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Enhancing Sorghum Productivity in Acidic Soils Through Lime–Fertilizer Synergism: Agronomic, Economic, and Composite Performance Analysis

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ABSTRACT

Sorghum productivity in Western Kenya is severely constrained by acidic soils, particularly Ferralsols and Acrisols prone to aluminum toxicity and phosphorus fixation. This study assessed the performance of lime-integrated fertilizer treatments under smallholder conditions using a randomized complete block design across three sites. Sorghum grain yield (SGY), agronomic efficiency (AE), nutrient uptake efficiency (NUE), and gross margin (GM) were measured alongside the formulation of a composite Performance Index (PI) designed to simulate both physiological and economic effects. We developed a composite Performance Index to integrate agronomic and economic outcomes, enabling balanced evaluation of lime–fertilizer strategies across acid-prone sites. The PI incorporated weighting scenarios reflecting equal and smallholder-adjusted preferences. Results showed that lime enhanced AE (up to 55%), NUE (up to 34.6%), and SGY $\geq$ 1.8 t ha^{-1} across sites, with intermediate fertilizer rates yielding superior performance. GM exceeding \$450 ha^{-1} and benefit–cost ratios over 2.0, demonstrating strong economic viability, Lime + $N_{37.5}P_{13}$ consistently outperformed other treatments, offering agronomic–economic balance and robust PI ranking across sensitivity models. Radar and contour plots identified optimal combinations and revealed trade-offs between efficiency and yield. These findings support lime as a foundational input rather than a supplemental one, and advocate for context-driven ISFM strategies aligned with smallholder realities. The PI framework offers a flexible and empirically grounded tool for sustainable intensification decisions in acid soil systems.

Keywords □Acidic Soils □Lime–Fertilizer Integration □Performance Index □Agronomic Efficiency □Gross Margin

INTRODUCTION AND BACKGROUND

Sorghum is a climate resilience and food security crop in sub-Saharan Africa, especially under smallholder systems. Due to its tolerance to drought and low inputs, it is capable of performing well on marginal lands; however, its productivity is severely limited by soil acidity that is prevalent in Western Kenya Ferralsols and Acrisols. They are characterized by low pH levels, high aluminum saturation, and phosphorus fixation, which together hinder root growth, nutrient acquisition, and plant performance.

Soil acidity impacts sorghum indirectly by disrupting chemical and biological processes. Root development and nutrient uptake are inhibited by aluminum toxicity, and phosphorus is trapped by precipitation with Fe and Al oxides. Kisinyo et al. [1] asserts that soils in which such occurrences are common include Western Kenya, where exchangeable Al levels are typically above threshold levels to crops and hence contribute to impaired recovery of nutrients and stunted growth. Gudu et al. [2] also illustrated that maize and sorghum yields decline considerably under these limitations even when fertilizer is used unless liming is used.

Liming has been broadly accepted as remedial measure. Lime alkalinizes soils which increases availability of certain essential nutrients (such as phosphorus, calcium, and magnesium), promotes root growth and decreases availability of exchangeable Al^{3+} by precipitating it. It was demonstrated by Opala [3] that application of lime enhances quite certainly the phosphorus uptake in acid soils and the build-up of biomass, particularly in combination with moderate rates of P fertilizers. Equally, Esilaba et al. [4] pointed out that as far as sustainable nutrient management in highland soils in Kenya is concerned, the application of lime is a critical aspect considering that it not only neutralizes the acid but also ensures that the fertilizer deployed is utilized effectively.

In spite of its demonstrated advantage, utilization of lime by the smallholders is not gaining a lot of headway and this is the effect of the cost, labor intensity and lack of awareness. A pragmatic way to eliminate these barriers is Integrated Soil Fertility Management or ISFM, which is advocated by Vanlauwe et al. [5]. ISFM promotes site-specific blends of mineral fertilizers, organic amendments and soil conditioners such as lime and focuses on targets of agronomic proficiency, economic feasibility and environmental sustainability.

Despite the prevalent application of single-variable metrics like grain yield or net returns to assess treatment effectiveness, these indicators frequently obscure essential trade-offs related to nutrient uptake, soil amendment efficiency, and farmer investment. Particularly in systems susceptible to acidity, where physiological limitations are intertwined with economic factors, there is a pressing need for a more comprehensive evaluative framework. In light of this, we propose a composite Performance Index (PI) that integrates agronomic and economic aspects into a cohesive scoring system. This methodology aids in the clearer identification of treatments that provide balanced benefits, enhances comparability across different sites, and addresses the persistent demand for multidimensional metrics in sustainable intensification research [5–7].

The current research lays on the ISFM paradigm to assess lime and fertilizer interaction in acidic soils through the use of sorghum as the test crop. A multiple index performance model is used where agronomic efficiency (AE), nutrient uptake efficiency (NUE), gross margin (GM), and grain yield (SGY) are combined in determining the best combinations of inputs. Basing the model on the multi-dimensional constructs by Congreves et al. [8] and Weih et al. [9] premises, the model employs sensitivity-weighted scoring to simulate sustainability limits and make decisions within the conditions of smallholder realities.

As depicted in Figure 1, the conceptual framework maps how acid soil constraints interact with nutrient dynamics to create a productivity gap, addressed through integrated liming and fertilization. The resulting outcomes—both physiological and economic—are captured through performance metrics feeding into a composite recommendation index.

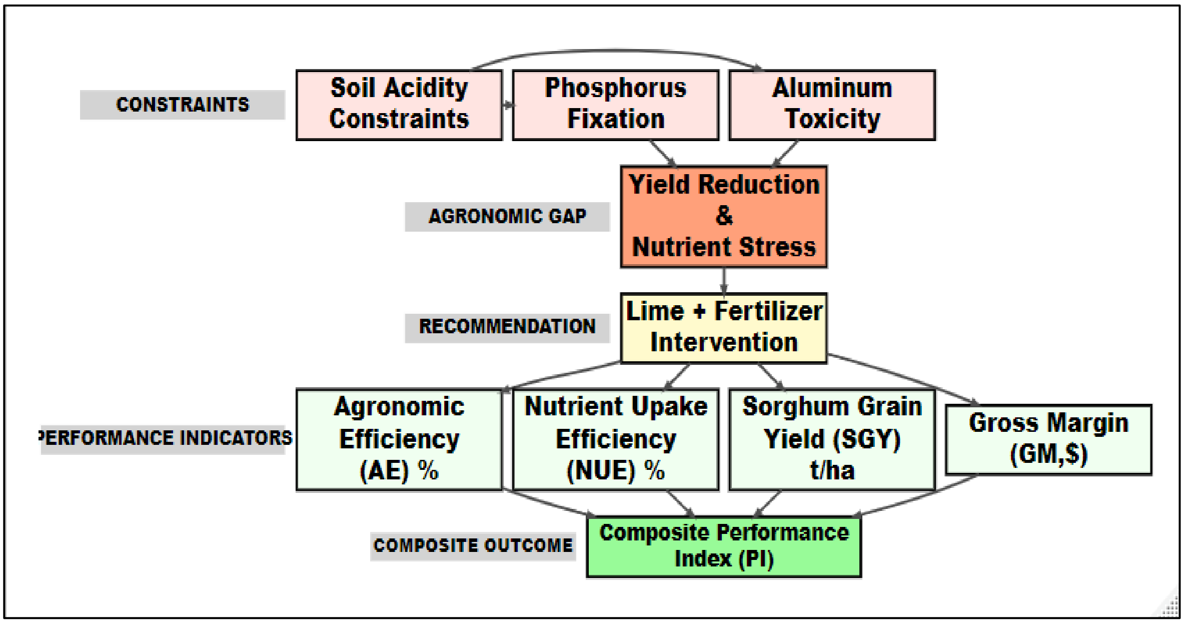

Fig. 1 Conceptual flow chart illustrating causal linkages from soil acidity to composite agronomic and economic outcomes via lime–fertilizer intervention

Footnote:

This diagram synthesizes the pathway from soil chemical limitations through physiological stress to nutrient interventions and composite performance metrics. Arrows represent directional influence, while node groupings reflect thematic domains of constraint, intervention, and outcome. Agronomic and economic indicators converge toward a composite index designed to guide smallholder decision-making under acid soil stress.

MATERIALS AND METHODS

2.1 Study Sites and Experimental Design

Field trials were conducted in three sites in Western Kenya: Siaya 1 (ferralsols), Kakamega (acrisols) and Level 2 (ferralsols) over two cropping phases. The experiments were executed on smallholder farmers' fields. The trials involved three replications per site, and their design was the randomized complete block (RCBD). A fertilizer dose of 0 and 4 t ha^{-1} of lime together with three levels of Nitrogen-Phosphorus fertilizer ($N_{18.8}P_{6.5}$, $N_{37.5}P_{13}$, and $N_{75}P_{26}$) were set as the treatments. The crop that was tested was sorghum. Lime was applied to all the plots before being planted and fertilizers were applied during the planting and top-dressing as recommended by the treatments.

Soil Sampling was done randomly from the demarcated experimental plots following a zig-zag procedure. Three composites of nine subsamples were done per replicate in each site to eliminate variability. This gave a total of nine samples per site and a grant total of twenty-seven samples. Each sample weighed 0.5 kg each, making 4.5 kg from each study site which were Kakamega, Siaya site 1 and Siaya Site 2, all being farmers' farms. Soils were then extracted by using a soil auguring at soil depths of 0-30cm. The samples collected at various points across the study sites and at the same depth were composited to make five packages per site. In total fifteen samples were submitted to the laboratory for selected chemical (pH. P, N SOC, exchangeable acidity), and physical (texture and bulk density) parameters as discussed in section 3.13.

2.2 Field Procedures and Agronomic Indices for Sorghum Evaluation

The experimentation of sorghum was done between 2016 and 2018 in the long rain seasons of Siaya, Koyonzo, Homa Bay, and Migori. One month before the sowing, lime-treated plots were prepared by broadcasting lime in the amount of 4.2 kg/10.5 m 2 and mixing it with the soil using hand hoes to provide time to reduce the acidity before planting took place. A basal level of fertilization, including 18 kg P_2O_5 ha^{-1} and 18.8 kg N ha^{-1} that was added to nutrient-amended plots was not applied on the control plots during the experiment. Harvesting was conducted on the four middle rows of each plot in order to limit edge effects, and the effective area per treatment shared by all the plots was 4.2 m^2. The total above-ground sorghum biomass, i.e., panicles, leaves, and stems, was removed by cutting all the plants at soil level and harvesting the entire fresh biomass directly in the field into a digital balance and weighing. Five representative samples were then taken from this bulk sample, put in ventilated bags, labeled, and air-dried in a greenhouse for 72 hours to estimate the fraction of dry matter, which was used to estimate dry biomass yields.

Grain and crop components were measured from the 4.2 m^2 harvested area and extrapolated to per-hectare output based on the standard 10,000 m^2 hectare scale. The proportion of the total fresh weight to the dry weight of the sample was determined to estimate grain yield (t ha^{-1}) by dividing by the effective area harvested. The nutrient uptake (kg ha^{-1}) was computed by dividing the nutrient content (kg N or P) by the crop dry mass percentage and multiplying by 100. Leaf sampling was conducted at silking stage to determine nitrogen (N) and phosphorus (P) uptake. In each plot, twelve randomly selected sorghum plants were used, with care taken to avoid contaminated or dust-laden leaves. Samples were air-dried in a greenhouse and ground into fine powder before digestion using a mixture of sulfuric acid, hydrogen peroxide, selenium powder, and lithium powder. Nutrient concentrations from the digested samples were analyzed following Okalebo et al. [10], and the results were used to compute total nutrient uptake by the crop.

Nitrogen and phosphorus in grain samples were determined by the same digestion procedure outlined here. The total nitrogen content in the soil was measured using the Micro-Kjeldahl digestion method, in line with the

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AOAC International standards set in 2000. This method involves breaking down soil samples with concentrated sulfuric acid along with a catalyst mix of potassium sulfate and copper sulfate. This process transforms the nitrogen that is organically bound into ammonium sulfate. After the digestion, the mixture is distilled to release ammonia, which is then measured through titration, allowing us to calculate the total nitrogen present. Grain yield percentage over control increase was calculated as (treatment - control yield)/control yield × 100 and gave an estimate of fertilization effect. Harvest index (HI) or the ratio of grain yield to total above-ground biomass, was computed according to the method of Bange et al. [11] for estimating biomass partitioning efficiency towards the grain. Agronomic efficiency (AE) was calculated as the incremental gain in grain yield due to nutrient application over the sum of nutrients applied, as per Vanlauwe et al. [12]. Finally, the uptake of nutrients in stover and grain was presented as kilograms per hectare and was determined by multiplying yield (kg ha^{-1}) with a fixed percentage of nutrients and dividing by 100. This whole set of parameters facilitated a proper assessment of treatments on sorghum growth, productivity, and nutrient uptake.

2.3 Performance Index (PI) and Sensitivity Analysis

A composite Performance Index (PI) was developed to integrate multiple agronomic endpoints into a single scoring framework in order to facilitate assessment of treatment performance along both physiological and economic endpoints. The PI integrated Sorghum Grain Yield (SGY), Gross Margin (GM), Agronomic Efficiency (AE), and Nutrient Use Efficiency (NUE) and allowed for integrative interpretation of trial data. The index was computed using the following formula:

$$PI=\alpha 1 \cdot AE+\alpha 2 \cdot NUE+\alpha 3 \cdot (GM/1000) +\alpha 4 \cdot SGY \quad (1)$$

The weights of each metric are represented by the coefficients α_i in this formula: α_1 for AE, which indicates responsiveness per unit input; α_2 for NUE, which indicates nutrient uptake effectiveness; α_3 for GM, which indicates economic return and is scaled to match the magnitude of other terms; and α_4 for SGY, which captures direct productivity. Two weighting scenarios were simulated. In the equal-weight scenario, all coefficients were set to 1.0, assuming uniform importance. A second scenario adjusted the weights to reflect smallholder priorities under low-input conditions: $\alpha_1 = 1.2$, $\alpha_2 = 1.3$, $\alpha_3 = 0.8$, and $\alpha_4 = 1.0$, thereby emphasizing efficiency metrics over financial yield.

The Performance Index was calculated by taking values of each combination of fertilizer and lime treatment. These contour plots were used to plot the surface slopes of the PI scores in order to identify the relevant areas of intervention. The radar charts have been used to give multivariate profiles of single interventions. Replication of context-dependent preferences and estimation by robustness included sensitivity analysis through comparison of ranks of treatments with both weighting procedures.

2.4 Statistical Analysis and Visualization

The one-way ANOVA was used to evaluate the treatment effects, and post hoc estimates were done using the Tukey HSD test at $p < 0.001$. Visualization of data in R was conducted in the ggplot2 package. The plots were overlain with thresholds to indicate the boundaries of sustainability performance, AE 20% and GM \$388 ha^{-1}. Simulation output was validated using cross-site comparisons and sensitivity mapping in order to determine the presence of optimal treatment zones.

RESULTS AND DISCUSSION

3.1 Sorghum Grain Yield and Biomass Response

Grain yield was boosted considerably by fertilizer application at all locations and times, with largest boost from the application of the full NPK rate ($N_{75}P_{26}$). Micro-dose applications ($N_{18.8}P_{6.5}$) increased SGY by 27–39%, and full-rate applications regained up to 58% gains. Lime application boosted Siaya 1 and Siaya 2 SGY consistently, but less so in Kakamega. Composite lime × fertilizer treatments yielded additive or weakly synergistic effects, especially with intermediate fertilizer application. Biomass yield was positively responsive to lime and fertilizer application. Maximum SBY was obtained under $N_{75}P_{26}$ where Kakamega was superior to Siaya sites.

Application of lime alone increased biomass significantly, notably in Kakamega and Siaya 1, suggesting increased root growth and nutrient uptake under optimal pH.

3.2 Agronomic Efficiency and Nutrient Uptake Efficiency

Agronomic efficiency (AE) was greatest with micro-dose applications of fertilizers and reduced with the rise in amounts of N and P. Lime enhanced AE in all locations with Siaya 2 responding highest. AE varied from 6.6% to 11.9% with lime + $N_{75}P_{26}$, but that of lime + $N_{37.5}P_{13}$ and lime + $N_{18.8}P_{6.5}$ varied between 25–55%, reaffirming the advantage of intermediate quantities of inputs for efficiency. Nutrient uptake efficiency (NUE) reflected trends in AE. The greatest NUE was realized with micro-dose application, while the lowest was with $N_{75}P_{26}$. Lime improved NUE at all sites, and Siaya 2 in the long rains of 2017 had the highest mean at 34.56%. Lime + $N_{37.5}P_{13}$ led in all cases in nutrient recovery.

3.3 Economic Performance: Gross Margin and Benefit–Cost Ratio

Gross margin (GM) analysis showed the highest GM for lime + $N_{75}P_{26}$ (\$507 ha^{-1}), followed by lime + $N_{37.5}P_{13}$ (\$451 ha^{-1}). Nonetheless, lime + $N_{37.5}P_{13}$ recorded better AE and NUE, making it the most sustainable treatment. Benefit–cost ratio (BCR) values > 2.0 were realized for lime + $N_{37.5}P_{13}$ and lime + $N_{18.8}P_{6.5}$, symbolizing high profitability at modest input investment. Lime-free treatments could not realize profitability levels, a testament to lime's catalytic effect on economic performance.

3.4 Treatment Rankings and Sensitivity Outcomes

Composite PI values revealed that treatments combining moderate lime rates with calibrated phosphorus inputs always ranked high in the equal-weight scenario. They offered balanced physiological response and economic return, in line with integrated amendment strategies. Under sensitivity-adjusted weighting, some mid-ranked treatments moved upward due to strong AE and NUE scores, while monetarily dominant but physiologically weak treatments declined slightly. Contour mapping defined optimal performance zones at lime application (4 t ha^{-1}) and mid-range P application. Radar plots confirmed multiple high-yielding options with low input-use efficiency, emphasizing the value of composite ranking. Key recommendations were consistent across weighting strategies, validating the PI as a stable and context-sensitive decision tool.

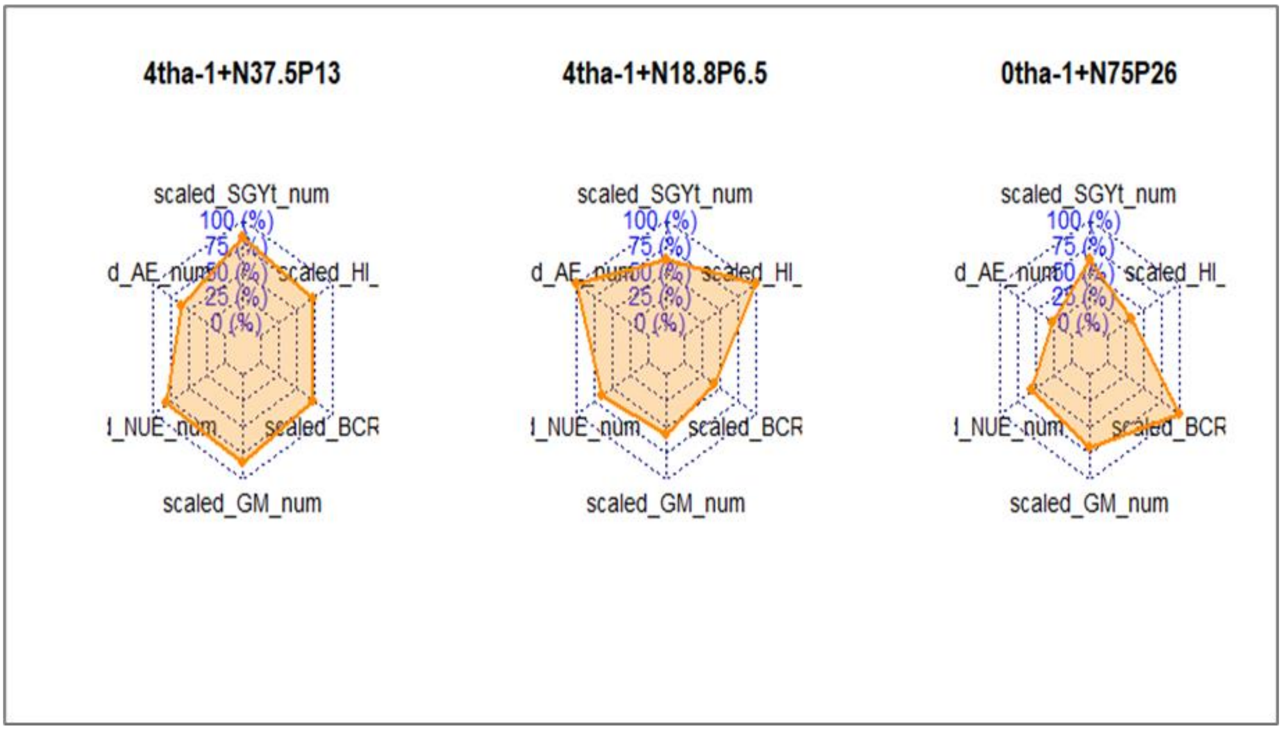

Fig. 2. Multi-metric performance profiles of selected lime–fertilizer treatments in sorghum production.

Keynotes:

Radar plots showing scaled performance across six metrics—grain yield (SGY, t ha^{-1}), agronomic efficiency (AE, %), nitrogen use efficiency (NUE, %), harvest index (HI), gross margin (GM, $), and benefit–cost ratio (BCR)—for three selected treatments: 4tha-1+$N_{37.5}P_{13}$, 4tha-1+$N_{18.8}P_{6.5}$, and 0tha-1+$N_{75}P_{26}$.

3.5 Integrated Performance Profiles and Composite Scoring

Figure 2 shows radar plots of six scaled performance indicators—SGY, AE, NUE, HI, GM, and BCR—of three selected treatments. Lime + $N_{37.5}P_{13}$ has a close-to-perfect hexagonal shape, indicating good agronomic as well as economic performance. Lime + $N_{18.8}P_{6.5}$ is high in AE and HI, and 0tha^{-1} + $N_{75}P_{26}$ is high in GM and BCR but low in physiological efficiency. Figure 2 is a normalized agronomic and economic score comparison of all eight treatments. Lime-treated sets are consistently higher than non-limed sets in both, with the highest composite scores being 4tha^{-1} + $N_{75}P_{26}$ and 4tha^{-1} + $N_{37.5}P_{13}$. Table 1 provides a general performance of all the treatments with statistical separation (LSD), coefficient of variation (CV%), and composite recommendation ranks. The overall best ranking is lime + $N_{75}P_{26}$ (score = 0.77), followed by lime + $N_{37.5}P_{13}$ (score = 0.76) and lime + $N_{18.8}P_{6.5}$ (score = 0.70). Non-limed treatments are categorized as "Moderately Recommended" or "Optional" based on performance.

3.6 Interaction of Efficiency and Yield Indicators

Figure 3 shows a graph of multi-index performance, where AE (x-axis), GM (y-axis), NUE (bubble size), and SGY (color gradient) are used. Simulated contours = composite PI values. Treatments nearest the center—most significantly lime + $N_{37.5}P_{13}$—had great agronomic-economic performance, with yield, efficiency, and profitability in a balance.

3.7 Economic Performance of Lime–Fertilizer Treatments

Figure 3 demonstrates the relationship between Nutrient Use Efficiency (NUE) and Gross Margin (GM_USD) of the treatments. Treatments were normalized and ranked into AE classes (High, Moderate, Low) with different marker shapes. A dotted threshold line at $300 ha^{-1} indicates economic viability. Treatments below this threshold suggest uneconomical realization of profits. Yet, treatments with medium to high NUE also surpassed the $300 ha^{-1} threshold, indicating economically responsive nutrient processes. The most economical treatments combined calcitic lime with moderate fertilizer rates, NUE = 2.1–2.5 and GM = $310–$420 ha^{-1}. These blends justify lime's role in enhancing input-use efficiency under acidic conditions.

3.8 Relationship Between AE and Gross Income (GI USD ha^{-1})

Figure 4 depicts AE vs. GI among lime–fertilizer treatment combinations. Each point is color-coded by AE class. Generally, a moderate positive relationship exists between AE and GI.

High AE treatments had GI of $580–$750 ha^{-1}, while Moderate AE treatments ranged from $350–$610 ha^{-1}. Some Low AE treatments posted GI over $400 ha^{-1}, suggesting factors beyond AE—like marketable yield or rainfall—also affect returns. Lime-fertilizer treatments excelled in both AE and GI, highlighting the importance of optimizing nutrient utilization for profitability in acidic soils.

3.9 Profitability Ratio Response to NUE Across Treatment Combinations

Figure 5 presents profitability ratio (GM ÷ TVC) versus NUE. A reference line at 1.5 marks viable smallholder returns. Many treatments with moderate NUE (~1.8) and high AE exceeded the profitability threshold. Treatments with high NUE (>2.0) but low profitability suggest input recovery alone does not ensure economic success. Efficient treatments yielded at least $2 per dollar invested, affirming well-balanced input strategies.

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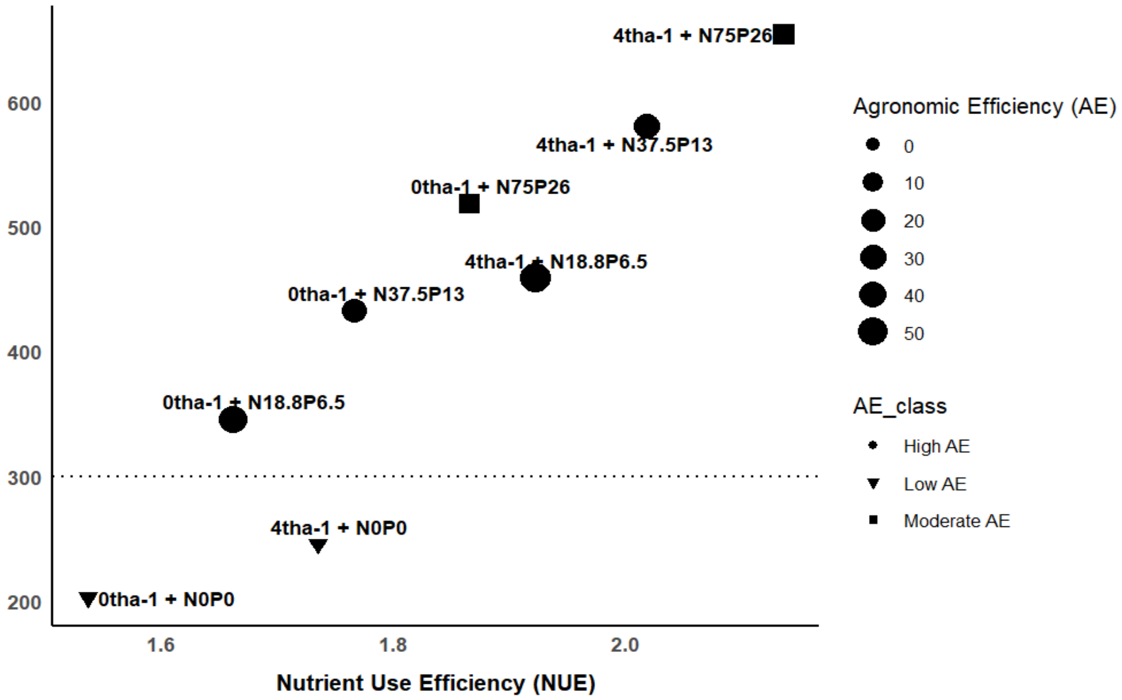

Fig. 3 Relationship Between NUE and GM (USD ha⁻¹) Across Lime–Fertilizer Treatments

Footnotes:

NUE is plotted along the X-axis and GM (USD ha^{-1}) along the Y-axis. Each treatment point is scaled by AE and categorized into AE classes (High, Moderate, Low) using distinct marker shapes, ensuring accessibility for all readers. A dotted line at \$300 ha^{-1} indicates the economic viability threshold. Treatment labels are positioned in high-contrast, bold font for clear legibility. This visualization highlights lime–fertilizer combinations that deliver both agronomic responsiveness and financial viability under acidic soil conditions.

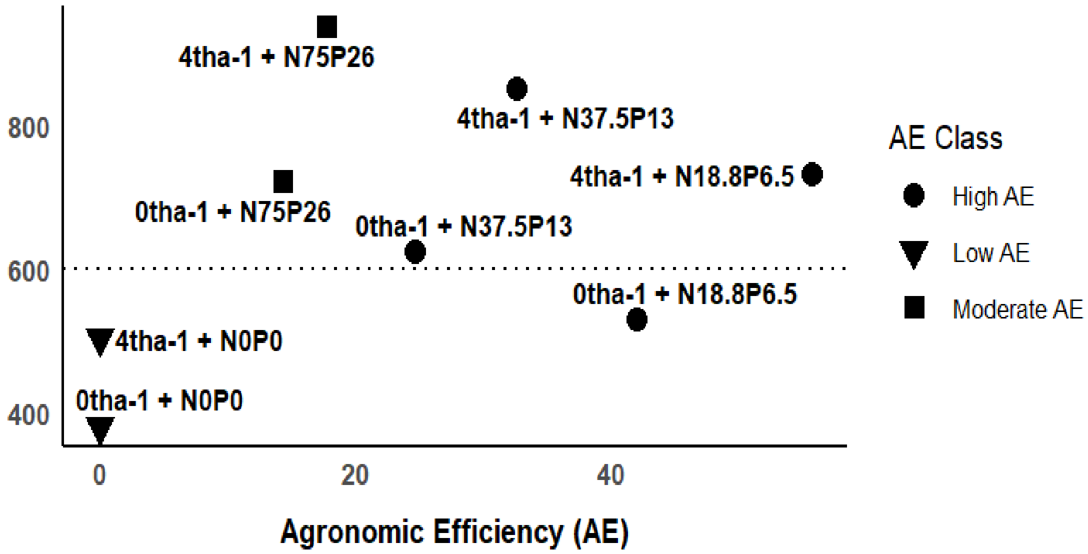

Fig. 4. Relationship Between AE and GI (USD ha^{-1}) Across Lime–Fertilizer Treatments

Footnotes:

AE is plotted along the X-axis and GI (USD ha^{-1}) on the Y-axis. Treatments are categorized by AE class (High, Moderate, Low) using shape-based markers to ensure accessibility for readers with color-vision deficiencies. Treatment labels are rendered in bold, high-contrast font for clarity. The plot reveals treatment combinations that yield higher income per hectare in conjunction with elevated AE levels, enabling selection of agronomically efficient and economically productive lime–fertilizer options.

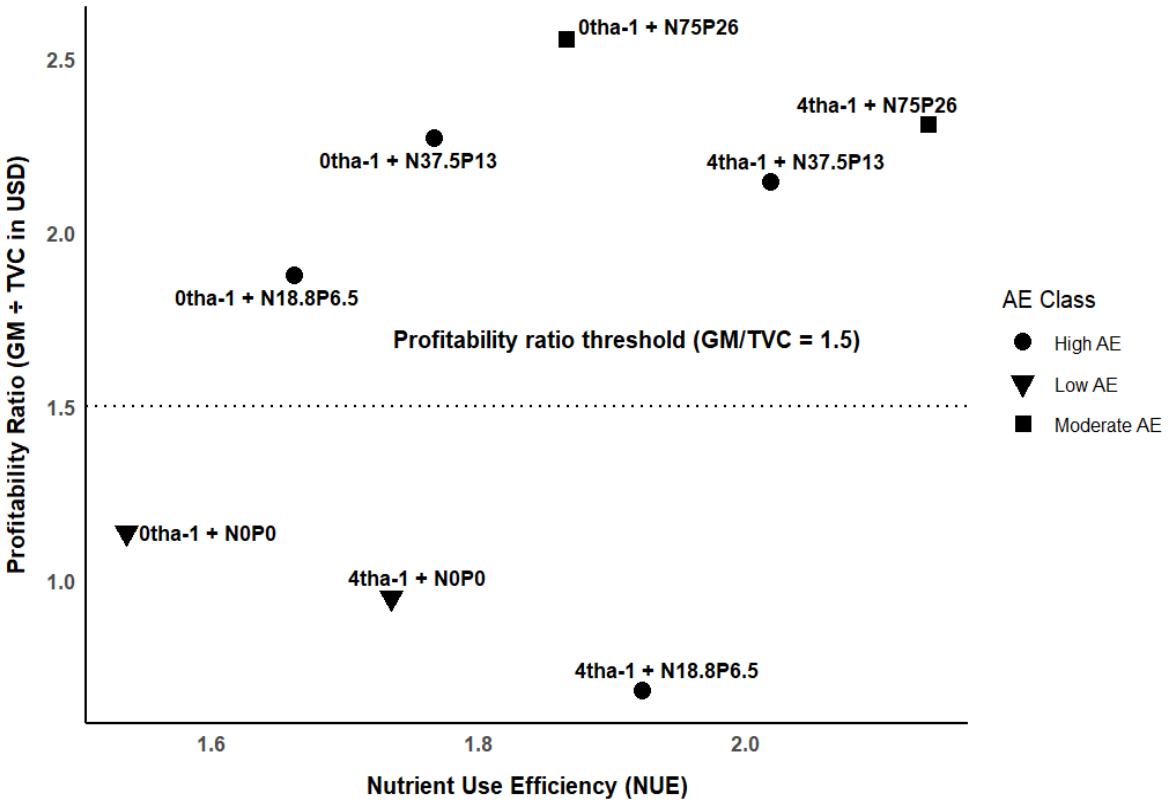

Fig 5 Relationship Between NUE and Profitability Ratio (GM/TVC) Across Lime–Fertilizer Treatments

Footnotes:

NUE is plotted along the X-axis and Profitability Ratio (GM ÷ TVC in USD) on the Y-axis. Treatments are categorized by AE class (High, Moderate, Low) using shape-based markers to enhance accessibility. A dotted line at a ratio of 1.5 marks the economic viability threshold. Treatment labels are rendered in bold, high-contrast text. This plot distinguishes lime–fertilizer treatments that optimize both nutrient use and financial efficiency.

DISCUSSION

4.1 Conceptual Alignment and Empirical Significance

These results support the theoretical depiction in Figure 1 that soil acidity is a root cause of nutrient stress. AE, NUE, GM, and SGY are perceived as a systemic sequence incorporated into the PI model based on both farmer and researcher interests. This aligns with recent studies in sub-Saharan Africa showing increased input recovery and profitability under integrated nutrient management, particularly in acid soils [5,13]. Compared to traditional yield-centric evaluations, the sensitivity analysis reorders treatments based on physiological and economic efficiency. This reflects localized assessment models that prioritize farmer realities [7]. The PI framework minimizes volatility among top-performing treatments and employs radar and contour visualizations to intuitively identify multidimensional synergies.

4.2 Lime as a Substratum Modifier: Unlocking Sorghum Response in Acidic Soils

The uniform enhancement of sorghum growth on the lime-treated plots mirrors the intrinsic function of lime in altering the soil substratum — not just for surface-acidity correction, but for redetermination of the root zone environment. By elevating pH and precipitating exchangeable Al^{3+}, lime reduces rhizotoxicity and increases root elongation, thus increasing the volume of soil utilized for nutrient acquisition. This substratum-level adaptation is of special significance in Ferralsols and Acrisols, where elevated Al saturation and limited base saturation limit root activity and mobility of nutrients [14,15].

4.3 Grain Yield and Biomass: Root-Zone Liberation and Nutrient Mobilization

The increased grain production under lime + fertilizer treatments noted are not only the result of nutrient supplementation, but also due to release of the root zone from chemical constraint by lime. The activity of lime increases the phosphorus availability by decreasing P fixation to Fe and Al oxides, a process with very active reaction in weathered tropical soils [16]. This response was seen in Siaya, since, at similar levels of fertilizer, the responses at lime + $N_{37.5}P_{13}$ and lime + $N_{18.8}P_{6.5}$ were very high. The response in biomass was also due to this effect: lime-amended plots had increased vegetative growth, presumably due to the increased availability of Ca^{2+} and Mg^{2+} and reduced proton toxicity, which collectively promote cell elongation and photosynthesis [17,18].

4.4 Agronomic and Nutrient Uptake Efficiency: Beyond Fertilizer Recovery

Maximum agronomic efficiency (AE) and nutrient uptake efficiency (NUE) in the lime-treated micro-dose plots revealed that lime is doing more than optimize fertilizer recovery—it reconstitutes the plant–soil interface. By suppressing Al-induced root pruning and root hair elongation, lime enables higher and longer-lasting nutrient uptake [19]. The higher AE and NUE of lime + $N_{37.5}P_{13}$ and lime + $N_{18.8}P_{6.5}$ treatments validate this substratum correction advantage. High-input non-lime treatment (e.g., 0tha^{-1} + $N_{75}P_{26}$) was linked with low efficiency owing to potential loss of nutrients by leaching and sorption in not corrected acidic profiles [20,21].

4.5 Economic Returns: Substratum Correction as a Profit Catalyst

The cost-effectiveness of lime + $N_{75}P_{26}$ was evident in gross margins but its efficiency indicators were behind that of lime + $N_{37.5}P_{13}$. What it means is profitability can accompany high-input systems but reduced physiological return. Lime's substratum correction makes intermediate-input treatment economically viable without compromising efficiency—a good deal for smallholder sustainability. Nyokabi et al. [22] and Kula et al. [23] research also revealed lime-integrated ISFM solutions to excel fertilizer-only conventional solutions economically and agronomically in acid soils.

4.6 Substratum Synergy and Sustainability Thresholds

The radar plots and composite Performance Index (PI) placed the lime + $N_{37.5}P_{13}$ treatment in the sustainability-performance consistently within beneficial range. In respect to this treatment, there was no reliance on high input use—it achieved strong yield, efficiency, and profitability based on substratum synergy. The simulation with weighted adjustments ensured that the action of lime to correct the root zone pH sufficiently enabling moderate fertilizer rates, giving Pareto-efficient performance for smallholder intensification. This result is consistent with Weih's [9] and Congreves' [8] multi-dimensional theories where nutrient recovery and robust physiology drive sustainable agriculture.

4.7 Economic Interpretation of Lime–Fertilizer Treatment Effects

4.7.1 Nutrient Use Efficiency and Gross Margin (USD ha^{-1})

The relationship of Nutrient Use Efficiency (NUE) and Gross Margin (GM) exhibited a stratified response to lime–fertilizer treatment. NUE treatments in excess of 2.0 fell near or above the $300 ha^{-1} economic break point, indicating that physiological efficiency could be translated into profitability when inputs are managed properly. This agrees with findings by Cheptoek et al. [24], who reported that when lime was combined with Minjingu Rock Phosphate and NPK fertilizers, maize productivity and P use efficiency was significantly improved, resulting in higher gross margins in acidic Kenyan soils. But the story also revealed treatments with improved NUE but below-threshold GM, which means responsiveness to nutrients is no guarantee for profitability. Such instances may be due to high input prices, unfavorable market price, or inefficient yield realization. This is an omen for the warning made by Fixen et al. [20], who laid emphasis on the aspect that NUE should be interpreted together with economic indicators to prevent false interpretation of input efficiency. The most economical treatments in our work were those with moderate NUE (1.8–2.3) offset by high AE and low TVC, confirming the fundamental hypothesis that optimal nutrient use is better than maximum uptake per se. These findings justify certain lime–fertilizer pairs as a method of maximizing both agronomic as well as economic returns under conditions of acid soil limitations.

4.7.2 Agronomic Efficiency and Gross Income (USD ha^{-1})

A plot of AE vs. GI showed a positive but non-linear correlation in which high-AE treatments resulted in higher overall gross income. Plots with high-AE in most cases recorded income levels above \$600 ha^{-1}, which reflected very high predictive capacity of agronomic efficiency. This agrees with Mucheru-Muna et al. [25] study in Tharaka-Nithi County, Kenya, where productivity and profitability of maize improved tremendously upon use of lime and inorganic fertilizer. Some of the treatments posted high gross income (GI) but it had moderate agronomic efficiency (AE). It implies that the increase in yield could be because of other factors which could be better soil structure, increase in micronutrient supply or improvement in the rainfall. These results endorse Dobermann [26] which said that AE is a temporal parameter and unable to depict an enduring or interacting state of impacts on soil amendment. Low AE treatments garnered more than \$400 ha^{-1} even so, which promotes situations in which an external market reward conceals internal agronomic fragilities. Nonetheless, these benefits cannot be maintained in case of shock in input prices or yield variability. That notwithstanding, AE is an excellent general guide to sustainable, or even intensification, in general, and of good input constraint to smallholder especially.

4.7.3 Profitability Ratio and Nutrient Use Efficiency

The overall image of economic costs between treatments was provided by the last figure, presenting the profitability ratio (GM/TVC) against NUE. Economically reasonable decisions were marked by the boundary ratio of 1.5; most treatments had ratios higher than 2.0, with the implication that they produced a return on investment of at least \$2 per dollar. These efficient treatments indicated the importance of well-balanced input strategies by having moderate NUE (1.8–2.2) augmented with greater AE and lesser TVC. The potential of physiological efficiency at the expense of economic gain is captured through treatments with NUE > 2.0 but profitability ratios < 1.5. This is often brought about by high fertilizer prices or diminishing marginal returns.

This observation agrees with that of Kiwia et al. [27], reported that profitability and fertilizer application efficiency varied significantly by soils and seasons in East Africa and some of the high-NUE treatments yielded low money return with increased production risk. On the other hand, low NUE profitability treatments with high profitability ratios indicate that it is possible to realize low NUE profits without optimizing nutrient uptake. That is particularly so whenever lime increases the pH of the ground and decreases the aluminum toxicity hence making the crops vulnerable and nutrients accessible [28]. In general, the current plot brings to the fore the necessity to assess NUE along with the measures of profitability to make input recommendations. It advocates the use of lime as a cheap amendment that will increase the nutrient responsiveness and the returns to the financial health of soil with acidic nature.

CONCLUSION AND RECOMMENDATIONS

This research proves that lime application, under complementation from moderate rates of nitrogen–phosphorus fertilizer, converts soil constraints due to acidity into agronomic advantages. Lime + $N_{37.5}P_{13}$ treatment always produced great grain yield, improved nutrient efficiency in uptake, and firm economic returns — not through input maximization, but by maximizing the soil–plant interface. Lime-induced substratum correction increased nutrient availability by the roots, relieved aluminum toxicity and partitioned the biomass to give rise to their success in utilizing the resources, even at low fertilizer rates. Lime + $N_{75}P_{26}$ had shown the most significant gross margin, but its declining agronomic and physiological efficiency shows the limitation of high-input strategies in acidic soils. Lime + $N_{18.8}P_{6.5}$, on the other hand, recorded efficient values coupled with lower profitability and is therefore suitable for low-resource systems where input recovery is a greater concern than high yield. The combined Performance Index (PI) validated Lime + $N_{37.5}P_{13}$ as the most balanced and sustainable treatment that held the position within the convergence zone where agronomic performance, economic profitability, and physiological stability meet. This result is consistent with the overall ISFM paradigm favoring context-oriented, efficiency-maximizing nutrient management. Sorghum intensification on Western Kenya's acidic soils is not input maximization but balance—and lime is the fulcrum on which this synergism turns.

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Author Contributions

Material preparation, data collection and analysis were performed by Edwin Kiprono Rotich. Conceptualization: The first draft of the manuscript was written by Edwin Kiprono Rotich while Prof. Peter Kisinyo and Prof. Peter Opala both refined to the current versions of the manuscript. All authors read and approved the final manuscript. Prof. Peter Kisinyo and, whose guidance was instrumental in shaping the experimental design while Prof. Peter Opala weighed in on refining the thesis from which this manuscript was developed.

Data Availability

The corresponding author will make the data available upon request.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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