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EDITED BY
Katharina Hildegard Elisabeth Meurer,
Swedish University of Agricultural Sciences,
Sweden

REVIEWED BY
Hamada Abdelrahman,
Cairo University, Egypt
Manuel Ângelo Rodrigues,
Centro de Investigação de Montanha (CIMO),
Portugal

*CORRESPONDENCE
Eric Scherwietes,
ericleon.scherwietes@zalf.de

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Local sediment and lime but no straw amendments can potentially improve barley biomass and yield at the field plot scale in Kenya

Eric Scherwietes[1]*, Johan Six[2], Titus Kiplagat Bawen[3] and Jörg Schaller[1]

[1]Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany, [2]Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland, [3]Department of Seed, Crop and Horticultural Sciences, School of Agriculture and Biotechnology, University of Eldoret, Eldoret, Kenya

Soil acidification and nutrient leaching are major agricultural challenges in East Africa, leading to aluminum (Al) toxicity and poor crop yields. Various soil amendments are used worldwide to increase soil pH and crop production. Local sediment amendments have been identified as a potential soil improvement in Kenya, but the mechanisms remain unclear. This study examined the effects of liming, straw return, and local sediment amendments on nutrient availability and barley yield in Eldoret, Kenya. Plots were established with 1% and 3% of two local sediments (from Baringo and Nakuru) or with 0.15% lime, each with and without straw addition. Baringo 3% and lime treatments significantly reduced soil Al availability and increased soil pH, soil phosphorous (P) availability and barley yield (Baringo 3%: 1.3 t ha^{-1}, Lime: 0.91 t ha^{-1}), while the control had no yield. However, only Baringo 3% also increased soil silicon (Si) availability, achieving the highest yield. Other treatments and straw return had no significant impact on nutrient availability and plant production. These results indicate that the increase in barley yield with local sediment may be driven mainly by carbonate dissolution raising soil pH, while higher Si availability and accumulation could further enhance plant production. However, the beneficial effects are dependent on the sediment material and amendment rate.

KEYWORDS

aluminum toxicity, crop production, liming, plant performance, silicon availability, yield

1 Introduction

About 30% of the global land surface is characterized as acidic (von Uexküll and Mutert, 1995), accounting for approximately 50% of the global arable land area (Dai et al., 2017). Soil acidity is one of the major challenges for agriculture in tropical Africa. In Kenya, around 13% of the total agricultural land is defined as acidified, resulting in barely fertile soils and low crop yields (Kanyanjua et al., 2002). The high incidence of acidic soils in Kenya is mostly due to the prevalence of Ferralsols in this region, which are characterized by pH of 4–5 (Nyachiro and Briggs, 1987; Soil Survey Staff, 1999). These soils are formed by long-term and intense weathering in a humid to sub-humid climate with high temperatures and moderate to high rainfall (Soil Survey Staff, 1999).

With ongoing soil acidification, hydrogen (H^+) and aluminum (Al^{3+}) ions are replacing essential cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+) and potassium (K^+), which are leached out during weathering processes (von Uexküll and Mutert, 1995; Agegnehu et al., 2021). Therefore, Ferralsols are characterized by low nutrient availability, a low pH and high contents of iron (Fe) and Al (Balland-Bolou-Bi and Livet, 2018; Du et al., 2020). Due to these characteristics, these soils are known to be less fertile, which results in low crop yields (Du et al., 2020). The decreasing pH and the replacement of cations by Al^{3+} ions promote Al toxicity for plants (von Uexküll and Mutert, 1995). At a pH value <5.5, the toxic effect of Al increases, as Al is dissolved as Al^{3+}, which is plant available and phytotoxic (Sade et al., 2016; Vega et al., 2019). A higher Al availability in the soil promotes the direct Al uptake by plants and its accumulation in plant tissues, resulting in poor crop growth, especially the roots, and thus decreased yields (Cocker et al., 1998; Lal and Singh, 1998).

Another major challenge for agriculture on Ferralsols is a high phosphorus (P)-fixation in the soil due to the high Fe and Al content, which has been discussed and published in many studies for decades (Kellogg, 1956; Russel et al., 1974; Sanchez and Uehara, 1980; Ayodele and Agboola, 1981). Iron and Al minerals have a high P-sorption capacity, as P binds strongly to Fe- and Al-oxides/hydroxides, resulting in a relatively high total, but mostly plant unavailable P content in the soil (Russel et al., 1974; Hengl et al., 2017; Du et al., 2020). The P-fixation is additionally promoted by soil acidity (Agegnehu et al., 2021). At a pH value <5.5, phosphates may already become inaccessible to plants; at a pH value <5, Fe- and Al-phosphates may precipitate (Russel et al., 1974; Sanchez and Logan, 1992; Agegnehu and Sommer, 2000). To compensate for the P deficiency caused by the high P fixation in tropical Africa, farmers have to apply large quantities of P fertilizers (up to 150 kg ha^{-1}) (Russel et al., 1974; Nziguheba et al., 2002; Achieng et al., 2017). However, many smallholders have limited access to P fertilizers due to high prices and poor availability, resulting in a lack of P for crop production and low yields (Sanchez et al., 1997; Nziguheba et al., 2002).

There are various ways to improve soil fertility and soil pH with a reduced need for mineral fertilizers, some of which have been known for a long time or are still being examined. Scherwietes et al. (2024) showed that the application of local sediments might be one option to increase soil pH and reduce the need for phosphorus fertilizers in Kenya from a biophysical perspective. In some cases, the addition of local sediments significantly increased soil pH, soil P availability and barley yield, and significantly decreased soil Al availability (Scherwietes et al., 2024). However, the extent of the positive effects of the added local sediments depended on the material and the application rate (Scherwietes et al., 2024). In this study, it was not possible to differentiate between the effects of a pH increase versus nutrient addition (Scherwietes et al., 2024). Liming with materials rich in Ca^{2+} and Mg^{2+} is another common practice that is used all over the world to improve soil fertility and crop yield by increasing soil pH (Wang et al., 2021). By neutralizing excessive H^+ ions in soil solution, liming could promote the immobilization of toxic heavy metals such as Al (Bolan et al., 2003; Fageria and Baligar, 2008) and may increase the availability of essential nutrients (e.g., P) that are more available at higher pH (Thomas and Hargrove, 1984). Besides, liming could also directly supply important cations (e.g., Ca^{2+}, Mg^{2+}) for crop production (Fageria and Nascente, 2014; Li et al., 2019).

A third method for improving soil fertility and crop yield, which is commonly used in most parts of the world but not in Africa, is straw return (Liang et al., 2023). While in Africa, residue retention in the field is very little done as straw is used as feed for livestock, in other parts of the world it is a widely available and abundant resource. Straw is known to be rich in nutrients and has already shown positive effects on soil properties and functions when returned to the fields (Li et al., 2024). Decomposition of straw can replenish assimilated nutrients (such as carbon (C), nitrogen (N), P and K), thereby increasing nutrient availability and soil organic matter (SOM) stocks in the soil (Yan et al., 2019). By replenishing base cations, returning straw to the field is also widely recognized as a method to reduce soil acidification and has been observed in various studies (Wang et al., 2012; Butterly et al., 2013). However, the decomposition of straw may also result in an increase in organic acids, which in turn could accelerate soil acidification (Katoh et al., 2005).

In this study, we aim to compare three soil fertility improvement methods—local sediment amendment, liming, and straw return—on acidic arable soils in Kenya. The study seeks to determine whether the potential positive effects observed with some of the sediments are primarily due to changes in soil pH (liming effect) or if they result from other processes. Specifically, we investigated the effects of these treatments on P availability, Al toxicity, and barley yield. We hypothesize that: (i) local sediment application will decrease soil Al availability, increase soil pH, improve P availability, and enhance barley yield, even 2 years after incorporation; (ii) liming will similarly increase soil pH, P availability, and barley yield, while reducing Al availability, but at a lower application rate than local sediment amendment; and (iii) straw return will improve crop yield, with the best results likely occurring when combined with liming.

2 Materials and methods

2.1 Study site and experimental design

The study site is located in western Kenya in Kaptagat, a village east of Eldoret in the Uasin Gishu County (0.4448 °N, 35.4685 °E). This area is characterized by a cool and temperate climate, the daily average temperature ranges between 8.4°C and 27°C. The average annual rainfall is 900–1,200 mm, distributed over two rainy seasons (Tsuma et al., 2015). The pedology in this area is dominated by Plinthic Ferralsols, which are characterized as low in pH and high in Fe content (Nyachiro and Briggs, 1987). The experiment of this study was conducted on the cropland of a local farmer at an elevation of 2,410 m. The pH of the soil of this study is 4.7, the cation exchange capacity (CEC) is 9.7 $cmol^+ kg^{-1}$ and the total organic carbon (TOC) is 2.6% (Scherwietes et al., 2024). The element composition and the composition of exchangeable cations of the soil are described in Scherwietes et al. (2024). The soil is strongly weathered, which is indicated by an oxalate/dithionite Fe (Fe_o/Fe_d) ratio of 0.04 (Moody and Graham, 1995; Scherwietes et al., 2024).

Two suitable local sediments from different locations in the EARS were identified (Scherwietes et al., 2024). One of the sediments was defined as splinter-like/molten Si-Al-containing particles of varying size and was located in the Nakuru district, south of Lake Nakuru (0.49726 °S, 36.091794 °E, Scherwietes et al., 2024). The second sediment was defined as a Ca-rich and aggregated sediment matrix with attached particles containing Al and Si. This was taken from an area west of Lake Baringo (0.574643 °N, 35.984597 °E, Scherwietes et al., 2024). Baringo sediment had a pH of 8.6, Nakuru sediment had a pH of 9.4 (Scherwietes et al., 2024). The detailed total elemental composition and the composition of exchangeable cations of the sediments are described in Scherwietes et al. (2024). The main components of the Baringo sediment were Si (21 wt%) and Ca (10.2 wt%), with further enrichment of P (0.13 wt%) and Mg (3.24 wt%; Scherwietes et al., 2024). The Nakuru sediment, on the other hand, consisted primarily of Si (30.2 wt%) and Al (8.3 wt%), with enrichment of Na (4.46 wt%) and K (4.27 wt%; Scherwietes et al., 2024). No harmful element or heavy metal enrichment was identified in either sediment materials (Scherwietes et al., 2024).

The experimental site covered an area of 30 × 19 m, with individual plot dimensions of 3 × 4 m. The experimental design included the incorporation of two local sediments at application rates of 1% and 3% by volume to a soil depth of 20 cm. This corresponded to application rates of 24 t ha^{-1} (Baringo 1%), 72 t ha^{-1} (Baringo 3%), 18 t ha^{-1} (Nakuru 1%), and 54 t ha^{-1} (Nakuru 3%). Sediment incorporation was carried out in April 2022 (Scherwietes et al., 2024). In 2023, additional plots were established to assess the effects of liming, with calcium hydroxide [$Ca(OH)_2$] applied at a rate of 0.15% by volume (equivalent to 4.5 t ha^{-1}) to adjust the soil pH to a range of 7–8. Untreated plots without any amendments were included as controls. To investigate the effects of straw addition, each plot was divided into two equal subplots (3 × 2 m). One subplot received shredded wheat straw from the previous growing season at a rate of 5 t ha^{-1}, while the other did not. The C/N ratio of the used wheat straw was 76:1 (CNS928-MLC, Leco Instruments Inc., St. Joseph, Michigan, United States). Each treatment was replicated four times, and for practical reasons, a non-randomized block design with a split-plot structure was used, with straw addition applied at the subplot level. To avoid interferences between the treatments, buffering zones of 1 m were set up between each plot (Supplementary Figure S1). All soil amendments were incorporated by hand and then mixed with hand hoes to a depth of 20 cm. To ensure the same physical disturbance for all treatments, the mixing was performed in the same way for the control plots.

Barley (*Hordeum vulgare* L., ev. Hessekwa) was sown by hand in all plots on the 10th of July 2023. Nitrogen (N) fertilizer was applied in form of urea on every plot after germination (50 kg ha^{-1}) and at stem extension (90 kg ha^{-1}). Low P fertilization (2.5 L ha^{-1}, YaraVita Crop Boost, Yara United Kingdom Ltd., York, United Kingdom) was performed on all treatments, including the controls, in form of foliar application during the vegetation period. At tillering stage, three irrigations of 200 L per plot were carried out once a week. Harvest was conducted on the 3rd of December 2023.

2.2 Sampling and analyses

Whole plants were taken at harvest, collected from random areas of 40 × 40 cm of each treatment. The plant samples were washed, dried and weighed to determine crop yield and biomass. One month after the application of lime and straw material, soil samples from the upper 15 cm were taken randomly with a small shovel and air dried. Soil pH was determined in water at 1:2.5 solid to solution ratio for each plot with and without straw addition (WTW pH/Cond 3,320 with Sentix41 electrode, Xylem Water Solutions, Washington, DC, United States). The soil samples were analyzed for available Ca, P, Si, Al and Fe using Mehlich III extraction (Sparks and Bartels, 2009). For this, 2 g of the soil sample was weighed into 50 mL centrifuge tubes, mixed with 42 mL Mehlich III extraction solution and shaken for 5 min. The suspension was centrifuged (3,200 g for 5 min) and filtered through 0.2 µm filters. The samples were then analyzed by ICP-OES (iCAP 6300 DUO, ThermoFisher Scientific Inc., Walham, Massachusetts, United States).

To determine the nutrient contents in different plant tissues at harvest, the plants were separated into leaves, leaf sheaths and grains. Subsequently, the plant material was analyzed using several extraction methods. Microwave digestion was performed to estimate Ca, P, and Al contents in plant tissues. Two ml of H_2O_2 and 3 mL of HNO_3 were mixed with 0.1 g of plant sample and placed in a closed vessel microwave digestion system (CEM-Mars6, CEM Corporation, Matthews, NC, United States). Subsequently, the extracts were made up to 20 mL with deionized water and filtered through 0.2 µm membrane filters. By use of Tiron extraction (Kodama and Ross, 1991), Si contents in plant tissues were determined. Therefore, 0.03 g of plant samples were mixed with 30 mL of 0.1 M Tiron solution in 50 mL centrifuge tubes and heated in a water bath for 1 h at 85°C. The samples were gently shaken by hand before heating and after 30 min. The extracted solutions were centrifuged (5,000 g for 5 min) and filtered through 0.2 µm pore size filters. The elemental contents of both the microwave and Tiron extractions were analyzed by ICP-OES (iCAP 6300 DUO, ThermoFisher Scientific Inc., Walham, Massachusetts, United States).

2.3 Statistics

The data were analyzed using RStudio (R Core Team, 2023). A linear mixed-effects model was fitted using treatment and straw addition as fixed effects, and block as a random effect. A two-way ANOVA was performed on the model, followed by Tukey's HSD post-hoc test using estimated marginal means (emmeans) to assess pairwise differences between treatment combinations.

3 Results

3.1 Soil nutrient availability depending on treatment

Significant changes in soil pH and nutrient availability (Ca, Si, P, Al, Fe) were observed in some treatments with sediment and lime amendments without straw addition (Figure 1). Both Baringo sediment treatments significantly increased soil pH compared to the control (pH 5.06 ± 0.05), with values of 5.77 ± 0.34 ($p = 0.004$, Tukey) for Baringo 1% and 6.73 ± 0.51 ($p < 0.001$, Tukey) for Baringo 3%. The highest pH was observed in the Lime treatment

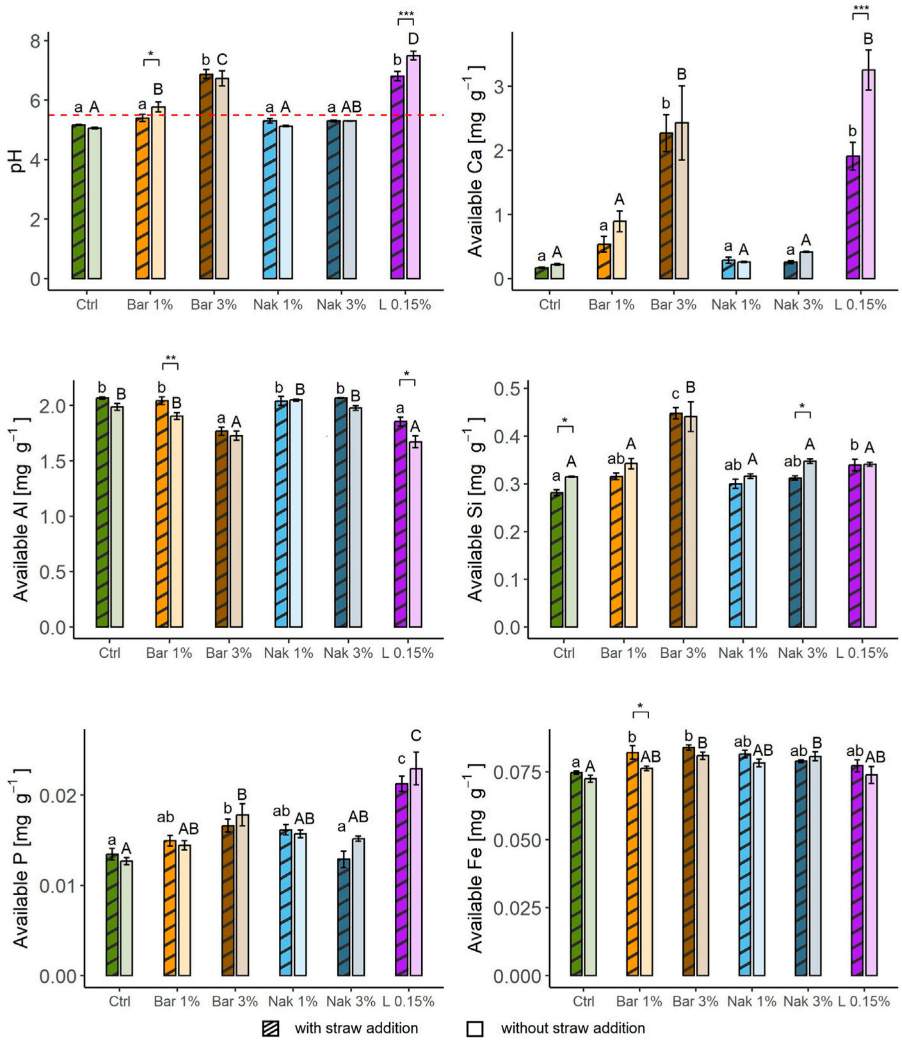

FIGURE 1
Sediment amendment and liming effects on soil pH, available Ca, Al, Si, P and Fe in the soil with (shaded) and without (not shaded) straw addition. The red dotted line shows the pH threshold of 5.5. Error bars indicate standard errors. Significant differences between all treatments with straw addition are shown as different lowercase letters, significant differences between all treatments without straw addition are shown as different capital letters. Common letters indicate no significant difference ($p < 0.05$). Significant differences between with and without straw addition of each treatment are shown as stars (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$).

(7.49 ± 0.30; $p < 0.001$). Neither Nakuru 1% nor Nakuru 3% significantly affected soil pH. Regarding nutrient availability, Baringo 1%, Nakuru 1%, and Nakuru 3% treatments did not cause significant changes in available Si, P, Al, or Ca compared to the control. In contrast, the Baringo 3% treatment significantly increased available Si (0.44 ± 0.06 mg g^{-1}; $p < 0.001$), P (0.017 ± 0.002 mg g^{-1}; $p = 0.002$), Ca (2,430 ± 1,160 g kg^{-1}; $p < 0.001$), and Fe (0.081 ± 0.002 mg g^{-1}; $p = 0.011$), while significantly decreasing available Al (1.72 ± 0.08 mg g^{-1}; $p < 0.001$). Similarly, the Lime treatment significantly increased available P (0.020 ± 0.004 mg g^{-1}; $p < 0.001$) and Ca (3,250 ± 630 g kg^{-1}; $p < 0.001$), and significantly reduced available Al (1.67 ± 0.11 mg g^{-1}; $p < 0.001$), compared to the control.

Similar patterns to those observed in the treatments without straw addition were found when comparing treatments with straw addition. Both the Baringo 3% and Lime treatments increased soil pH (6.88 ± 0.29 for Baringo 3%; 6.80 ± 0.31 for Lime; $p < 0.001$ for both, Tukey) and available Ca (2,270 ± 580 g kg^{-1} for Baringo 3%; 1910 ± 430 g kg^{-1} for Lime; $p < 0.001$ for both, Tukey), while significantly decreasing Al availability (1.77 ± 0.07 mg g^{-1} for Baringo 3%; 1.85 ± 0.08 mg g^{-1} for Lime; $p < 0.001$ for both, Tukey) compared to all other treatments. The Baringo 3% treatment had the highest available Si (0.45 ± 0.02 mg g^{-1}; $p < 0.001$, Tukey), but Lime treatment with straw also significantly increased Si availability (0.34 ± 0.02 mg g^{-1}) compared to the control (0.28 ± 0.01 mg g^{-1}; $p = 0.013$, Tukey). The highest available P was observed in the Lime treatment (0.021 ± 0.002 mg g^{-1}; $p < 0.001$, Tukey), while Baringo 3% also significantly increased P availability (0.017 ± 0.001 mg g^{-1}) compared to the control (0.013 ± 0.001 mg g^{-1}; $p = 0.014$, Tukey). Both Baringo treatments significantly increased Fe availability compared to the control ($p = 0.036$ for Baringo 1%, $p = 0.005$ for Baringo 3%, Tukey), but neither the two Nakuru treatments ($p = 0.066$ for Nakuru 1%, $p = 0.486$ for Nakuru 3%, Tukey) nor the Lime treatment ($p = 0.887$, Tukey) showed significant changes.

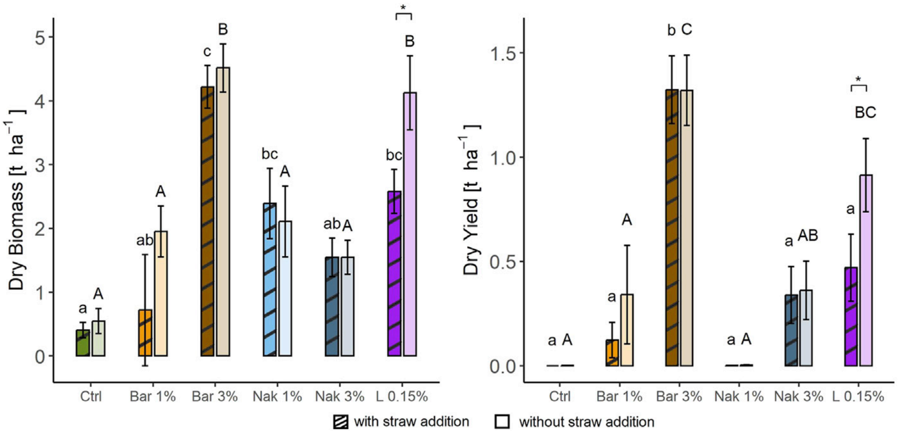

FIGURE 2
Effects of sediment amendment and liming on the biomass and yield of barley with (shaded) and without (not shaded) straw addition to the soil. Error bars indicate standard errors. Significant differences between all treatments with straw addition are shown as different lowercase letters, significant differences between all treatments without straw addition are shown as different capital letters. Common letters indicate no significant difference ($p < 0.05$). Significant differences between with and without straw addition of each treatment are shown as stars (* = $p < 0.05$).

The addition of straw material significantly altered pH and element availability in some treatments compared to those without straw addition (Figure 1). Straw addition significantly decreased the pH of the Baringo 1% treatment ($p = 0.044$, Tukey) and of the Lime treatment ($p < 0.001$, Tukey). The addition of straw significantly decreased available Ca in the Lime treatment ($p < 0.001$, Tukey), while it significantly increased Al availability in the Baringo 1% ($p = 0.006$, Tukey) and Lime treatments ($p < 0.001$, Tukey), and significantly decreased available Si in the control ($p = 0.049$, Tukey) and Nakuru 3% treatments ($p = 0.036$, Tukey) compared to treatments without straw addition. No significant differences in P availability were observed between treatments with and without straw addition.

3.2 Treatment effect on yield and biomass

Significantly higher yields were obtained with the Baringo 3% treatment (1.32 ± 0.33 t ha^{-1}; $p < 0.001$) and the Lime treatment without straw addition (0.91 ± 0.35 t ha^{-1}; $p < 0.001$) compared to the control and the Nakuru 1% treatment, both of which produced almost no yield (<0.1 t ha^{-1}, Figure 2). Baringo 3% and Lime treatments resulted in significantly higher biomass than the control ($p < 0.001$ for both; Tukey test). No significant differences in biomass or yield were observed for Baringo 1% and either Nakuru treatments with straw addition compared to the control.

When comparing all treatments with straw addition, Baringo 3% (4.22 ± 0.67 t ha^{-1}, $p = 0.02$, Tukey), Nakuru 1% and Lime treatment showed a significantly higher biomass than the control (0.41 ± 0.24 t ha^{-1}; Figure 2), but only Baringo 3% resulted in a significantly higher yield (1.32 ± 0.32 t ha^{-1}, $p < 0.001$, Tukey). No significant differences in the yield were observed among the other straw-amended treatments, including the Control, Baringo 1%, the two Nakuru treatments, and Lime.

Straw addition only did significantly affect biomass and yield in the lime treatments, decreasing it significantly compared to the treatment without straw. However, a trend of reduced yield with straw addition was also observed in the Baringo 1% treatment (−63%) compared to the treatment without straw.

4 Discussion

4.1 Effects on soil pH and nutrient availability

Scherwietes et al. (2024) showed that the addition of local sediments to Kenyan ferralitic arable soil can potentially increase soil pH and nutrient availability (such as P and Si) and decrease Al availability. These findings are consistent with the results of the present study. Even 2 years after sediment incorporation, significant increases in soil pH, available P, available Si and available Ca were observed in the Baringo 3% treatment. In addition, the Al availability and thus potentially the Al toxicity for plants was reduced by the treatment with Baringo 3%. However, no significant changes were observed in the availability of nutrients (Ca, Si, P) or in the levels of Al in the soil across the other sediment treatments. The decrease in Al availability in the 3% Baringo treatment may be due to two processes that may be the driving factors for the observed effects: (i) the increase in soil pH and (ii) the increase in available Si in the soil. Both are due to the chemical composition of the Baringo sediment, which is characterised as a Ca-rich lacustrine sediment with low crystalline Si as the main component (Scherwietes et al., 2024). During the weathering of the sediments, carbonates are released that buffer the pH value of the soil. A rising soil pH changes the mobility of Al in the soil solution, as it controls Al speciation (Bojórquez-Quintal et al., 2017). At a $pH < 5$, the phytotoxic and highly solubilised Al^{3+} is the dominant species in the soil solution (Kochian et al., 2004). As the soil pH increases, the dominant Al species changes to $Al(OH)_2^+$ at pH 5.5–6.5 and to $Al(OH)_3$ at neutral pH (Bojórquez-Quintal et al., 2017). In addition to carbonates, the weathering of the Baringo sediment also release Si, resulting in a higher available Si in soil solution. Scherwietes et al. (2024) found that the Baringo sediment has a high content of amorphous Si (ASi), which is less crystalline and releases a lot of silicic acid into the soil solution (Schaller et al., 2021). The presence of silicic acid in soil solution may also reduce Al availability as it could interact with Al and form aluminosilicates (SROAS) (Exley et al., 2019; Lenhardt et al., 2021). The observed reduction in available Al in the soil due to the addition of Baringo 3% may therefore be attributed to both processes, the increase in soil pH and the increase in Si in the soil.

However, these processes not only promote the decrease in available Al, but may also favour the increase in available P in the soil observed with the Baringo 3% treatment (Schaller et al., 2021). Particularly in Ferralsols with their high Fe and Al content, a low soil pH (<5.5) may greatly reduce the availability of P due to binding of it to Fe- and Al-oxides and hydroxides (Sanchez and Logan, 1992; Agegnehu et al., 2021). Furthermore, previous studies revealed, that silicic acid may absorb to mineral surfaces, competing with P for binding sites and exchanging it from minerals like Fe-oxides (Taylor, 1995; Dietzel, 2002). The increase in soil pH, but also the increase in available Si in the soil due to the addition of Baringo 3% may therefore promote lower Al availability and higher P availability in the present study. However, Scherwietes et al. (2024) have already pointed out the difficulty of distinguishing between these processes and finding out in a field study which is the driving factor for the change in nutrient availability. In the present study, additional lime treatments (4.5 t ha^{-1}) were applied to compare the effects on nutrient availability between the sediment treatments and liming. It is known that lime increases soil pH by neutralizing excessive H^+ ions due to its high release of carbonates during weathering (Bolan et al., 2003; Wang et al., 2021). This process was also observed in the present study, with Ca availability and soil pH increasing with liming. Liming does not add any additional Si to the soil solution, but the increase in soil pH can potentially increase the Si availability (Haynes, 2019). However, this process was not observed in this study, as Si availability did not increase with liming while soil pH was increased. Nevertheless, the available Al decreased to a similar extent as in the 3% Baringo treatment, and the P availability increased even more than in the 3% Baringo treatment. This indicates that the increase in pH due to the supply of carbonates from the added material may be the driving factor for the reduction in Al availability and the increase in P availability in the soil.

Several studies have shown that straw return may serve as an effective method to increase soil pH and enhance the availability of essential nutrients, such as phosphorus, through the gradual release of nutrients during decomposition (Butterly et al., 2013; Yan et al., 2019). However, such effects were not observed in the present study. On the contrary, a significant decrease in soil pH was recorded following straw return in both the Baringo 1% and Lime treatments. Furthermore, when straw was applied in combination with sediment, no additional improvements in nutrient availability or soil pH were observed beyond those achieved by sediment alone. Initially, it was hypothesized that the combination of straw return and lime application would provide the most effective soil improvement. However, the results contradicted this hypothesis: a significant reduction in Ca availability was observed, which may have contributed to a subsequent decrease in soil pH and an increase in available Al.

4.2 Effects on plant production

Our results indicate potential positive effects of both amending local sediments and liming on barley biomass production and yield, which is in line with many other studies (Li et al., 2019; Wang et al., 2021; Scherwietes et al., 2024). Liming is already known for decades to be a very effective practice to promote plant production (Foy et al., 1965). In this study, liming (with a rate of 4.5 t ha^{-1}) resulted in a significant increase in biomass production of 650% (4.13 ± 1.16 t ha^{-1}) compared to the control (0.55 ± 0.39 t ha^{-1}). Scherwietes et al. (2024) found that the addition of local sediments could potentially increase the plant production and barley yield. In this study, these results could have been verified again 2 years after incorporation. However, the 3% Baringo treatment was the only treatment with added sediment that showed a significant increase (4.52 ± 0.75 t ha^{-1}, +722% compared to control) in biomass production, which was even slightly higher than the lime treatment (+9% compared to lime). The yield effect was even higher for the 3% Baringo compared to the lime treatment (Lime: 0.91 ± 0.35 t ha^{-1}; Baringo 3%: 1.32 ± 0.34 t ha^{-1}; +45% compared to lime). However, due to the complete lack of rainfall in the tillering stage and irregular rainfall throughout the growing season, the overall yield in this study was very low. Irrigation was required at the tillering stage, which was carried out at 200 L per plot once a week for 3 weeks. Apparently, the control and Nakuru 1% treatments suffered the most from the low water supply, resulting in no heading and no yield by the end of the growing season. The yields of Nakuru 3% (0.36 ± 0.28 t ha^{1}), Baringo 1% (0.34 ± 0.47 t ha^{-1}), Baringo 3% and Lime treatment were all well below the 5-year average 2019/20–2023/24 (3.5 t ha^{-1}) and also well below the annual average of 2023 (3.0 t ha^{-1}; USDA, 2024).

Nevertheless, the addition of 3% Baringo sediment and lime partially resulted in better plant growth compared to the control and may have promoted higher tolerance to drought stress at tillering stage, which was an advantage over the control and the treatment with 1% Nakuru. One possibility is that the lower Al availability resulted in lower Al toxicity, the main toxic effect of which is inhibition of root growth and elongation (Foy et al., 2003; Kochian et al., 2004). Therefore, the plants may have developed a better root system from the beginning and may have had better water uptake under drought stress. In addition, the higher soil Si availability resulted in a higher Si uptake and accumulation in plant tissues (Supplementary Figure S2, 3). Silicon is known to promote plant tolerance to drought stress through various mechanisms, which could explain the slightly better yield of Baringo 3% compared to Lime (Coskun et al., 2016). For example, water uptake may be improved by promoting root growth and by the deposition of Si in the endodermal cell wall (Steudle and Peterson, 1998; Dakora and Nelwamondo, 2003). In addition, the deposition of Si in the stomata may reduce water loss via the stomata during drought stress (Gao et al., 2005).

In the present study, straw return at 5 t ha^{-1} had no positive effect on plant production or barley yield. It was initially assumed that straw return would enhance crop production, as reported in several studies (Butterly et al., 2013; Yan et al., 2019). However, a significant reduction in biomass production and barley yield was observed in the Lime treatment. This outcome may be attributed to a decrease in Ca availability, which led to a reduction in soil pH and an increase in Al availability, thereby contributing to enhanced toxicity.

As originally assumed, the lime treatment and local sediment amendment (but only in the form of treatment with Baringo 3%)

increased the biomass and yield of barley. These effects may be due to the increase in soil pH and the associated increase in P availability and decrease in Al availability. Nevertheless, Baringo 3% still performed slightly better in biomass production (+9%) and yield (+45%), which might be due to the supplementation of Si and its higher availability. However, the effects of the lime treatment appear to be more effective in the short term, as not significantly lower yields and biomass were achieved with significantly less added material (Lime: 4.5 t ha^{-1}; Baringo 3%: 72 t ha^{-1}). However, the long-term effect of the added materials must also be taken into account, as the local sediments were already in their second growing season and still resulted in slightly better crop production. It is known that lime dissolves within a short time and thus loses its activity. Further studies should be carried out in order to evaluate the different amendments from an economic perspective in addition to the biophysical perspective of this study.

5 Conclusion

The present study showed that there are differences between the effects of local sediment amendment, liming and straw return on soil fertility. While straw return did not improve soil fertility and barley yield, liming and certain local sediment amendments resulted in better growth and higher yield of barley. The results showed that the application of local sediment could be still effective even 2 years after incorporation. However, the improvement depends on the sediment source and amendment rate. One of the driving factors for the improvement in soil fertility with the addition of local sediments (Baringo 3%) is probably the addition of Ca and consequently the increase in soil pH, which could promote a higher soil P availability and reduce the soil Al availability and its toxicity. However, Baringo 3% still resulted in 45% more yield compared to the Lime treatment. This indicate that Si supplementation by the sediment might also play a beneficial role in crop production, as Baringo 3% increased soil Si availability, but Lime did not. Nevertheless, the yields of Baringo 3% and Lime treatment were still well below the average barley yield in Kenya, probably due to lack of rainfall and water supply. In conclusion, the addition of local sediments or liming could make agriculture in Kenya more sustainable from a biophysical perspective. However, the effects of local sediment on soil fertility were still observed 2 years after incorporation, depending mainly on the sediment material and the rate of application. Lime was applied in smaller quantities, but is probably dissolved more quickly and thus loses its activity. Further studies are needed to investigate the potentials of local sediment amendments and liming for agriculture in Kenya from an economic perspective.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

ES: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review and editing, Formal Analysis. JhS: Supervision, Writing – review and editing. TB: Writing – review and editing, Methodology. JrS: Writing – review and editing, Conceptualization, Funding acquisition, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2025.1572266/full#supplementary-material

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