS (3:2) + CCB (5 t ha^{-1}) @ 75 per cent LR which differed remarkably from other treatments. At 15-30 depth, ½ LR as BL + ½ as PG + CCB (5t/ha) @ 100 per cent LR registered the lowest potential and pH dependent acidity values of 24.0 meq 100g^{-1} and 23.623 meq 100g^{-1} respectively while at 60-90 cm depth, ½ LR as BL + ½ as PG + CCB (5t/ha) @ 100 per cent LR registered the lowest potential and pH dependent acidity values of 32.0 meq 100g^{-1} and 30.943 meq 100g^{-1} respectively. At 15-30 cm, ½ LR as BL + ½ as PG + CCB (5t/ha) @ 100 per cent LR was comparable with 1/2 LR as BL + ½ as PG & MS (3:2) + CCB (5 t ha^{-1}) @ 75 per cent LR (26.0 meq 100g^{-1}, 25.307 meq 100g^{-1}) whereas at 60-90 cm, ½ LR as BL + ½ as PG + CCB (5t/ha) @ 100 per cent LR was on par with ½ LR as BL + ½ as PG & MS (3:2)+ CCB (5t/ha) @ 100 per cent LR (33.3 meq 100g^{-1}, 32.203 meq 100g^{-1}) and 1/2 LR as BL + ½ as PG & MS (3:2) + CCB (5 t ha^{-1}) @ 75 per cent LR (34.0 meq 100g^{-1}, 29.123 meq 100g^{-1}). At 30-60 cm depth, ½ LR as DL + ½ as PG + CCB (5t/ha) @ 100 per cent LR recorded the lowest potential and pH dependent acidity (28.0 meq 100g^{-1}, 27.123 meq 100g^{-1}) which was on par with 1/2 LR as BL + ½ as PG & MS (3:2) + CCB (5 t ha^{-1}) @ 75 per cent LR (29.3 meq 100g^{-1}, 28.413 meq 100g^{-1}) and ½ LR as BL + ½ as PG & MS (3:2)+ CCB (5t/ha) @ 100 per cent LR (30.0 meq 100g^{-1}, 29.123 meq 100g^{-1}) respectively. This might be due to the higher availability of soluble Ca and Mg and its faster movement into the subsoil aided by CCB.

3.4 Aluminium Saturation

The treatments 1/2 LR as BL + ½ LR as PG + CCB (5 t ha^{-1})) @ 100 per cent LR showcased the lowest Al saturation values of 3.66 per cent, 8.36 per cent, 21.5 per cent and 22.3 per cent respectively at 0-15, 15-30. 30-60 and 60-90 cm depths (Table 7). At 0-15 cm, 1/2 LR as BL + ½ LR as PG + CCB (5 t ha^{-1})) @ 100 per cent LR was comparable with 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (3.82%) and 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR (5.57%). At 15-30 cm, 1/2 LR as BL + ½ LR as PG + CCB (5 t ha^{-1})) @ 100 per cent LR varied remarkably from other treatments. At 30-60 and 60-90cm, 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR was statistically on par with 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (22.0%, 22.8%), 1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR (22.4%, 23.3%) and 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 75 per cent LR (24.4%, 25.4%) respectively.

3.5 Plant Biometric Observations

The effect of treatments on the biometric observations (Table 8) of fodder sorghum plants at harvest stage reveals that the average plant height and root length was the maximum for 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR (3.50 m, 60.1 cm). The average plant height for 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR was comparable with 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha)) @ 100 per cent LR (3.06 m). The root volume was the highest for 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha)) @ 75 per cent LR (42.3 cm^3) which was statistically similar to 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (36.8 cm^3).

The shoot fresh weight was the highest for 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR (588 g plant^{-1}) which exhibited significant variation from the other treatments. 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR was followed by 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (476 g plant^{-1}) and 1/2 LR as DL + 1/2 as PG + CCB (5t/ha) (445 g plant^{-1}) @ 75 per cent LR respectively. The maximum value of root fresh weight was showcased by 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (288 g plant^{-1}) which was commensurate with 1/2 LR as BL + 1/2 as PG + CCB (5t/ha)) @ 75 per cent LR (277 g plant^{-1}), T_3 (275 g plant^{-1}) and 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR (274 g plant^{-1}). The dry weight of shoot was the highest for 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR (339 g plant^{-1}) which differed significantly from other treatments. The application of 1/2 LR as BL + 1/2 as PG + CCB (5t/ha)) @ 75 per cent LR showcased the highest root dry weight of 122 g plant^{-1} which was statistically similar to 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (116 g plant^{-1}), 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR (109 g plant^{-1}), 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha)) @ 75 per cent LR (108 g plant^{-1}) and 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (108 g plant^{-1}) (Table 8).

The influence of treatments on green fodder yield and shoot, root and total dry matter yield of fodder sorghum is depicted in Table 9. 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR recorded the maximum green fodder yield of 86.7 t ha^{-1} which differed prominently from the other treatments. The shoot dry matter yield was the highest for 1/2 LR as BL + ½ LR as PG +CCB (5t ha^{-1}) depicting a mean value of 50.1 t ha^{-1} which exhibited significant variation from other treatments. 1/2 LR as BL + 1/2 as PG + CCB (5t/ha) @ 75 per cent exhibited the highest root dry matter yield of 18.0 t ha^{-1} which was comparable with 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) @ 100 per cent LR (17.2 t ha^{-1}), 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR (16.1 t ha^{-1}), 1/2 LR as BL + 1/2 as PG & MS (3:2) + CCB (5t/ha) (15.9 t ha^{-1}) and 1/2 LR as DL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR (15.9 t ha^{-1}). The total dry matter yield was observed to be the highest for T_2 showcasing a mean value of 66.2 t ha^{-1}. 1/2 LR as BL + 1/2 as PG+ CCB (5t/ha) @ 100 per cent LR exhibited remarkable variation from other treatments.

The higher increment in soil pH, efficient alleviation of different forms of acidity and replacement of Al^{3+} ions with Ca or Mg ions by these treatments along with the application of recommended dose of NPK fertilizers promotes root penetration into deeper layers of soil enhancing water and nutrients extraction efficiency (Nair et al., 2019). Thus, improving overall crop growth.

4. CONCLUSION

An integrated approach involving conventional liming materials like burnt lime and dolomite with soluble Ca and Mg sources like phosphogypsum and magnesium sulphate along with co-composted biochar having higher alkalinity and basic cation content can effectively mitigate the ill effects of surface and subsoil acidity and enhance crop productivity.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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