# Soil acidity status and lime requirements for agricultural lands in Kenya †

# [Estado de acidez del suelo y necesidades de cal para tierras agrícolas en Kenia]

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## SUMMARY

**Background.** Soil acidity is a major soil health challenge that impacts agricultural productivity in Kenya while information on its national extent and severity remains limited. **Objective**. To determine national extent and spatial distribution of soil acidity, estimate the number of farming households affected and quantify lime requirements for acid soils within the Country. **Methodology**. This was achieved through application of data-driven approach, utilizing existing soil data collected at 0 -30 cm depth between 2012 and 2024, gridded environmental GIS layers, digital farmer registry data and geospatial analysis techniques. Soil pH and exchangeable acidity were then integrated to map acidity classes, estimate affected land area and households, and compute lime requirements for soils with pH$\leq$5.5. **Results.** Soil pH ($H_2O$) across the Agricultural soils ranged from 3.7 to 10. 8. Approximately 13.29% (7.7 million ha) of the national land area was affected by soil acidity (pH $\leq$ 5.99), comprising < 1% (< 100 ha) extremely acid (pH $\leq$ 4.5), 0.2% (0.12 million ha) very strongly acid (pH 4.51 – 4.99), 5.5% (3.16 million ha) strongly acid (pH 5.00 – 5.50) and 7.6% (4.4 million ha) moderately acid (pH 5.51 – 5.99). The soil acidity problem spanned across 29 counties, with higher severity in Western, Rift Valley and Central Kenya**.** The counties with largest proportion of acidic land were Kisii (100%), Nyamira (100%), Vihiga (93%), Nandi (91%) and Kakamega (91%). Out of the 6.4 million digitally-registered farming households nationwide, Kisii County had the highest number (184,103) and proportion (83.6%) affected. Additionally, lime requirements at pH <5.5 were observed to vary widely ranging from 269 metric tons (MT) in Kakamega to 8 MT in Kisumu, and 0.58 ± 0.08 t ha$^{-1}$ in Nakuru to 1.51 ± 0.07 t ha$^{-1}$ in Nyamira. **Implications.** Obtained spatially-explicit soil acidity maps and lime requirement estimates provides evidence for supporting government and stakeholders in operationalization of soil health interventions, lime use policies, subsidy programs and prioritization of acid soil remediation and research. **Conclusion.** This study provides a nationally representative, spatiall assessment of soil acidity and lime requirements, offering critical guidance for targeted remediation and integrated soil health management approaches.

**Key words:** Acidic soils; Kenya; lime; soil pH.

## RESUMEN

**Antecedentes.** La acidez del suelo es un importante problema para la salud del suelo que afecta la productividad agrícola en Kenia, mientras que la información sobre su extensión y gravedad a nivel nacional sigue siendo limitada. **Objetivo.** Determinar la extensión nacional y la distribución espacial de la acidez del suelo, estimar el número de hogares agrícolas afectados y cuantificar las necesidades de cal para suelos ácidos en el país. **Metodología.** Esto se logró mediante la aplicación de un enfoque basado en datos, utilizando datos de suelo existentes recopilados a una profundidad de 0 a 30 cm entre 2012 y 2024, capas de SIG ambientales en cuadrícula, datos de registros digitales de agricultores y técnicas de análisis geoespacial. El pH del suelo y la acidez intercambiable se integraron posteriormente para mapear las clases de acidez, estimar la superficie y los hogares afectados, y calcular las necesidades de cal para suelos con un pH $\leq$ 5.5. **Resultados.** El pH del suelo (H2O) en los suelos agrícolas osciló entre 3.7 y 10.8. Aproximadamente el 13.29 % (7.7 millones de ha) de la superficie nacional se vio afectada por la acidez del suelo (pH

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† *Submitted April 20, 2025 – Accepted January 25, 2026.* http://doi.org/10.56369/tsaes.6288

ISSN: 1870-0462.

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≤ 5.99), que comprende <1 % (<100 ha) extremadamente ácido (pH ≤ 4.5), 0.2 % (0.12 millones de ha) muy fuertemente ácido (pH 4.51 – 4.99), 5.5 % (3.16 millones de ha) fuertemente ácido (pH 5.00 – 5.50) y 7.6 % (4.4 millones de ha) moderadamente ácido (pH 5.51 – 5.99). El problema de la acidez del suelo se extendió por 29 condados, con mayor gravedad en Kenia occidental, del valle del Rift y central. Los condados con la mayor proporción de tierras ácidas fueron Kisii (100%), Nyamira (100%), Vihiga (93%), Nandi (91%) y Kakamega (91%). De los 6.4 millones de hogares agrícolas registrados digitalmente en todo el país, el condado de Kisii tuvo el mayor número (184.103) y proporción (83.6%) afectados. Además, se observó que los requisitos de cal a un pH <5.5 variaban ampliamente, desde 269 toneladas métricas (TM) en Kakamega hasta 8 TM en Kisumu, y 0,58 ± 0,08 t ha-1 en Nakuru hasta 1,51 ± 0,07 t ha-1 en Nyamira. **Implicaciones**. Los mapas de acidez del suelo espacialmente explícitos obtenidos y las estimaciones de los requisitos de cal proporcionan evidencia para apoyar al gobierno y a las partes interesadas en la puesta en práctica de intervenciones de salud del suelo, políticas de uso de cal, programas de subsidios y priorización de la remediación de suelos ácidos e investigación. **Conclusión.** Este estudio proporciona una evaluación espacial y representativa a nivel nacional de la acidez del suelo y los requerimientos de cal, ofreciendo una guía crítica para la remediación específica y enfoques de gestión integrada de la salud del suelo.

**Palabras clave:** Suelos ácidos; Kenia; cal; pH del suelo

## INTRODUCTION

Soil is a fundamental natural resource that provides essential ecosystem services for sustainable agricultural production. However, soil degradation remains a significant global challenge particularly in Africa (Liana and Pozza, 2020). Currently, about 33% of the world's soils are moderately to highly degraded, with about 40% of these degraded soils located in Africa (Kopittke *et al*., 2019). Approximately 75 to 80% of Africa’s cultivated land is degraded (AUDA-NEPAD, 2023), while about 14% of East Africa’s total land area is experiencing severe to very severe degradation (UNEP, 2006). Overall, soil degradation impacts over 485 million people in Africa and costs Sub-Saharan Africa (SSA) approximately USD 68 billion per year (Zingore *et al*., 2023). It also reduces SSA’s annual agricultural Gross Domestic Product (GDP) by 3%. This situation poses a serious threat to food and nutrition security, rural livelihoods, ecosystem sustainability, and the achievement of Sustainable Development Goals (SDGs) in the region.

Kenya, just like the other SSA and East African countries, has been experiencing low crop productivity due to soil degradation driven primarily by poor management practices, including unbalanced fertilization, continuous cropping without organic inputs, and lack of soil conservation measures (Mganga, 2022; Erica and Larrea, 2024). This has culminated in a decline of soil’s biological, chemical, and physical properties, reducing its capacity to support production and ecological functions. An important aspect of soil degradation that is critical and has impacted Kenyan agriculture is soil acidity. Acidic soils are widespread and occupy approximately 13% (7.5 million hectares) of Kenya’s total physical land area, translating to 63% of the total arable land (Kanyanjua *et al*., 2002). This problem is expanding both in area and severity.

Soil acidity *per se* is an index of the activity of Hydrogen ion ($H^+$) as it interacts with soil components, nutrients in the soil solution and root rhizosphere (Sanchez, 2019). It is a complex natural process that soils go through with time, and is driven by climate, particularly heavy rainfall and associated leaching of base cations, acidic parent material, organic matter decay, nutrient mining, atmospheric depositions, landscape position, vegetation, and management practices, such as continuous application of acid-forming fertilizers (Zingore *et al.*, 2023). Acidic soils with pH lower than 5.5 negatively affect the availability of plant nutrients (e.g., Phosphorus), soil bioactivity and biodiversity, and availability of toxic elements in the soil (e.g., Aluminum and Manganese) (Weil and Brady, 2017; Esilaba *et al*., 2023). Consequently, crops are unable to extract nutrients from the soil that are fed to them through the application of fertilizers. This limits plant growth, root development and crop yields (Muindi *et al*., 2016; Zingore *et al.*, 2023). Like most parts of SSA, Kenya’s soil acidity is majorly associated with a combination of geological, agronomic and climatic factors. The regions mostly affected by elevated soil acidity levels include the food baskets in Central, Western, Rift Valley and parts of Nyanza, as well as parts of Eastern and Coastal Kenya (Esilaba *et al*., 2023). These areas are dominated by a wide range of soil types, including Nitisols, Andosols, Acrisols, Ferralsols and Cambisols, whose parent materials are inherently acidic (Gachene and Kimaru, 2003; Van Wijk *et al*., 2020).

Previous research has demonstrated that soil acidity can be managed by adopting soil health management strategies such acid-tolerant crops, use of organic amendments, judicious use of fertilizers and liming (Agegnehu *et al*.., 2019; Hijbeek *et al*., 2021; Kibet *et al*., 2023). Despite the availability of these management strategies, soil acidity remains a serious environmental threat in Kenya. This is because implementation of the strategies is hardly based on reliable and actionable information, indicating the extent, distribution, population of farming households and liming requirements for the areas affected by soil acidity. Such information is crucial for evidenced-based and spatially-targeted interventions to rehabilitate acidic soils; yet, it is not readily available.

To fill this gap in knowledge, this study analyzed the existing data to yield new information and insights into the spatial patterns and extent of soil acidity, number of farming households affected by soil acidity, and liming requirements in Kenya. It is a key step towards embracing and implementing data-driven and targeted soil health interventions to enhance crop productivity, strengthen food and nutrition security, restore soil health, build environmental resilience, and secure a sustainable future for Kenyans.

## MATERIALS AND METHODS

### Description of the study area

This study was conducted in Kenya, which is located on the eastern side of the African continent between latitudes 5.4° N and 4.5° S, and between longitudes 34° E and 42° E (Survey of Kenya, 2014). The country is bordered to the north by South Sudan and Ethiopia, to the east by Somalia and the Indian Ocean, to the south by Tanzania, and to the west by Lake Victoria and Uganda (Figure 1). It occupies an area of about 582,646 km$^2$, of which 1.9% (11,230 km$^2$) is under water, 14% (81,416 km$^2$) is of medium to high agricultural potential, and the remaining 84.1% (490,000 km$^2$) comprises the arid and semi-arid lands (ASALs) (National Land Commission [NLC], 2023). The medium and high potential lands support over 80% of the human population and diverse crops (e.g., tea, coffee, vegetables, maize, potatoes and bananas), while the ASALs support the remaining 20%, in addition to wildlife, livestock and drought-tolerant crops (e.g., sorghum and millet).

Kenya’s soils are mainly Acrisols, Alisols, Andosols, Arenosols, Calcisols, Cambisols, Chernozems, Ferralsols, Fluvisols, Gleysols, Gypsisols, Leptosols, Lithosols, Lixisols, Luvisols, Nitisols, Phaeozems, Planosols, Regosols, Solonchaks, Solonetz, Vertisols and Xerosols according to the FAO-UNESCO soil classification system (FAO, 1988)The topographic profile is very distinctive, with the altitude stretching from sea level near the Indian Ocean at the coast to

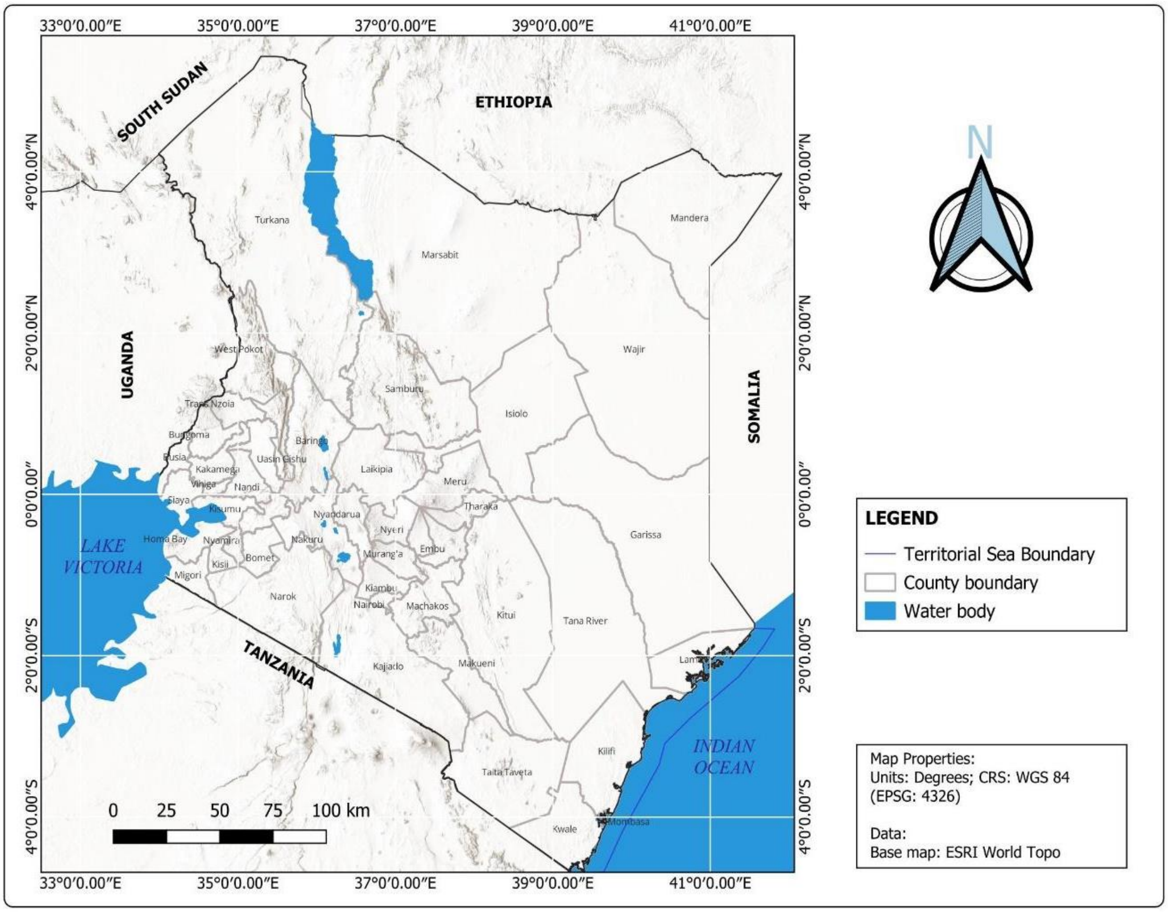


**Figure 1. Geographic location of Kenya (Source: Authors).**

about 5,200 m (17,057 ft) at the peak of Mt. Kenya. The geology is characterized by the: (i) Archean rocks of the Nyanzian and Kavirondian systems found to the west around Lake Victoria, (ii) Proterozoic rocks of the Mozambique belt (Basement) and Bukoban system, which cover parts of western, coast, eastern, Rift Valley and northeastern regions, (iii) Palaeozoic and Mesozoic formations found near the coast and northeastern Kenya, (iv) Tertiary and Quaternary volcanics, covering the central parts from south to north, occurring in the floor of the Rift Valley and on the peneplains west and east of the valley, and (v) Tertiary and Quaternary sediments, occurring in various parts of the country (Pulfrey, 1969; Akech *et al*., 2013).

The climate is moderate tropical, which is determined by its proximity to the equator, altitude, diverse topographical features, presence of large water bodies (e.g., Lake Victoria and the Indian Ocean), as well as the movement of the Inter-Tropical Convergence Zone (Gichaba, 2013). The country experiences two seasonal rainfall peaks of the long rains (March to May) and short rains (October to December) in most places, except for the very high-altitude areas, which have one long rainy season. The spatial distribution of the rainfall is quite uneven, varying from 150 to 500 mm per annum in the arid east and northeast of the country, from 500 - 1000 mm in the semi-arid regions, and from 1,000 - 2,700 in the more humid areas in the highlands and near Lake Victoria. According to Kenya's agro-climatic zonation (Sombroek *et al*., 1982), these are Zone VI – VII, Zone V, and Zone 1 – IV, respectively. The average potential evaporation varies from less than 1,200 mm to 2,500 mm, while the mean annual temperatures range from less than 10º to 30º C. Low temperatures characterize the Central and Rift Valley highlands, such as Kericho, Nandi and Nyandarua counties, while high temperatures are typical of the arid regions of northern and eastern Kenya, including Mandera and Turkana counties (NLC, 2023).

## Data sources

### Soil data

Three soil databases were used for this study; namely the (i) Kenya Agricultural and Livestock Research Organization (KALRO) - National Accelerated Agricultural Inputs Access Programme (NAAIAP) soil database, (ii) KALRO Legacy soil database, and (iii) KALRO - Ministry of Agriculture and Livestock Development (MoALD) soil database. The KALRO NAAIAP soil database consisted of soil samples that were collected from 4,800 smallholder farms in the maize-growing areas in the country between 2012 and 2014 under NAAIAP. The farms were located in 164 sub-counties where the project was implemented (Figure 2). One of the key objectives of the project was to recommend the most appropriate fertilizer formulations and soil fertility combinations for the cropping systems, as well as to recommend liming rates where soil acidity was a major crop-yield limiting factor. In each farm, areas with similar characteristics were delineated as sampling units, after which two composite soil samples of about 500 g each were collected using a soil auger at 0 - 30 cm depth in the two biggest sampling units (NAAIAP, 2014). Thus, a total of 9,600 soil samples were collected and transported to the National Agricultural Research Laboratories where they were analyzed for soil pH ($H_2O$) and exchangeable acidity. Soil pH was measured using a pH meter with a ratio of 1:2.5 soil to water, while exchangeable acidity was determined by leaching with potassium chloride followed by titrating with 0.02M HCl as described by Okalebo *et al*. (2002).

The KALRO Legacy soil database contained 8,107 soil samples that had been brought to the National Agricultural Research Laboratories for analysis by farmers, research scientists and other stakeholders between 2016 and 2022. These samples were collected from all Kenyan counties, excluding the cities of Nairobi and Mombasa (Figure 2), and were representative of most soils where crops are grown, except for the coffee, tea and sugar soils. All soils had been sampled at 0 – 30 cm depth.

Lastly, the KALRO - MoALD soil database comprised 814 soil data points that were collected at 0 – 30 cm depth in seven counties, including Narok, Nakuru, Nandi, Uasin Gishu, Trans Nzoia, Kakamega and Bungoma for a project that was implemented by MoALD between February and June 2024. One of the objectives of the project was to manage soil acidity for improved maize productivity in Kenya.

Where the soil data had missing coordinates, reverse-geotagging was done either by matching the registered farmers' names, telephone numbers and locations with the corresponding details in the national digital farmers' registry, or by assigning geographic coordinates of the nearest schools, churches, hospitals, market centres, or any other locational attribute that had been provided by the clients in the soil sample reception records. The latter step involved extracting the name of the nearest landmark from the record and reading its coordinates from Google Earth. Thereafter, the three collated and georeferenced soil datasets were cleaned and prepared for use in digital mapping of soil pH. Data cleaning entailed the removal of missing and unusual values, duplicates and outliers. Finally, geographically-referenced soil databases, containing the geographic coordinates of each soil sampling point were developed in QGIS software and also structured in Microsoft Excel format for statistical analysis. Pearson's correlation and descriptive statistical summaries, including the mean, standard deviation and range were computed at 95% confidence level.

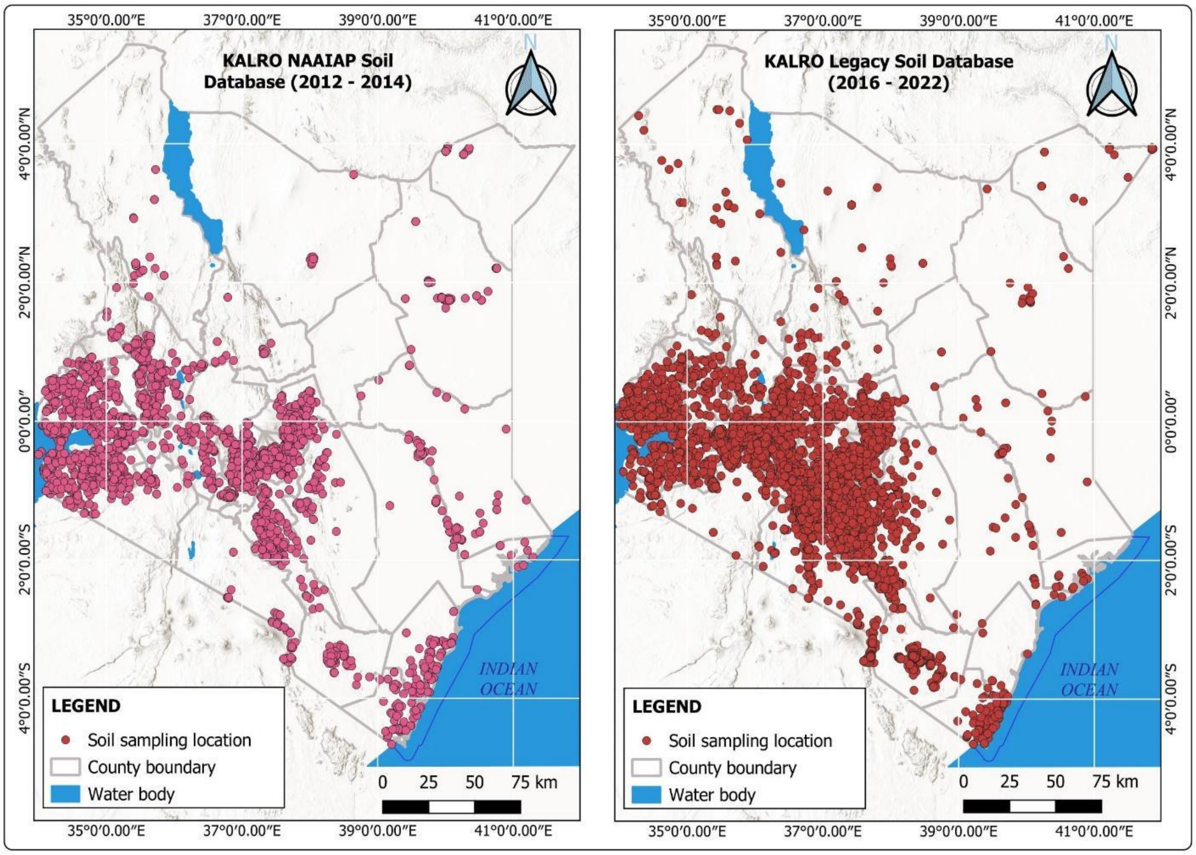


**Figure 2. Spatial distribution of the KALRO NAAIAP and Legacy soil data points (Source: Authors).**

## Farmer registry and existing GIS data

Geo-referenced data of about 6.4 million farming households were obtained from the Kenya Integrated Agriculture Management Information System (KIAMIS) platform (MoALD, 2024). Besides this, a suite of 33 readily-available gridded GIS layers (environmental covariates), representing different soil-forming factors (e.g., climate, organisms and terrain) were retrieved from Google Earth Engine (GEE) and processed for digital mapping of soil pH. Terrain data included elevation and its derivatives, such as slope, terrain wetness index and curvature. Climate data consisted of elements, such as air temperature, precipitation, and evapotranspiration. Organism data comprised land cover, fraction of absorbed photosynthetically active radiation (FAPAR), vegetation indices, and others. Selection of these covariates was informed by the ongoing Global Soil Nutrient and Nutrient Budget mapping (GSNmap) initiative under FAO Global Soil Partnership (GSP), which is utilizing the same datasets to develop national and global soil nutrient maps at 0 – 30 cm depth (Suleymanov *et al*., 2024). Processing of the environmental covariates entailed harmonizing them to a common coordinate referencing system of WGS 84, a common spatial resolution of 1,000 m and a common extent.

## Data analysis

### Spatial coverage of the areas affected by soil acidity

This involved developing soil pH maps, based on quantitative relationships between the soil observations and environmental covariates, to show the spatial distribution of soils by pH classes and specific places affected by acidity. After cleaning, the soil data points and environmental covariates were merged into a new dataset, which served as input data for model calibration and evaluation. That is, the covariates were stacked together and their values extracted to the soil data points. Model calibration involved quantifying the functional relationships between the environmental covariates and soil attributes using Random Forests (RF), a well-tested machine learning algorithm for spatially-predicting soil attributes (Were *et al*., 2015). The performance of the RF models that had been calibrated was measured using three accuracy metrics, including the Root Mean Squared Error (RMSE), Mean Error (ME), and coefficient of determination ($R^2$). After calibrating RF models, the parameters were applied to the stack of environmental covariates to create prediction surfaces (i.e., gridded layers) for pH. The prediction surfaces were, ultimately, used to design soil pH maps, which were reclassified based on the ratings (classes) shown in Table 1.

**Table 1. Soil pH ratings and classification.**

| Soil pH | Classification |
|---|---|
| ≤ 4.5 | Extremely acid |
| 4.51 – 4.99 | Very strongly acid |
| 5.00 – 5.50 | Strongly acid |
| 5.51 – 5.99 | Moderately acid |
| 6.00 – 6.50 | Slightly acid |
| 6.51 – 6.99 | Near neutral |
| ≥ 7.0 | Alkaline |

**Source:** Adapted with some modifications from Mehlich *et al*. (1964) and USDA (2022).

### Extent of land affected by soil acidity

To determine the land area affected by soil acidity in Kenya, the total number of pixels with pH value ≤ 5.5 were counted for each soil pH class in the map and then multiplied by the pixel area (where a pixel in this case covered 1,000 × 1,000 m). Similarly, to determine the total land area affected by soil acidity in each County, the reclassified soil pH map was spatially overlaid with the County map in a GIS and, using zonal statistics routines, the total number of pixels with pH value ≤ 5.5 were counted for each County. The resultant pixel counts were multiplied by the area of a pixel to get the area in hectares for each county. To support prioritization of the areas for liming, the counties were then ranked based on the proportion of their total land areas affected by soil acidity.

### Number of farming households affected by soil acidity

To establish the number of farming households affected by acidity in each County, the reclassified soil pH map was first converted to polygons (i.e., vectorized) and then intersected with the digital farmer registry data. Thereafter, the number of digitally-registered farming households falling within the three classes with pH value ≤ 5.5 were counted for each county from the resultant attribute table.

### Amount of lime required to amend soil acidity

Lime Requirement (LR) refers to the quantity of liming material that must be applied to a soil to raise its pH from acid condition to a near-optimal level for plant growth (McLean et. al., 1978). In this study, the exchangeable acidity method (Kamprath, 1970) was used to estimate LR. Exchangeable acidity is a measure of the amount of soil and Cation Exchange Capacity (CEC) that is occupied by acidic cations, which generally refer to $H^+$ and Aluminium ions ($Al^{3+}$) although they can also include Iron ($Fe^{2+}$) and Manganese ($Mn^{2+}$) cations. The exchangeable acidity method used Equation 1 to calculate LR:

$$LR = 1.5 \times HP \times 2.2 \qquad \text{Equation (1)}$$

where, LR = Lime requirement (t $ha^{-1}$), HP = Exchangeable acidity (me%), 1.5 = neutralization constant, and 2.2 = conversion factor (kg to tons of soil at depth 0 – 30 cm)

## RESULTS AND DISCUSSION

### Descriptive statistics of soil pH and exchangeable acidity

Table 2 presents the statistical summaries of soil pH based on KALRO Legacy, NAAIAP and MoALD data. The three datasets had normal distribution and low variability of soil pH values as indicated by the mean, median and skewness. The soil pH values ranged from 3.80 to 8.90 for NAAIAP, from 3.70 to 10.80 for KALRO Legacy and from 4.03 to 7.70 for MoALD data, with a standard deviation of 0.99, 0.92 and 0.60, respectively.

Similarly, Table 3 displays the statistical summaries of soil exchangeable acidity and the correlation with pH for the soils with pH values ≤ 5.5 based on KALRO NAAIAP and MoALD data. The two datasets had normal distribution and low variability of exchangeable acidity values as indicated by the mean, median and skewness. The exchangeable acidity values ranged from 0.08 to 1.00 cmol $kg^{-1}$ for NAAIAP and from 0.10 to 1.60 cmol $kg^{-1}$ for MoALD data, with a standard deviation of 0.19 and 0.29, respectively. Disaggregation of the data based on counties indicated that Nyamira (0.46), Makueni (0.43), Bungoma (0.41), Kisii (0.40) and Kericho (0.37) had the highest levels of exchangeable acidity (Figure 3). These exchangeable acidity values fall within the ranges reported by Kisinyo *et al*. (2013; 2015a), Muindi (2016), Opala *et al*. (2018) and Kibet *et al*. (2023) who conducted their studies in the acid soils of east and west of the Rift Valley. Unlike pH, exchangeable acidity considers both the $H^+$ and $Al^{3+}$ ions; hence, it is also a useful indicator of Al toxicity in acidic soils (Owusu *et al*., 2024).

**Table 2. Descriptive statistical summaries of soil pH.**

| Data | *n* | Mean | SD | Median | Min. | Max. | Range | Skewness |
|---|---|---|---|---|---|---|---|---|
| NAAIAP | 4,013 | 5.93 | 0.99 | 5.80 | 3.80 | 8.90 | 5.10 | 0.70 |
| Legacy | 8,107 | 6.00 | 0.92 | 5.90 | 3.70 | 10.80 | 7.10 | 0.43 |
| MoALD | 791 | 5.22 | 0.60 | 5.13 | 4.03 | 7.70 | 3.67 | 0.86 |

Note: *n* = sample size; SD = standard deviation; Max. = maximum; Min. = Minimum

**Table 3. Descriptive statistical summaries of soil pH and exchangeable acidity.**

| **KALRO NAAIAP Soil Data** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | ***n*** | **Mean** | **SD** | **Median** | **Min.** | **Max.** | **Range** | **Skewness** |
| Exch. acidity (cmol kg$^{-1}$) | 1475 | 0.31 | 0.19 | 0.30 | 0.08 | 1.00 | 0.92 | 1.31 |
| Soil pH | 1475 | 5.00 | 0.32 | 5.00 | 3.80 | 5.80 | 2.00 | -0.59 |
| *r* | | -0.69 | | | | | | |
| **KALRO MoALD Soil Data** | | | | | | | | |
| Exch. acidity (cmol kg$^{-1}$ ) | 567 | 0.62 | 0.29 | 0.50 | 0.10 | 1.60 | 1.50 | 0.80 |
| Soil PH | 567 | 4.92 | 0.32 | 4.93 | 4.03 | 5.49 | 1.46 | -0.24 |
| *r* | | -0.90 | | | | | | |

**Note:** *n* = sample size; Exch. acidity = Exchangeable acidity; SD = standard deviation; Max. = maximum; Min. = Minimum; *r* = correlation coefficient

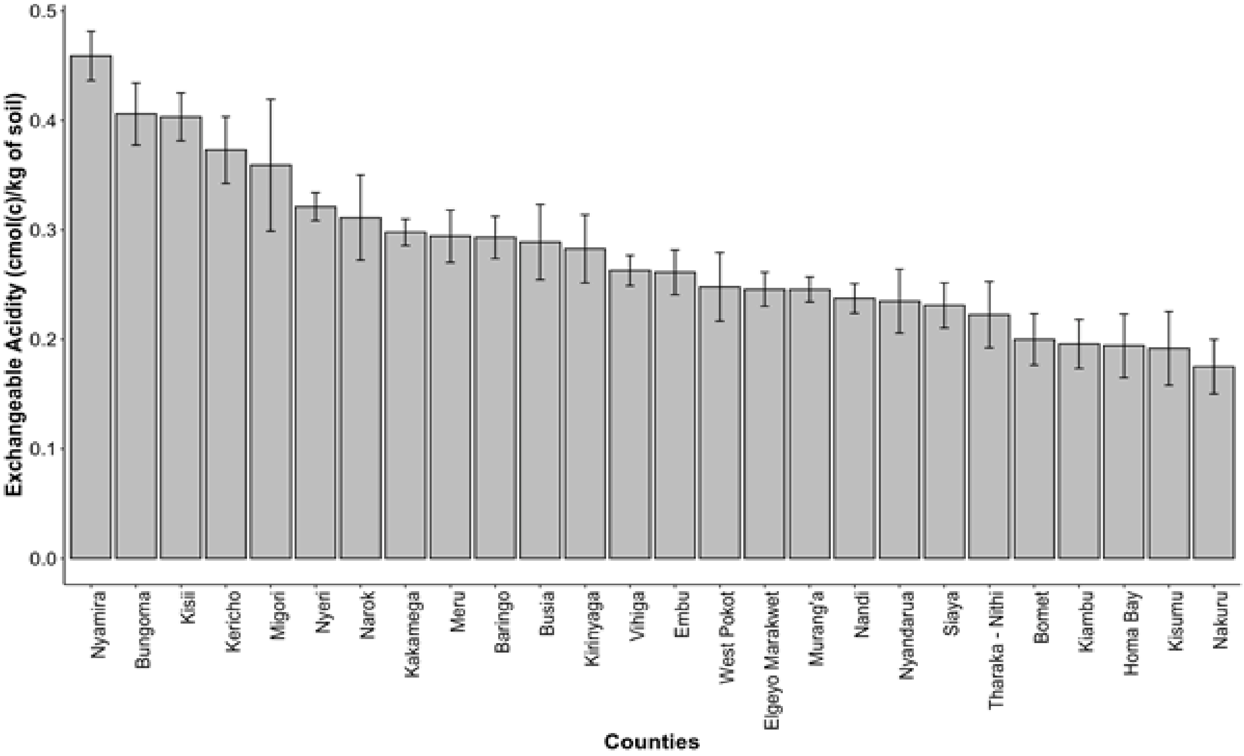


**Figure 3. Exchangeable acidity by County based on the KALRO NAAIAP data. Note: The error bars indicate the uncertainty of the mean values of exchangeable acidity for the counties.**

Moreover, there was significant ($p < 0.001$) negative correlation between soil pH and exchangeable acidity, with a Pearson coefficient of -0.69 and -0.90 for KALRO NAAIAP and MoALD data, respectively. The inverse relationship between soil pH and exchangeable acidity can be attributed to the increase in the concentration of $H^+$ in soil solution as soil pH decreases, and $Al^{3+}$ becomes more soluble and available for exchange (Owusu *et al*., 2024). This observation agrees with the results obtained by

Agegnehu *et al*. (2019), Laekemariam and Kibret (2021) and Zama *et al*. (2022), which indicated that exchangeable acidity tends to increase with soil pH decrease and vice versa.

## Soil acidity levels based on the soil pH data

Soil acidity levels, in reference to the pH ratings (Table 1), varied slightly among the three datasets (Figure 4). Three, 14 and 2% of the KALRO Legacy, MoALD and NAAIAP soil data, respectively, had pH values ≤ 4.5, falling under the extremely acid class, while 29, 36 and 39% had pH values between 4.51 and 5.50, and fell within the very strongly to strong acid range. Overall, 50, 69 and 57% of the KALRO Legacy, MoALD and NAAIAP soil data, respectively, had pH values ≤ 5.99. Soils with pH ≤ 5.99 are commonly associated with acidity challenges due to either elemental toxicities or deficiencies, which negatively affect soil health and nutrient uptake by plants and soil microbes (Zama *et al*., 2022). Productive utilization of the soils, therefore, requires raising the pH by adding lime, adopting acid-tolerant crops, alongside proper nutrient management.

## Spatial distribution of soil pH

The digital soil pH maps generated using KALRO NAAIAP and Legacy soil data exhibited similar spatial patterns of acidic soils across Kenya (Figure 5 and Figure 6). The strongly acid (pH 5.0 - 5.5), very strongly acid (pH 4.51 - 4.99), and extremely acid (pH ≤ 4.5) areas were concentrated in the Western, Rift Valley and Central parts, highlighting the impact of soil acidity on crop yields in Kenya's food basket regions. This is consistent with the findings of Kanyanjua *et al*. (2002). Kisinyo *et al*. (2014) attributed acidity in these regions to the geology, which is predominated by non-calcareous and inherently acidic parent materials, such as granite, granodiorites and rhyolitic tuff. The acidic nature of the soils is also explained by poor agronomic and soil health practices, including continuous use of acidifying farm inputs (Esilaba *et al*., 2023). Since most of these areas are found in the highlands with humid climate, the soils are prone to leaching of basic cations, resulting in accumulation of $H^+$, $Mn^{2+}$ and relatively immobile ions, such as $Al^{3+}$ and $Fe^{3+}$ (Kisinyo *et al.*, 2014, 2015b; Muindi *et al*., 2020; Desta *et al*., 2021; Esilaba *et al*., 2023). There is a need for rehabilitation of the acid soils in the Western, Rift Valley and Central parts of Kenya with lime and organic amendments for sustained agricultural productivity gains and maintenance of soil health.

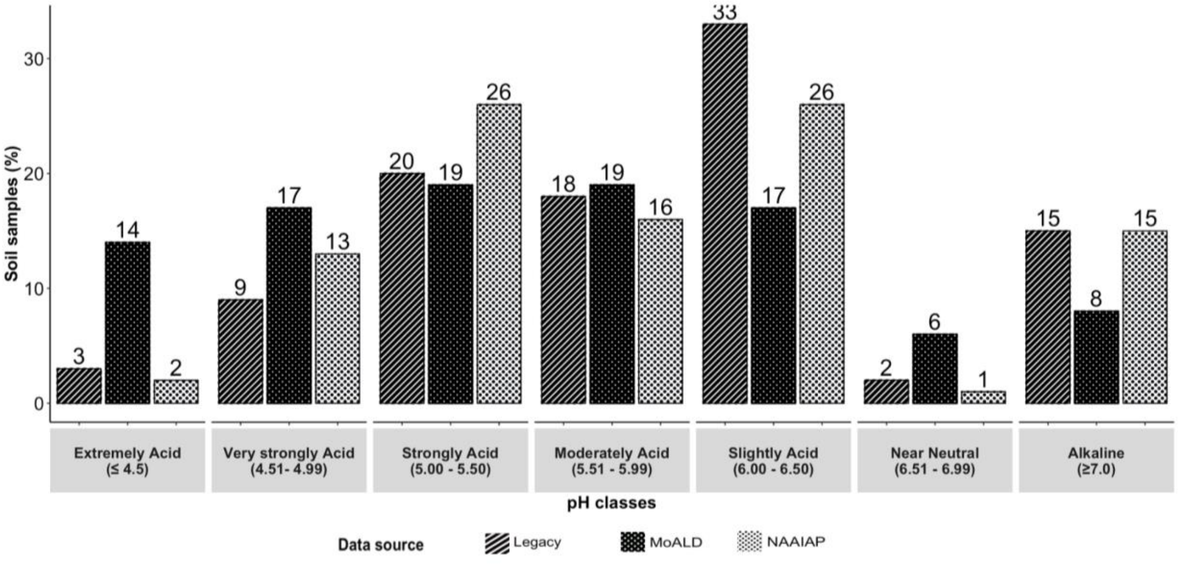
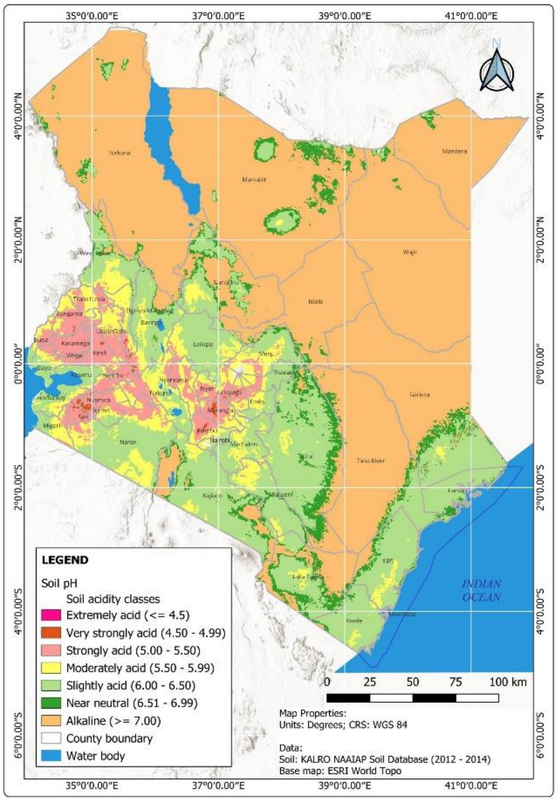


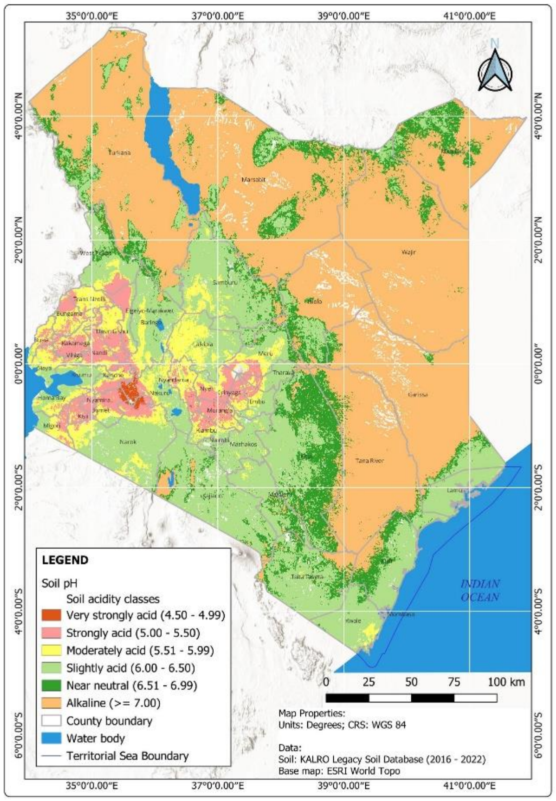
**Figure 4. Distribution of soil samples by pH class based on the KALRO Legacy, MoALD and NAAIAP data.**



Map Properties:
Units: Degrees; CRS: WGS 84

Data:
Soil: KALRO NAAIAP Soil Database (2012 - 2014)
Base map: ESRI World Topo

**Figure 5. Spatial distribution of soils by pH classes (KALRO NAAIAP Soil Database).**



Map Properties:
Units: Degrees; CRS: WGS 84

Data:
Soil: KALRO Legacy Soil Database (2016 - 2022)
Base map: ESRI World Topo

**Figure 6. Spatial distribution of soils by pH classes (KALRO Legacy Soil Database).**

## Extent of land affected by soil acidity

Based on the digital soil pH map produced using KALRO NAAIAP soil data (Figure 5), approximately 13.29% (7.7 million ha) of the total land area was affected by soil acidity (pH ≤ 5.99), out of which 5.65% (3.3 million ha) was strongly to extremely acidic (pH ≤ 5.5) and 7.64% (4.4 million ha) was moderately acidic (pH 5.5 – 5.99). Similarly, the map generated using KALRO Legacy soil data showed that acid soils (pH ≤ 5.99) covered approximately 11.92% (6.8 million ha) of Kenya’s total land area, out of which 4.99% (2.8 million ha) were strongly to extremely acidic and 6.93% (3.9 million ha) were moderately acidic (Table 4). These results are in agreement with those of Kanyanjua *et al*. (2002) who also reported that acid soils cover about 13% (7.5 million ha) of Kenya’s agricultural land. This also demonstrates the validity of the soil pH maps generated in this study. The slight discrepancies in the acreage of acid soils reported by the two studies can be attributed to multiple factors, including differences in the characteristics of the soil data and models used. Considering that the areas mostly affected by acidic soils occur in the rain-fed agricultural landscapes, which contribute significantly to the Kenyan economy through crop and dairy production, immediate remedial interventions, such as liming are requisite.

Figure 7 illustrates the proportion of total land area affected by soil acidity (pH ≤ 5.5) in 29 counties based on the evaluated KALRO Legacy soil data. Kisii and Nyamira were the most affected, with 100 percent of their total land area covered by acid soils. These were closely followed by Vihiga (93%), Nandi (91%) and Kakamega (91%), while West Pokot (2%) had the least coverage of soils affected by acidity. The other 16 counties, excluding Nairobi and Mombasa, which are not shown in Figure 7 had a very small proportion (< 1%) of their total land area affected by soil acidity. These counties include Makueni, Kilifi, Machakos, Kajiado, Garissa, Taita Taveta, Isiolo, Kitui, Kwale, Lamu, Mandera, Marsabit, Samburu, Tana River, Turkana, and Wajir.

**Table 4. Summary of the share of Kenya's physical land area under each soil pH class based on the KALRO Legacy and NAAIAP soil databases.**

| **KALRO NAAIAP Soil Data 2012 – 2014** | | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Extremely acid (≤ 4.50)** | **Very strongly acid (4.51 – 4.99)** | **strongly acid (5.00 – 5.50)** | **Moderately acid (5.51 – 5.99)** | **Slightly acid (6.00 – 6.80)** | **Near neutral (6.81 – 6.99)** | **Alkaline (≥ 7.00)** |
| Area (Ha) | 99.20 | 116,661.5 | 3,159,384.3 | 4,428,574.3 | 14,019,916.0 | 3,159,681.9 | 33,101,316.5 |
| % share | 0.0002 | 0.2012 | 5.4486 | 7.6374 | 24.1783 | 5.4491 | 57.0854 |
| **KALRO Legacy Soil Data 2016 – 2022** | | | | | | | |
| Area (Ha) | 8,800 | 157,800 | 2,664,550 | 3,931,412.5 | 15,795,112.5 | 6,109,887.5 | 28,090,412.5 |
| % share | 0.0155 | 0.2780 | 4.6946 | 6.9266 | 27.8289 | 10.7648 | 49.4916 |

Results further revealed that counties on the west of the Rift Valley had higher proportions of land under acid soils compared to the ones in the central highlands, with western and Kisii regions taking the lead followed by the larger Rift Valley region. Within the central highlands, Murang'a County (66%) took the lead followed by Kirinyaga County (56%), while West Pokot had the least (2%) proportion of land under acid soils. Soil acidity trends in these regions are driven by lithology, soil type and climate. For example, the soils of Kisii, Nyamira, Kakamega and Vihiga are developed on acid igneous rocks with high silica content, such as andesites, granites and granodiorites, while those of Murang'a and Kirinyaga are developed on undifferentiated basement system rocks predominated by gneisses, which are acidic in nature (Jaetzold *et al*., 2012). The major soil types in these counties are Nitisols, Acrisols, Ferralsols and Andosols, most of which are developed on silicate-rich parent materials and are strongly weathered, with low base saturation and high levels of exchangeable Al, Fe and Mn. These characteristics account for their acidic nature (Sileshi *et al*., 2022). In addition, most Andosols are rich in humus complexes of Al and Fe, which makes them acidic. High acidity in Nitisols were also observed by Desta *et al*. (2021) in the rain-fed agricultural areas of Ethiopia.

## Farming households affected by soil acidity

Figure 8 shows that Kisii County (84%) had the highest proportion of digitally-registered farming households affected by soil acidity (pH ≤ 5.5) followed by Nyamira (80%) and Murang'a (77%). The proportion of farming households affected by soil acidity can be attributed to the proportion of the total land area covered by acidic soils in a given county. Therefore, the farming households mostly affected by soil acidity were from the 29 counties shown in Figure 7, with the remaining counties having no significant soil acidity problem.

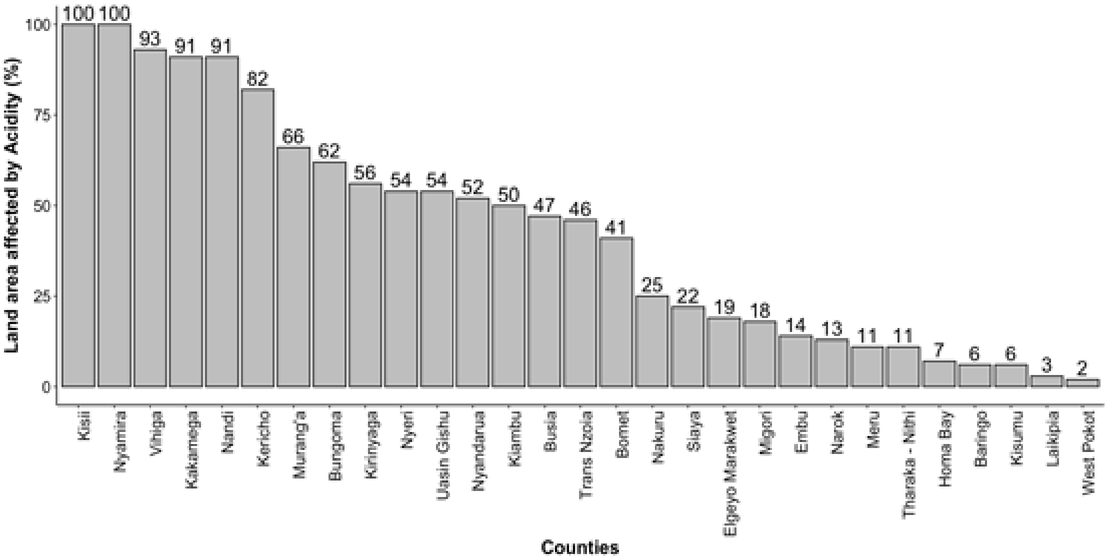


**Figure 7. Proportion of County land area affected by soil acidity (pH ≤ 5.5).**

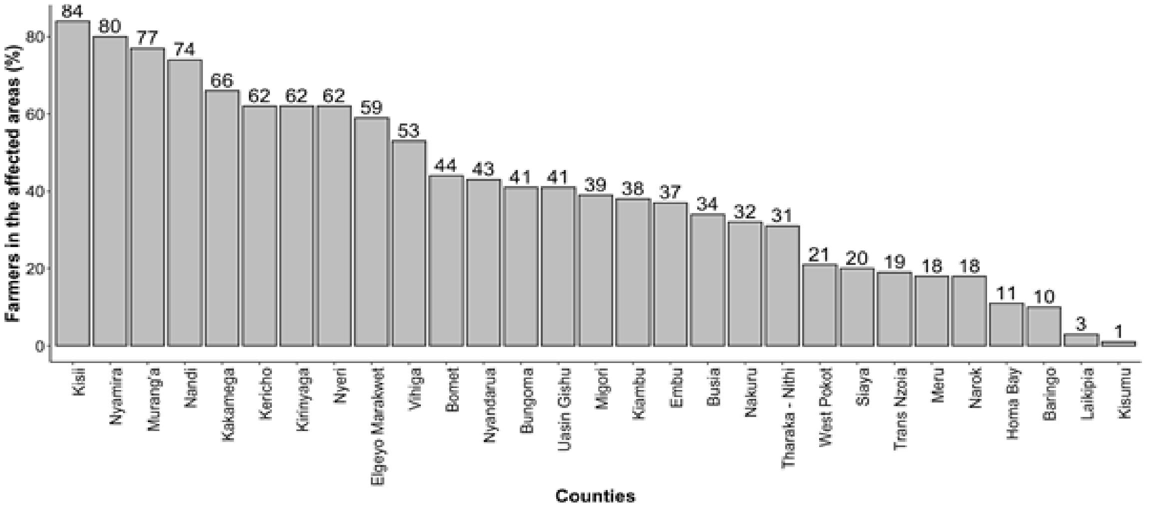


**Figure 8. Proportion of farming households affected by soil acidity (pH < 5.5) within counties.**

## Quantity of lime required for soil acidity amendment

Figure 9 and 10 present the total amount of lime and rate of application required to neutralize soil acidity in 26 out of the 29 most affected counties based on NAAIAP data. Lime requirements for the other three most affected counties (i.e., Trans-Nzoia, Laikipia and Uasin Gishu) were not estimated for lack of soil exchangeable acidity data. The acid soils within and west of the Rift Valley required higher amounts of lime compared to the central and eastern highland acid soils. Kakamega County (269 MT) had the highest amount of lime required followed closely by Kericho (262 MT), Bungoma (244 MT), Narok (240 MT) and Nandi (203 MT), while Kisumu (8 MT) had the lowest. Similarly, the estimated lime rates varied from 0.58 ± 0.08 t ha $^{-1}$ in Nakuru to 1.51 ± 0.07 t ha $^{-1}$ in Nyamira County. The variations in lime requirements and rates can be explained by the differences in the levels of exchangeable acidity (Figure 3) and total land area affected by acidity (Figure 7) in a county. These results correspond with the previous reports on lime requirements and rates in Kenya by Kanengereh (1979) and Esilaba *et al*. (2023). It should, however, be noted that the lime requirements and rates were calculated without considering the acid-tolerance levels of crops, soil types, lime types, and farming methods in the counties. These factors should be considered in future studies. Moreover, Laekemariam and Kibret (2021) emphasized that liming should be combined with balanced fertilization and the rates of application adjusted annually based on soil testing to guarantee higher yields.

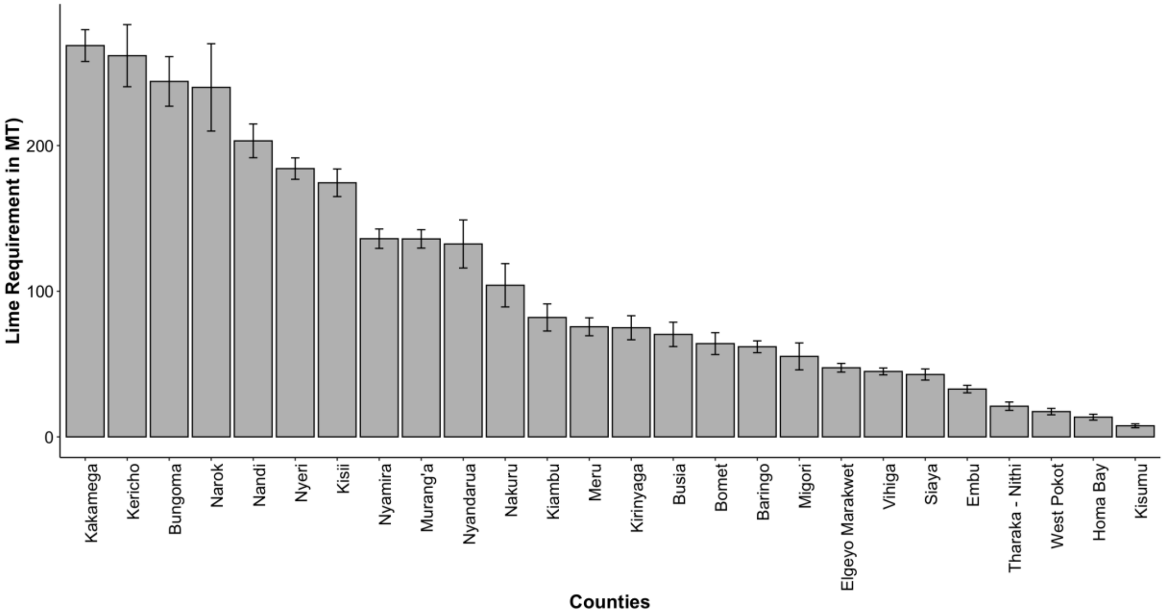


**Figure 9. Lime requirements for acid soil remediation.**

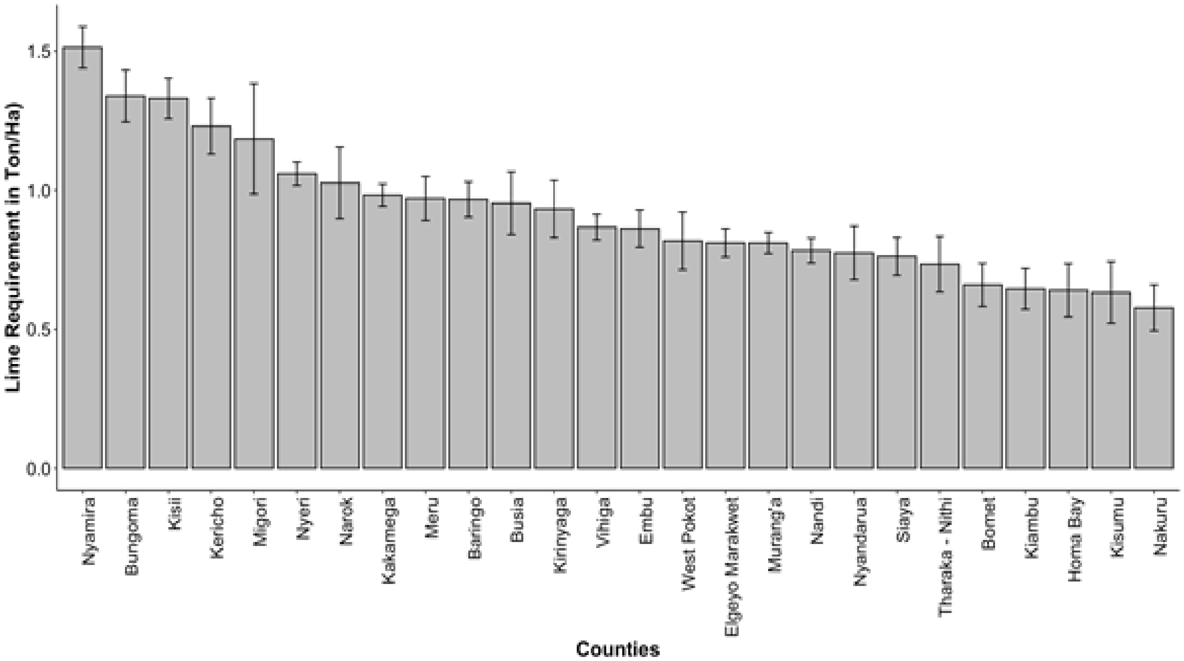


**Figure 10. Lime rates for acid soil remediation.**

### Significance of the study

Our findings provide actionable insights and expand knowledge on the spatial distribution and extent of land affected by soil acidity, number of farming households affected by soil acidity, and liming requirements in Kenya. The study also provides a practical framework for implementing data-driven and targeted soil health interventions. Additionally, the spatially-explicit soil information and maps generated will be useful resources and evidence to the government, development partners and other stakeholders for advancing integrated soil health management practices, such as application of liming, organic amendments and acid-tolerant crops. The results will also inform lime use policies, subsidy programs, as well as prioritization and targeting of agricultural areas for liming. Furthermore, the results on the quantity of lime required for managing acidic soils provide an opportunity for commercialization of liming interventions. Overall, the results will contribute to enhanced soil health, crop productivity, food and nutrition security.

### Limitations of the study

We acknowledge the limitations of this study. Firstly, the sparse spatial coverage of soil data points, particularly, in the ASALs could have affected the accuracy of the predicted soil pH values in these areas. Secondly, as already mentioned in the methods section, some of the GPS positions of the KALRO Legacy soil samples were approximated. This may have introduced errors that could have also affected the quality of the generated digital soil pH maps. Again, most of the freely available, gridded environmental GIS layers used for creating the digital soil pH maps are derived from other spatial models with inherent uncertainties, hence the risk of error propagation (Muthoni *et al.*, 2017). However, these were the best available data at the time, although there are ongoing initiatives to collect high quality soil data in the whole country, utilizing uniform protocols of data collection and analysis.

## CONCLUSIONS

In conclusion, this study has determined the extent and distribution of soil acidity, as well as the lime requirements for acid soil remediation in Kenya. About 13.29% of the total land area (7.7 million ha) is affected by soil acidity (pH ≤ 5.99). Out of this, 5.65% (3.3 million ha) is strongly to extremely acidic (pH ≤ 5.5) and 7.64% (4.4 million ha) is moderately acidic (pH 5.5 – 5.99). The problem of soil acidity spans across 29 counties, but most of the acidic soils are found in the Western, Rift Valley and Central parts of Kenya. Kisii, Nyamira, Vihiga, Nandi and Kakamega are the top 5 most acidic counties based on the proportion of land affected by soil acidity. Similarly, Kisii County has the highest number and proportion of digitally-registered farming households affected by soil acidity. Lime requirements and rates for rehabilitating the acid soils (pH ≤ 5.5) vary from one county to another, depending on the levels of exchangeable acidity and total land area covered by acid soils. Lime requirements range from 269 metric tons (MT) in Kakamega to 8 MT in Kisumu County, while lime rates vary from 0.58 ± 0.08 t ha$^{-1}$ in Nakuru to 1.51 ± 0.07 t ha$^{-1}$ in Nyamira County. Management of soil acidity constraints is crucial for sustaining soil health and agricultural production to feed the ever-growing Kenya's population. However, it should be noted that lime application rates for this study were calculated without considering the acid-tolerance levels of crops.

Future studies should focus on lime deposits in the country, lime production and utilization guidelines, impact of liming on the yields of priority crops, economic returns from liming, and alternative acid-soil remediation strategies.

**Acknowledgements**
The authors acknowledge the Ministry of Agriculture and Livestock Development and National Agricultural Research Laboratories for provision of soil data used in this study. We are also grateful to Fredrick Wandera, Stephen Kimani and Harun Odhiambo for their technical support, and Jack Ouda for his constructive criticism and review.

**Funding.** Kenya Agricultural and Livestock Research Organization (KALRO) funded the development and publication of the manuscript.

**Conflict of interest.** The authors declare that they have no conflict of interest.

**Compliance with ethical standards.** The nature of the work does not require approval by a (bio)ethical committee.

**Data availability.** The data is available with the corresponding author (golichdub@yahoo.com) upon reasonable request.

**Author contribution statement (CRediT). D. Golicha** – Conceptualization, Project administration, Funding acquisition, Validation, Writing - review and editing; **E.M. Muindi** – Conceptualization, Methodology, Visualization, Writing - original draft, review and editing; **K. Were** – Conceptualization, Data curation, Methodology, Formal analysis, Visualization, Validation, Writing - original draft, review and editing; **H. Ochieng** – Data curation, Formal analysis, Visualization, Methodology, Writing - review and editing; **J. A. Omwakwe** – Methodology, Writing - review and editing; **D. Kamau** – Project administration, Funding acquisition and Validation.

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