Integrated Effects of Lime and Fertilizer Applications on Soil Properties and Sorghum Performance in Acidic Soils of Western Kenya

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ABSTRACT

Acidic soils cover significant portions of agricultural land in tropical regions, particularly in sub-Saharan Africa, where soil acidity limits crop productivity through multiple mechanisms, including aluminum toxicity, phosphorus fixation, and impaired nutrient cycling. In Western Kenya, where smallholder farmers predominantly grow sorghum (Sorghum bicolor L.) as a staple crop, these soil constraints contribute to chronic yield gaps. While agricultural lime and mineral fertilizers are recognized solutions for soil acidity amelioration, their site-specific interactions and comprehensive effects on both soil health and crop performance remain insufficiently documented. This study evaluated the effects of liming and nutrient microdosing on soil chemical properties and sorghum (Sorghum bicolor (L.) Moench) productivity in the acidic soils of Western Kenya, using factorial field trials conducted in Kakamega and Siaya counties. Treatments combined two lime levels (0 and 4 t ha^{-1}) with varying nitrogen (0, 18.8, 37.5, and 75 kg N ha^{-1}) and phosphorus (0, 6.5, 13, and 26 kg P ha^{-1}) rates. Application of 4 t ha^{-1} lime significantly ($p \leq 0.05$) improved soil chemical properties, increasing soil pH by 20–27%, reducing exchangeable aluminum by 56–89%, enhancing available phosphorus by up to 57%, and increasing total nitrogen by 8–17%. Additionally, soil organic carbon was significantly elevated ($p < 0.001$), with the greatest improvement (39%) observed in Siaya. Microdosing at 37.5 kg N and 13 kg P ha^{-1} ($N_{37.5}P_{13}$) produced the highest sorghum biomass and grain yield responses, with biomass yield increasing by 62–69% and grain yield significantly enhanced at Kakamega ($p < 0.001$). Grain yield over the control rose by 73%, while agronomic efficiency peaked at 24.1 kg grain kg^{-1} nutrient at Siaya. Nutrient uptake also improved under liming and optimal fertilization, with stover nitrogen uptake increasing by 55% at Kakamega and grain phosphorus uptake rising by 44% at Siaya Site 2 ($p < 0.05$). These findings demonstrate that integrating site-specific liming with nutrient microdosing can substantially improve soil fertility and sorghum productivity in acid-degraded soils of Western Kenya.

Keywords: Soil acidity, Liming, Nutrient microdosing, Sorghum productivity, Western Kenya

INTRODUCTION

Nearly 4000 million hectares of the global land is composed of acid soils. This is almost 30 % the total ice-free land and makes approximately 40 % of the arable land world over (Zheng, 2010). Historically, acid soils have resisted agricultural use principally for the high level of toxic aluminum and their high phosphorus fixation capacity. This P transformation process is pH-regulated, organic matter content and soil biological properties (Asomaning, 2020; Prasad & Chakraborty, 2019). The addition of chemical P fertilizers leads to an initial spike in P availability(Sato & Comerford, 2005), followed by P adsorption and precipitation, which will result in a substantial decrease in P availability over time (Muindi et al., 2015).

Liming is an ancient agronomic practice of correction of soil acidity, especially under tropical conditions in which acidic soils constrain agricultural yields.

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Lime application neutralizes acidity in the soil through reaction with hydrogen (H^+) and aluminum (Al^{3+}) ions and, thereby, raises the pH of soil and lowers aluminum toxicity (Mullen et al., 2016). This chemical reaction increases the availability of these necessary nutrients, mainly nitrogen and phosphorus, that tend to be deficient in acidic soils because they are fixed by aluminum and iron compound materials (Gatiboni & Hardy, 2023).

Soil pH increase as a result of liming also enhances a more optimal soil microbial community environment. Soil microorganisms like nitrifying bacteria are activated at higher pH, leading to increased nitrogen cycling and availability (Mitsuta et al., 2025). Specifically, the nitrogen concentration of plants is promoted by the process of ammonium to nitrate conversion, which is readily absorbed by plants (Mitsuta et al., 2025).

In sorghum development, efficient use of nitrogen during early stages of growth is required in order to promote yield and vigor. Any enhancement in nitrogen availability through liming can therefore play a critical role in sorghum development, especially during the

Plants cannot absorb soil P at low pH because pH conditions form insoluble iron (Fe) and aluminum oxides complexes. The alkaline nature of lime reduces the solubility of Fe and Al compounds when the pH reaches neutral levels thus enabling the release of plant-available P (Wagner, 2024). The early development of sorghum roots depends heavily on adequate P accessibility during its initial growth stages. The agricultural benefits derived from lime treatment in soils require further evaluation of possible adverse consequences. High levels of lime treatment coupled with pH values higher than 6.5 results in the formation of additional chemical factors that can obstruct plant growth. Soil pH increases create a situation where the solubility of micronutrients zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu) decreases making them less available to plants (Fageria et al., 2002; Gondal et al., 2021; Rengel, 2003; Riaz et al., 2020). Sufficient micronutrients are essential for sorghum reproductive development and enzyme activities and photosynthesis regardless of any limiting factors. Excessive lime concentrations in the environment result in nutrient deficiencies which produces interveinal chlorosis while damaging grain formation.

Soil phosphorus availability depends intensively on pH and the concentration of calcium ions (Ca^{2+}) in the soil. Acidic soil conditions (pH lower than 5.0) allow phosphate ions to combine with iron (Fe) and aluminum (Al) to form insoluble compounds that plants cannot access. In alkaline solutions with more than 6.0 pH phosphate ions bind with calcium to produce insoluble tricalcium phosphate and other poorly absorbable calcium phosphate compounds (Mkhonza et al., 2020). Soil pH should be kept at about 6.0 to provide plants with the best available phosphorus levels.

Liming soil with high pH and calcium content leads to insoluble calcium phosphate compounds which form in phosphate-treated soils. liming therefore, leads to a reduction in phosphorus fertilizer effectiveness and creates an impact on the available amount of phosphorus for plants.

Lime applications to soil enhance pH levels which results in elevated nitrate (NO_3^-) concentrations in the soil. The liming process combined with calcium application creates insoluble precipitates of calcium phosphate that become abundant. Such treatment renders soil P inaccessible to plants thus leading to reduction in their efficiency levels (Mkhonza et al., 2020).

In crops like sorghum, which are sensitive to nutrient stress, such nitrogen losses through leaching can lead to poor performance and decreased yields. Therefore, careful management of nitrogen fertilization and liming is essential to minimize leaching losses and optimize nitrogen use efficiency.

The successful application of nitrogen fertilizers and liming programs will protect soil from harmful leaching effects and make nitrogen more accessible to farmers. Research shows that the effects of liming in sorghum production systems rely on both the amount of applied lime plus the time of season application. Soil nutrient equilibrium becomes permanently damaged as farmers choose to over-lime their land or introduce lime before the appropriate time. The application of excessive lime or premature distribution causes yield reductions in crops. Farmers in Brazil achieved improved sorghum yields through liming their fields in combination with proper phosphorus applications (Silveira et al., 2018). The research highlighted how achieving best outcomes requires balancing the applications of lime together with fertilizer.

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The outcome of applying specific lime rates to soil will vary according to initial nutrient content alongside soil texture and organic matter levels. Soil analysis results should determine specific treatments with lime which avoids damaging chemical balances in the soil (Omollo et al., 2016). Research in Kenya demonstrates that crop productivity is directly influenced by how lime is distributed either by broadcasting or banding alongside rates of application. The research demonstrates that localized approaches to lime management will help achieve maximum agricultural output.

MATERIALS AND METHODS

Study Sites

The study was conducted across three sites with contrasting edaphic properties in Western Kenya. The Kakamega site (KK) featured Ferralsols with an initial pH of 3.38 ± 0.10 and available phosphorus of 3.26 ± 0.35 mg kg^{-1}. Sega 1 (SY1) and Sega 2 (SY2) both had Acrisols, with SY1 showing higher initial acidity (pH 3.51 ± 0.11) compared to SY2 (pH 3.40 ± 0.09). Baseline available phosphorus was 2.98 ± 0.36 mg kg^{-1} at SY1 and 2.59 ± 0.46 mg kg^{-1} at SY2.

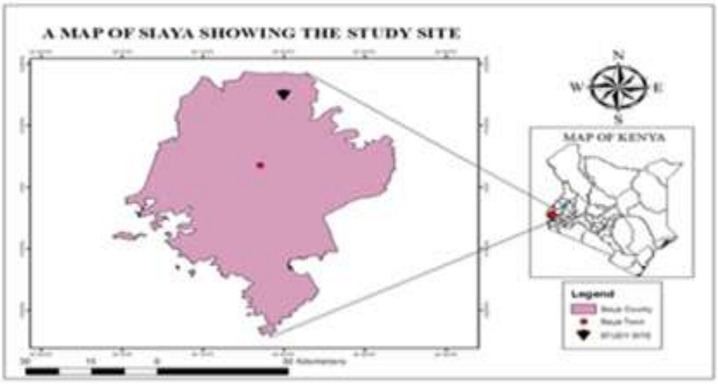

Fig. 1: Map showing Siaya experimental site

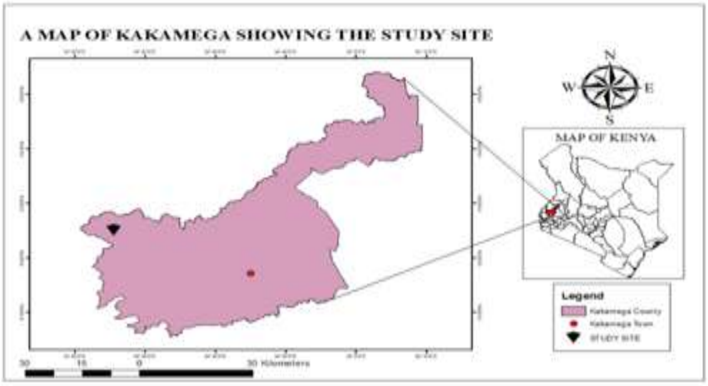

Fig. 2: Map showing Kakamega experimental site

Experimental Design

A factorial experiment combining two lime levels (0 and 4 t ha^{-1}) with three NP fertilizer doses (N_0P_0, $N_{37.5}P_{13}$, and $N_{75}P_{26}$) was implemented in a randomized complete block design with three replications at each site. The lime treatment used finely ground agricultural limestone (85% calcium carbonate equivalent), while fertilizer treatments applied urea and triple superphosphate as N and P sources, respectively.

Data Collection and Analysis

Soil samples were collected at 0-20 cm depth before planting and after harvest for analysis of pH (1:2.5 soil: water), available phosphorus (Bray-1 method), exchangeable aluminum (1M KCl extraction), total carbon and nitrogen (dry combustion). Sorghum grain yield was determined at physiological maturity from net plot harvests, while biomass yield included total above-ground plant material. Statistical analysis employed two-way ANOVA to assess main and interaction effects, with mean separation using Tukey's HSD test at $p < 0.05$. Regression analyses examined relationships between fertilizer doses and response variables. Model adequacy was evaluated through R^2 values and residual analysis.

RESULTS

Soil pH

Soil pH was likewise observed to rise steadily and significantly following the application of lime, and all sites showing some modification. Unamended soils (0tha x N_0P_0) ranged in pH from 4.63 to 5.19, which provided a definition of strong to moderate acidity. Alkalinization followed subsequently after the application of 4 t ha^{-1} of lime. The largest fluctuation was seen in the 4tha x $N_{75}P_{26}$ treatment where soil pH increased to a level of 6.23, which shows a general increase of 0.8 to 1.6 units of pH from control. These increases were up to 34% rise in the soil pH over the initial level. Low doses of fertilizer, i.e., 4tha x $N_{37.5}P_{13}$, raised high levels of pH by 0.9–1.4 units, testifying to the synergistic action of lime with some fertilization. Statistical significance of the lime effect was very significant ($p < 0.001$) at all the locations, but the effect of the fertilizer dose alone was moderate at one location only ($p = 0.024$).

Available phosphorus

Available phosphorus (P) was very responsive to application of lime and fertilizer rate (Table 1). Control plots were characterized by low P concentration levels ranging from 2.01 to 2.92 mg kg^{-1}, which conformed to P fixation in acidic soils. The addition of lime, particularly under more nutrient-deficient regimes, elevated the availability of P significantly. The 4tha x $N_{75}P_{26}$ treatment yielded the largest P values, 7.52 to 8.16 mg kg^{-1}, increases of over 160–300% above control. Mid-level treatments 4tha x $N_{37.5}P_{13}$ and 4tha x $N_{18.8}P_{6.5}$ also achieved sizable gains, typically double P values above baseline. Lime ($p < 0.001$) and fertilizer ($p < 0.001$) were significant statistically, with the recommendation that integrated management was advisable for use in recovering phosphorus in acid-affected soils.

Exchangeable Aluminum

Exchangeable aluminum (Al), being one of the primary indicators of acid toxicity, fell significantly with the addition of lime (Table 1). Control plots yielded 1.59–2.00 Cmol kg^{-1} values, which are low for root growth and nutrient acquisition. The 4tha x N75P26 treatment brought Al values down to 0.87 Cmol kg^{-1} or decreases of 44–57% relative to control.

Reductions were strongest in blends of lime with moderate to high application rates of nutrients, i.e., 4tha x $N_{37.5}P_{13}$ and 4tha x $N_{18.8}P_{6.5}$, where contents of Al reduced consistently below 1.25 Cmol kg^{-1}. Lime had significant effects on Al at all sites ($p < 0.001$), and an interaction effect between fertilizer and lime was significant ($p < 0.05$) in the most acid-sensitive soils, which suggests that amelioration as measured by aluminum is greater when the two amendments are applied together.

Table 1: Effects of Lime and Nutrient Microdosing on Soil pH, Available Phosphorus (P), and Exchangeable Aluminum (Al) Across Three Study Sites (Kakamega, Sega 1, and Sega 2)

	-----------Soil pH --------			----- Soil P (mg kg^{-1}) ----			----- Soil Al (Cmol kg^{-1}) -----		
Treatment	KK	SY1	SY2	KK	SY1	SY2	KK	SY1	SY2
0tha x N_0P_0	5.19^{abc}	4.63^{a}	5.14^{a}	2.68^{a}	2.92^{a}	2.01^{a}	2.23^{c}	1.86^{b}	1.59^{b}
0thaxN18.8P6.5	5.11^{ab}	4.67^{a}	5.16^{a}	3.75^{ab}	3.09^{a}	2.76^{ab}	$2b^{c}$	1.83^{b}	1.6^{b}

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0tha x $N_{37.5}P_{13}$	5.4^{abcd}	4.72^{a}	5.29^{ab}	4.07^{ab}	3.48^{ab}	3.26^{abc}	1.62^{abc}	1.79^{b}	1.56^{b}
0thax$N_{75}P_{26}$	5.07^{a}	4.68^{a}	5.42^{ab}	4.27^{abc}	3.87^{ab}	4.15^{abcd}	1.61^{abc}	1.73^{b}	1.5^{b}
4tha x N_0P_0	5.87^{cd}	5.46^{b}	5.8^{bc}	4.25^{ab}	3.22^{a}	4.82b^{cd}	1.13^{ab}	1.09^{a}	1.43^{b}
4tha x $N_{18.8}P_{6.5}$	5.76^{abcd}	5.65^{b}	5.83^{bc}	4.73^{bc}	3.9^{ab}	5.57^{cde}	1.25^{ab}	0.92^{a}	1.17^{a}
4tha x $N_{37.5}P_{13}$	5.77b^{cd}	5.32^{b}	6.04^{c}	6.16^{cd}	4.93^{ab}	6.25^{de}	1.11^{ab}	0.88^{a}	1.11^{a}
4tha x $N_{75}P_{26}$	6.04^{d}	5.48^{b}	6.23^{c}	7.52^{d}	5.42^{b}	8.16^{e}	0.89^{a}	0.87^{a}	1.12^{a}
SED	0.22	0.14	0.18	0.61	0.65	0.83	0.29	0.19	0.06
CV%	8.49	5.67	6.8	27.47	35.63	38.03	41.71	29.82	9.13
P-value (Lime)	<0.001	<0.001	<0.001	<0.001	<0.05	<0.001	<0.001	<0.001	<0.001
P-value (Fert)	NS	NS	0.0238	<0.001	<0.05	<0.001	NS	NS	<0.001
P-value (Lime x Fert)	NS	NS	NS	NS	NS	NS	NS	NS	<0.05

Oil Nitrogen

Table 2 shows that soil nitrogen was significantly increased after fertilizer and lime application with equal trends at all trial sites. The sum of total nitrogen varied from 0.03% to 0.16% in control (0tha x N_0P_0), indicating low fertility of acid-stressed plots.Application of fertilizer alone raised nitrogen content moderately. However, 4 t ha^{-1} lime and nutrient microdosing provided the most significant improvement. Both 4tha x $N_{75}P_{26}$ and 4tha x $N_{37.5}P_{13}$ treatments had 0.25% N, an absolute increase of as much as 0.22% or relative increases of as much as 733% compared to initial values in the driest location. Statistical analysis confirmed that both lime and fertilizer both significantly ($p < 0.001$) affected nitrogen at all locations. Lime and fertilizer rate improved added N availability and retention, and fertilizer rate improved N with

Table 2: Effects of Lime and Nutrient Microdosing on Total Soil Nitrogen (N), Soil Organic Carbon (SOC), and Carbon-to-Nitrogen Ratio (C:N) Across Three Sites (Kakamega, Sega 1, and Sega 2)

	--------Soil N (%) -------			--------Soil OC (%) ------			-------Soil CNR------		
Treatment	KK	SY1	SY2	KK	SY1	SY2	KK	SY1	SY2
0tha X N_0P_0	0.16^{a}	0.03^{a}	0.08^{a}	1.98^{a}	1.37^{a}	1.26^{a}	12.69^{b}	64.53^{b}	15.8^{a}
0tha X $N_{18.8}P_{6.5}$	0.19^{ab}	0.09^{bc}	0.08^{ab}	2.16^{abc}	1.48^{ab}	1.34^{ab}	11.53^{ab}	16.1^{a}	14.13^{a}
0tha x $N_{37.5}P_{13}$	0.2^{b}	0.13^{c}	0.09^{ab}	2.26^{bcd}	1.6^{bcd}	1.44^{abc}	11.27^{ab}	13.16^{a}	14.3^{a}
0tha X $N_{75}P_{26}$	0.21^{bc}	0.14^{cd}	0.1^{abc}	2.33^{cde}	1.73^{cde}	1.54^{bcd}	11.23^{ab}	12.42^{a}	13.92^{ab}
4tha x N_0P_0	0.19^{ab}	0.04^{ab}	0.09^{ab}	2.09^{ab}	1.54^{abc}	1.57^{bcd}	11.82^{ab}	58.36^{b}	16.19^{a}
4tha x $N_{18.8}P_{6.5}$	0.23^{cd}	0.13c	0.1bc	2.37^{cde}	1.69^{bcd}	1.7^{cde}	10.14^{abc}	13.94^{a}	14.63^{a}
4tha x $N_{37.5}P_{13}$	0.25^{d}	0.15^{cd}	0.12^{cd}	2.47^{de}	1.81^{de}	1.78^{de}	10.01a	13.14^{a}	13.42^{a}
4tha x $N_{75}P_{26}$	0.25^{d}	0.2d	0.13^{d}	2.54^{e}	1.95^{e}	1.92^{e}	10.13^{ab}	10.82^{a}	12.12^{a}
SED	0.01	0.02	0.01	0.07	0.07	0.09	0.85	8.41	1.46
CV%	9.94	35.1	15.14	6.43	9.08	11.75	16.27	70.52	21.58
P-value (Lime)	***	***	***	***	***	***	**	NS	NS
P-value (Fert)	***	***	***	***	***	***	**	***	**
P-value (Lime X Fert)	NS	NS	NS	NS	NS	NS	NS	NS	NS

a normal dose-response relationship. The findings confirm the need for the use of lime in conjunction with a particular input of nutrient to rebuild the level of soil nitrogen under acid-degraded conditions.

Soil Organic Carbon

Treatment effects on SOC content also rose in a parallel manner as shown in Table 2. Control plots recorded moderate carbon stocks of between 1.26% and 1.98% SOC. SOC was somewhat improved with fertilizer alone treatment but was optimized when lime was added. SOC contents between 1.92% and 2.54% were recorded in 4tha x $N_{75}P_{26}$ treatment, representing a 51% increase from the control. Comparable 0.3–0.5 percentage point or 20–40% gains were achieved by mid-treatment applications like 4tha x $N_{37.5}P_{13}$ and 4tha x $N_{18.8}P_{6.5}$, indicating that moderate fertilizer application with addition of lime can consistently enhance organic matter. Both lime and fertilizer significantly increased SOC at all sites ($p < 0.001$). Lack of interaction between fertilizer and lime suggests additive rather than synergistic action. The results support the suggestion that enhanced root biomass, microbial activity, and residue incorporation due to relieved acidity limitation could be accountable for carbon sequestration under fertilizer and lime treatment.

Soil C:N Ratio

Table 2 shows that Carbon-to-Nitrogen (C:N) ratio decreased largely at Siaya Site 1 and Kakamega. With a mean of 12.7 in Kakamega, close to well-composted organic waste, and up to 64.5 at Siaya Site 1, C:N in control treatments (0tha x N_0P_0) ranged widely. The C:N ratio was reduced quite noticeably by fertilizer alone, especially at medium to high levels (e.g., $N_{37.5}P_{13}$ and $N_{75}P_{26}$), indicating higher availability of nitrogen than carbon content. For instance, at Siaya Site 1, C:N was reduced over 75% for the 4tha x $N_{37.5}P_{13}$ and 4tha x $N_{18.8}P_{6.5}$ treatments, from 64.5 in the control to approximately 13.2–13.9. This also verifies the restorative action of simultaneous nutrient supplementation to the organic matter balance. Concurrently, the C:N ratio declined to approximately 10.0–10.1 in the case of 4tha x $N_{37.5}P_{13}$ and 4tha x $N_{75}P_{26}$ treatments at Kakamega by up to 21% less than control. This implies that applications of fertilization and liming led to enhanced microbial digestion and nitrogen mineralization.

Performance of Sorghum Grain and Biomass Yield

Sorghum grain yield (Fig.3) likewise shared comparable patterns of treatment sensitivity, albeit with relatively smaller treatment ranges than biomass. Control levels at 0.5 and 0.81 t ha^{-1} were used as the points of reference from which the treatments were derived. Treatment 4tha x $N_{75}P_{26}$ demonstrated highest improvement in SGY with a maximum of 3.0 t ha^{-1} and showing 270–350% yield improvement above control. Of particular interest, 150–250% advances were generated by treatments qualifying as moderate inputs, like 4tha x $N_{18.8}P_{6.5}$ and 4tha x $N_{37.5}P_{13}$, with mean values for SGY of 1.4 to 2.5 t ha^{-1} across sites. Throughout all the treatments, increase in gain yield was most significantly associated with the application of lime because unlimed plots always produced less than limed plots at any fertilizer level. These results demonstrate the potential of lime to enhance nutrient uptake and subsoil limitations, and induce measurable increases in sorghum grain yields with integrated management practice.

Biomass yield of sorghum showed a consistent upward response to lime application combined with increasing levels of fertilizer microdosing (Fig.3). Across sites, the control treatment (0tha x N_0P_0) resulted in the lowest SBY values, ranging from approximately 2.0 to 4.3 t ha^{-1}, depending on baseline soil conditions. On the other hand, maximum biomass was seen with 4tha x $N_{75}P_{26}$ with SBY to the value of 14.4 t ha^{-1} in conditions of optimal growth — an increase by over 250–400% over control. Intermediate rates using half of the nutrient rates like 4tha x $N_{37.5}P_{13}$ and 4tha x $N_{18.8}P_{6.5}$ also showed impressive improvement with biomass yields considerably more than 10 t ha^{-1}, which is equivalent to a 130–250% increase above non-fertilized treatments. The results

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show that application of lime is a major yield booster, especially when combined with medium rates of nitrogen and phosphorus application. The low nutrient rates alone were inconsistent in performance, but improved drastically when applied in combination with lime, hence confirming the synergistic action of acidity increase towards optimizing biomass production.

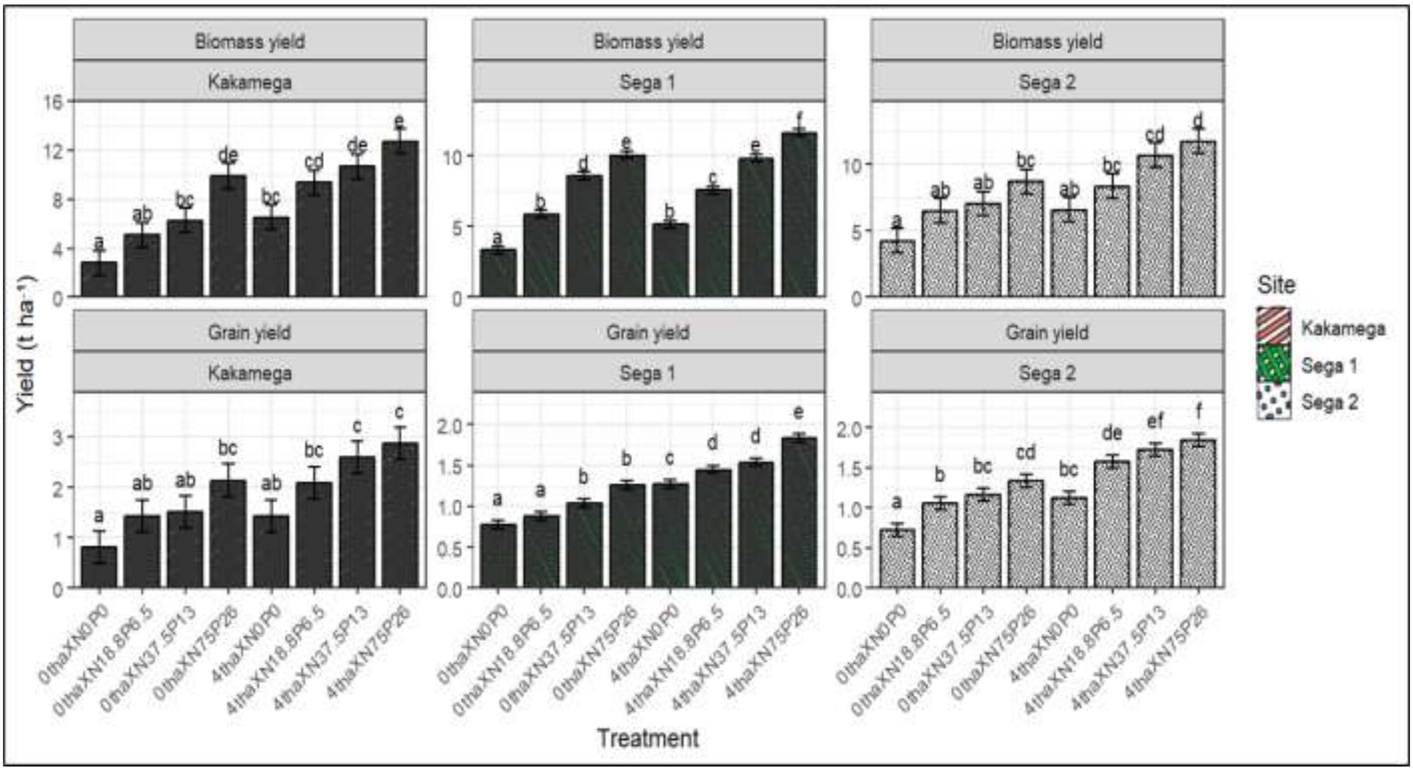

Fig. 3: Effect of Lime and Nutrient Microdosing on Sorghum Biomass and Grain Yield Across Kakamega, Sega 1, and Sega 2 Sites

Correlation Between Soil Chemical Properties and Sorghum Yield Components

Pearson correlation analysis was conducted to explore the relationships between soil chemical properties and sorghum grain yield (SGY) and biomass yield (SBY) across the three study sites (Kakamega, Sega 1, and Sega 2). The analysis revealed several significant relationships that underscore the pivotal role of soil amelioration in enhancing crop productivity in acidic soils.

Soil pH showed a strong positive correlation with SGY ($r = 0.76$, $p < .001$) and SBY ($r = 0.71$, $p < .001$), suggesting that liming substantially improved sorghum performance by reducing soil acidity. Conversely, exchangeable aluminum exhibited a strong negative correlation with SGY ($r = -0.72$, $p < .001$) and SBY ($r = -0.70$, $p < .001$), indicating that higher Al toxicity adversely affected yield outcomes.

Available phosphorus was positively associated with both SGY ($r = 0.66$, $p < .001$) and SBY ($r = 0.68$, $p < .001$), demonstrating the importance of P availability, likely enhanced by pH correction and targeted fertilization. Similarly, total soil nitrogen showed moderate to strong positive correlations with SGY ($r = 0.61$, $p < .01$) and SBY ($r = 0.63$, $p < .01$), while soil organic carbon was also positively related to both yield parameters ($r = 0.59$ and 0.60 for SGY and SBY, respectively, $p < .01$).

DISCUSSION

Soil pH

Progressively increasing soil pH with the treatments is due to the neutralizing effect of farm lime, primarily calcium carbonate ($CaCO_3$). While reacting with hydrogen ions (H^+) from acidic components of the soil upon contact, lime decreased proton activity in soil solution and thereby increased the pH:

$CaCO_3+2H \rightarrow Ca^{2+}+H_2O+CO_2\uparrow$

In addition to the reduction in soil acidity, this reaction allowed for exchange of exchangeable Al^{3+} and H^+ on colloidal surfaces, with an overall increase in base saturation of the soil. The observed maximum increase in pH, 6.23 in treatment 4tha x $N_{75}P_{26}$, was an indication of additive influence of lime buffering and possible rhizosphere crop of pH due to root activity following fertilization.

Similar pH increase in weathered soils across tropical regions was monitored by Kisinyo et al. (2015) and Anderson et al. (2013) after applying lime to soils and synergistic pH increase in acid soils across Kenya was monitored by Muindi et al. (2015) after they added moderate amounts of phosphorus to Kenyan acid soils and lime. Acidification under fertilizer-alone treatment, especially where ammonium-sourced nitrogen was used, is also in line with reported nitrification processes:

$NH_4^++2O_2 \rightarrow NO_3^-+2H^++H_2O$

This produces more H^+ ions, which again decrease pH unless regulated by liming.

Available Phosphorus

In highly acidic soils, phosphate ions (PO_4^{3-}) can be susceptible to fixation by Al^{3+} and Fe^{3+} through precipitation reactions:

$Al^{3+}+H_2PO_4^- \rightarrow AlPO_4\downarrow+2H^+$

These reactions constrain phosphorus availability. By raising soil pH and diminishing Al^{3+} activity, lime interferes with such fixation processes and increases P solubility. This is evidenced by the elevation in accessible P values of 2.01-2.92 mg kg^{-1} in control plots to 7.52-8.16 mg kg^{-1} in 4tha x $N_{75}P_{26}$.

Patterns of simultaneous P recovery were similarly mentioned by Haynes (1982) and Sanchez & Uehara (1980), and recently by Opala (2023) especially when liming had reduced, but before Al saturation, before phosphorus addition. Increased pH could have also triggered microbial P mineralization and desorption by roots from colloidal surfaces into solution, enhancing mid-level nutrient treatments availability.

Though lime minimized P fixation, fertilizer application provided labile P, which — under conditions of lowered Al toxicity — was held in solution within the soil and was more easily absorbed. Literature warns that overliming will ultimately result in precipitation of calcium phosphate if pH levels are greater than optimal levels (>6.5), although all levels taken during this trial were below this figure.

Exchangeable Aluminum

Exchangeable aluminum (Al^{3+}), which is characteristic of acid soils with pH <5.5, decreased substantially after lime treatment. Al^{3+} increases in solubility in acid soils and can drastically suppress root elongation and nutrient uptake. The increase in exchangeable Al — as much as 57% in limed plots — indicated hydrolysis and precipitation of Al^{3+} in the form of insoluble aluminum hydroxide:

$Al^{3+}+3OH^- \rightarrow Al(OH)_3\downarrow$

Such a process is favored by soils with high pH and basic to neutral conditions. Haynes (1982) labeled such a path as a critical process for alleviating aluminum toxicity following liming, a process evidenced in African acid soils where lime caused substantial reduction of active fractions of Al in a matter of years (Muindi et al., 2015; Wilding & Drees, 1985).

The absence of a large lime × fertilizer interaction on Al indicated that the liming effect-controlled aluminum detoxification and could be partly independent of fertilizer application in the short term.

Soil Organic Carbon (SOC)

Addition of fertilizer and lime favorably enhanced soil organic carbon (SOC), and the latter showed a progressive increase with the intensity of treatments. The initial values of SOC from the control plots ranging from 1.26% to 1.98% agreed with the moderate organic matter accumulation in tropical upland soils. Lime exhibited the greatest SOC gain, while sole fertilizer treatment had the lowest. The 4tha x $N_{75}P_{26}$ yielded 1.92% to 2.54% SOC levels equivalent to absolute gains of 0.56 percentage points, or a 51% improvement over control. Lime and microdose treatments, like 4tha x $N_{37.5}P_{13}$ and 4tha x $N_{18.8}P_{6.5}$, generated 20–40% gains consistent with the function of moderate fertilizer microdosing under the relief of pH constraints simultaneously.

Greater production of root biomass and associated microbial activity by removal of the acidity constraint would in turn facilitate such an enhancement. Acid soils result in organic matter accumulation due to sluggishness in microbial degradation and decomposition. Microbial enzymes, namely cellulases and proteases that function optimally at neutral pH have been found to be suppressed by the addition of lime (Sumner & Noble, 2003). Also, increased availability of nutrients favors plant growth, which favors return of residues and rhizodeposition, further increasing the reserve of organic carbon. Incidentally, additive effect is supported by statistical independence of lime and fertilizer effects since none of the interactions were significant.

This is consistent with research findings of Chimdi et al. (2012), which indicate that SOC increased in Ethiopian acid soils resulted independently from liming and fertilizer addition with additive effects from different physiological as well as chemical pathways.

C:N Ratio

There were treatment-specific decreases in the carbon-to-nitrogen (C:N) ratio, notably in Siaya Site 1 and Kakamega. Rats in control conditions varied immensely; in Kakamega, they were 12.7, analogous to stabilized compost values (Stevenson, 1994); in Siaya Site 1, 64.5, with nitrogen-deficient organic matter that would tend to immobilize by microorganisms.

C:N ratios were greatly lowered by fertilizer treatment per se, especially at the moderate to high regimes. Co-application of lime-fertilizer enhanced the trend. For instance, 4tha x $N_{37.5}P_{13}$ and 4tha x $N_{18.8}P_{6.5}$ lowered the C:N ratio at Siaya Site 1 to approximately 13.2-13.9, i.e., over 75% lower compared to the control. Similarly, under these treatments, Kakamega dropped to 10.0–10.1, i.e., enhanced nitrogen mineralization.

These results imply several interconnected mechanisms: lime treatment promoted microbial breakdown of organic refuse, mobilizing additional nitrogen through ammonification; supplemental N augmented inorganic N availability, complementing the C:N deficiency. Furthermore, alleviating root stress and promoting greater rhizodeposition of labile carbon substrates, alleviated aluminum toxicity may have indirectly contributed to increased microbial activity.

In Andosols of volcanism, Inoue et al. (2001) likewise showed similar declines in C:N under limed fertilizer treatment. Combined amendments enhanced stoichiometry of the soil through compulsion of decomposition equilibrium to net mineralization. Directionality of fertilizer and lime effect on C:N signals complementarity in function, although no interaction effect was statistically significant.

Scientific Implications

These results collectively highlight the critical role of lime in managing acid soils. Beyond raising pH, lime reduces toxic aluminum levels and unlocks phosphorus that might otherwise remain unavailable. Fertilizers, while essential for supplying nutrients, can further acidify soils if applied without liming, potentially exacerbating constraints on root growth and nutrient uptake. Moreover, the subtle but positive influence of lime on organic matter dynamics (C:N ratio and SOC) suggests additional long-term benefits for soil biological functioning and fertility.

Integrated soil fertility management—specifically combining lime with balanced fertilization—is clearly more effective than using either input in isolation. Such strategies are especially vital for smallholder systems in acid soil regions, where restoring soil health is foundational to achieving reliable crop productivity.

The results of this study reinforce the critical role of integrated soil fertility management (ISFM) in improving sorghum productivity in acidic tropical soils. The observed improvements in soil chemical properties—particularly increased pH, reduced exchangeable Al, and enhanced phosphorus availability—translate directly into increased sorghum grain and biomass yields. These outcomes are consistent with earlier findings in acid soil contexts, where lime application has been shown to correct soil acidity, alleviate aluminum toxicity, and improve nutrient use efficiency (Nziguheba et al., 2022; Vanlauwe et al., 2015).

Physiological and soil chemical drivers of sorghum yield response

Under combined applications of lime and fertilizer, sorghum grain and biomass yields were significantly increased, reflecting a mix of chemical amelioration of the soil and physiological stimulation. The underlying modification of the chemical root zone environment accounted for the evenly distributed increase in yields across treatment levels for the 2016–2018 seasons. In acidic soils, exchangeable acidity and aluminum saturation are known to significantly limit root growth and nutrient uptake. Lime application, especially at 4 t ha^{-1}, was crucial in neutralizing these conditions (Fageria & Baligar, 2008). In addition to detoxifying Al^{3+} via hydroxide precipitation, the pH rise also altered the sorption equilibria that control phosphorus dynamics. Phosphate ions are held in acid soils by complexation with Al and Fe oxides. Liming would most likely have released plant-available phosphorus by increasing the pH and inhibiting the formation of insoluble aluminum phosphate complexes.

Considering improved sorghum grain yield (up to 3.0 t ha^{-1} under $4tha^{-1}xN_{75}P_{26}$) and biomass yields (up to 14.4 t ha^{-1}), the subsequent chemical changes created an improved permissive nutrient acquisition environment. Central metabolic processes were physiologically boosted by the increased availability of nutrition. Nitrogen availability facilitated the development of proteins and chlorophyll, which was vital to grain development and photosynthetic function. Phosphorus uptake simultaneously stimulated root architecture development and ATP synthesis, enhancing the plant's capacity to absorb water and other nutrients. Reproductive success and enhanced vegetative growth were the increased outcomes. Also, by increasing pH to levels most conducive to enzymatic activity, liming could have initiated population growth among rhizosphere microbes. Liming, as per Enesi et al. (2023), enhanced mineralization and bioavailable nutrient release by stimulating bacterial populations involved in organic matter turnover that are suppressed at pH values less than 5. Even at reduced application levels, this action most likely enhanced the efficiency of microdosed fertilizer applications. In spite of the use of fertilizer, continued poor productivity on the unlimed plots ensured that acid subsoil conditions remained a limiting factor until they were corrected. Even with external inputs, nutrient uptake becomes inefficient in such conditions because roots are restricted both geographically and functionally (Sanchez, 1976). Thus, the application of lime served as a structural facilitator of physiological processes as well as a chemical modification. These results were similar to those published by Getahun et al. (2019) and Soileau & Bradford (1985) on sorghum in similarly acidic tropical soils, where liming significantly increased dry matter buildup and grain filling capacity. The present study's responsiveness to moderate fertilizer doses under limed conditions, however, suggested a threshold-based yield dynamic, beyond which diminishing returns might occur. This phenomenon needs more investigation in relation to the nutrient use efficiency of sorghum under various edaphic constraints.

Correlation Analysis

Sorghum yields and chemical soil factors were positively correlated by Pearson correlation analysis at the Kakamega, Sega 1, and Sega 2 locations. Grain yield (SGY; $r = 0.76$, $p < 0.001$) and biomass yield (SBY; $r = 0.71$, $p < 0.001$) were directly correlated with soil pH, affirming the vital role that correction of acidity plays in boosting yields. The increase in pH following lime addition likely stimulated root and microbial growth and reduced aluminum saturation and enhanced nutrient solubility. The positive correlation showed that the greater volume of rooting and increased chemical conditions generated by correction of pH were advantageous to sorghum.

On the other hand, exchangeable aluminum (Al^{3+}) negatively correlated with SGY ($r = –0.72$, $p < 0.001$) and SBY ($r = –0.70$, $p < 0.001$), indicating that aluminum toxicity remained the prime constraint under the acid conditions which had not been altered. Al^{3+} has been known to inhibit symbiotic microbial processes, nutrient uptake, and root growth, and hence this finding was expected. The reverse correlation validated previous findings that lime amendment enhanced sorghum yields and root-zone parameters by precipitating and hydrolyzing Al^{3+} as $Al(OH)_3$.

Both SGY ($r = 0.66$, $p < 0.001$) and SBY ($r = 0.68$, $p < 0.001$) were significant positive correlations with available phosphorus (P), and this might be due to more P desorption and less fixation at high pH values. Formation of insoluble aluminum phosphates constrains phosphorus solubility under acid soils; the pH-related correlation established herein validated that phosphate ion release controlled by pH directly influenced sorghum nutrient and dry matter uptake.

Grain yield ($r = 0.61$, $p < 0.01$) and biomass yield ($r = 0.63$, $p < 0.01$) were significantly positively correlated with the total soil nitrogen, and thus nitrogen supply was again an important factor determining yield. Nitrogen supply could have increased due to the fact that pH recovery stimulated nitrification and mineralization processes. Equally, SOC was significantly correlated with SGY ($r = 0.59$) and SBY ($r = 0.60$), the latter two also significant at $p < 0.01$, indicating its role in enhancing soil structure, microbial activity, and the ability of cation exchange for nutrients.

All these interconnections established that sophisticated chemical and physiological feedbacks triggered by soil amendments were responsible for the increments in sorghum production. In acidic tropical systems, the interplay among pH, aluminum, phosphorus, nitrogen, and carbon reiterated that global soil fertility restoration was indispensable in order to acquire the optimum agronomic results.

CONCLUSIONS

The research proved that the integration of 4 t ha^{-1} application of agricultural lime with moderate to high microdosed applications of fertilizers markedly enhanced sorghum yield and chemical soil properties in acidic western Kenyan soils. $N_{37.5}P_{13}$ and $N_{75}P_{26}$ lime treatments consistently increased soil pH by as much as 1.6 units, lowered exchangeable aluminum by as much as 57%, and increased available phosphorus by more than 300% compared to controls. The application of chemicals gave grain yield of 3.0 t ha^{-1} and biomass yield of as much as 14.4 t ha^{-1}, which equal relative increases of 270–400% at the locations in question.

Correlation analysis also revealed strong positive associations between sorghum yield and soil pH, available phosphorus, total nitrogen, and organic carbon, and negative association of exchangeable aluminum with grain and biomass yields. Of treatment combinations, lime at 4 t ha^{-1} with intermediate nutrient rates (e.g., $N_{37.5}P_{13}$) had persistent agronomic and chemical impacts under different soil conditions.

But where high application rates of fertilizers like $N_{75}P_{26}$ are applied, careful adoption is indicated where buffer potential and initial baseline fertility are low. High fertilizer uses entails risks like nutrient imbalance, inadvertent acidification, or economic inefficiency in resource-constrained systems. Just as lime was required to counteract acidity, excessive lime application in low-buffer potential soils might entail raising pH beyond optimal ceilings, reducing solubility of phosphorus or upsetting microbial balance. Therefore, on-site calibration of fertilizer and lime applications remains critical for sustainable soil fertility recovery as well as for maximization of crop performance.

These results support the chemical and biological significance of targeted amendments in tropical acid and acid-degraded soil rehabilitation and represent an integrated strategy towards improving the productivity of sorghum based on equilibrated input utilization.

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