



Influence of Crop Farming on Soil Chemical Properties and Sustainable Watershed Management in the Tungu–Nithi Sub-Catchment, Kenya

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Article History:

Received: 07-01-2026
Revision: 04-02-2026
Accepted: 11-02-2026
Publication: 12-03-2026

Cite this article as:

Kibaara, W. S., Kathuri, M. N., Kibetu, D. K., & Riungu, J. M. (2026). Influence of Crop Farming on Soil Chemical Properties and Sustainable Watershed Management in the Tungu–Nithi Sub-Catchment, Kenya. *Sustainability Quest*, 3(1), 1-10. doi.org/10.36923/SQ.v3i1.418

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Abstract: This study assessed the influence of crop farming on soil chemical properties within the Tungu–Nithi sub-catchment, Tharaka Nithi County, Kenya. Soil samples were collected from twelve sites, comprising six crop (T1–T6) and six non-crop (N1–N6) locations across the upper, middle, and lower sections of the watershed. The parameters analyzed included soil pH, nitrate, phosphate, and sulfate. In addition, farmer perceptions regarding the influence of agricultural practices on soil quality were evaluated using a structured Likert-scale questionnaire. Data were analyzed using descriptive statistics and the non-parametric Kruskal–Wallis test. The results revealed significant spatial and land-use variations in soil properties ($p < 0.05$). Cultivated areas exhibited consistently lower pH values, indicating increased soil acidity associated with the application of ammonium-based fertilizers in tea, maize, and coffee farming. Nitrate concentrations were significantly higher in crop sites across all sections, with peak levels recorded in the middle section. Similarly, phosphate and sulphate concentrations were elevated in cultivated soils, particularly in the middle and lower sections, reflecting intensive farming practices, fertilizer inputs, irrigation, and nutrient transport processes. Farmer perception data supported these findings, as the majority of respondents acknowledged that fertilizer use, irrigation, pesticide application, and monocropping influence soil conditions. These findings demonstrate that crop farming significantly alters soil chemical properties within the sub-catchment, highlighting the need for sustainable soil and watershed management strategies to prevent nutrient accumulation and environmental degradation.

Keywords: Crop farming, Soil chemical properties, Sub-catchment, Soil acidity, Nutrient dynamics, Watershed management, Sustainable agriculture

1. Introduction

Agriculture remains a foundational pillar of global economic development, food security, and rural livelihoods. It contributes substantially to national GDPs, employment generation, and international trade, particularly in developing economies (Michelle et al., 2023). However, the rapid intensification of agricultural production over the past two decades has generated significant environmental externalities, including soil degradation, nutrient enrichment, freshwater pollution, and biodiversity loss. In 2022, global primary crop production reached approximately 9.6 billion tonnes, representing a 56% increase since 2000 (Ashoka, 2023). While this expansion has increased food availability, it has also intensified pressure on soil and water systems, particularly in river sub-catchments.

From a sustainability perspective, agriculture operates within a delicate balance between productivity and ecological resilience. The United Nations 2030 Agenda for Sustainable Development emphasizes sustainable resource management, climate neutrality, and ecosystem protection as integral components of long-term food system transformation (United Nations, 2024). Agriculture accounts for nearly 70% of global freshwater withdrawals and is a leading contributor to diffuse nutrient pollution through fertilizer application, soil erosion, and surface runoff (Ingrao et al., 2023). Consequently, sustainable intensification frameworks increasingly advocate for nutrient-use efficiency, conservation agriculture, agroecological practices, and watershed-based management approaches to mitigate environmental degradation while sustaining yields.

Empirical evidence from Europe shows that agricultural land accounts for nearly 40% of total land area, contributing significantly to diffuse pollution from excessive fertilizer and pesticide use (Vincent et al., 2023). Nutrient runoff alters freshwater ecosystems through eutrophication, oxygen depletion, and biodiversity decline (Claudia, 2022). Importantly, agricultural intensity has been shown to correlate strongly with ecological status in adjacent river systems (Vincent et al., 2023), underscoring the interconnectedness of land-use practices and watershed health. These findings highlight the need to adopt catchment-level sustainability assessments rather than relying solely on farm-level analyses.

In Sub-Saharan Africa, where over 80% of the rural population depends on smallholder agriculture (Oyatola et al., 2020), the sustainability challenge is particularly acute. Conversion of natural vegetation into cropland in riverine ecosystems has accelerated soil erosion, nutrient

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leaching, and deterioration of water quality (Waal et al., 2022). However, small river systems and sub-catchments often remain underrepresented in global environmental monitoring databases (World Water Development Report, 2021), limiting context-specific sustainability interventions. Wetlands and riparian zones provide critical ecosystem services,

including nutrient retention, sediment filtration, and hydrological regulation, but face mounting threats from agricultural expansion and climate variability (Syed et al., 2022). Sustainable land management strategies such as agroforestry, contour farming, and ecological infrastructure development have demonstrated potential to enhance ecosystem resilience and reduce nutrient transport (Fen et al., 2025).

In Kenya, agriculture contributes approximately 51% of national GDP, 26% directly and 25% indirectly, and provides over 60% of employment (Marta et al., 2022). Despite its economic significance, agricultural intensification has contributed to nutrient stress in several catchments, including the River Sosiani (Ontumbi et al., 2015) and Ngong River systems (Mary et al., 2023). Soil erosion associated with crop farming increases sedimentation and nutrient loading in rivers, thereby disrupting aquatic ecosystems and reducing downstream water quality (Sabiti, 2021; Stenfert Kroese et al., 2020). These dynamics reflect a broader sustainability dilemma: agricultural productivity gains may undermine long-term ecosystem health if soil nutrient management is not balanced with conservation measures.

Although prior studies in Kenya have examined water quality degradation in river systems (Chamia, 2022; Onyango et al., 2024), limited research has systematically analyzed how spatial variations in crop farming practices influence soil chemical properties within sub-catchment systems (Fen et al., 2025). Understanding these soil-level changes is critical because soil acts as both a nutrient reservoir and a source of diffuse pollution when mismanaged. Furthermore, few studies integrate empirical soil analysis with local farmer perceptions to assess the socio-ecological dimensions of sustainability within agricultural landscapes (Berthet et al., 2021).

The Tungu–Nithi Sub-Catchment in Tharaka Nithi County is a socio-ecological system characterized by diverse crop production, including tea, maize, coffee, beans, and horticultural crops, distributed across upper-, middle-, and lower-elevation zones. Increasing fertilizer use, irrigation practices, and land-use transformation raise concerns regarding soil acidification, nitrate accumulation, phosphate enrichment, and sulphate mobility (Thuo, 2020; Franziska et al., 2023). However, the extent to which crop farming practices differentially affect soil chemical properties across spatial gradients within this sub-catchment remains insufficiently understood.

Grounded in a watershed sustainability framework, this study examines the influence of crop farming on key soil chemical parameters, pH, nitrates, phosphates, and sulphates, across stratified sections of the Tungu–Nithi Sub-Catchment. Specifically, the study aims to assess spatial variations in soil chemical properties between crop and non-crop sites across the upper, middle, and lower sections of the sub-catchment; determine whether crop farming significantly influences soil nutrient dynamics using nonparametric statistical tests; and examine farmers' perceptions of the sustainability implications of crop farming practices.

The Tungu–Nithi sub-catchment supports diverse agricultural activities that are central to local livelihoods and regional food security. However, growing concerns about soil degradation and nutrient accumulation have raised questions about the long-term sustainability of current farming practices in the watershed. Although previous studies have examined agricultural impacts on water quality and ecosystem health, limited attention has been given to spatial variations in soil chemical properties across sub-catchment gradients in this region. Therefore, this study investigates the influence of crop farming on soil pH, nitrate, phosphate, and sulphate levels across the upper, middle, and lower sections of the Tungu–Nithi sub-catchment. By integrating laboratory analysis with farmer-perception data, the study seeks to generate evidence to inform sustainable land-use planning and soil management strategies that maintain soil productivity while protecting watershed integrity.

2. Materials and Methods

2.1. Study Design and Sampling Framework

This study employed a cross-sectional field and laboratory-based design to assess the influence of crop farming on selected soil chemical properties within the Tungu–Nithi Sub-Catchment, Tharaka Nithi County, Kenya. A watershed-based stratification approach was adopted to capture spatial variability along the hydrological gradient. The sub-catchment was divided into three elevation-defined sections based on topography and flow direction: upper, middle, and lower zones.

To ensure representativeness and reduce sampling bias, a stratified random sampling strategy was implemented. Within each spatial zone, two crop sites and two non-crop (reference) sites were randomly selected from pre-identified potential locations mapped during a pilot survey using GPS coordinates. In total, twelve sampling points were selected: six crop sites (T1–T6) and six non-crop sites (N1–N6). At each sampling point, three soil sub-samples were collected within a 5 m radius using a soil auger at a depth of 0–20 cm, representing the active root zone most influenced by agricultural practices. The three sub-samples were homogenized to form one composite sample per site, yielding 12 composite samples for laboratory analysis.

2.2. Soil Preparation and pH Determination

Soil samples were air-dried at room temperature and sieved through a 2 mm mesh prior to analysis. Soil pH was determined using the soil–water suspension method at a 1:2 ratio (w/v). Specifically, 10 g of sieved soil was mixed with 20 mL of distilled water, stirred thoroughly, and allowed to equilibrate for 30 minutes. The pH was measured with a calibrated glass electrode pH meter. Calibration was conducted using standard buffer solutions at pH 4.0 and 7.0 prior to each measurement session to ensure analytical accuracy. Measurements were expressed as unitless pH values.

2.3. Nitrate (NO₃⁻) Determination

Soil nitrate concentration was determined using the brucine colorimetric method, as described by Belete & Yadete (2023). A sodium acetate extraction solution was prepared by dissolving 50 g of sodium acetate in 250 mL of distilled water, then adding 30 mL of concentrated acetic acid. The solution was diluted to 1 L with distilled water. For extraction, 5 g of sieved soil was placed in a shaking bottle with 20 mL of extracting solution and a small amount of activated charcoal to remove organic color interference. The mixture was shaken for 2 minutes and filtered. An aliquot (1 mL) of filtrate was transferred into a test tube, followed by the addition of 0.5 mL brucine reagent and 2 mL concentrated sulfuric acid (H₂SO₄). After mixing and standing

for 5 minutes, 2 mL of distilled water was added. The solution was allowed to cool for 15 minutes. Absorbance was measured at 470 nm using a spectrophotometer. Nitrate concentrations were calculated from a standard calibration curve and expressed in mg kg^{-1} dry soil.

2.4. Sulphate (SO_4^{2-}) Determination

Sulphate concentration was determined by turbidimetric analysis (Tabatabai, 1974). An extracting solution was prepared by dissolving 0.5 g $\text{KH}_2\text{PO}_4 \cdot 2\text{H}_2\text{O}$ in 1 L of distilled water. Five grams of air-dried, sieved soil were placed in a 250 mL conical flask, and 25 mL of extracting solution was added. The mixture was shaken mechanically for 10 minutes and filtered. A 10 mL aliquot of filtrate was transferred into a 25 mL volumetric flask, diluted to 20 mL with distilled water, and 1 mL of 10% BaCl_2 was added to precipitate sulphate as barium sulphate. The mixture was shaken for 30 minutes, and turbidity was measured at 420 nm using a spectrophotometer. Sulphate concentration was calculated from a laboratory-generated standard curve and expressed in mg kg^{-1} .

2.5. Phosphate (PO_4^{3-}) Determination

Available phosphate was determined using the Bray and Kurtz (1965) extraction method, as modified by Jackson (1962). The extracting solution was prepared by adding 15 mL of 1.0 M ammonium fluoride solution to distilled water and diluting to 500 mL. One gram of sieved soil was weighed into a centrifuge tube and extracted with 7 mL of the solution by shaking for 5 minutes on an orbital shaker. The mixture was centrifuged at 2000 rpm for 10 minutes. Two milliliters of supernatant were transferred into a test tube, followed by the addition of 5 mL distilled water, 2 mL ammonia solution, and 1 mL stannous chloride reagent to develop color. Absorbance was measured at 660 nm using a spectrophotometer. Phosphate concentrations were determined from a calibration curve prepared with standard phosphate solutions and expressed in mg kg^{-1} .

2.6. Statistical Analysis

Data were analyzed using descriptive statistics and non-parametric inferential testing. Given the small sample size and potential nonnormality, the Kruskal–Wallis H test was used to assess differences in soil chemical properties between crop and non-crop sites across spatial zones. Statistical significance was determined at $p < 0.05$. Post-hoc pairwise comparisons were conducted to identify spatial contrasts among the upper, middle, and lower sections, with significant differences observed. All nutrient concentrations were expressed on a dry weight basis (mg kg^{-1}). Data analysis was performed using appropriate statistical software (specify software and version).

4. Results and Discussion

The study sought to determine the influence of crop farming on soil chemical properties within the Tungu–Nithi sub-catchment. Soil samples were collected from six crop sites (T1–T6) and six non-crop sites (N1–N6). The sub-catchment was stratified into three spatial sections, upper, middle, and lower, based on elevation and hydrological flow patterns. In each section, two crop sites and two non-crop sites were examined. The analysis focused on four soil chemical properties: pH, nitrates, phosphates, and sulphates. The findings are presented in Tables 1–4.

4.1. Soil pH Levels

The study sought information on soil pH levels across different sections of the Tungu–Nithi sub-catchment. The findings were presented in Table 1.

Table 1: Soil pH Levels

Sample point	Soil Samples				Mean
Upper Section of the Sub-catchment					
	A	B	C	Crop point	
T1	5.84	5.82	5.81		5.82
T2	5.69	5.70	5.72		5.70
N1	7.10	7.13	7.14	Non-Crop	7.12
N2	7.02	7.04	7.05		7.04
Middle Section of the Sub-catchment					
T3	5.91	5.90	5.89	Crop Point	5.90
T4	5.88	5.85	5.84		5.85
N3	6.82	6.81	6.79	Non-Crop	6.80
N4	6.30	6.29	6.31		6.30
Lower Section of the Sub-catchment					
T5	6.09	6.10	6.12	Crop Point	6.10
T6	6.18	6.17	6.15		6.16
N5	6.29	6.30	6.28	Non-Crop	6.29
N6	6.62	6.63	6.59		6.61

Source: by the author

The analysis of soil pH revealed clear spatial and land-use variations across the Tungu–Nithi sub-catchment (Table 1). In the upper section, crop sites (T1 and T2) recorded mean pH values of 5.82 and 5.70, respectively, indicating moderately acidic conditions. In contrast, non-crop sites (N1 and N2) exhibited substantially higher mean values of 7.12 and 7.04, reflecting near-neutral conditions. A similar pattern was observed in the middle section, where crop sites (T3 and T4) recorded mean pH values of 5.90 and 5.85, while non-crop sites (N3 and N4) recorded 6.80 and 6.30. In the lower section, pH values increased relative to the upper and middle zones. Crop sites (T5 and T6) showed mean values of 6.10 and 6.16, whereas non-crop sites (N5 and N6) recorded 6.29 and 6.61.

Across all three spatial sections, crop sites consistently had lower pH values than adjacent non-crop sites. The magnitude of this difference was most pronounced in the upper section, where the disparity between cultivated and non-cultivated soils

exceeded one pH unit. Furthermore, a downstream gradient was evident, with soil pH generally increasing from the upper to the lower section of the sub-catchment. The Kruskal–Wallis test confirmed that these differences were statistically significant ($p < 0.05$), indicating that both spatial position within the watershed and land-use type significantly influenced soil acidity. Post-hoc comparisons demonstrated significant differences between the upper and middle sections, upper and lower sections, and middle and lower sections, thereby reinforcing the presence of a spatially structured pH gradient.

These results indicate that cultivated soils are systematically more acidic than non-cultivated soils within the sub-catchment. In addition, the observed downstream increase in pH suggests that topographical and hydrological positioning within the watershed is associated with variations in soil chemical conditions (David et al., 2021). Therefore, both agricultural activity and spatial location appear to be linked with soil acidity patterns across the Tungu–Nithi sub-catchment.

4. 2. Soil Nitrates Level

Soil nitrate concentrations exhibited substantial spatial and land-use variation across the Tungu–Nithi sub-catchment (Table 2). In the upper section, cultivated sites (T1 and T2) recorded mean nitrate concentrations of 1.059 g kg^{-1} and 1.068 g kg^{-1} , respectively. In contrast, adjacent non-crop sites (N1 and N2) recorded markedly lower mean concentrations of 0.41 g kg^{-1} and 0.52 g kg^{-1} . This indicates that nitrate levels in cultivated soils were more than twice those observed in non-cultivated soils within the same elevation zone (Shen et al., 2025).

A more pronounced divergence was observed in the middle section. Crop sites (T3 and T4) exhibited the highest nitrate concentrations in the study, with a mean of 2.828 g kg^{-1} . Conversely, non-crop sites (N3 and N4) recorded considerably lower mean concentrations of 0.636 g kg^{-1} and 0.628 g kg^{-1} , respectively. The magnitude of difference between crop and non-crop soils in this section exceeded 2.0 g kg^{-1} , representing the strongest land-use contrast within the sub-catchment.

In the lower section, crop sites (T5 and T6) recorded mean nitrate concentrations of 1.615 g kg^{-1} and 1.620 g kg^{-1} . Although these values were lower than those observed in the middle section, they remained substantially higher than those at the non-crop sites (N5 and N6), which recorded mean concentrations of 0.265 g kg^{-1} . Notably, non-crop soils in the lower section exhibited the lowest nitrate concentrations across the entire watershed.

When examined along the spatial gradient, nitrate concentrations increased from the upper to the middle section and subsequently declined toward the lower section; however, crop soils consistently maintained higher nitrate levels than non-crop soils in all sections. The Kruskal–Wallis test confirmed statistically significant differences across sections ($p < 0.05$), indicating that nitrate distribution within the watershed is structured both by elevation and land-use category.

Table 2: Soil Nitrates Levels

Sample point	Soil Samples				Mean
Upper Section of the Sub-catchment					
	A	B	C	Crop point	
T1	1.064	1.059	1.054		1.059
T2	1.069	1.068	1.068		1.068
N1	0.41	0.41	0.41	Non-Crop	0.41
N2	0.52	0.52	0.52		0.52
Middle Section of the Sub-catchment					
T3	2.828	2.829	2.828	Crop Point	2.828
T4	2.826	2.831	2.829		2.828
N3	0.636	0.633	0.638	Non-Crop	0.636
N4	0.631	0.625	0.629		0.628
Lower Section of the Sub-catchment					
T5	1.571	1.615	1.660	Crop Point	1.615
T6	1.620	1.620	1.620		1.620
N5	0.259	0.265	0.270	Non-Crop	0.265
N6	0.264	0.264	0.265		0.265

Source: by the author



Figure 1: Nyayo Tea Zone (Upper Section of Tungu–Nithi Sub-Catchment). Source: Field observation, Tungu–Nithi Sub-Catchment.

The upper section of the watershed is characterized by extensive tea cultivation, particularly within the Nyayo Tea Zone, which functions as a buffer adjacent to Mount Kenya Forest. This land-use configuration corresponds spatially with the nitrate concentrations recorded in the upper section.

4.3. Soil Phosphate Levels

Soil phosphate concentrations demonstrated substantial variation across both land-use categories and spatial sections within the Tungu–Nithi sub-catchment (Table 3). In the upper section, crop sites (T1 and T2) recorded mean phosphate concentrations of 8.63 mg kg⁻¹ and 9.86 mg kg⁻¹, respectively. In contrast, non-crop sites (N1 and N2) exhibited lower mean values of 4.86 mg kg⁻¹ and 4.90 mg kg⁻¹. Thus, cultivated soils in the upper section contained nearly double the phosphate concentration observed in adjacent non-cultivated soils. A marked increase in phosphate concentration was observed in the middle section. Crop sites (T3 and T4) recorded mean values of 19.82 mg kg⁻¹ and 19.79 mg kg⁻¹, whereas non-crop sites (N3 and N4) recorded considerably lower mean values of 5.12 mg kg⁻¹ and 5.22 mg kg⁻¹. The magnitude of difference between crop and non-crop soils in this section exceeded 14 mg kg⁻¹, indicating a strong land-use effect.

The lower section exhibited the highest phosphate concentrations recorded in the study. Crop sites (T5 and T6) showed mean values of 23.58 mg kg⁻¹ and 23.65 mg kg⁻¹, respectively. In contrast, non-crop sites (N5 and N6) recorded 7.89 mg kg⁻¹ and 7.86 mg kg⁻¹. Although phosphate concentrations were elevated in both land-use categories relative to the upper section, crop soils consistently exhibited substantially higher values. Across the watershed gradient, phosphate concentrations increased progressively from the upper to the lower section. Furthermore, crop sites maintained significantly higher phosphate levels than non-crop sites in all spatial zones. The Kruskal–Wallis test confirmed that differences across sections were statistically significant ($p < 0.05$), indicating that phosphate distribution within the sub-catchment is structured by both elevation and land-use type.

The observed spatial pattern indicates that phosphate accumulation is most pronounced in the lower section, followed by the middle section, while the upper section recorded comparatively lower concentrations. In addition, the magnitude of difference between crop and non-crop soils was greatest in the middle and lower sections. These results suggest that cultivated soils are associated with greater phosphate accumulation than non-cultivated soils across the sub-catchment. Although phosphate values in the upper section were comparatively lower, concentrations increased substantially in the middle and lower sections, which correspond with areas characterized by more diverse crop cultivation. These findings align with reported associations between intensive crop farming and elevated phosphorus concentrations (Carver et al., 2022; Marco et al., 2022). However, within the present analysis, the data primarily demonstrate that both land-use type and watershed position are significantly associated with soil phosphate variability.

Table 3: Soil Phosphate Levels

Sample point	Soil Samples				Mean
Upper Section of the Sub-catchment					
	A	B	C	Crop point	
T1	8.09	9.01	8.79		8.63
T2	9.84	9.87	9.87		9.86
N1	4.84	4.86	4.87	Non-Crop	4.86
N2	4.90	4.90	4.91		4.90
Middle Section of the Sub-catchment					
T3	19.81	19.82	19.84	Crop Point	19.82
T4	19.86	19.79	19.71		19.79
N3	5.12	5.13	5.12	Non-Crop	5.12
N4	5.21	5.25	5.21		5.22
Lower Section of the Sub-catchment					
T5	23.63	23.52	23.60	Crop Point	23.58
T6	23.63	23.66	23.66		23.65
N5	7.94	7.92	7.80	Non-Crop	7.89
N6	7.91	7.93	7.74		7.86

Source: by the author

4.4. Soil Sulphate Levels

Soil sulphate concentrations exhibited clear spatial and land-use variation within the Tungu–Nithi sub-catchment (Table 4). In the upper section, crop sites (T1 and T2) recorded mean sulphate concentrations of 12.99 mg kg⁻¹ and 12.96 mg kg⁻¹, respectively. In contrast, non-crop sites (N1 and N2) recorded lower mean values of 7.76 mg kg⁻¹ and 7.60 mg kg⁻¹. Thus, cultivated soils in the upper section contained approximately 5 mg kg⁻¹ more sulphate than adjacent non-cultivated soils.

In the middle section, crop sites (T3 and T4) recorded the highest sulphate concentrations observed in the study, with mean values of 22.12 mg kg⁻¹ and 22.10 mg kg⁻¹, respectively. Conversely, non-crop sites (N3 and N4) recorded substantially lower concentrations of 6.49 mg kg⁻¹ and 6.45 mg kg⁻¹. The difference between crop and non-crop soils in this section exceeded 15 mg kg⁻¹, representing the most pronounced land-use contrast within the dataset. In the lower section, crop sites (T5 and T6) recorded mean sulphate concentrations of 15.42 mg kg⁻¹ and 15.35 mg kg⁻¹. Non-crop sites (N5 and N6) recorded the lowest sulphate concentrations across the sub-catchment, with mean values of 3.48 mg kg⁻¹ and 3.49 mg kg⁻¹. Although sulphate concentrations declined from the middle to the lower section in cultivated soils, they remained considerably higher than those recorded in non-cultivated soils.

Across all spatial sections, crop sites consistently exhibited elevated sulphate concentrations relative to non-crop sites. Furthermore, sulphate accumulation followed a spatial gradient, increasing from the upper to the middle section and then declining in the lower section, although it remained above upper-section levels in cultivated soils. The Kruskal–Wallis test confirmed that differences in sulphate concentrations across sections were statistically significant ($p < 0.05$). Post-hoc comparisons revealed significant differences between the upper and middle sections, the upper and lower sections, and the middle and lower sections. Therefore, sulphate distribution within the sub-catchment is structured by both elevation and land-use category. The observed patterns indicate that cultivated soils have substantially higher sulphate concentrations than non-cultivated soils throughout the watershed. In addition, sulphate accumulation is most pronounced in the middle section,

suggesting spatial concentration within this zone. These results demonstrate that both crop farming and watershed position are linked with sulphate variability within the Tungu–Nithi sub-catchment.

Table 4: Soil Sulphate Levels

Sample point	Soil Samples				Mean
Upper Section of the Sub-catchment					
	A	B	C	Crop point	
T1	12.99	13.00	12.97		12.99
T2	12.96	12.95	12.98		12.96
N1	7.46	7.94	7.87	Non-Crop	7.76
N2	7.62	7.60	7.55		7.60
Middle Section of the Sub-catchment					
T3	22.14	22.10	22.13	Crop Point	22.12
T4	22.13	22.17	22.03		22.10
N3	6.49	6.45	6.54	Non-Crop	6.49
N4	6.45	6.49	6.41		6.45
Lower Section of the Sub-catchment					
T5	15.42	15.39	15.45	Crop Point	15.42
T6	15.39	15.31	15.35		15.35
N5	3.52	3.49	3.43	Non-Crop	3.48
N6	3.52	3.49	3.46		3.49

Source: by the author

To determine whether crop farming significantly influenced soil chemical properties within the Tungu–Nithi sub-catchment, a Kruskal–Wallis H test was conducted. The results are presented in Table 5.

Table 5: Influence of Crop Farming on Soil Properties within Tungu-Nithi Sub-catchment

Null Hypothesis	Sig.	Post – Hoc Test
There was no significant influence of crop farming on soil pH in the sub-catchment	0.004	Upper vs Middle: $p = 0.028$ Upper vs Lower: $p = 0.002$ Middle vs Lower: $p = 0.015$
There was no significant influence of crop farming on soil phosphates in the sub-catchment	0.001	Upper vs Middle: $p < 0.001$ Upper vs Lower: $p < 0.001$ Middle vs Lower: $p = 0.004$
There was no significant influence of crop farming on soil nitrates along in sub-catchment	0.004	Upper vs Middle: $p = 0.003$ Upper vs Lower: $p = 0.012$ Middle vs Lower: $p = 0.021$
There was no significant influence of crop farming on soil sulphates in the sub-catchment	0.004	Upper vs Middle: $p = 0.001$ Upper vs Lower: $p = 0.006$ Middle vs Lower: $p = 0.019$

Source: by the author

The Kruskal–Wallis analysis revealed statistically significant differences across spatial sections for all four soil properties ($p < 0.05$). Therefore, the null hypotheses stating that crop farming had no significant influence on soil pH, phosphates, nitrates, and sulphates were rejected. Post-hoc comparisons further demonstrated that differences were significant between upper and middle sections, upper and lower sections, and middle and lower sections for all tested parameters. Notably, phosphates exhibited the strongest statistical differentiation ($p = 0.001$), followed by pH, nitrates, and sulphates ($p = 0.004$). These results confirm that soil chemical properties vary significantly along the watershed gradient and between cultivated and non-cultivated zones. Moreover, the consistent statistical significance across all parameters indicates that crop farming is associated with measurable alterations in soil chemistry within the sub-catchment.

Table 6: Analysis of Farmer Perceptions on the Influence of Crop Farming on Soil Properties within Tungu-Nithi Sub-catchment

Influence of Crop Farming on Sub-catchment	SD (%)	D (%)	N (%)	A (%)	SA (%)
Farmers in River Tungu and Nithi sub-catchment believed that excessive use of fertilizers influenced the soil properties within the sub-catchment.	2.3	2.05	0.5	44.6	50.51
Pesticides use in the farms to control pest and diseases influenced the soil properties.	4.8	4.1	0.8	41.8	48.5
Crop farming methods have increased the rate of soil erosion within the sub-catchment degrading the soil.	4.1	4.4	0.5	46.1	45.4
Poor farming practices such as monocropping had exposed the soil to agents of soil erosion.	6.9	8.4	1.0	40.3	43.3
Prolonged use of irrigation had led to leaching of soil thus reducing its fertility.	7.7	5.8	1.2	43.3	42
Most of the farmers within the sub-catchment rely on water from River Tungu and Nithi to carry out irrigation farming.	6.4	6.9	0.23	40.0	46.4
The type of crops grown in different sections of the sub-catchment varied, hence influence on the soil properties differed across the upper, middle and lower sections.	3.6	5.4	0.5	50.3	40.3

Source: by the author

The perception data indicate strong agreement among respondents that agricultural activities influence soil properties within the sub-catchment. Specifically, 95.11% of respondents agreed that excessive fertilizer use alters soil chemistry, while 90.3% acknowledged the influence of pesticides. Similarly, over 92% associated crop farming methods with increased soil erosion. Furthermore, 85.3% of respondents believed that prolonged irrigation contributes to soil leaching, while 86.4% confirmed reliance on River Tungu and Nithi for irrigation farming. These perceptions align with laboratory findings showing elevated nutrient concentrations in cultivated soils, particularly within the middle and lower sections. A substantial majority (90.6%) also agreed that crop types vary across spatial sections, thereby influencing soil properties differently along the watershed gradient. This perception corresponds with observed spatial variability in nitrates, phosphates, sulphates, and pH levels. Overall, farmer perceptions reinforce the statistical and laboratory evidence indicating that crop farming practices are associated with alterations in soil chemical properties across the Tungu–Nithi sub-catchment.

5. Discussion

The findings of this study demonstrate that crop farming significantly influences soil chemical properties within the Tungu–Nithi sub-catchment. The spatial patterns observed across upper, middle, and lower sections indicate that both land-use intensity and watershed position play a critical role in shaping soil chemistry. Specifically, cultivated sites consistently exhibited elevated concentrations of nitrates, phosphates, and sulphates compared to non-crop sites, while soil pH in cultivated areas tended to be lower, particularly in the upper and middle sections. This pattern suggests that agricultural activities contribute to measurable alterations in soil nutrient dynamics and acidity levels within the sub-catchment.

The lower pH values observed in crop areas, particularly in the upper and middle sections, can be linked to the intensive use of ammonium-based fertilizers such as ammonium sulphate and diammonium phosphate. These fertilizers are widely applied in tea and maize cultivation and are known to contribute to soil acidification over time. This finding aligns with Fentanesh et al. (2023), who reported that conversion of natural vegetation to agricultural land significantly alters soil nutrient composition and pH. Similarly, Han et al. (2024) noted that high concentrations of ammonium-based compounds can negatively affect water quality and promote eutrophication. Therefore, the observed soil acidity in cultivated zones may reflect long-term fertilizer application practices within the watershed.

Nitrate concentrations were significantly higher in crop sites across all sections, with the middle section exhibiting the highest values. This spatial concentration of nitrates suggests that agricultural intensification is particularly pronounced in this zone. The elevated nitrate levels are consistent with findings by Adams et al. (2020) and Raw 2024, who reported that fertilizer application is a major driver of soil nitrate accumulation. Furthermore, Liu et al. (2021) demonstrated that cropland-dominated areas exhibit higher nitrate concentrations due to fertilizer runoff and leaching. The present study similarly indicates that nitrate enrichment in cultivated soils may result from nitrogen-based fertilizer inputs combined with surface runoff and leaching, especially in areas with moderate slopes and active farming.

Although nitrate concentrations declined slightly in the lower section relative to the middle section, they remained significantly higher in crop areas than in non-crop sites. This pattern suggests downstream nutrient transport within the watershed. Kipngeno et al. (2020) reported that surface runoff effectively transports nitrates from higher elevations to lower areas within sub-catchments. Consequently, the spatial gradient observed in this study may reflect cumulative nutrient movement from upper and middle farming zones toward lower sections.

Phosphate concentrations followed a similar trend, increasing progressively from the upper to the lower section, with markedly higher values in cultivated soils. The high phosphate concentrations in crop areas can be attributed to fertilizer use, particularly di-ammonium phosphate, as well as organic matter decomposition. Marco et al. (2022) found that intensive farming practices are strongly associated with elevated phosphorus levels due to agricultural runoff. Similarly, Carver et al. (2022) observed that upper watershed zones with less intensive farming exhibit comparatively lower phosphate concentrations. The present findings reinforce these observations, indicating that land-use intensity significantly influences phosphorus accumulation within soil systems.

Sulphate concentrations also demonstrated strong land-use differentiation, with cultivated soils consistently recording higher values across all sections. The middle section exhibited peak sulphate levels, which may reflect intensive fertilizer application and organic matter decomposition. Mwanake et al. (2023) and Suman (2023) reported that crop farming within sub-catchments significantly affects soil properties, particularly where fertilizer use is intensive. In addition, the EPA (2024) identified anthropogenic activities as a primary contributor to rising sulphate levels in river systems. Therefore, the elevated sulphate concentrations observed in crop areas may be linked to ammonium sulphate fertilizers and related agricultural inputs.

Farmer perception data further support the laboratory findings. A substantial majority of respondents acknowledged that excessive fertilizer use, pesticide application, irrigation practices, and monocropping influence soil properties within the sub-catchment. These perceptions correspond closely with the measured nutrient gradients. For example, 95.11% of respondents agreed that fertilizer use affects soil properties, which aligns with the elevated nitrate and phosphate concentrations observed in cultivated soils. Similarly, 85.3% associated prolonged irrigation with soil leaching, which corresponds with the nutrient mobility patterns identified in the study. These findings are consistent with Nusrat et al. (2025) and Mostapha et al. (2024), who reported that agricultural intensification and agrochemical use contribute to soil and water quality degradation. Likewise, Bijay and Eric (2021) linked fertilizer application to nitrate pollution in surface and groundwater systems.

The combined evidence from laboratory analysis and farmer perceptions indicates that agricultural intensification within the Tungu–Nithi sub-catchment is associated with nutrient enrichment and altered soil chemistry. However, non-crop areas, particularly those characterized by natural vegetation such as Mount Kenya Forest, consistently exhibited lower nutrient concentrations and relatively higher pH values. This suggests that natural vegetation plays a buffering role in regulating nutrient cycling and reducing soil chemical alteration. Suzanne et al. (2018) similarly reported that forested areas maintain lower nitrate concentrations due to efficient nitrogen retention mechanisms.

From a watershed management perspective, the findings highlight the interconnected nature of land use, nutrient dynamics, and environmental sustainability. Elevated nutrient concentrations in soils increase the risk of downstream transport into River Tungu and River Nithi, potentially affecting aquatic ecosystems. Synan et al. (2024) emphasized that agrochemical

contamination can disrupt aquatic food webs and reduce biodiversity. Therefore, without appropriate soil conservation and nutrient management strategies, continued agricultural intensification may compromise both soil health and water quality within the sub-catchment.

The discussion indicates that crop farming significantly modifies soil chemical properties across spatial gradients within the watershed. The interactions among fertilizer application, irrigation practices, crop type variation, and topographical positioning collectively shape nutrient distribution patterns. Consequently, sustainable land management practices, including controlled fertilizer application, improved irrigation efficiency, soil conservation techniques, and vegetation buffers, are essential to mitigate nutrient accumulation and promote long-term environmental sustainability within the Tungu–Nithi sub-catchment.

6. Conclusion

The study established that crop farming significantly influences soil chemical properties within the Tungu–Nithi sub-catchment. Cultivated areas recorded lower pH values (5.70–5.90) compared to non-crop areas (6.30–7.12), indicating increased soil acidity associated with ammonium-based fertilizer application in tea and maize farming. In contrast, the lower section exhibited relatively higher pH values (6.16–6.61), likely reflecting reduced farming intensity and the presence of natural vegetation.

Nitrate concentrations were highest in crop areas, particularly in the middle section (2.828 g kg⁻¹), suggesting a strong influence from nitrogen fertilizer use. Similarly, phosphate and sulphate concentrations were consistently elevated in cultivated soils across all sections. Statistical analysis confirmed significant spatial differences ($p < 0.05$), indicating that crop farming plays a measurable role in shaping soil nutrient dynamics within the watershed. Overall, the findings demonstrate that agricultural practices contribute to nutrient enrichment and soil chemical alteration, with implications for watershed sustainability and downstream water quality. These findings contribute to sustainability scholarship by demonstrating how agricultural intensification influences soil chemical dynamics within a watershed system, thereby highlighting the importance of sustainable land-use planning and nutrient management in safeguarding long-term ecosystem resilience.

7. Recommendations

The study recommends promoting balanced fertilizer application based on soil testing to reduce excessive nutrient accumulation and soil acidification. The use of organic amendments and precision agriculture techniques should be encouraged to improve nutrient efficiency. In addition, conservation practices such as contour farming, crop rotation, cover cropping, and riparian vegetation protection should be implemented to minimize soil erosion and nutrient runoff. Optimizing irrigation practices and strengthening farmer education programs will further support sustainable soil management and protect water quality within the Tungu–Nithi sub-catchment.

Acknowledgement Statement: I sincerely thank the reviewers and all contributors to this study.

Conflicts of 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.

Authors' contribution statements: Author 1 contributed to the Conceptualization, Methodology, Formal Analysis, and Writing - Original Draft; Author 2 contributed to Software, Validation, and Data Curation; Author 3 contributed to Validation, Investigation, and Resources; Author 4 contributed to Validation, Data Curation, Investigation, and Project Administration.

Funding statements: As no external funding was received for this research, the study was conducted without financial support from any funding agency or organization.

Data availability statement: Data is available upon request. Please contact the corresponding author for any additional information on data access or usage.

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Declaration of generative AI and AI-assisted technologies in the writing process: During the preparation of this work, the author(s) used ChatGPT for copy-editing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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