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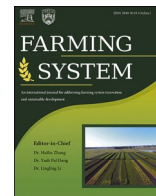


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Biophysical and farm management drivers of soil fertility under African Leafy Vegetable production small-scale systems in Kenya

Enos Onyuka^{a,b,*}, Godfrey Nambafu^{a,c}, Darius Andika^b, Samwel Mwonga^d, Joseph Gweyi-Onyango^e, Harun Gitari^e, Franklin S. Mairura^f

^a Humboldt-Universität zu Berlin, Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences (ADTI), Germany

^b Jaramogi Oginga Odinga University of Science and Technology, Department of Plant, Animal and Food Sciences, P.O. Box 210, 40601, Bondo, Kenya

^c Murang'a University of Technology, School of Agriculture and Environmental Sciences, Department of Plant and Animal Sciences, P.O. Box 75-10200, Muranga, Kenya

^d Egerton University, Department of Crops, Horticulture and Soils, P.O. Box 536 - 20115, Egerton-Njoro, Kenya

^e Kenyatta University, School of Agriculture and Environmental Sciences, Department of Agricultural Sciences and Technology, P.O. Box 43844, 00100, Nairobi, Kenya

^f University of Embu, School of Agriculture, Department Water and Agricultural Resource Management, P.O. Box 6- 601600, Embu, Kenya

ARTICLE INFO

Keywords:

Soil micronutrients
Soil macronutrients
Soil acidity
Small-scale farmers
Soil fertility
Human health

ABSTRACT

While several studies have examined soil fertility management systems under key food and cash crops in the Sub-Saharan Africa (SSA) region, there is a knowledge gap on soil fertility management under African Leafy Vegetables (ALV) small-holder farming practices particularly in Kenya. The objective of this study was to evaluate the influence of agronomic management and socio-economic factors on soil chemical fertility in the major ALV production zones in Kenya. Farm surveys were used to gather socio-economic data, while soil sampling was undertaken in all fields to collect soil chemical data. The findings indicated that Kisii County was characterized by higher proportions of wealthy and more educated farmers, with higher frequencies of input applications relative to Kakamega County. The soil pH was highest in Kenyenyia, followed by Gucha, Butere, Mumias, and Khwisero. Gucha and Kenyenyia had significantly the highest record of soil carbon concentrations of 3.2 and 3.1 %, respectively compared to other sites, such as Butere (2.0 %) and Khwisero (1.8 %), which had similar soil carbon concentrations, with Khwisero having the least (1.5 %) soil C. The highest mean Zn concentration was recorded in Gucha (6.5 mg kg⁻¹), followed by Kenyenyia (6.4), Mumias (4.3), Butere (3.1) and Khwisero (3.0). The study showed that soil fertility under ALV farms in western Kenya was influenced by socio-economic factors and agronomic management factors. In general, the soil fertility status in Kisii County was better, compared to Kakamega County. Soil carbon was significantly influenced by site, soil texture, plot distance, fertilizer sources, and organic and inorganic fertilizer application frequencies. Gucha and Kenyenyia Sub-Counties had higher SOC levels, averaging at 1.2 and 1.1 % higher, vis-a-vis Butere Sub-County, while Mumias and Khwisero Sub-Counties had lower average SOC levels in contrast to Butere Sub-County. Site differences can differentiate soil nutrient distribution due to inherent differences in soil characteristics and indirect effects arising from localized soil management practices.

1. Introduction

African Leafy Vegetables (ALVs) include a variety of African indigenous or traditional vegetables whose leaves, young shoots and flowers are consumed for food (Maundu, 1997). There are approximately 210 ALV species that are used in Kenya (Maundu, 1997). The vegetables are native in Africa, comprising approximately 1000 different species of which 80 % are leafy vegetables. The vegetables have been used in many parts of Kenya historically for a long time (Grubben and Denton, 2004;

Ngugi et al., 2022). Currently, there is a renewed interest in ALV by policymakers, scientists, consumers and the international community due to their high potential that is not fully exploited. Empirical evidence suggests that ALV have several multi-faceted benefits, including high nutritional content and medicinal benefits, agronomic advantages and their potential to contribute to food, nutrition and income generation (Ngaiza et al., 2024). Effective soil fertility management is essential in ALV farming systems to ensure sustainable productivity and profitability in the crucial food security sector. Knowledge gaps have been identified

* Corresponding author. Humboldt-Universität zu Berlin, Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences (ADTI), Germany.

E-mail address: enosonyuka@gmail.com (E. Onyuka).

<https://doi.org/10.1016/j.farsys.2025.100157>

Received 9 April 2025; Received in revised form 8 June 2025; Accepted 9 June 2025

Available online 20 June 2025

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in soil management practices for ALVs, particularly relating to crop nutrient requirements, soil health, and the impact of production practices. ALVs remain significantly underrepresented in soil fertility management research, despite their high adaptation potential to climate variability due to their short maturity periods, multiple harvest cycles, high market values, and resilience to harsh environmental conditions (Stephen et al., 2025). While several studies have examined soil fertility management systems under key food and cash crops in the SSA region, there is a knowledge gap on soil fertility management under ALV small-holder farming practices, particularly in Kenya. Kodzwa et al. (2023) observed that there is scarce knowledge on ALV performance under diverse soil fertility management systems and agroecological zones. There is specific need to develop adequate recommendation domains for intensified commercial ALV farming systems focused on soil nutrient balances, field organic resource utilization, soil macronutrient and micronutrient requirements and soil acidity correction.

ALV production presents high potential income generation enterprises for farmers in rural and peri-urban zones in Kenya (Adebooye and Opabode, 2004; Frederike, 2017). Soil chemical fertility parameters including soil pH, total soil nitrogen and carbon concentration and other plant available macronutrients and micro-nutrients are influenced by a variety of factors that can be grouped into natural site conditions, agronomic management and socio-economic factors. Farmers with low resource endowment are likely to invest in poor soil fertility management practices and are likely to experience capital and labour shortages in their farms (Crowley and Carter, 2000; Tittonell et al., 2005). In many SSA countries, on farm and landscape level nutrient outflows often exceed inflows of major nutrients (nitrogen, phosphorus, potassium), resulting in negative nutrient balances (Okalebo et al., 2007; Chepkorir, 2024). The predominant nutrient stocks and balances have been investigated for crop systems including cereals, legumes, selected cash crops and fodder crops (Shadrack et al., 2020). Most small-scale farmers use low quantities of organic and inorganic fertilizers (Tittonell et al., 2005), but few studies have sufficiently evaluated input utilization and soil fertility management under ALV cultivation.

Multiple soil fertility management practices such as fertilizer type, quality and quantity play an important role in soil fertility maintenance (Okalebo et al., 2007; Heydarzadeh et al., 2023) and can influence ALV productivity. Farm livestock intensity is an important factor that can influence soil organic matter and pH through manure supply, thus potentially benefiting ALV production in Kenya. High livestock densities are also related to high farm resource endowments, which can positively influence soil fertility (Tittonell et al., 2005; Mwakidoshi et al., 2023) and small-scale ALV production.

This study aimed to evaluate the status of soil fertility in the major ALV producing zones in Western Kenya. Soil nutrient characterization is a prerequisite for strategic soil fertility management and enhanced production of ALV crops under small-scale farming systems. The study's principal objective was to evaluate the influence of common agronomic management practices and socio-economic factors on soil chemical fertility in the major ALV production zones in Kenya. The study hypothesized that farm socio-economic factors and soil fertility management can influence soil chemical characteristics under major ALV farming systems in Kenya. The specific study objectives included the following:

- To evaluate the major soil fertility constraints to ALV production in Western Kenya, focusing on soil macronutrient and micro-nutrient characteristics.
- To determine the relationship between soil fertility parameters, agronomic management and socio-economic factors in western Kenya.

2. Materials and methods

2.1. Site selection and sampling

The following survey was carried out in Kakamega and Kisii Counties (Fig. 1a and b) mainly recognized for ALV production in Western Kenya. Five Sub Counties (Butere, Khwisero and Mumias in Kakamega, and Gucha and Kenyenyia in Kisii Counties) were selected for the study. The study sites were selected because they are recognized as major ALV producing zones in Kenya characterized by intensive production, supplying vegetables for local consumption and urban markets in Kenya, including the capital city (Nairobi). The sites were selected from a survey of ALV households conducted in 2014 by the HORTINLEA project (Horticultural Innovation and Learning for Improved Nutrition and Livelihood in East Africa) project (<https://www.agrar.hu-berlin.de/en/institut-en/departments/dao/gp-en/projects/project-hortinlea>). In total, 150 farms and 413 cropping fields were selected (Table 1).

2.2. Study area description

Kakamega County has its capital in Kakamega which is located at latitudes $0^{\circ} 15'$ and $1^{\circ} N$ and longitudes $34^{\circ} 20'$ and $34^{\circ} 45' E$, covering 3050 km^2 (CGOK, 2023). The County has 1,867,579 inhabitants and a population density of 618 persons km^{-2} (KNBS-Kenya National Bureau of Statistics, 2019). The study area was located in the sugarcane agro-ecological zone (Jaetzold et al., 2007), at an average altitude of $1379 \pm 37 \text{ m asl}$. The region has a humid climate with a mean annual temperature ranging from 20.8 to $22.0^{\circ} C$ and mean annual rainfall of $1800\text{--}2000 \text{ mm}$ (Jaetzold et al., 2007). The precipitation is distributed throughout the year, with heavy rains in March and July, and light rains in December and February, resulting in low evaporation ($1600\text{--}1800 \text{ mm per year}$). The dominant soil types include *orthic* and *ferralsol-orthic Acrisols*, *orthic Ferralsols* and one part with *rhodic Ferralsols* combined with *eutric Nitisols* (Jaetzold et al., 2007). The parent rock material comprises of basic igneous rocks, biotite gneisses and acid igneous rocks. The soils are well drained, deep to very deep, friable to firm with sandy clay to clay texture (Jaetzold et al., 2007). The major staple food in the region is maize while other main crops include beans, cassava, finger millet and sorghum. The key livestock kept include chicken (92 %), cattle (53 %), sheep (22 %), goats (11 %) and pigs (2 %).

Kisii County covers an area of 1333 km^2 and lies between latitude $00^{\circ} 30'$ and 100 South and longitude $34^{\circ} 38'$ and 35° East. The Kisii highlands are one of the most densely populated regions in Western Kenya ($445 \text{ persons km}^{-2}$) with a population of 2.2 million inhabitants (KNBS-Kenya National Bureau of Statistics, 2019). The study area was situated in the western part in the coffee-tea zone with an average altitude of $1719 \pm 70 \text{ masl}$. Kisii County has a humid climate with mean annual temperatures of $16.2\text{--}18.0^{\circ} C$ and mean annual precipitation of $1600\text{--}1800 \text{ mm}$. The rainfall is reliable and offers a continuous annual water supply without real dry seasons such that the growing periods are normally permanent but with drier months from December to February (Jaetzold et al., 2007). Main cultivated crops include maize, bananas, beans, potatoes, tea, sugarcane, coffee and horticultural crops. The predominant soil type includes red volcanic soils (*Nitisols*) which are deep, well-weathered soils, while the rest of the County has clay soils which have poor drainage (*Phaeozems*), red loams and sandy soils (Jaetzold et al., 2007).

2.3. Farmer interviews

The ALV farmers were interviewed using a semi-structured questionnaire addressing agronomic field management and socio-economic conditions of individual farm households. The households were classified into three wealth classes (poor, medium and rich) based on resource endowment visible during the farm visit and farmers' information. The predominant type of roofing and walling material that consisted of farm

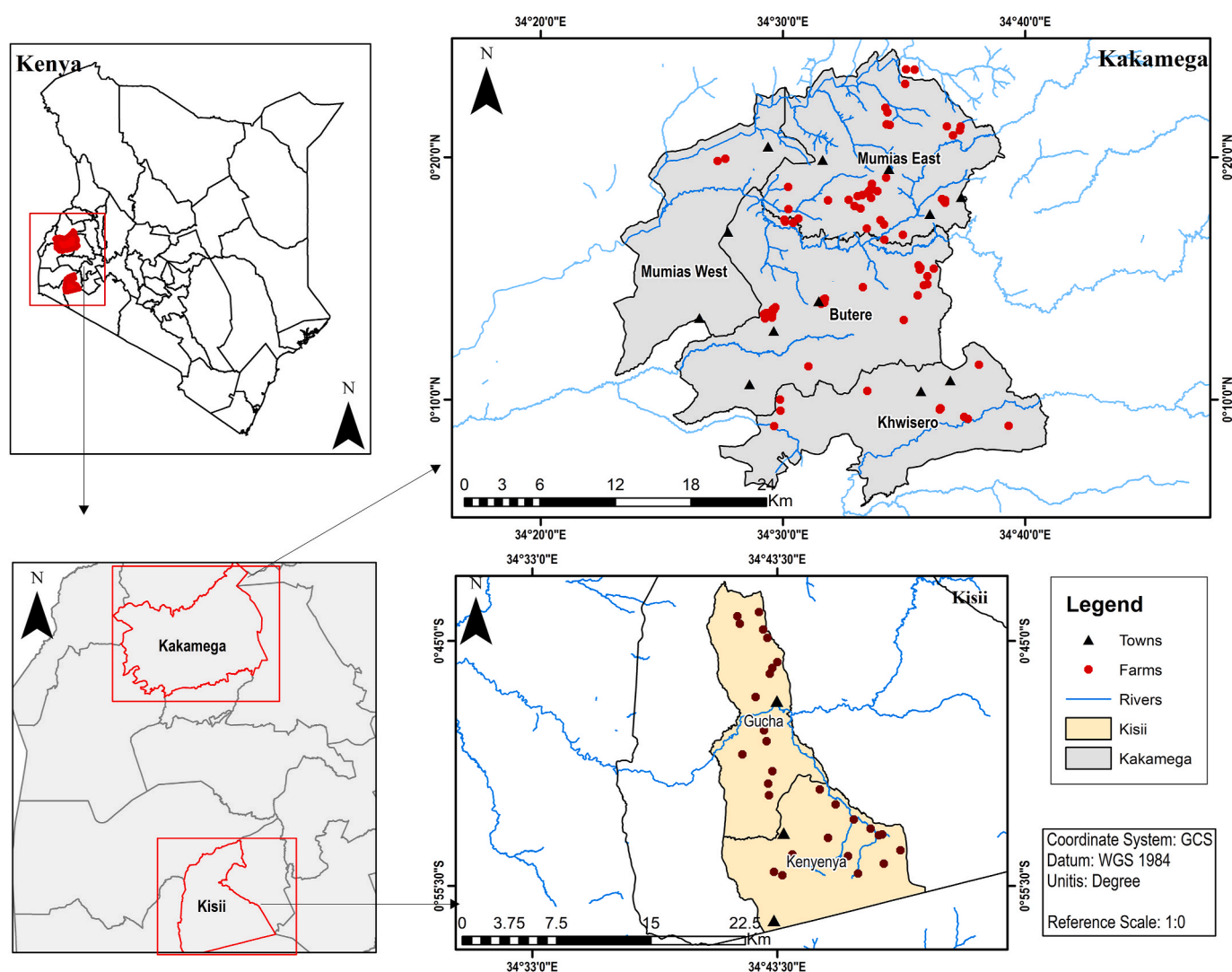


Fig. 1. Location of study farms in Kakamega and Kisii Counties.

Table 1

Distribution of study farms and fields within Western Kenya.

County	Sub-County	Number of farms	Number of fields
Kakamega	Butere	25	78
Kakamega	Khwisero	16	39
Kakamega	Mumias	49	130
Kisii	Gucha	30	84
Kisii	Kenyanya	30	82

dwelling was used as a visual criteria to classify the households into three wealth categories (Karigi, 2014). In the said method, homesteads with less permanent building materials such as earth walls/grass roofing comprising all or most of the buildings were considered to be poor households. Medium wealth households mainly comprised homesteads with a mixture of permanent and semi-permanent materials, such as bricks/earth/and timber components, while wealthy farm households constructed their dwellings predominantly with permanent building materials including stone/concrete, and iron-sheets/or roofing tiles. The proportion of permanent or semi-permanent building materials that comprised the homestead was used as a criteria in the assessment, as some households use a mixture of building materials based on their wealth endowment. In addition, monthly household income data was requested from household heads, and compared with the visual

classification criteria (Supplementary Materials 1) using mean income distribution (Ngo, 2012; Balen et al., 2010; Tittone et al., 2010). The farms were also classified according to land ownership and further according to the farmer's educational levels. Data on soil fertility management included fertilizer type used (organic vs inorganic), frequency of fertilizer application and sources of organic fertilizers (inside and/or outside of the farm). Livestock density was represented as Tropical Livestock Unit per acre (TLU/acre) using the following conversion ratios/factors: Cattle = 0.5, chicken = 0.01, ducks = 0.03, goats/sheep = 0.1, pigs = 0.2, rabbits = 0.02 (Peregrine et al., 2020).

2.4. Soil sampling and analysis

Soil sampling was conducted following a zigzag scheme from six sampling points in each ALV field (Okalebo et al., 2002) using an Edelman soil auger at 0–20 cm depth. The core samples were composited, air dried and ground to pass through a 2-mm sieve. About 125 g sub-samples were packed in zipped air-tight bags and stored at room temperature for laboratory analysis at Albrecht Daniel Thier-Institute of Agricultural and Horticultural Sciences, Humboldt University in Berlin, Germany. Soil texture was determined in triplicates using the 'feel method' (Thien, 1979; Estefan et al., 2013) which allows the differentiation of 12 distinct soil texture classes. The soil pH was determined electrometrically in 0.01 M CaCl₂ at a 1:2.5 soil: solution ratio

(weight/volume). Total soil carbon, total soil nitrogen and inorganic carbon were analyzed with dry Dumas combustion technique by element analyzer 'vario MAX cube' (Elementar) (Buckee, 1994). The soil samples were oxidized at 1200 °C, the components separated through specific adsorption columns while a detector measured thermal conductivity. In order to estimate the proportion of organic and inorganic carbon within total carbon contents, 20 'reference' soil samples with high pH and wide C/N ratios were sampled and analyzed. For determination of inorganic carbon, concentrated hydrochloric acid was added to soil samples and the subsequent released carbon dioxide (mainly from carbonates) was measured in the elemental analyzer. Total organic carbon was calculated as the difference of the total carbon and inorganic carbon (DIN ISO 10694).

Other soil macronutrients, micronutrients, and heavy metals were extracted using a Mehlich 3 reagent at a 1:20 soil-to-solution ratio with 5 min of shaking (Mehlich, 1984). The Mehlich 3 reagent comprises 0.2M CH₃COOH (acetic acid), 0.25M NH₄NO₃ (ammonium nitrate), 0.013M HNO₃ (nitric acid), 0.015M NH₄F (ammonium fluoride), and 0.001M EDTA (ethylene diamine-tetraacetic acid). The preference for the Mehlich 3 method was based on its applicability over a wide range of soil pH, especially for acidic soils, as is the case in this study, and the advantage of multi-element analysis in one analytical process. The soil extracts were analyzed for P, K, S, Ca, Mg, Zn, Cu, Mn, Pb, and Cd at their respective wavelength ranges by the inductively coupled plasma optical emission spectrometry (ICP-OES) using the ICP multi-element standard solution IV (Douvris et al., 2023).

2.5. Data analysis

The soil chemical data were compared to soil reference data, to evaluate potential soil fertility constraints, after which the proportion (%) of fields constrained by each soil chemical property were derived using Microsoft Excel worksheet conditional functions. The critical soil values were derived from Okalebo et al. (2002). In order to assess farm variability in soil chemical properties, two-way ANOVA models followed by post-hoc tests were implemented using *agricolae* R package (Supplementary Materials). The comparisons included Sub-County main effects (1-way ANOVA), and Sub-County interactions (2-way ANOVA) with field location, soil texture, fertilizer type, and crop type. Multiple linear regression procedures were used to predict soil fertility parameters with biophysical and socio-economic factors using R *glm* regression procedures. Factor analysis by Principal Components Analysis (PCA) was conducted to isolate constructs in the data which explained underlying patterns in soil chemical characteristics. Varimax rotation with Kaiser Normalization was used because it results in a factor pattern that loads highly significant variables into one factor, which was considered to offer a theoretically plausible and acceptable interpretation of the resulting factors. Factors were retained for interpretation if the Eigen

values were >1. Communalities are the proportion of each variable's variance that can be explained by the factors, defined as the sum of squared factor loadings for the variables. Percentage (%) of Variance contains the percent of total variance accounted for by each factor while the cumulative % contains the cumulative percentage of variance accounted for by the current and all preceding factors (Norusis, 2008).

3. Results

3.1. Farm socio-demographic characteristics in Sub-Counties

The farm socio-demographic and field characteristics of ALV farmers in Kakamega and Kisii County are presented in Table 2. The respondents comprised of 70 % males and 30 % females across sites, while poor farmers comprised 23 %, medium (70 %) with wealthy farmers consisting 7 % of the respondents. In addition, most of the farms were private owned (97 % of households). The wealthy farms comprised the highest proportion in Kenyenyia (20 %), while medium wealth farms comprised 56.7 %–81.2 % of the farmers in all sites (Sub-Counties). The poor farms ranged from 19 % to 25 % of the farmers in the different Sub-Counties. In regard to education, Gucha and Butere comprised the highest proportions (44 % and 43.3 %) of farmers without formal education respectively. Primary school graduates comprised 62.5 % of the farmers in Khwisero, while they were 34.7 % in Mumias and 30 % in Kenyenyia. Kenyenyia Sub-County recorded the highest proportion of secondary and tertiary graduates (college and university). The male farmers comprised high proportions of farmers in Khwisero, Gucha and Kenyenyia (70–84 %). Farmers managed an average of 2.4–2.8 fields, while farm sizes were larger in Butere and Mumias (1.7 acres/hh) compared to Kenyenyia (1.5), Gucha (1.3) and Khwisero (1.4). The farm TLU was largest in Khwisero (1.8) and lowest in Gucha (0.8) (Table 2).

Fig. 2a–g reports the field characteristics of individual farm households. In all sites, most of the fields were located close to the homestead (36.6 %), second field (35.1 %) or third field (22.1 %), while only 6.1 % were located in the furthest fourth field (Fig. 2a). Khwisero featured the highest proportion of fields close to the homestead (44.4 % of fields). In Mumias, most fields were close to the homestead (37 %) or the second fields (37 %), while in Gucha, they were located close or up to the third field. It is only Butere that had 13 % of fields located in the fourth field, the longest relative distance from the homestead. In terms of soil texture (Fig. 2b), 41.7 % were clay soils, 31.4 % were clay loam + silty clay soils while sandy clay + sandy clay loams comprised 26.7 % of the soils. Most soils in Khwisero and Butere were dominated by clay and clay + silty clay loams, while they were clay and sandy clay + sandy clay loams in Mumias. Gucha and Kenyenyia were dominated by clay and clay + silty clay loam soils, while Mumias featured clay and sandy clay + sandy clay loam soils. Only 12.3 % of fields were not applied with fertilizers (Fig. 2c), while inorganic fertilizers were used in 19.4 % of fields in all

Table 2
Farm socio-demographic characteristics by Sub-Counties.

Variables		Khwisero	Butere	Mumias	Gucha	Kenyenyia
Wealth status	Poor	3 (18.8)	6 (24)	3 (24.5)	6 (20)	7 (23.3)
	Medium	13 (81.3)	18 (72)	34 (69.4)	23 (76.7)	17 (56.7)
	Rich	0 (0)	1 (4)	3 (6.1)	1 (3.3)	6 (20)
Tenure	Individual	16 (100)	24 (96)	47 (95.9)	29 (96.7)	30 (100)
	Communal	0 (0)	1 (4)	0 (4.1)	1 (3.3)	0 (0)
Education of head	None	1 (6.3)	11 (44)	19 (38.8)	13 (43.3)	8 (26.7)
	Primary	10 (62.5)	6 (24)	10 (34.7)	9 (30)	5 (16.7)
	Secondary	4 (25)	4 (16)	11 (22.4)	7 (23.3)	12 (40)
	Tertiary	1 (6.3)	4 (16)	1 (4.1)	1 (3.3)	5 (16.7)
Gender of head	Female	7 (43.8)	4 (16)	19 (38.8)	9 (30)	6 (20)
	Male	9 (56.3)	21 (84)	9 (61.2)	21 (70)	24 (80)
2016 number of fields		2.4 ± 1.4	3.1 ± 1.1	2.7 ± 0.8	2.8 ± 0.5	2.7 ± 0.6
2016 total farm size (acres)		1.4 ± 1.1	1.7 ± 1.6	1.7 ± 1.6	1.3 ± 0.8	1.5 ± 1.2
2016 TLU		1.8 ± 1.7	1.0 ± 0.9	1.2 ± 2.0	0.8 ± 0.8	0.9 ± 0.7

Values are frequencies and column percentages (categorical variables) and means ± standard deviations (numeric variables).

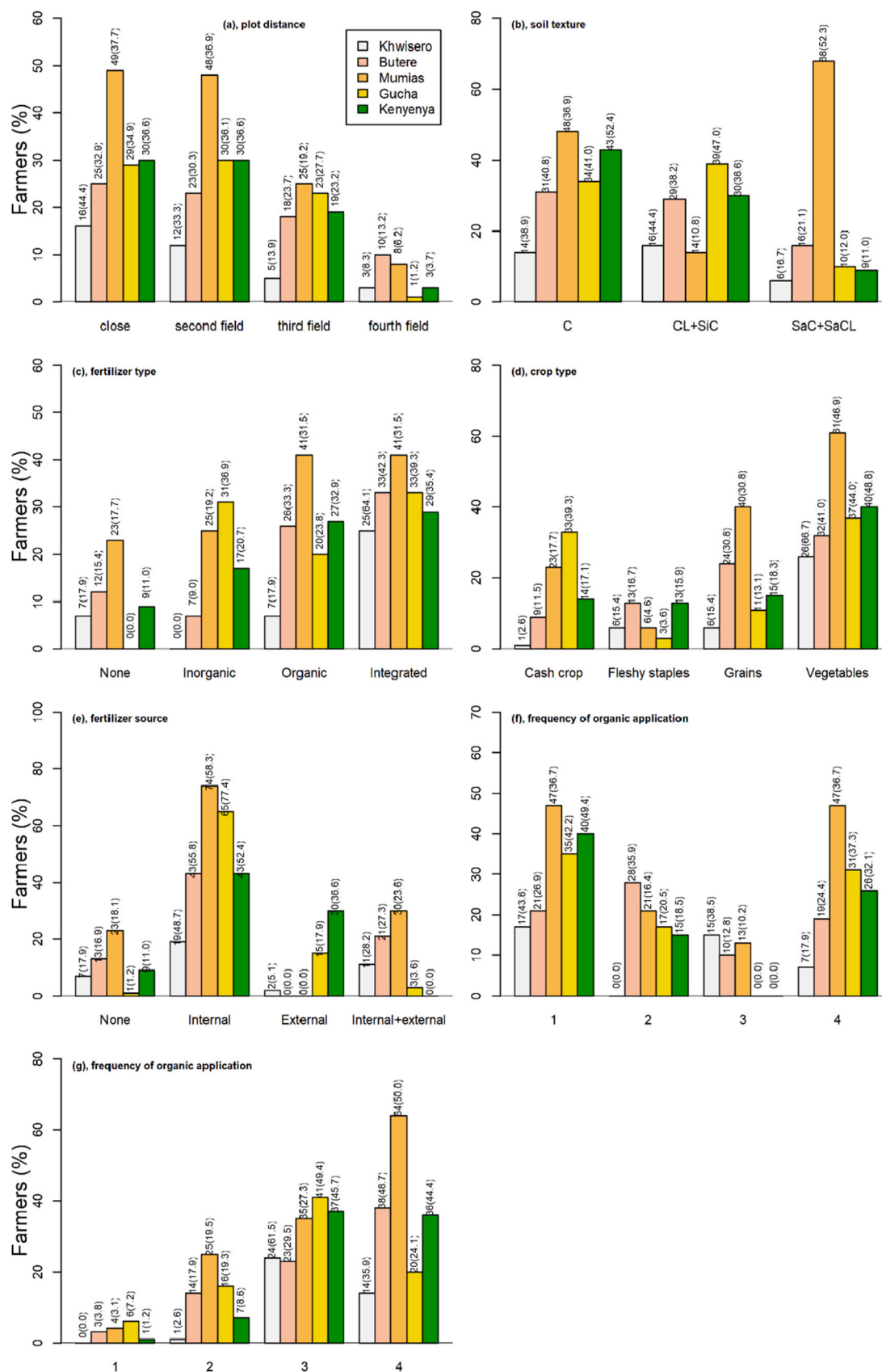


Fig. 2. Field characteristics among farm households by Sub-Counties, including field location (a), soil texture (b), fertilizer type (c), crop type (d), fertilizer source (e), frequency of organic (f) and inorganic applications (g).

sites. In addition, 29.3 % and 39 % used organic or integrated fertilizers respectively. Most of the fields were cultivated with vegetables (47.5 %), grains (23.3 %), cash crops (19.4 %) or root and tuber crops (fleshy staples, 9.9 %) (Fig. 2d). Majority of the farmers in all sites used fertilizers from on-farm sources (internal, 49 %–77 %) (Fig. 2e) while 36.6 % of fields in Kenya applied external sourced inputs. Frequency of organic applications was mostly once (39 %) in all sites (Fig. 2f), while most of the farmers applied fertilizers 4 times (42 %), thrice (39 %),

twice (15 %) or once (3 %). About 24 %–50 % of the fields received inorganic fertilizers 4 times in all sites, while this was 27 %–61 % for 3 applications in all the sites (Fig. 2g).

3.2. Variation in soil fertility parameters and major soil constraints by site

The boxplots of soil macronutrient distribution by Sub-County and critical limits are shown in Fig. 3. The soil carbon concentration was

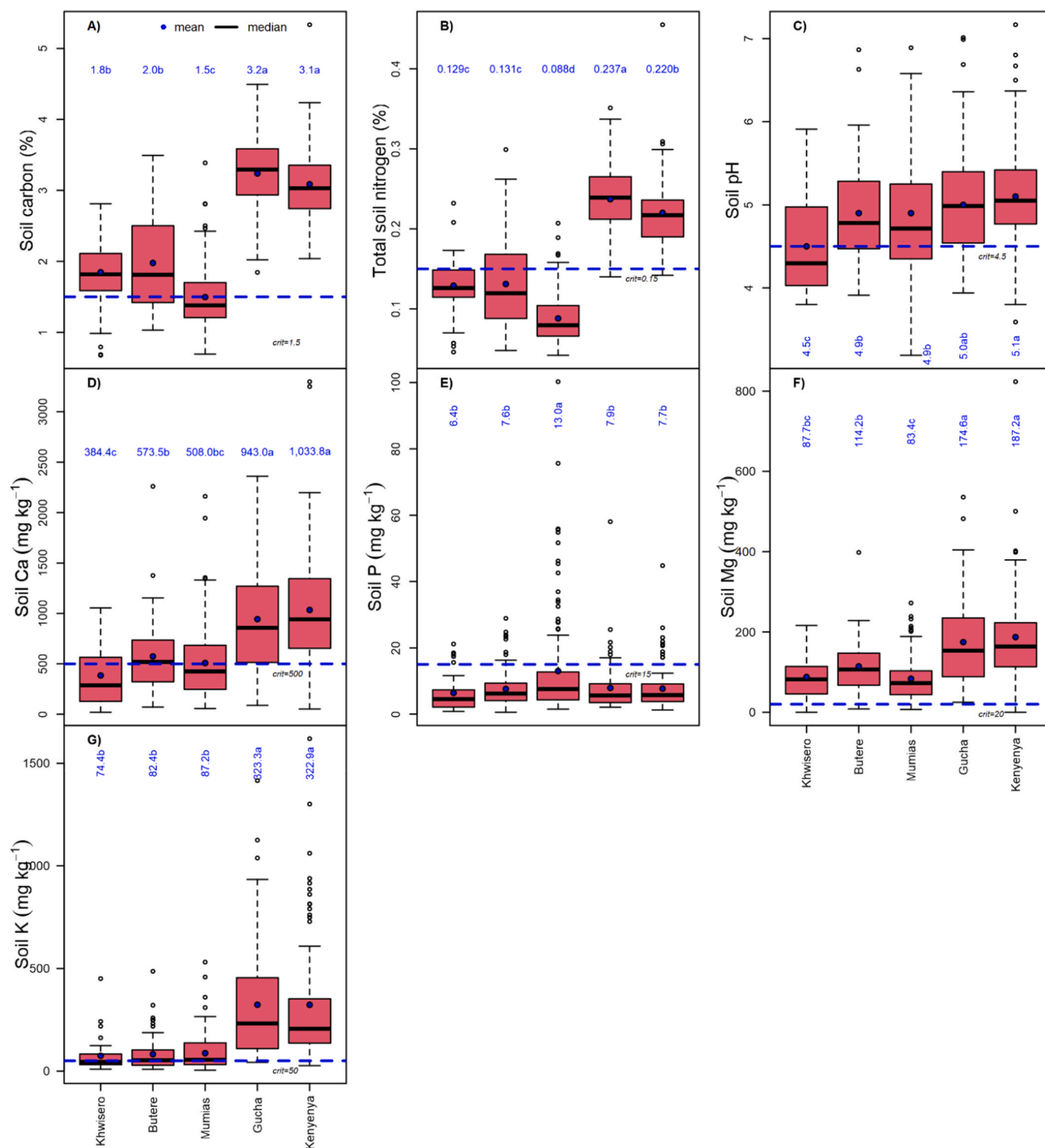


Fig. 3. Boxplots and critical limits for soil macronutrients by Counties including soil carbon (a), soil total N (b), soil pH (c), soil Ca (d), soil P (e), soil Mg (f) and soil K (g). Critical soil values (horizontal dotted lines) are shown. Means followed by different letters are significantly different (LSD tests, Sub-County main effects)

significantly different by sites ($p = 0.000$), with Gucha and Kenyenyia recording high soil C means (3.2, 3.1 %), which were different from sites in Kakamega County (Fig. 3a). Butere (2.0) and Khwisero (1.8) recorded significantly higher soil C means compared to Mumias (1.5) with the least soil C concentration. There were significant differences in soil nitrogen distribution by site ($p = 0.000$). About the soil nitrogen level, Kenyenyia and Gucha recorded the highest concentrations, which were above the critical level (0.15 %), while Butere, Khwisero and Mumias (in

descending order), recorded lower total soil N than the critical level (Fig. 3b). The mean soil pH recorded significant differences by sites ($p = 0.000$). The soils in Kakamega County sites recorded higher soil pH (Fig. 3c), compared to Kisii County sites, but most of the observed fields were above the critical soil pH level. Only some farms in Khwisero had critically acidic soils. In relation to soil Ca values (Fig. 3d) ($p = 0.000$ based on site means), Khwisero, Butere and Mumias recorded values lower than the critical level, while the mean level in Gucha and

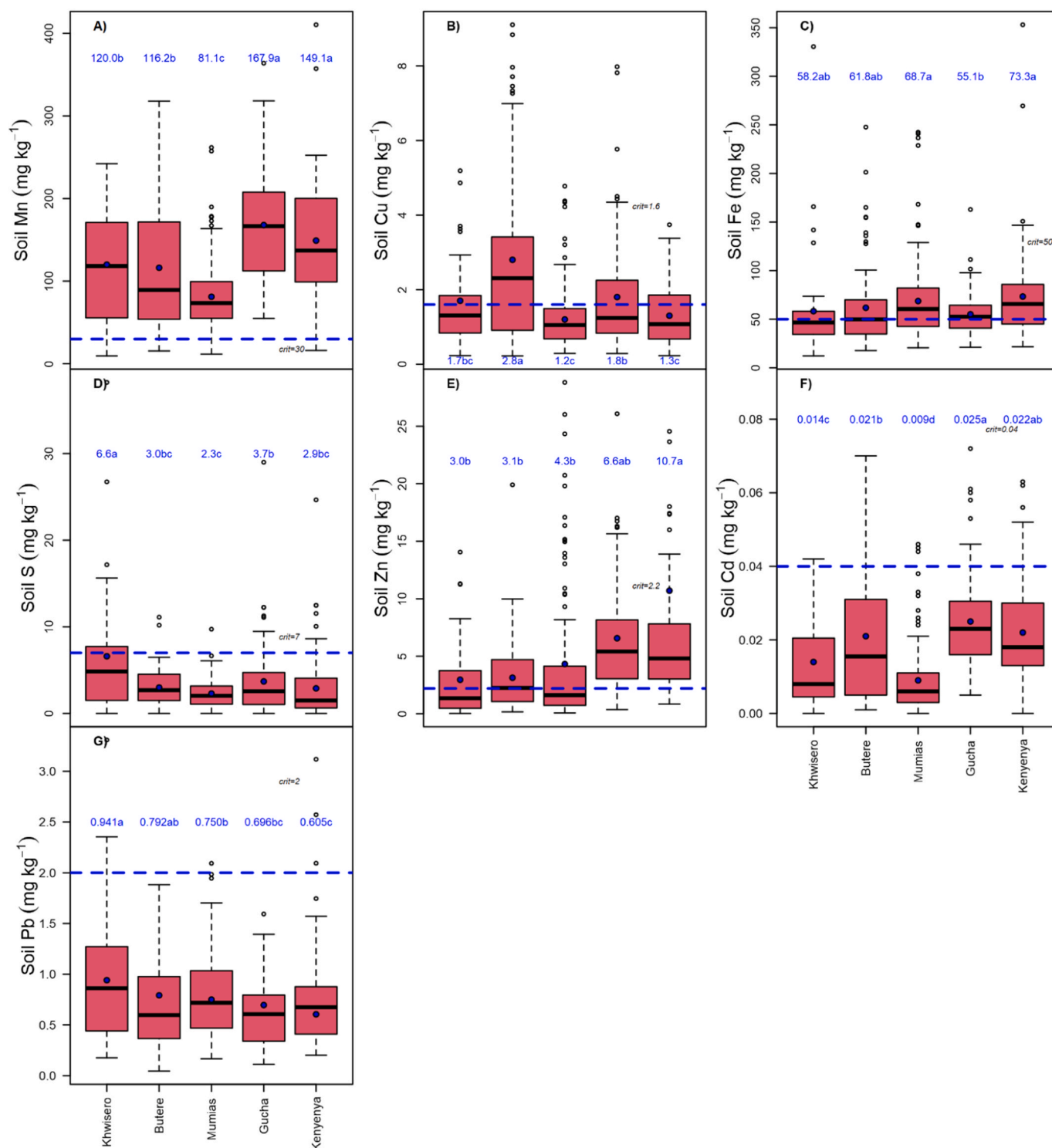


Fig. 4. Boxplots and critical limits for soil micronutrients by Counties including soil manganese (a), soil copper (b), soil Fe (c), soil Sulphur (d), soil Zinc (e), soil cadmium (f) and soil lead (g). Critical soil values (horizontal dotted lines) are shown. Means followed by different letters are significantly different (LSD tests, Sub-County main effects)

Kenya was higher than the critical level. Khwisero recorded the lowest soil Ca, followed by Mumias, Butere, Gucha and Kenya. The soil P level means were lower than the critical level in all Sub-Counties (15 mg kg^{-1}). The mean highest soil P was recorded in Mumias (13.0 mg kg^{-1}), while other sites recorded soil P concentrations ranging from 6.4 to 7.9 mg kg^{-1} (Fig. 3e). The soil Mg level was significantly higher in Gucha and Kenya, followed by Butere, Khwisero and Mumias Sub-Counties (Fig. 3f). Most of the farms and all mean soil Mg values were higher than the critical limit (20 mg kg^{-1}). In addition, there were significant site differences in soil Mg levels ($p = 0.000$). Kenya and Gucha also recorded the highest soil Mg which were not different, while Butere and Khwisero (114, 87.7) were not significantly different in soil Mg characteristics. Most of the farms recorded soil C values ($p = 0.000$) above the critical level (1.5 %), but some farmers in Khwisero and Mumias had soils lower than the critical soil C level. In relation to soil K, Gucha and Kenya recorded higher means relative to the critical level (Fig. 3g). Khwisero, Butere and Mumias recorded significantly lower soil K in comparison with Gucha and Kenya, which were not significantly different. There were significant differences in soil macronutrient distribution by County, with all macronutrients other than soil P recording higher values in Kisii, vis-a-vis Kakamega County. Mean soil carbon was 1.7 % and 3.2 % in Kakamega and Kisii County. Other soil macronutrients were as follows; soil N (0.1, 0.2 %), soil pH (4.8, 5.1), soil Ca (504.9, 986.4), soil P (10.3, 7.8), soil Mg (93, 180.4), and soil K (83, 322.0) for Kakamega and Kisii Counties respectively (Supplementary Material 1).

The soil micronutrient distribution was significantly different by site including soil Mg ($p = 0.000$), soil Cu ($p = 0.000$), Fe ($p = 0.05$), S ($p = 0.000$), Cd ($p = 0.000$) and Pb ($p = 0.002$). The mean soil Manganese and Zinc content was significantly higher in Kisii, contrasted with Kakamega, while mean soil Pb was higher in Kakamega. The soil Cd levels were not different in the Counties (Supplementary Material 1). Fig. 4 shows the boxplots for soil micronutrients with their critical limits, and means. The survey showed that soil Mn was mostly above the critical limit (30 mg kg^{-1}) (Fig. 4a). The highest mean soil Mn was in Gucha (170 mg kg^{-1}), followed by Kenya (149 mg kg^{-1}), which were not significantly different. Khwisero and Butere recorded similar soil Mn means, while Mumias recorded the least soil Mn (81 mg kg^{-1}). Soil Cu was highest in Butere (2.8), and significantly different from all sites (Fig. 4b). This was followed by Gucha, Khwisero, Kenya and Mumias with the least. All sites recorded soil Fe mean values being above the critical limit (Fig. 4c), while all field soil S means were below the critical limit (Fig. 4d). Soil Zn concentration was highest in Kenya, followed by Gucha, Mumias, Butere and Khwisero which recorded the least concentrations (Fig. 4e). Most of the fields were above the critical soil Zn limit. The mean soil Cd concentration was highest in Gucha, followed by

Kenya, Butere, Khwisero, and Mumias (Fig. 4f). The Kisii County sites had significantly higher mean soil Cd, relative to sites in Kakamega County. The soil Pb concentration was highest in Khwisero, followed by Butere, Mumias, Gucha and Kenya (Fig. 4g). There were significant interaction differences in soil parameter distribution by site and distance from homestead (Supplementary Table 2a), site and soil texture (Supplementary Table 2b), site and fertilizer type (Supplementary Table 2c), and site by crop type (Supplementary Table 2d).

The percentage of fields with soil fertility constraints are shown in Table 3. The carbon constraints were highest in Mumias based on field proportions, followed by Butere, Khwisero, while Gucha and Kenya did not record any soil C constraints. Mumias recorded 93 % of fields with N constraints, followed by Khwisero and Butere (>60 % of fields), while Gucha and Kenya recorded fewer constraints. Soil pH constraints were highest in Khwisero Sub-County (59 % of fields), followed by Mumias, Butere, Gucha, while Kenya reported the least soil pH constraints based on percentage of fields with the constraint ($\text{pH} < 4.5$).

The soil calcium constraints were also higher in Kakamega County sites, in contrast to Kisii County. Most of the soils were soil-P constrained, indicating widespread soil P constraints, with high proportions of fields (83–97.5 %) in the Sub-Counties. Khwisero recorded the highest constraints, followed by Gucha, Kenya, Butere, and Mumias. The survey showed that soil Mg was not a major challenge for farms, based on low proportions of fields with the constraint (0–12 %). The percentage fields in Kisii Sub-Counties were very low with K constraints, while they were most prevalent in Khwisero, Butere and Mumias. For soil micronutrients, soil Mn was not a major constraint (0–8 %). The soil Cu constraints were also higher in Mumias, followed by Kenya, Khwisero, Gucha, and Butere. The soil Fe constraints were higher in Khwisero, followed by Butere, Gucha, Mumias and Kenya. The soil S constraints were most prevalent in Mumias, Butere, Kenya, Gucha, and Khwisero Sub-County, which recorded the least prevalence. In addition, the soil Zn constraints were highest in Khwisero, followed by Mumias, Butere, Gucha and Kenya Sub-County. The study found that soil Cd and Zn concentrations were below the soil toxic levels for plant growth in most sites, with few farms exceeding the threshold levels.

3.3. Multivariate pattern in soil fertility parameters among ALV small-scale farmers

A Factor analysis of 14 soil chemical properties revealed 5 factors showing the correlation patterns of the soil properties, explaining 74 % of the total variance in soil properties (Table 4). The first factor was described as the “organic matter” factor due to high positive loadings between total N, carbon, Soil K and factor 1. The second factor was characterized by high correlations between soil pH, soil P, soil Ca, and

Table 3
Percentage of fields with constraints based on soil critical nutrient levels.

Parameter [critical level]	Khwisero	Butere	Mumias	Gucha	Kenya	Across site
Macronutrients						
Carbon [< 1.5 %]	7(17.9)	22(28.2)	76(58.5)	0(0.0)	0(0.0)	105(25.4)
N [< 0.15 %]	29(74.4)	50(64.1)	121(93.1)	3(3.6)	2(2.4)	205(49.6)
Soil pH [< 4.5]	23(59.0)	20(25.6)	47(36.2)	20(23.8)	11(13.4)	121(29.3)
Ca [$< 500 \text{ mg kg}^{-1}$]	27(69.2)	35(44.9)	80(61.5)	19(22.6)	9(11.0)	170(41.2)
P [$< 15 \text{ mg kg}^{-1}$]	38(97.4)	72(92.3)	108(83.1)	80(95.2)	76(92.7)	374(90.6)
Mg [$< 20 \text{ mg kg}^{-1}$]	3(7.7)	4(5.1)	6(4.6)	0(0.0)	1(1.2)	14(3.4)
K [$< 50 \text{ mg kg}^{-1}$]	25(64.1)	38(48.7)	63(48.5)	2(2.4)	1(1.2)	129(31.2)
Micro-nutrients						
Mn [$< 30 \text{ mg kg}^{-1}$]	5(12.8)	2(2.6)	8(6.2)	0(0.0)	1(1.2)	16(3.9)
Cu [$< 1.6 \text{ mg kg}^{-1}$]	25(64.1)	36(46.2)	102(78.5)	51(60.7)	59(72.0)	273(66.1)
Fe [$< 50 \text{ mg kg}^{-1}$]	24(61.5)	40(51.3)	50(38.5)	38(45.2)	30(36.6)	182(44.1)
S [$< 2.2 \text{ mg kg}^{-1}$]	25(64.1)	76(97.4)	129(99.2)	69(82.1)	72(87.8)	371(89.8)
Zn [$< 7 \text{ mg kg}^{-1}$]	24(61.5)	38(48.7)	76(58.5)	12(14.3)	10(12.2)	160(38.7)
Cd [$< 0.004 \text{ mg kg}^{-1}$]	38(97.4)	64(82.1)	127(97.7)	73(86.9)	69(84.1)	371(89.8)
Pb [$< 2 \text{ mg kg}^{-1}$]	37(94.9)	77(98.7)	128(98.5)	84(100.0)	79(96.3)	405(98.1)

Values are number of fields and percentage plots with constraints. Critical soil values were adopted from Okalebo et al. (2002).

Table 4
PCA analyses of soil properties in Kakamega and Kisii Counties.

Parameters	Component					Communalities
	1	2	3	4	5	
Nitrogen (%)	0.944					0.917
Carbon (%)	0.937					0.910
K(mg kg ⁻¹)	0.658					0.742
pH		0.847				0.830
P (mg kg ⁻¹)		0.702				0.590
Ca (mg kg ⁻¹)		0.672				0.878
Mg (mg kg ⁻¹)		0.598				0.788
Pb (mg kg ⁻¹)			0.830			0.770
Fe (mg kg ⁻¹)			0.700			0.606
S (mg kg ⁻¹)			0.587			0.612
Cu (mg kg ⁻¹)				0.891		0.824
Mn (mg kg ⁻¹)				0.585		0.752
Zn (mg kg ⁻¹)					0.861	0.761
Cd (mg kg ⁻¹)					0.496	0.406
Eigen values	4.6	1.9	1.6	1.2	1.0	
% of Variance	32.9	13.7	11.7	8.8	7.2	
Cumulative variance %	32.9	46.5	58.2	67.0	74.2	

Cut-off point for loadings = 0.4.

soil Mg, and thus was described as the “*exchangeable bases and soil acidity factor*”. The third factor was characterized by high loadings between soil Pb, soil Fe, and soil S, while factor 4 was characterized by high loadings from soil Cu and Mn. Factor 5 was defined by high loadings between soil Zn and soil Cd with factor 5.

The factors influencing soil macronutrient distribution are shown in Table 5.

Soil carbon distribution was significantly influenced by site effects, soil texture, plot distance, fertilizer sources, and organic and inorganic fertilizer application frequencies. Gucha and Kenyena Sub-Counties

recorded higher SOC levels, averaging 1.2 and 1.1 % higher on average, compared to Butere Sub-County, while Mumias and Khwisero Sub-Counties recorded lower average SOC levels in comparison with Butere Sub-County. In addition, sandy clay loam soils recorded 0.25 % lower SOC concentrations, vis-a-vis clay soils. Plots located at longer distances from the homestead recorded lower SOC levels, with fourth fields recording 0.25 % lower soil carbon concentrations, while this was 0.20 and 0.15 % respectively for third and second fields respectively. Fertilizer sources including internal and external sources recorded 0.57 % higher soil carbon concentrations, relative to no-input applications,

Table 5
Glm model of soil macronutrient distribution (beta co-efficients and significance).

Parameter	Carbon	Nitrogen	pH	Ca	P	Mg	K
Intercept	1.364*	0.086*	4.987***	727.2	26.2*	111.6	160.8
Sub-County:Gucha	1.236***	0.105***	0.139	386.3***	0.1	78.1***	267.1***
Sub-County:Kenyena	1.100***	0.089***	0.147	426.1***	0.0	92.0***	249.7***
Sub-County:Khwisero	-0.251*	-0.009	-0.282*	-199.5*	-0.1	-16.1	15.4
Sub-County:Mumias	-0.437***	-0.040***	-0.073	-61.0	5.2**	-24.1*	-2.4
Texture:silty clay loam	0.057	0.004	-0.053	6.4	-0.9	0.2	-46.2*
Texture:sandy clay loam	-0.249***	-0.018***	-0.020	-76.3	0.4	-15.9	1.4
Crop:Fleshy staples	-0.154	-0.014	-0.053	23.1	1.1	0.1	-49.8
Crop:Grains	-0.039	-0.004	0.273**	149.4*	3.1*	15.0	30.2
Crop:Vegetables	-0.010	-0.002	0.307**	90.2	3.6*	7.2	35.5
Wealth:poor	-0.057	-0.003	0.040	32.9	0.3	-4.1	-3.6
Wealth:rich	-0.032	0.002	0.158	108.1	-0.7	-1.6	-21.4
Plot distance: fourth field	-0.250*	-0.019*	-0.304*	-264.5*	1.1	-39.0*	-90.3*
Plot distance:third field	-0.201*	-0.015*	-0.391***	-238.5***	-2.0	-49.6***	-114.6***
Plot distance:second field	-0.152*	-0.010*	-0.301***	-183.4**	-4.4**	-33.3**	-98.1***
Livestock unit	-0.001	0.001	0.008	13.2	0.0	4.3	10.5
Farmsize (acres)	-0.034	-0.003	-0.055*	-30.3	-0.6	-6.1*	-13.6*
Field size (acres)	0.037	0.003	-0.052	-7.9	-0.6	2.1	8.5
Tenure:individual	-0.038	0.001	0.061	-4.8	5.4*	-7.6	30.7
Fertilizer type:mineral	0.204	0.036	-0.165	15.8	-9.5	33.7	17.1
Fertilizer type:organic	-0.566	-0.044	-0.136	-79.6	-5.6	-6.1	9.7
Fertilizer type: integrated	0.268	0.031	-0.154	-62.4	19.6*	31.9	41.3
Fertilizer source:internal	0.544*	0.033*	0.258	35.9	1.5	0.0	3.9
Fertilizer source:external	0.471*	0.028	0.225	38.3	0.8	-36.2	39.7
Fertilizer source: internal and external	0.565*	0.036*	0.152	-1.5	0.3	-0.3	3.5
Manure frequency:twice	-0.041	0.000	0.021	-3.9	0.5	12.6	57.0*
Manure frequency:thrice	0.262*	0.019*	-0.092	100.2	-0.2	12.1	20.3
Manure frequency:four times	0.002	-0.009	-0.033	-108.0	-7.8	-20.1	-3.5
Fertilizer frequency: twice	0.008	-0.007	-0.158	-65.7	-1.9	-2.9	-110.7*
Fertilizer frequency:thrice	0.051	-0.002	-0.027	-39.7	0.2	-16.9	-94.7*
Fertilizer frequency: four times	0.906*	0.077**	0.111	70.0	11.9*	48.3	7.5

Base categories arranged alphabetically include Butere (for site), clay (texture), cash crops (crop), medium (wealth),first field (plot distance), communal (tenure), no fertilizer (fertilizer type and source), 1 (one) application (fertilizer and manure frequency), Significance codes are included as follows (*p = 0.01 to 0.05, **, p = 0.001 to 0.01, and ***p = 0 to 0.001).

while sole internal (0.54 %) and external applications (0.47 %) recorded intermediate differences in comparison with no-input regimes. Higher manure (+0.26 %) and fertilizer application frequencies (+0.91 %) recorded significantly higher soil carbon concentrations, relative to sole applications of either of the input types. The soil carbon concentration was significantly influenced by site, crop system, distance, and farm size. Khwisero site recorded 0.28 lower pH units (more soil acidity), contrasted with Butere Sub-County, while fields under grain and vegetable production recorded 0.27 and 0.31 higher soil pH units, compared to cash crop production. The soil nitrogen concentration was influenced by site, crop system, distance, fertilizer source, and the fertilizer and manure application frequencies. Gucha (by 0.11 % on average) and Kenyenia Sub-Counties (0.09 %) recorded higher soil N levels in contrast to Butere Sub-County, while Mumias Sub-County recorded lower soil N levels contrasted with Butere. Sandy clay loam soils recorded significantly lower soil N, relative to clay soils. The silty clay loam and clay soils did not vary significantly in their soil N concentrations. The plot distance also recorded significantly lower soil N concentrations with increasing distance from homesteads. The internal fertilizer sources and higher manure frequencies (three applications) recorded significantly higher soil N (+0.26 % N) concentrations relative to manure non-applied plots. Soil Ca concentrations were significantly influenced by site, crop system and plot distance. Farms in Gucha (+39 mg kg⁻¹ on average) and Kenyenia Sub-County (+43 mg kg⁻¹) recorded higher soil Ca concentrations, relative to Butere (base category). In addition, Khwisero recorded 199.5 mg kg⁻¹ lower soil Ca concentrations, vis-a-vis Butere. Plots under grain cultivation also recorded higher soil Ca levels, in contrast to cash crops, while plot distance recorded declining soil Ca concentrations with plot distance. The soil P concentration was influenced by site, crop system, distance, land tenure, fertilizer type and frequency of input applications. The Mumias site recorded higher soil P, relative to Butere while grain and vegetable

cultivated plots recorded higher soil P concentrations, relative to cash cropping (base category). Land under private ownership recorded higher soil P levels relative to communal land, while integrated fertilizers and higher fertilizer frequencies (4 times) recorded higher average soil P levels, compared with fertilizer non-applications. The soil Mg levels recorded significant effects with site, distance and farm sizes. The Gucha and Kenyenia Sub-Counties (both in Kisii County) recorded higher soil Mg concentrations, in comparison with Butere. In addition, Khwisero recorded 199.5 mg kg⁻¹ less soil Mg concentrations, relative to Butere. The distant fields (fourth) also tended to record lower soil Mg concentrations compared to the second fields, relative to the first field. Larger farm sizes recorded lower soil Mg concentrations, with increased 1 acreage unit reducing the Mg concentrations by 6.1 mg kg⁻¹ on average. The soil K levels were influenced by site, soil texture, distance, farm size, and manure and fertilizer frequencies. The fields in Gucha and Kenyenia Sub-County recorded higher soil K concentrations, in comparison with Butere, while silty clay loams recorded lower soil K (by 46.2 mg kg⁻¹ on average), compared to clay soils. All plots located further from homesteads recorded lower soil K levels, while larger farms recorded lower average concentrations.

Table 6 shows the regression estimates of factors influencing soil micronutrient distribution.

Soil Mn concentrations recorded significant effects by site, texture, distance, fertilizer source, and input (manure and fertilizer) application frequency. Gucha recorded higher soil Mn concentrations while Mumias recorded lower soil Mn, vis-a-vis Butere. In addition, the sandy clay loams recorded lower soil Mn on average, contrasted with clayey soil types. Plot distance (fourth fields), recorded lower soil Mn concentrations relative to first fields by 26.5 mg kg⁻¹, averagely, while three manure applications recorded higher soil Mn concentrations, compared to manure non-application. In addition, higher fertilizer frequencies (3–4 times) resulted in higher soil Mn, compared to fertilizer non-

Table 6

Glm model of soil micronutrient distribution (beta co-efficients and significance).

Parameter	Mn	Cu	Fe	S	Zn	Cd	Pb
Intercept	13.1	1.809	102.8*	0.174*	10.680*	0.074	1.067*
Sub-County:Gucha	37.2**	-1.161***	-8.3	0.227	2.460	0.015	0.000
Sub-County:Kenyenia	18.8	-1.628***	11.1	0.025	2.680*	0.003	0.173*
Sub-County:Khwisero	-0.7	-1.407***	-9.9	3.892	-0.500*	0.003	0.192*
Sub-County:Mumias	-36.2***	-1.586***	5.0	-0.637**	1.809*	-0.012	0.138*
Texture:silty clay loam	9.9	0.232	-2.5	-0.016	3.376	-0.005	-0.067
Texture:sandy clay loam	-14.2*	-0.497**	-4.9	-0.626	-0.106	-0.009	-0.022
Crop:Fleshy staples	-10.1	-0.335	9.7	-0.893	7.937	-0.023*	0.044
Crop:Grains	-4.1	0.225	-4.1	-0.816*	1.202	-0.013	0.015
Crop:Vegetables	-16.1	0.066	12.7*	-0.203*	0.026	-0.029**	0.033
Wealth:poor	0.5	-0.229	1.0	-0.363	0.193	-0.003	-0.049
Wealth:rich	7.4	0.568*	-16.6*	-1.626	8.294***	0.005	-0.302***
Distance: fourth field	-26.5*	-0.782*	1.7	0.450	-2.505	-0.019	0.012
Distance:third field	-7.6	-0.490*	4.1	0.331	-3.065	-0.019*	-0.050
Distance:second field	-6.9	-0.354*	3.6	0.194**	-1.261	-0.015*	-0.066
Livestock unit	-3.1	-0.138*	-1.2	0.016	-0.676	-0.002	0.028
Farmsize (acres)	-2.9	-0.116*	0.0	0.316	-0.494	-0.002	0.018
Fieldsize (acres)	1.6	0.028	7.9*	-0.577	-0.099	0.002	-0.005
Tenure:individual	4.2	0.263	6.6	-1.257*	0.838	0.005	-0.005
Fertilizer type:mineral	64.8	1.133	37.9	4.173	-1.880	0.016	0.277
Fertilizer type:organic	-14.7	-0.858	-46.3	-0.293	0.879	-0.006	-0.010
Fertilizer type: integrated	61.6	0.750	-39.1	2.295*	-7.186	-0.003	-0.097
Fertilizer source:internal	34.0	0.500	-17.0	0.082	-0.887*	-0.009	-0.338*
Fertilizer source:external	49.3*	0.208	-15.0	-0.496	6.035*	-0.009	-0.340*
Fertilizer source: internal and external	39.1	0.704	-23.0	-0.803	-0.234*	-0.009	-0.394*
Manure frequency:twice	-7.8	-0.228	-2.5	-0.124	-2.218*	0.013*	0.132*
Manure frequency:thrice	36.2**	0.720*	7.7	-0.327	-0.053	0.008	0.084
Manure frequency:four times	14.5	-0.500	-77.5**	-1.148	-6.352	-0.026	-0.278
Fertilizer frequency: twice	20.2	0.106	18.8	1.318	-1.769	-0.012	-0.049
Fertilizer frequency: thrice	33.9*	0.500	3.1	0.749	0.268	-0.011	-0.066
Fertilizer frequency: four times	105.8*	2.060*	20.0	3.954*	-3.291	0.007	-0.069

Base categories arranged alphabetically include Butere (for site), clay (texture), cash crops (crop), medium (wealth),first field (plot distance), communal (tenure), no fertilizer (fertilizer type and source), 1 application (fertilizer and manure frequency), Significance codes are included as follows (*p = 0.01 to 0.05, **, p = 0.001 to 0.01, and ***p = 0 to 0.001).

application. Soil Cu concentrations recorded lower average concentrations in all sites, compared to Butere, while sandy clay loams recorded less soil Cu, vis-a-vis clay soils. The wealthy farmers recorded higher soil Cu concentrations, in comparison with medium wealth farms, while soil Cu concentrations tended to decline significantly with increasing distance from homesteads. Higher manure and fertilizer applications (3 and 4 respectively), resulted in higher average soil Cu concentrations, compared to non-application of the inputs. The soil Fe concentration was influenced by crop system, wealth, field size, and manure application frequency. In addition, the soil S concentration was significantly influenced by site, crop system, distance, land tenure, fertilizer type and fertilizer application frequencies. Mumias Sub-County recorded lower soil S concentrations, contrasted with Butere while grain and vegetable fields recorded lower soil S contents, compared to cash cropping. Integrated fertilizers and higher fertilizer frequencies resulted to higher soil S contents, relative to manure non-application and single fertilizer application. Soil Zn concentrations were higher in Kenyenia (+2.68 mg kg⁻¹) and Mumias Sub-Counties (+1.809 mg kg⁻¹), in contrast to Butere while, they were lower in Khwisero (by 0.50 mg kg⁻¹ on average), compared to Butere site. Wealthy farmers recorded significantly higher soil Zn concentrations, compared to moderately wealthy farmers. External inputs resulted in higher average soil Zn concentrations by 6 mg kg⁻¹, compared to non-applied fields. Soil cadmium concentrations were higher in cash crop fields, vis-a-vis annual crops and tended to decline with plot distance. The soil Pb content was significantly higher in Kenyenia, Khwisero and Mumias, in contrast to Butere, while wealthy farms recorded lower soil Pb levels, compared to moderately wealthy farms. Non-fertilized fields recorded lower Pb levels, while manure frequency (twice) recorded higher average Pb levels, relative to manure non-applications.

4. Discussion

4.1. Socio-demographic characteristics

The study showed that there were diverse socio-economic characteristics among ALV farmers in western Kenya. For instance, farmers in Kenyenia recorded higher proportions of wealthy farmers, compared to other Sub-Counties. The findings indicated Kisii County being characterized by higher proportions of wealthy farmers, relative to farms in Kakamega County. In Khwisero Sub-County, there were no wealthy farm households. Concerning educational characteristics, the proportion of secondary and tertiary graduates was higher in Kenyenia Sub-County, while Gucha, Khwisero and Mumias recorded the highest proportions of farmers without formal education. Studies have shown that educated farmers are more likely to decipher information and apply more specialized knowledge compared to less-educated farmers, including better utilization of soil inputs, which can influence ALV soil fertility and productivity (Ndiritu et al., 2014). Mwakidoshi et al. (2023) and Muru-Ng'ang'a (2017) showed that education influenced farmer adoption and utilization of resource-intensive and knowledge-intensive soil fertility management technologies.

The soil texture data signified different soil textural distribution patterns, which can influence inherent soil fertility patterns in western Kenya. The non-application of fertilizers was more prevalent in Kakamega County sites, compared to sites in Kisii County, while application of fertilizers was more prevalent in Kisii County sites. Kakamega Sub-Counties recorded the highest proportions of farmers who did not use any soil inputs, in contrast to Kisii County. The cultivation of cash crops was more prevalent in Kisii County, compared to Kakamega sites, while most inputs and fertilizers used were sourced internally in all sites, but there was a higher proportion of external sourcing of inputs in Gucha and Kenyenia, relative to Kakamega County sites. Input sourcing from external sources is an important factor influencing farm nutrient balances and nutrient cycling, which can regulate soil nutrient stocks and fertility for ALV production.

4.2. Agro-ecological and socio-economic factors influencing ALV soil fertility

The data on soil constraints indicated that Kisii County soils were characterized by high soil C, while soil N levels were below the critical limits in Kakamega County soils. Khwisero soils were also characterized by high soil acidity, while Gucha and Kenyenia recorded lower soil acidity. The soil P was a major constraint in all sites in Western Kenya, but the soil P was much lower in Khwisero, partly due to high acidity that leads to soil P fixation that may limit ALV productivity. In tropical acidic soils, soil P is susceptible to strong fixation by amorphous Fe and Al hydroxides, making soil P unavailable for plant growth (Alhammad et al., 2023). The higher soil C concentrations in Kisii County are likely to improve the levels of Ca and Mg, which leads to lower soil pH and reduced soil nitrate leaching, which accounts for differences in basic cations and pH in Kisii and Kakamega Counties. The findings are consistent with the study results which indicate high soil Ca, Mg, and soil K in Gucha and Kenyenia Counties, while Kakamega County sites recorded lower soil cation concentrations.

Soil acidity is associated with nutrient deficiencies such as soil P, Ca, Mg, Mo and K (Otieno et al., 2022; Nungula et al., 2023) coupled with Al, Fe, and Mn toxicity. Soil acidity was a constraint for ALV production in all Sub-counties, especially Khwisero (Ileri et al., 2015). Mugo et al. (2021) found that *Solanum tuberosum* yield reduced with increasing soil acidity. Soil carbon is an important indicator of soil fertility which regulates several soil nutrients, including potassium, whose leaching can be enhanced in low carbon soils that were observed in western Kenya.

Soil micronutrient distribution differed significantly by Sub-County. The soil Mn level was above the critical level in all sites, but they were higher in Kisii, compared to Kakamega sites. The soil Fe levels were above the critical limits in all sites, but higher in Kenyenia and Mumias, while they were low in Khwisero and Gucha. In addition, soil S concentration was highest in Khwisero, while it was lowest in Mumias. The soil S concentration was not a constraint in all sites in western Kenya. The soil Pb concentration was lowest in Kisii County sites and highest in Kakamega sites, and tended to increase with soil acidity in western Kenya, though it was below the critical level. In addition, soil cadmium was also below the critical level in all sites, but was higher in Kisii sites relative to Kakamega sites.

Several soil characteristics including the soil pH, redox potential, soil organic matter dynamics, interaction among soil ions and soil microbes regulate the micronutrient availability in soils (Dhaliwal et al., 2021). Soil minerals and organic matter are the primary source of micronutrients through weathering and mineralization. Soil Mn concentration is usually high at low soil pH and low redox potential, and Mn²⁺ in the soil solution is precipitated as MnO₂ with increasing soil pH, which was consistent with the study findings showing higher soil Mn in Kisii County, in contrast to Kakamega sites.

The regression models of soil properties with socio-economic and agronomic parameters signify the influences of these characteristics on soil macronutrient and micronutrient distribution. The soil carbon distribution was influenced by site, soil texture, plot distance, fertilizer sources and fertilizer and manure application frequency. Site differences signify differences in soil texture and soil fertility management, while fertilizer application frequencies and organic matter can influence soil organic matter dynamics at the farm level (Mugo et al., 2021). Sandy clay loam soils recorded lower soil carbon contents, in comparison with clay soils which was expected. Fine soil particles have higher specific surface area and are more reactive than coarse particles, thus clay-textured soils store higher amounts of carbon than sandy soils (Kornei, 2022). Plot distance revealed a declining pattern of soil C and total soil N concentration with increased distance from the household.

Woomer et al. (1998) found that farmers managed livestock sheds and home gardens in 'homesites' while 'in-fields' included valued crops intended for markets. In addition, 'outfields' consisted of fodder crops with low fertilizer inputs which were harvested for livestock in the

'homesites'. The continuous nutrient mining of 'outfields' leads to infertile sites within farms. Within the 'in-fields', farmers tend to grow preferred crops where manure and fertilizer inputs are applied. Accordingly, soil carbon and nutrients accumulate in the 'home sites' and 'in-fields', often at the cost of 'outfields'. The soil pH readings were influenced by site, crop system, plot distance, and farm size. The soil pH tended to decrease with increasing plot distance, mainly due to the change in soil carbon between the plots. In Kakamega County, there was a higher proportion of fields that were not fertilized, relative to Kisii County, while in Gucha, all fields received fertilizers. Lack of fertilization can lead to depletion of organic matter and soil nutrients, particularly soil N. Inorganic fertilizers increase organic matter through the increment of root biomass and crop residues that potentially return to soils (Shao et al., 2024; Nasar et al., 2025). The soil cations (Ca, Mg, K and P) were mainly influenced by site and plot distance from the homestead, likely resulting from the effect of soil carbon changes on these nutrients.

For soil micronutrients, only soil Mn and soil Cu were influenced by site differences. There was a declining trend in soil Mn and soil Cu with plot distance, possibly due to the changes in soil C and soil pH with increasing distance from homesteads. Soil Mn was also higher in fields that applied externally sourced inputs and where higher input application frequencies were observed. Soil Fe recorded higher values in vegetable fields, relative to cash crops, while high manure frequencies enhanced soil Fe. Soil S was strongly influenced by crop system, with vegetable and grain plots recording lower soil S relative to cash crops. Integrated soil inputs and higher fertilizer frequencies led to higher soil S concentrations. The variations in soil S were likely to be associated with changes in soil acidity and organic matter, due to cropping and input application patterns. The soil Zn distribution was influenced by site and wealth, with wealthy farms recording higher soil Zn, while external inputs recorded higher soil Zn values relative to non-application. The soil Zn levels were highest in Kisii, relative to Kakamega soils, likely due to the variation in soil C and soil pH.

Cadmium availability in soils is influenced by several variables such as total Cd content, soil pH, soil organic matter (SOM), cation exchange capacity (CEC), and clay content (Ngugi et al., 2021). Soil acidity is important because it influences the solubility and mobility of Cd in the soil, with higher acidity increasing Cd availability. Higher manure application frequencies were associated with lower soil Cd levels, consistent with Hamid et al. (2019) and Sairaam et al. (2023), who observed an ameliorant effect of organic soil inputs in reducing the plant bioavailability of Cd. In addition, internal inputs reduced soil Cd availability, while external inputs increased soil Cd concentrations, possibly because internal sourced inputs were predominated with organic fertilizers, while external inputs were likely dominated by fertilizer types that increased soil acidity. In addition, the fertilizer use practices by small-scale farmers may influence soil acidification processes. The soil Pb levels were also highest in western Kenya sites, compared to Kisii sites, possibly due to differences in soil acidity. The availability of soil Pb depends on how tightly it is held by soil particles and on its solubility (how much of it will dissolve in water). At low soil pH (pH < 5.0, acidic conditions), lead is held less tightly and is more soluble. In high pH soils, soil lead solubility is very low, while increasing soil organic matter reduces Pb availability.

4.3. Multivariate assessment of soil fertility patterns

In terms of independent soil fertility dimensions, the five factors highlight soil fertility processes influencing ALV soil fertility in western Kenya, providing potential dimensions for soil fertility management. The principal components revealed the main processes of underlying soil fertility in ALV farms of western Kenya. The multivariate structure suggests that soil organic matter, exchangeable bases and soil acidity were key drivers of ALV soil fertility. The study has revealed key patterns in soil micronutrient and heavy metal distribution in western

Kenya. The five reduced soil factors can be used to elicit soil fertility management domains in ALV farm systems by identifying the most important soil characteristics and reducing complex data into a manageable set of indicators. This can facilitate more efficient assessment of soil fertility and the development of tailored management strategies. The loadings of each soil parameter on the components can be used to understand which parameters contribute most to each factor and to the overall soil quality (Shukla and Sharma, 2023). The first factor was characterized by increasing soil C, soil N and soil K with increasing PC1 scores. This suggests that soil C and soil N were the key drivers of soil fertility in ALV farms, suggesting that adequate organic matter management strategies are necessary for soil fertility management in ALV farming systems. Sustainable soil organic matter management is a key factor for adequate ALV soil fertility management, due to high loadings on soil C, soil N and soil K and the high variance explained by this factor. The high variance for the first factor imply that soil organic processes explained 32.9 % of the total variance in soil characteristics. Secondly, adequate management of soil acidity and exchangeable bases is needed to enhance ALV soil fertility, through liming and adequate applications of deficient exchangeable bases. The third, fourth and fifth factors were linked to soil micronutrients, including factor 3 (soil Pb, Fe, and S), factor 4 (soil Cu and Mn), and factor 5 (soil Zn and Cu). The components indicate the need to include micronutrient fertilizer options, based on identified deficiencies, because the loading structure indicates underlying soil fertility processes in the ALV farming systems based on the correlation structure of soil nutrients. Factor 5 was related to soil Zn and Cd correlation structure. Zinc (Zn) and Cadmium (Cd) are heavy metals with similar mineralogical structure and electronegativity (Hassan et al., 2020). The mining and processing of Cd and Zn has caused sufficient exposure of both heavy metals in the environment (Emmanuely et al., 2024). Fertilizer application in soils can introduce soil Cd contamination, adversely affecting plant growth and posing human health risks. The survey found that the mean soil Cadmium and Zinc levels were lower than the reference values in all Counties, above which concentrations are considered harmful to human health and the environment (FAO, 2004). Heavy metals can accumulate in living organisms for long periods due to their indigestibility. Some heavy metals including zinc, selenium, manganese and iron are recognized to play important cellular and metabolic functions but are required in trace amounts (Wan et al., 2024). However, other heavy metals such as lead, mercury and cadmium are non-beneficial to the body and can pose profound health complications even at very low concentrations. Bioaccumulation of such metals can cause several effects, including congenital deformities, DNA destruction, gastrointestinal disease, cancers of the brain, liver, and kidney, and ultimately mortality (Dias, 2012). The study results showed that the ALV farm systems were safe for most of the heavy metals, especially Zn and Pb, whose reference values were recommended as 200 mg kg⁻¹ (Zn), 400 mg kg⁻¹ (Pb) and Cd (0.03 mg kg⁻¹). However, in Gucha, Kenyenyia and Mumias, a few of the farms were detected to have exceeded the reference Cd safety levels, and appropriate soil-crop management practices are needed to reduce heavy metal risks in vegetable production systems in Kenya.

The study has used a cross-sectional survey design, which was beneficial in capturing the status of intensified ALV farm systems in Kenya including soil characteristics. Though the survey approach was limited in demonstrating cause-and-effect relationships such as soil changes under ALV farm systems resulting from farm management practices, this has been addressed by experimental studies that were undertaken in the same study, but reported elsewhere (Svenja, 2017; Nambafu, 2018, 2020). The risks of sampling bias were addressed by defining a clear target population (farmers involved in intensive ALV production) and using probability sampling techniques.

5. Conclusions and recommendations

In general, the soil fertility status in Kisii County soils was much

better, compared to Kakamega County along soil macronutrient and micronutrient indicators. The site differences (Sub-County factor) clearly differentiated soil nutrient distribution due to inherent differences in soil characteristics and indirect effects arising from localized differences in soil management practices. Soil toxicity parameters including soil Cd and soil Pb can be ameliorated by soil C and soil pH management options, including neutralizing soil acidity and enhancing soil C concentrations. The widespread soil acidity in both Counties and low carbon and nitrogen concentrations in Kakamega sites can constitute a constraint for ALV cultivation that needs to be adequately addressed. The study has revealed specific soil constraints that can limit ALV productivity and profitability under intensive production systems. Soil organic carbon was generally low in Khwisero, Butere and Mumias, relative to Kisii ALV sites. In addition, soil acidity, coupled with soil P deficiency was detected in all sites. Micro-nutrient deficiencies including soil Cu, were prevalent in Mumias, Gucha, and Kenyena, while soil S was limiting in all sites, other than Khwisero based on assessments of soil critical values. Soil critical values can provide a basis to address general soil fertility constraints for ALV farm systems, however specific recommendations are needed for diverse farm systems and ALV species. The study findings suggest that sustainable soil management practices are needed for the ALV farm sector, targeting organic resource management, soil acidity correction using liming and sufficient utilization of macronutrient and micronutrient fertilizers. Lime applications should be used by farmers to correct for soil acidity, and the application rates vary by soil acidity levels, following laboratory soil analyses. Application of organic manure at rates varying from 10 to 30 tha^{-1} is recommended to enhance soil organic carbon, and address multiple soil fertility constraints including soil acidity, macronutrient and micronutrient deficiencies. The amount of nutrients exported from soils per ton of edible yield strongly differs among ALV species. The fertilizer recommendations for leafy vegetables should be species-specific with regard to the species off-take and fertilizer nutrient ratios.

CRedit authorship contribution statement

Enos Onyuka: Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Godfrey Nambafu:** Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Darius Andika:** Software, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Samwel Mwonga:** Validation, Resources, Project administration, Methodology, Investigation, Conceptualization. **Joseph Gweyi-Onyango:** Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Harun Gitari:** Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Franklin S. Mairura:** Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported by the Project HORTINLEA (Horticultural Innovation and Learning for Improved Nutrition and Livelihood in East Africa) which was funded by the German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry of Economic Cooperation and Development (BMZ) within the frame-work of the program GlobE – Global Food Security. The authors are thankful to Prof.

Dr. Christof Engels for conceptualization and technical mentorship in the research; and the technical staff of Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences, Humboldt - Universität zu Berlin for the technical facilitation of the study. The authors also recognize the Ministry of Agriculture staff and the farmers in Kisii and Kakamega Counties for their support during the survey.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.farsys.2025.100157>.

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