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Effect of Lime on Different Forms of Soil Acidity and Phosphorus Availability in Acid Soil

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Abstract: The incubation study was carried out in the summer of 2023 to investigate the impact of lime on various forms of soil acidity and phosphorus availability in acid soils. at Faculty of Agricultural Sciences, Siksha 'O' Anusandhan, Bhubaneswar Odisha. Red and laterite soil that were taken from the experimental field were used in two incubation investigations lab. Four amounts of lime were administered to both soils, along with two levels of phosphorus (P_0-P control & P_1-P @ 40kg/ha (0.066g/pot). In red soil the levels of lime were L_1-0.1 LR (0.2g/pot), L_2-0.2 LR (0.4g/pot), L_3-0.5 LR (1.0g/pot), In laterite soil the levels of lime were: L_1-0.1 LR (0.1g/pot), L_2-0.2 LR (0.2g/pot), L_3-0.5 LR (0.5g/pot)]. The pH of the soil increased as the lime used increased, but it decreased as the incubation times increased. After a week of incubation, the highest was P_1L_3, where 40 kg of P_2O_5 per hectare was treated in conjunction with lime application at 0.5LR. P_0L_3 showed the lowest value, with lime treatment at 0.5LR without phosphorus (6.66). Depending on the incubation period, applying varying amounts of phosphorus and lime gradually lowers the exchangeable H^+. After seven days of incubation, exchangeable H^+ in laterite soil ranged from 0.04 to 0.12 meq/100g. Following six weeks of incubation, ranged between 0.12 and 0.14 meq/100g and grew steadily. The red soil exchangeable Al^{3+} contents were considerably reduced when lime and P treatment rates increased, as well as by the combined impacts of the two applications. Following a 6-week incubation period, exchangeable $H^+ + Al^{3+}$ in red soil decreased, while the addition of varying phosphorus and lime levels resulted in an increase in exchangeable $H^+ + Al^{3+}$ in laterite soil. Following the addition of varying quantities of phosphorus and lime to red soil and laterite soil, range of organic carbon was 1.03 to 1.81% and 0.25 to 0.67% respectively. The rate of lime was when increased in both red and laterite soil, the change in available P gradually reduced. The amount of accessible calcium and magnesium also increased during 42-day incubation period.

***Keywords*:** Lime, pH, Exchangeable H^+, Exchangeable Al^{3+}, Available P, Red soil, Laterite soil

Globally, soil acidity is acknowledged as a significant issue that has a negative impact on agricultural productivity, either directly or indirectly, particularly in temperate and tropical regions of the world (Asrat 2021). It is well recognized that soil acidity has a negative impact on nutrient availability, which in turn has a negative direct and indirect influence on crop growth. Highly worn acid soils in the tropics have low phosphorus (P) availability and a high P fixation by massive amounts of aluminium (Al) and iron (Fe) oxides (Rajneesh et al., 2018). Phosphate is applied and quickly reacts with large amounts of iron and aluminium oxides, making it less soluble in acidic soils (Bolan et al., 2003). Al oxide, which dissolves with additional acidity and eventually saturates the soils' cation exchange sites with exchangeable Al, is a typical buffer for the pH of acidic soils. Acidic soils have lesser capacity to retain water and nutrients, which results in decreased moisture and nutrient uptake as well as low biotic activity (Asrat 2021).

The phosphorus (P) is a necessary element for plant growth labile forms in soil are comparatively rare when compared to other main macronutrients (Jain et al., 2012). This is because P is naturally soluble in low solubility soil compounds and minerals. Because liming materials have such powerful acid neutralizing capabilities and may effectively eliminate existing acid, increase biological activity, and reduce toxicity of heavy metals. Lime oxides, hydroxides, carbonates, slag, and other liming materials are a few of these (Singh et al., 2023). The best way to produce crops on acid soils is to apply lime and fertilizer (phosphorus in particular). When lime is applied to the soil, Ca^{2+} and Mg^{2+} ions replace H^+, Fe^{2+}, Al^{3+}, Mn^{4+}, and Cu^{2+} ions from soil adsorption sites, raising the pH of the soil. Depending on the type of liming materials used, lime can also provide sizable amounts of Ca and Mg. Lime has indirect benefits that include better soil structure in some situations, enhanced availability of P, Mo, and B, and more favourable conditions for microbially mediated reactions including nitrification and nitrogen fixation (Nekesa et al., 2005). The current study was to assess the effect of different lime concentrations on soil pH and various types of soil acidity (pH-dependent and exchange acidity), as well as the phosphorus dynamic in acid soils treated with lime and to determine the optimum dose of lime to correct soil acidity.

MATERIAL AND METHODS

Incubation study was conducted during summer 2023 at

Faculty of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar Odisha to observed the effect of lime on different forms of soil acidity and phosphorus availability in acid soils. The tropical climate at the experimental site ranges from a maximum of 25.7 to 40.7˚C to low of 12.8 to 27.9˚C. In addition, the experimental site saw 10.30 mm of rainfall on average. Two distinct locations with varying pH values inside the experimental site yielded two different types of soil: red soil (pH-5.18) and laterite soil (pH-5.78). There were eight treatments made up the factorial complete randomized design with three replications. Following crop harvest, soil samples were taken from the experimental field, allowed to air dry, and then sieved through a 2 mm mesh sieve before being stored for analysis. In each container, 750 g of soil samples were collected. Three levels of lime (0.1, 0.2, and 0.5 LR) and two levels of phosphorus (P_0-no phosphorus & P_1-P_2O_5 @ 40 kg per hectare) were given to both soils in accordance with the treatment details. Pure $CaCO_3$ lime was used. The beakers' mouths were open, and they were set up like labs. Every two days, the weight of the beakers was recorded, and the soil's field capacity was maintained by adding an appropriate amount of distilled water to offset moisture loss. Sample of the soil was taken from each pot every seven days, i.e., after seven, fourteen, twenty-one, thirty, and forty-two days. On February 24, 2023, red soil was collected, and on June 6, 2023, laterite soil was obtained. The soil was kept in a laboratory setting for a period of six weeks. Using accepted techniques, the different physico-chemical characteristics of the experimental soil, such as its texture, pH, organic carbon, available phosphorus, exchangeable acidity, available calcium, and magnesium, were ascertained. The analysis was done by DMRT method by SPSS software.

RESULTS AND DISCUSSION

Soil pH: Soil pH increased as lime treatment levels rose (Table 1), but it decreased as incubation times increased. pH range in red soil was 5.8 to 7.12. Following a week of incubation, the highest was in P_0L_3, where lime was treated at 0.5LR with no phosphorus level, followed by P_1L_3 (where 40kg of P_2O_5 per hectare was applied at 0.5LR,) and the lowest value was in the control. After an incubation period of 42 days, the same patterns persisted. The application 0.5LR of lime increased the soil pH as compared to other levels of lime i.e., 0.1 LR & 0.2 LR.

The pH range in laterite soil was 5.56 to 6.69. After a week of incubation, the highest was in P_1L_3, where 40 kg of P_2O_5 per hectare was treated in conjunction with lime application at 0.5LR. P_0L_3 showed the lowest value, with lime treatment at 0.5LR without phosphorus. Following 42 days of incubation, the highest was in P_0L_3, where lime was applied at 0.5LR without any phosphorus. This was followed by P_1L_3, where lime was applied at 0.5LR with 40kg P_2O_5 per hectare, and P_0L_1 showed the lowest value. When lime and phosphorus were not added, the control group did not experience any notable alterations.

Limes needed to neutralize harmful components in the soil and raise the pH of acidic soil. The pH scale is used to represent soil reactivity and determine if the soil is neutral, acidic, or alkaline. The molar activity, or concentration, of hydrogen ions in the soil solution is measured by soil pH (Moody and Cong 2008). The pH of the soil can be used to determine the kind of chemical reactions that are probably occurring there. It influences microbial activity, root growth, and the availability and toxicity of nutrients. Liming is done to raise the pH to the range of 5.5 to 6.5, which is ideal for most plant growth. Liming is one of the management techniques for managing soil fertility since it lowers the acidity of the soil.

Exchangeable H^+: Depending on the incubation period, applying varying amounts of phosphorus and lime gradually lowers the exchangeable H^+ (Table 2). After seven days of incubation, the exchangeable H^+ in red soil ranges from 0.04 to 0.12 meq/100g. The highest exchangeable H^+ was in P_1L_0, where no lime was applied along with 40kg P_2O_5 per hectare. The exchangeable H^+ ion concentration was observed to be steadily declining after 6 weeks of incubation periods.

After seven days of incubation, exchangeable H^+ in laterite soil ranged from 0.04 to 0.12 meq/100g. The P_0L_2 had

Table 1. Effect of different levels of lime and phosphorus on soil pH (days after incubation)

Treatment	Red soil		Laterite soil	
	7	42	7	42
	pH	pH	pH	pH
P_0L_0	5.8	5.3	5.5	6.22
P_0L_1	5.98	5.74	6.5	6.14
P_0L_2	6.31	5.8	6.63	6.44
P_0L_3	7.12	6.31	6.66	6.58
P_1L_0	5.81	5.28	6.08	6.43
P_1L_1	5.9	5.56	6.39	6.25
P_1L_2	6.24	5.7	6.4	6.31
P_1L_3	6.37	6.28	6.69	6.51
CD (p=0.05)				
P	NS	NS	NS	0.091
L	0.443	0.263	0.256	0.129
P × L	NS	NS	0.362	0.183

P_0 and P_1 are no phosphorus and 40kg P_2O_5 per hectare respectively, L_0, L_1, L_2 and L_3 are no lime, 0.1 LR, 0.2 LR, 0.5 LR respectively the exchangeable H^+ when no phosphorus and lime @0.2LR were treated, while the P_1L_0 area had the lowest, when no lime and 40kg P_2O_5 per hectare were applied. Following six weeks of incubation, the concentration of Exchangeable H+ ions varied from 0.12 to 0.14 meq/100g and was progressively elevated. Lime dissociates into $Ca^{2+}$and OH^- ions when it is applied to acid soils with H^+ concentrations. The pH of the soil solution will rise as a result of the hydroxyl ions' reaction with the hydrogen-forming water (Buni 2014).

Exchangeable Al^{3+}: The red soil's exchangeable Al^{3+} concentrations were considerably reduced when lime and P application increased, along with the combined impacts of the two applications. The exchangeable Al^{3+} in red soil ranged from 0.02 to 0.06 meq/100g. After incubation for seven days, P_1L_2 had the highest exchangeable Al^{3+}, followed by P_0L_2 and the control with the lowest value. It the exchangeable Al^{3+} had nearly completely disappeared after 6 weeks of incubation. The exchangeable aluminum content of the soil was significantly decreased by P's interaction with lime (Opala et al., 2018). When combined with 40kg of P_2O_5 per hectare, the entire dose of lime (0.5 LR) needed to neutralize the soil considerably decreased the amount of soil exchangeable Al to nearly zero (Table 3).

Exchangeable Al^{3+} levels in laterite soil were also shown to be considerably reduced with increased lime and P application rates as well as by the interaction effects of lime and P application. Exchangeable Al^{3+} was ranged from 0.001 to 0.02 meq/100g. When no phosphorus and lime @0.2LR were administered, the maximum value of exchangeable Al^{3+} was obtained in P_0L_2, while the lowest value in P_1L_3, when 40 kg P_2O_5 per hectare and lime @ 0.5 LR were applied after 7 days of incubation. The exchangeable Al^{3+} had nearly completely disappeared after 6 weeks of incubation. Exchangeable Al^{3+}increased with addition of different levels of phosphorus and lime levels but declined with increasing incubation periods (Table 3).

Table 2. Effect of different levels of lime and phosphorus on exchangeable H^+ (days after incubation)

Treatment	Red soil		Laterite soil	
	7	42	7	42
	H^+	H^+	H^+	H^+
P_0L_0	0.08	0.05	0.1	0.12
P_0L_1	0.04	0.04	0.11	0.12
P_0L_2	0.04	0.02	0.12	0.14
P_0L_3	0.04	0.02	0.1	0.13
P_1L_0	0.12	0.05	0.04	0.12
P_1L_1	0.1	0.04	0.08	0.13
P_1L_2	0.07	0.03	0.06	0.13
P_1L_3	0.08	0.01	0.08	0.14
CD (p=0.05)				
P	0.021	NS	0.030	NS
L	0.030	0.013	NS	NS
P × L	NS	NS	NS	NS

Table 3. Effect of different levels of lime and phosphorus on exchangeable Al^{3+} (days after incubation)

Treatment	Red soil		Laterite soil	
	7	42	7	42
P_0L_0	0.02	0.01	0.01	0.00
P_0L_1	0.04	0.01	0.01	0.00
P_0L_2	0.05	0.01	0.02	0.00
P_0L_3	0.04	0	0.01	0.00
P_1L_0	0.03	0	0.01	0.00
P_1L_1	0.04	0	0.008	0.00
P_1L_2	0.06	0	0.005	0.00
P_1L_3	0.04	0	0.001	0.00
CD (p=0.05)				
P	NS	NS	NS	NS
L	0.019	NS	NS	NS
P × L	NS	NS	NS	NS

The exchangeable acidity in soils is caused by Al^{3+} ions. This is because, in soils that are moderately to strongly acidic, only Al^{3+} is a common exchangeable cation (Bohn et al., 2001). Achalu et al. (2012) observed that applying lime at a rate of 10 tons per hectare reduced the soil's exchangeable acidity by approximately 90.7%, from 2.80 cmol (+) kg in the control to 0.26 cmol (+) kg. Temesgen *et al.* (2017), observed that lime application rates increased, exchangeable acidity and Al^{3+} dropped significantly. Because lime-added CO_3^{2-} surfaces reduce active acidity by consuming H+ in soil solution, Al is exchanged for added base cations (mostly lime-borne divalent alkaline earths Ca and Mg) and precipitates as insoluble $Al(OH)_3$ due to its dramatically reduced solubility in circum neutral pH values (Antoniadis et al., 2015).

The red soil's exchangeable H^+ + Al^{3+} levels were considerably reduced when lime and P application rates increased, along with the combined impacts of the two applications. Exchangeable $H^+ + Al^{3+}$ranged from 0.08 to 0.16 meq/100g in red soil. After incubation for seven days, P_1L_0 (i.e., 0.16 meq/100g) had the highest value of exchangeable H^+ + Al^{3+},where no lime and 40 kg P_2O_5 per hectare were applied. P_1L_1 (0.14 meq/100g) had the lowest value, with no phosphorus and lime @0.1LR applied, and P_0L_3 (0.08 meq/100g) had the highest value. The exchangeable $H^+ + Al^{3+}$ decreased after six weeks of incubation. The interaction of lime by P highly reduced the exchangeable $H^+ + Al^{3+}$ content of the soil (Opala et al., 2018).

Exchangeable H^+ + Al^{3+} levels in laterite soil were also considerably elevated with increasing lime and P application rates as well as by the interaction effects of lime and P application. Exchangeable H^+ + Al^{3+} ranged from 0.05 to 0.13 meq/100g. When no phosphorus and lime @0.2LR were applied, the maximum value of exchangeable Al^{3+} was in P_0L_2 (0.13 meq/100g), while the lowest was in P_1L_0 (i.e., 0.05 meq/100g), where, after 7 days of incubation, 40kg P_2O_5 per hectare was applied along with no lime. Following six weeks of incubation, adding varying amounts of lime and phosphorus led to an increase in exchangeable H^+ + Al^{3+} (Table 4). Highest was in P_0L_2 (i.e., 0.14 meq/100g) which was at par with P_1L_3.

Available phosphorus: As application of lime increased, the change in available P gradually decreased (Table 5). After seven days of incubation, the amount of accessible phosphorus in red soil ranged from 25.67 to 88 kg ha^{-1}. P_1L_3 had the highest, 88 kg ha^{-1}, when lime @0.5LR and 40-kilogram P_2O_5 per hectare were administered. P_1L_2 had the second-highest, 85 kg ha-1, when lime @0.2LR and 40 kg P_2O_5 per hectare were applied. The control group, which received neither lime nor phosphorus, had the lowest. Following 42 days of incubation, the highest 63.12 kg ha^{-1} was in P_1L_2, while the lowest 24.4 kg ha^{-1} was in P_0L_1. This suggests that phosphorus availability increases when lime is applied alone, but decreases when both lime and phosphorus are added.

After 7 days of incubation, the amount of accessible phosphorus in laterite soil ranged from 34.33 to 80.8 kg ha^{-1}. The lowest was in control, or no phosphorus and lime were applied. After incubation for 42 days, the highest was in P_1L_3 or 68.2 kg ha^{-1}, while the lowest was in P_0L_2, where lime @0.2LR was applied in addition to no phosphorus. This suggests that phosphorus availability increases when lime is applied alone, but availability decreases where both lime and phosphorus were added.

Penn and Camberato (2019), observed that fixing of P by Ca and adsorption of P to Fe and Al oxide surfaces are likely the main causes of the decrease in soil accessible P following lime application, rather than pH changes in the soil. In order to improve the release of phosphate ions fixed by Al and Fe ions into the soil solution, liming acidic soils may raise the pH of the soil. Achalu et al. (2012) concluded that acid soil can be limed to raise the pH above 6 and remedy the P shortage. Lime application increases accessible P because it improves soil acidity, which increases P availability (Kisinyo 2016). The small quantity of fixed P was released into the soil by lime, making it available for the crop. In order to hydrolyze the Al and Fe ions that accumulated with P, agricultural liming materials are a lucrative soil addition (Kiflu et al., 2017). As a result, the phosphate ion that precipitated was released into the soil solution and became available for plant absorption. By promoting the mineralization of soil organic phosphorus, liming can raise the availability of phosphate (Ameyu et al., 2019).

Available calcium:. After 7 days of incubation, accessible calcium varied from 0.094 to 0.112% (Table 6). The highest was found in P_1L_3, or 0.112%, where 40 kg of P_2O_5 and lime at 0.5LR were administered. The lowest was in control, or 0.094%, where neither phosphorus nor lime were treated.

Table 4. Effect of different levels of lime and phosphorus on exchangeable acidity (H^++ Al^{3+}) (days after incubation)

Treatment	Red soil		Laterite soil	
	7	42	7	42
P_0L_0	0.1	0.06	0.12	0.12
P_0L_1	0.1	0.05	0.12	0.12
P_0L_2	0.09	0.03	0.13	0.14
P_0L_3	0.08	0.02	0.1	0.13
P_1L_0	0.16	0.06	0.05	0.12
P_1L_1	0.14	0.04	0.08	0.13
P_1L_2	0.13	0.03	0.06	0.13
P_1L_3	0.12	0.02	0.08	0.14
CD (p=0.05)				
P	0.020	NS	0.030	NS
L	NS	0.024	NS	NS
P × L	NS	NS	NS	NS

Table 5. Effect of different levels of lime and phosphorus on Avail P (kg/ha) (days after incubation)

Treatment	Red soil		Laterite soil	
	7	42	7	42
P_0L_0	25.67	29.19	34.33	39.5
P_0L_1	29.01	24.4	35.5	39.64
P_0L_2	30.36	30.17	37.8	39.28
P_0L_3	35	34.12	40.64	39.45
P_1L_0	66.91	27.4	52.1	49.93
P_1L_1	75	37	41	66.15
P_1L_2	85	63.12	75.43	52.65
P_1L_3	88	32.61	80.8	68.2
CD (p=0.05)				
P	9.233	7.319	4.092	4.759
L	NS	10.350	5.786	6.730
P × L	NS	14.638	8.183	9.518

Table 6. Effect of different levels of lime and phosphorus on avail Ca & Mg (%) (days after incubation)

Treatment	Red soil				Laterite soil			
	7		42		7		42	
	Ca	Mg	Ca	Mg	Ca	Mg	Ca	Mg
P_0L_0	0.094	0.024	0.112	0.001	0.082	0.045	0.124	0.067
P_0L_1	0.096	0.024	0.125	0.004	0.078	0.054	0.132	0.069
P_0L_2	0.108	0.024	0.122	0.004	0.077	0.067	0.14	0.063
P_0L_3	0.109	0.026	0.12	0.002	0.07	0.06	0.145	0.08
P_1L_0	0.096	0.024	0.116	0.004	0.074	0.081	0.08	0.074
P_1L_1	0.104	0.021	0.129	0.003	0.078	0.076	0.092	0.104
P_1L_2	0.109	0.026	0.12	0.001	0.077	0.077	0.085	0.076
P_1L_3	0.112	0.027	0.154	0.006	0.085	0.074	0.088	0.072
CD (p=0.05)								
P	NS	NS	0.008	0.001	NS	0.009	0.014	0.004
L	0.012	NS	0.011	0.001	NS	NS	NS	0.006
P × L	NS	NS	0.015	0.002	0.010	NS	NS	0.008

Following 42 days of incubation, the accessible calcium content increased in accordance with the incubation duration and same pattern was followed, with P_1L_3 exhibiting the highest 0.154 percent and the control group exhibiting the lowest 0.112%.

After seven days of incubation, accessible calcium in laterite soil ranged from 0.070 to 0.085%. The highest was in P_1L_3, where 40 kg of P_2O_5 and lime @ 0.5LR were applied, and the lowest was recorded in P_0L_3, where neither phosphorus nor lime @ 0.5LR were administered. Following 42 days of incubation, the accessible calcium content increased in accordance with the incubation time. The maximum was, 0.145%, in P_0L_3, while the lowest of 0.112%, was in P_1L_0, where no lime was applied with 40 kg of P_2O_5 per hectare.

Acidic cations such as H, Al, and Fe replace base cations on exchange sites and in the soil solution when base cations are removed, particularly by leaching and erosion (Johnston, 2004). Extremely low amounts of exchangeable calcium are in highly worn tropical soils, such as Oxisols; crops grown on these soils show signs of calcium insufficiency when exchangeable calcium is less than 1 cmol kg^{-1}. Soil exchangeable calcium (Ca) and magnesium (Mg) can be increased by applying limestone (calcium carbonate) or dolomatic lime (Ca and Mg bicarbonate). Achalu et al. (2012) observed that application of lime neutralizes part of the acidity of the soil, releasing negative charges that are subsequently filled by basic cations in the soil exchange complex. The applied lime increases the concentration of Ca^{2+} and raises the pH of the soil by dissociating agricultural lime and replacing H^+ and Al^{3+} in the soil solution and soil exchange complex. This explains the direct relationships observed between pH, exchangeable Ca^{2+}, and CEC with increasing lime rates. Similar to this, the presence of pH-dependent negative charges, which might rise in response to an increase in soil pH brought on by the application of agricultural lime, may be the cause of the direct correlation between CEC and pH. (Ameyu 2019)

Available magnesium: After seven days of incubation, accessible magnesium varied from 0.024 to 0.027% (in P_1L_3, 40 kg of P_2O_5 and lime at 0.5LR were applied. Following 42 days of incubation, available magnesium content increased to 0.068%, in P_1L_0, where no lime was applied along with 40 kg P_2O_5 per hectare, and the lowest was 0.041%, in P_1L_1, where 40 kg P_2O_5 per hectare was applied along with lime @0.1LR (Table 6). After seven days of incubation, accessible magnesium in laterite soil varied from 0.045 control to 0,081%. P_1L_0T. Following 42 days of incubation, the available magnesium content increased in. The highest was 0.104%, in P_1L_1, where 40 kg of P_2O_5 per hectare was applied along with lime @0.1LR, and the lowest value, was f in P_0L_2, where no phosphorus was applied along with lime @0.2LR.

Acidic cations such as H, Al, and Fe replace base cations, particularly Mg, that are removed from exchange sites and the soil solution through leaching and erosion (Johnston, 2004). The availability of orthophosphate ($H_2PO_4^-$), nitrate (NO_3^-), and sulfate (SO_4^{2-}) anions to plant roots and the activities of exchangeable basic (Ca^{2+}, Mg^{2+}, and K^+) cations with soil organic matter content may be hindered by acidifying ions. Soil exchangeable calcium (Ca) and magnesium (Mg) can be increased by applying limestone (calcium carbonate) or dolomatic lime (Ca and Mg bicarbonate) Achalu et al. (2012), observed that when lime is applied to neutralize some of the acidity of the soil, the negative charges within the soil exchange complex are released, allowing basic cation.

CONCLUSION

Extremely acidic soils require limes and fertilizers, especially in phosphorus-deficient soils. Lime combined with the least amount of chemical fertilizer specifically, phosphorus is thought to be a more affordable, environmentally friendly, and long-lasting option than chemical fertilizer alone. This applying varying amounts of phosphorus and lime steadily reduced the exchangeable H^+ and exchangeable Al^{3+} over the course of the incubation time. It was shown that applying varying amounts of phosphorus and lime to an exchangeable acidity gradually reduces its value in accordance with the incubation duration. When lime is the only material applied, phosphorus availability rises; when both lime and phosphorus are treated, availability falls. An efficient way to mobilize and make more phosphorus available for plant uptake and soil pH management, which further affects nutrient availability, is to add lime to acidic soils. Different lime and phosphorus applications greatly raised the pH and accessible P of the soil, but they also dramatically reduced the exchangeable acidity of acidic soils.

AUTHORS CONTRIBUTION

G. Sahu conceived and designed, performed data analysis, and wrote the initial draft of the manuscript. D. Panda conducted experiments, collected data, and contributed to the interpretation of results. B. Bhuyan provided critical revisions, assisted in methodology design, and supervised the research. S. Mishra contributed to writing the manuscript, created visualizations, and coordinated submission processes. All authors read and approved the final manuscript.

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