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Original Research Article

Altitudinal and Agroecological Control on Soil Chemical and Physical Variability in Rwanda's Marshland Rice Systems

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Abstract

This study assessed the relative influence of agroecological zones (AEZs) and altitude on soil nutrient dynamics to guide site-specific management. Soil samples from 20 marshlands across seven AEZs, spanning 944 to 1900 m a.s.l., were collected from 0–30 cm and analysed for pH, exchangeable bases (Ca, Mg, K, and Na), organic carbon (OC), total nitrogen (TN), available phosphorus (P), and texture using ANOVA, Welch's tests, and PCA. Fertility varied markedly among AEZs: the Imbo zone exhibited near-neutral pH and higher base cations, while *Mayaga* and the *Congo Nile Watershed Divide* were acidic and nutrient-poor. Low-elevation sites (944–1044 m a.s.l.) had higher pH (6.32) and base cations, whereas high-altitude soils (>1800 m a.s.l.) were acidic (pH 4.92) and depleted. Effect size analysis confirmed altitude's stronger explanatory power for Ca ($\eta^2 = 0.53$ vs. $\eta^2 = 0.49$), Mg ($\eta^2 = 0.54$ vs. $\eta^2 = 0.37$), K ($\eta^2 = 0.47$ vs. $\eta^2 = 0.29$) and pH ($\eta^2 = 0.45$ vs. $\eta^2 = 0.33$), while AEZs better explained TN ($\eta^2 = 0.27$ vs. $\eta^2 = 0.09$), though altitude produced a notable mid-elevation TN peak (1345–1544 m a.s.l.), and OC ($\eta^2 = 0.31$ vs. $\eta^2 = 0.10$). Integrating altitude with AEZ-based frameworks and applying organic amendments in high-altitude acidic zones can improve nutrient use efficiency, rice yield, and sustainable marshland productivity in Rwanda.

Key words: Nutrient dynamics, rice production, marshland soils, site-specific management, soil chemistry

INTRODUCTION

Agriculture continues to serve as the backbone of Rwanda's economy, employing more than half of the labour force and contributing approximately one-quarter of the national GDP, while underpinning rural livelihoods and food security (World Bank, 2025). Rice production in Sub-Saharan Africa is largely undertaken by smallholder farmers, typically managing fragmented plots averaging 0.5–1 ha, which constrains mechanisation and efficiency (Flor et al., 2024). Rice ranks as a key staple crop for food security and income generation, mainly cultivated in marshlands and lowland valleys that benefit from irrigation and suitable hydrology for high-intensity production. Yet, the sector grapples with land shortages, soil fertility decline, and climate vulnerabilities (De Vos et al., 2023).

Rwanda's Crop Intensification Program (CIP) sought to enhance productivity by expanding smallholder access to subsidised fertilisers and certified seeds, thereby strengthening national food security strategies (Nahayo et al., 2017; Bizoza, 2021). Fertiliser use for rice has increased, yet yield responses remain modest, with limited productivity gains despite fiscal savings (Spielman et al., 2025). Constraints such as inappropriate fertiliser use, abiotic stresses, and biotic pressures continue to limit yields (Diagne et al., 2013). National yields of 4.1–4.2 t/ha remain below the agroecological potential of 7–10 t/ha (Senthilkumar et al., 2020), necessitating imports to meet domestic demand (Yuan et al., 2024). Although marshland expansion improves water and nutrient retention (Vanlauwe et al., 2015), fertiliser recommendations remain uniform across environments.

Across Rwandan rice-growing areas, a blanket fertiliser recommendation of 200 kg/ha NPK 17–17–17 and 100 kg/ha urea is routinely applied without regard to soil-test outcomes or site-specific nutrient requirements (Chuma et al., 2020). This one-size-fits-all approach fails to account for the considerable variability in soil characteristics across different marshland environments, frequently leading to poor nutrient use efficiency and inconsistent yield responses (Dobermann and Fairhurst, 2000; Alivelu et al., 2006; Cyamweshi et al., 2017).

Altitude, as a key environmental factor, drives the heterogeneity of soil properties by influencing temperature, rainfall, and hydrology, which in turn governs nutrient transformations and plant uptake efficiency. Nutrient availability is influenced by temperature, precipitation, and leaching, all of which change with elevation (Nabahungu and Visser, 2011; Shrestha et al., 2011). A report by He et al. (2016) indicated that linear declines in soil temperature at 0–10 cm depth with altitude reduce microbial activity and nutrient mineralisation. Similarly, Teron et al. (2026) showed that elevation modifies rainfall, temperature, soil moisture, and nutrient cycling, while Griffiths et al. (2010) found that higher elevations favour organic matter accumulation and mineralizable nitrogen. Lal (2020) observed that nutrient distribution patterns vary nonlinearly across altitudinal gradients. Collectively, these studies confirm that altitude indirectly governs soil fertility through microclimate, hydrology, and biogeochemical processes, implying that uniform fertiliser regimes may be inefficient.

The Agroecological Zone (AEZ) framework has traditionally guided fertiliser planning by incorporating climate, soil, and topographic attributes. However, AEZs often mask finer-scale variability, especially in marshlands that span large elevation ranges from the low-lying Imbo plains to mid- and high-altitude plateaus. While altitude is embedded within broader zonation frameworks such as the FAO-GAEZ system and the Land-Soil-Crop Hubs (LSC-Hubs) for Rwanda, the specific zonation system used in national fertiliser planning which groups marshlands by AEZ without explicit altitude-stratified recommendations, does not adequately capture elevation-driven gradients in nutrient availability. No previous study in Rwanda has directly compared altitude and AEZs as independent drivers of soil nutrient variability within marshland rice ecosystems. This knowledge gap limits efforts to implement site-specific fertiliser strategies aligned with climate-smart and sustainable production goals.

This study assessed the relative influence of AEZs and altitude on soil nutrient dynamics to guide site-specific management. This study tests the hypothesis that altitude exerts a stronger and more direct influence on marshland soil nutrient dynamics than AEZ classification, resulting in spatial patterns of nutrient availability not fully captured by existing AEZ-based recommendations. The causal basis for altitude effects lies in its influence on soil genesis: higher elevations tend to experience lower temperatures, higher precipitation, and greater leaching intensity, which collectively deplete base cations (especially Ca and Mg), promote soil acidification, and reduce microbial mineralisation rates. Conversely, lower-elevation alluvial and colluvial deposits accumulate eroded materials and benefit from run-on water, resulting in higher base saturation and more favourable pH. The specific objectives of this study are: (1) to assess major soil chemical and physical properties across AEZs and altitudinal classes in Rwandan marshlands; (2) to quantify the extent to which altitude and AEZ classification explain variability in soil nutrients; and (3) to identify whether altitude or AEZ better accounts for observed nutrient distribution patterns. By explicitly contrasting these two spatial frameworks, the study makes a novel contribution to soil fertility research in Rwanda's marshlands, offering a scientific basis for more precise, site-specific fertiliser recommendations.

MATERIALS AND METHODS

Study Area

This study was carried out across Rwanda's major marshland rice production areas from April 2022 to December 2024, across AEZs (Figure 1) along an altitudinal gradient. AEZs are defined by elevation,

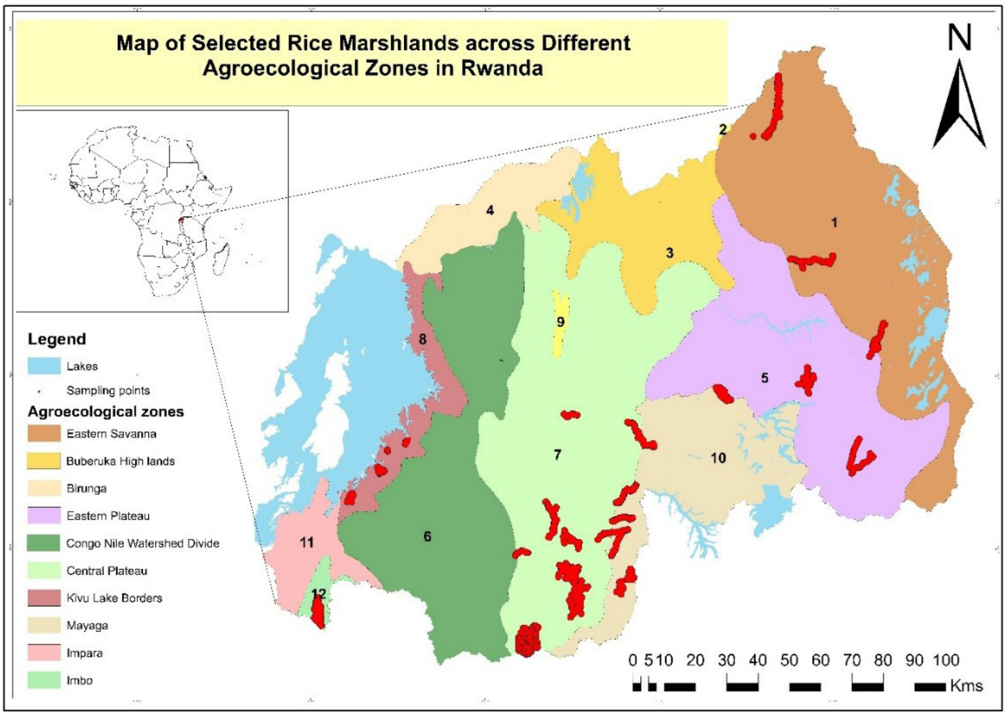

Figure 1. Rwandan agroecological zones and sampling points
Note: Samples were collected in agroecological zones: *Eastern Savanna* (1), *Eastern Plateau* (5), *Congo Nile Watershed Divide* (6), *Central Plateau* (7), *Kivu Lake Borders* (8), *Mayaga* (10), and Imbo (12)
Source: adapted from Verdoodt and Van Ranst (2003)

climate, and soil type, which influence soil formation, water retention, and nutrient availability.

The Low-lying Imbo marshlands have fertile alluvial *Fluvisols* and *Vertisols*, while *Eastern Plateau*, *Mayaga*, and *Central Plateau* contain acidic, nutrient-depleted *Ferralsols* and *Acrisols*. Volcanic zones such as the *Congo Nile Watershed Divide* and Kivu Lake Borders are dominated by *Nitisols* and *Andosols* with higher organic matter contents. *Eastern Savanna* soils are coarse, with low water retention, requiring irrigation (Table 1).

The marshlands selected for this study represent this diversity and span elevations from 944 m a.s.l. in

Table 1. Altitude range, climate, soil types, marshlands, and sample distribution across agroecological zones (AEZs) in Rwandan marshlands.

Agroecological zone	Altitude range (m a.s.l.)	Annual temperature range (°C)	Annual rainfall range (mm / yr)	Dominant Soil Types	Marshland(s)	Number of samples
Imbo	944–1200	22–30	900–1100	Vertisols, Fluvisols, Cambisols; fertile clayey alluvial soils	Bugarama	38
Kivu Lake Borders	1200–1600	17–22	1200–1500	Andosols, Nitisols, Cambisols; well-structured volcanic soils	Kirimbi, Mugonero	22
Eastern Plateau	1200–1700	19–23	900–1200	Ferralsols, Acrisols, Lixisols; acidic, low nutrient soils	Cyaruhogo, Cyunuzi, Rwinkwavu, Muvumba	124
Mayaga	1300–1700	20–25	900–1200	Ferralsols, Acrisols; moderately acidic, low N and P	Mirayi	37
Central Plateau	1400–1900	17–21	1000–1400	Ferralsols, Acrisols, Nitisols; loamy soils with moderate fertility	Cyiri, Mukunguri, Nyarubogo, Mwogo, Rusuli, Rwasave I/II/III, Rugeramigozi	264
Congo Nile Watershed Divide	1500–1800	16–19	1100–1600	Nitisols, Andosols, Cambisols; humic, well-drained volcanic soils	Nyaruguru I/II/III, Kamiranzovu	108
Eastern Savanna	944–1400	20–26	700–1000	Arenosols, Lixisols, Regosols; coarse-textured, low fertility soils	Ntende, Rurambi	53

Source: Verdoodt and Van Ranst (2003); Authors' Compilation (2025).

the Bugarama lowlands to 1,900 m a.s.l. in high-altitude wetlands such as Rugeramigozi and Nyaruguru. Multiple marshlands fall within each AEZ, reflecting the spatial overlap between topography, hydrology, and land-use patterns. For instance, the *Eastern Plateau* includes Cyaruhogo, Cyunuzi, Rwinkwavu, and Muvumba marshlands, while the *Central Plateau* contains Mukunguri, Mwogo, Rusuli, and Rwasave (Table 1).

Soil sampling and analysis

Within each 50-ha sampling unit, **8–10 individual soil samples were collected and combined to form a single composite sample**, ensuring that spatial variability across the area was accurately represented.

Samples were taken from the **0–30 cm depth**, corresponding to the plough layer or active rooting zone of rice in marshland ecosystems, where most nutrient uptake occurs. This depth is therefore critical for assessing **soil fertility, nutrient availability, and potential limitations for crop growth**. The collected samples were air-dried, sieved (2 mm), and stored in labelled bags prior to laboratory analysis.

Soil samples were analysed in the laboratory following the methods of analysis revised by Okalebo et al. (2002) for the following parameters: soil reaction **pH H2O** was determined in a 1:2.5 soil-to-water suspension using a calibrated pH meter. **Soil organic carbon (OC)** was determined by the Walkley-Black wet oxidation method, while total nitrogen (**TN**) was measured using the Kjeldahl digestion method. Available phosphorus (P) was determined using Bray-1 (0.03 M NH_4F + 0.025 M HCl) for acidic soils and Olsen (0.5 M $NaHCO_3$, pH 8.5) for volcanic soils to account for differences in P binding and accurately assess plant P in the study soils (Okalebo et al., 2002). Exchangeable potassium (**K), calcium (Ca), magnesium (Mg), and sodium (Na)** were extracted with 1 M ammonium acetate (pH 7) and measured using flame photometry (K and Na) or atomic absorption spectroscopy (AAS ContrAA 800D, Jena, Germany) (Ca and Mg), with results expressed in cmolc/kg. Cation exchange capacity (CEC) was determined by saturating soils with 1 M ammonium acetate (pH 7), followed by displacement with 1 M KCl and quantification of adsorbed NH_4^+. Soil texture (particle size distribution) was determined using the hydrometer method after dispersion with sodium hexametaphosphate.

Statistical Analysis

This study recognises an imbalance in sampling across sites and AEZs, resulting from differences in marshland size, accessibility, and the spatial distribution of rice schemes. Not all national AEZs were represented; the *Impara*, *Birunga*, and *Buberuka* Highlands AEZs were excluded because rice-based marshland systems are absent in these regions. Consequently, the findings apply only to the AEZs included in the analysis.

Before statistical analysis, all soil chemical and physical variables were standardised to zero mean and unit variance to ensure comparability across parameters with different measurement scales. Data distribution was initially assessed using the Shapiro–Wilk normality test. Because several variables deviated from normality and sample sizes were large and unbalanced across groups, parametric analyses were retained based on the robustness of ANOVA to moderate departures from normality. No further data transformations were applied, and inference focused on variance robustness and effect size interpretation.

Differences in soil properties across AEZs and altitude classes were evaluated using one-way analysis of variance (ANOVA). Homogeneity of variances was assessed using Levene's test. Where significant heteroscedasticity was detected ($p < 0.05$), Welch's ANOVA was applied to confirm the robustness of statistical significance under unequal variances. To maintain analytical coherence and comparability, classical ANOVA results were retained as the basis for effect size estimation, while Welch's ANOVA served solely as a robustness check for inference.

Post-hoc comparisons were conducted using Tukey's Honest Significant Difference (HSD) test at $\alpha = 0.05$ for parameters meeting homogeneity assumptions. Effect sizes were quantified using eta-squared (η^2), calculated as the ratio of between-group to total sum of squares, and interpreted using established benchmarks (Cohen, 1988; Olejnik and Algina, 2003). Multivariate patterns were further explored using PCA on standardised variables. All analyses were performed using R version 4.5.1 (R Core Team, 2025).

RESULTS

Effects of agroecological zones (AEZs) on soil chemical parameters

Because variance heterogeneity was common across soil variables, Welch's ANOVA results are reported alongside classical ANOVA statistics to confirm the robustness of significance, while effect sizes are based on classical ANOVA estimates. The influence of agroecological zones and altitude on soil properties was examined using analysis of variance (ANOVA). ANOVA and Welch's tests confirmed strong AEZ effects ($p < 0.001$) on all parameters, indicating pronounced nutrient differences. Effect sizes (η^2) were highest for

Table 2. ANOVA, Levene's and Welch's tests summary for soil chemical parameters across agroecological zones with effect size and variance components

Parameter	DF (Between; Error)	F-value	*p*-value	η^2	Levene's (F; p)	Welch's F	Welch's p
pH	6; 639	45.37	<0.001	0.33	5.96; <0.001	107.23	<0.001
TN	6; 639	34.13	<0.001	0.27	17.83; <0.001	11.35	<0.001
P	6; 639	5.80	<0.001	0.06	2.11; <0.001	5.1	<0.001
K	6; 639	36.33	<0.001	0.29	8.58; <0.001	32.8	<0.001
OC	6; 639	41.65	<0.001	0.31	12.28; <0.001	7.59	<0.001
Ca	6; 639	88.60	<0.001	0.49	14.40; <0.001	111.09	<0.001
Mg	6; 639	52.69	<0.001	0.37	8.81; <0.001	53.66	<0.001
Na	6; 639	31.48	<0.001	0.26	3.91; <0.001	33.25	<0.001
CEC	6; 639	15.86	<0.001	0.13	3.37; 0.003	30.18	<0.001
Sand	6; 639	49.05	<0.001	0.32	2.03; 0.003	49.13	<0.001
Silt	6; 639	60.50	<0.001	0.36	2.04; 0.006	62.07	<0.001
Clay	6; 639	19.59	<0.001	0.16	9.24; <0.001	47.03	<0.001

Note: Welch's ANOVA was used only to confirm statistical significance under unequal variances, while effect sizes (η^2) were derived exclusively from classical ANOVA to ensure comparability. CEC (Cation exchange capacity)
Source: Authors' Analysis (2025).

Table 3. Mean (±SD) of soil chemical properties across agroecological zones. Based on data collected between April 2022 and December 2024

Agroecological zone	pH	TN (%)	OC (%)	P (mg/kg)	Ca (cmolc/kg)	Mg (cmolc/kg)	K (cmolc/kg)	Na (cmolc/kg)
Eastern Plateau	5.67 ± 0.52ab	0.23 ± 0.12ab	2.50 ± 0.81ab	9.20 ± 9.87ab	10.41 ± 4.28b	2.36 ± 1.41b	0.76 ± 0.68a	0.44 ± 0.37a
Eastern Savanna	5.86 ± 0.47ab	0.20 ± 0.07ab	2.87 ± 1.16ab	6.80 ± 7.27b	11.13 ± 6.48b	3.14 ± 1.39ab	0.37 ± 0.16b	0.24 ± 0.16ab
Imbo	6.32 ± 0.24a	0.15 ± 0.05b	2.35 ± 0.91ab	11.08 ± 9.70a	15.22 ± 3.60a	3.85 ± 1.52a	0.83 ± 0.29a	0.13 ± 0.10bc
Central Plateau	5.46 ± 0.58ab	0.21 ± 0.16ab	2.22 ± 2.28ab	5.63 ± 4.80c	4.88 ± 3.44c	1.37 ± 1.12c	0.25 ± 0.19b	0.18 ± 0.17b
Kivu Lake Borders	5.23 ± 0.19bc	0.30 ± 0.10a	3.00 ± 0.62a	5.81 ± 4.92c	3.51 ± 1.16c	1.14 ± 0.57c	0.20 ± 0.10b	0.09 ± 0.03c
Mayaga	5.11 ± 0.64bc	0.26 ± 0.15ab	2.68 ± 1.45ab	6.51 ± 8.35bc	5.92 ± 3.17c	1.78 ± 1.24c	0.24 ± 0.16b	0.26 ± 0.11ab
Congo Nile Watershed Divide	4.91 ± 0.42c	0.20 ± 0.07ab	2.20 ± 0.84b	9.78 ± 10.85a	2.54 ± 1.75d	0.70 ± 0.62d	0.31 ± 0.22c	0.13 ± 0.09bc
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: Values represent mean ± standard deviation (SD). Within each column, means followed by different lowercase letters are significantly different among agroecological zones based on one-way ANOVA followed by post-hoc multiple comparison tests ($p < 0.05$).
Source: Authors' Analysis (2025)

Ca (0.49), Mg (0.37), OC (0.31), K (0.29), and TN (0.27; Table 2).

Imbo soils showed significantly higher pH (6.32), Ca (15.22 cmolc/kg), and Mg (3.85 cmolc/kg) than soils of the *Congo Nile Watershed Divide* (pH 4.91), *Mayaga* (pH 5.11), and *Kivu Lake Borders* (pH 5.23), which were significantly more acidic and base-poor (Table 3). TN and OC did not differ significantly between most AEZ pairs; *Kivu Lake Borders* had significantly higher TN (0.30%) than Imbo (0.15%), though neither differed statistically from most other zones (Table 3).

Available P differed significantly across AEZs (Table 2). *Imbo* (11.08 mg/kg) and *Congo Nile Watershed Divide* (9.78 mg/kg) had significantly higher P than the *Central Plateau* (5.63 mg/kg) and *Kivu Lake Borders* (5.81 mg/kg); Imbo P was not statistically different from the *Eastern Plateau* (9.20 mg/kg). For rice, P is considered adequate above 8 mg/kg (Dobermann and Fairhurst, 2000); several zones showed P values below this threshold, indicating potential deficiency. Exchangeable K was significantly higher in Imbo and *Eastern Plateau* than in other zones, while Na showed relatively small but significant differences across AEZs (Table 3). These fertility gradients reflect differences in parent material, weathering, hydrology, and land use.

Soil texture differed significantly across AEZs (Table 2). The *Central Plateau*, *Mayaga*, and *Congo Nile Watershed Divide* had significantly higher sand content than the *Eastern Plateau* and *Eastern Savanna*. The Imbo zone exhibited significantly lower clay (13.29%) and a silt-loam textural class, consistent with its Fluvisol and Vertisol soil types formed from recent alluvial parent material. Silt proportions in the Imbo zone (39.16%) were not statistically different from those of the *Eastern*

Plateau (36.25%), *Eastern Savanna* (36.11%), or Kivu Lake Borders (33.55%) at the specified significance level, although they were numerically higher (Table 4). Clay content was broadly similar across most zones (21–29%), with Imbo being the only zone significantly lower.

Clay content was generally moderate across most zones (21–29%), except in the Imbo zone where clay was significantly lower (13.29%), suggesting younger and less weathered soils. The *Eastern Plateau*, *Eastern Savanna*, *Kivu Lake Borders*, *Central Plateau*, *Mayaga*, and *Congo Nile Watershed Divide* all exhibited similar clay proportions, indicating broadly comparable paedogenic development despite climatic and altitudinal differences. CEC was significantly higher in the *Eastern Plateau, Eastern Savanna*, and *Imbo* zones than in *the Central Plateau, Mayaga*, and *Congo Nile Watershed Divide* zones (Table 4), reflecting differences in soil texture and organic matter content.

Effects of altitude on soil chemical parameters

Analysis of variance revealed significant effects of **altitude** on all measured soil parameters. Soil pH, exchangeable Ca, Mg, and K showed particularly strong altitude-related variation, with high F-values and large coefficients of determination ($\eta^2 = 0.45–0.54$), indicating substantial explanatory power. Ca ($F = 119.97$, $\eta^2 = 0.53$) and Mg ($F = 123.83$, $\eta^2 = 0.54$) exhibited the strongest altitude dependence. In contrast, TN, P, OC and CEC showed weaker but still significant relationships ($\eta^2 = 0.09–0.14$). Soil texture also varied with altitude, with silt ($F = 53.11$, $\eta^2 = 0.33$) and sand ($F = 35.63$, $\eta^2 = 0.25$) contributing most to variation among elevation classes (Table 5).

Table 4. Mean (±SD) of soil texture composition and cation exchange capacity (CEC) across agroecological zones. Based on data collected between April 2022 and December 2024

Agroecological zone	Sand (%)	Silt (%)	Clay (%)	CEC (cmolc/kg)	Soil Textural Class
Eastern Plateau	39.89 ± 13.17b	36.25 ± 10.70a	23.86 ± 9.05a	23.14 ± 8.29a	Loam / Clay loam
Eastern Savanna	35.43 ± 11.58b	36.11 ± 11.12a	28.45 ± 9.22a	26.89 ± 24.19a	Clay loam
Imbo	47.55 ± 13.10b	39.16 ± 11.83a	13.29 ± 3.46b	26.68 ± 5.41a	Silt loam
Central Plateau	55.90 ± 11.97a	22.03 ± 9.40b	22.06 ± 6.48a	15.28 ± 12.79b	Sandy loam / Sandy clay loam
Kivu Lake Borders	42.18 ± 7.93b	33.55 ± 7.40a	24.27 ± 5.87a	18.62 ± 6.05ab	Loam
Mayaga	56.96 ± 13.74a	21.43 ± 8.67b	21.61 ± 7.34a	14.35 ± 5.95b	Sandy loam
Congo Nile Watershed Divide	60.06 ± 12.00a	19.14 ± 8.19b	20.55 ± 6.96a	14.85 ± 8.25b	Sandy loam
p-value	<0.001	<0.001	<0.001	<0.001	–

Note: Values represent mean ± standard deviation (SD). Within each column, means followed by different lowercase letters are significantly different among agroecological zones based on one-way ANOVA followed by *post-hoc* multiple comparison tests ($p < 0.05$). N indicates the number of soil samples analysed per agroecological zone. Sand, silt, and clay are expressed as percentages (%).
Source: Authors' Analysis (2025)

Table 5. ANOVA, Levene's and Welch's tests summary for soil chemical parameters across altitudes with effect size and variance components

Parameter	DF (Between; Error)	F-value	p-value	η^2	Levene's (F; p)	Welch's F	Welch's p
pH	6; 639	70.67	<0.001	0.45	9.60; <0.001	149.87	<0.001
TN	6; 639	10.32	<0.001	0.09	2.67; <0.001	12.45	<0.001
P	6; 639	15.45	<0.001	0.13	1.71; <0.001	6.21	<0.001
K	6; 639	96.12	<0.001	0.47	7.86; <0.001	43.3	<0.001
OC	6; 639	11.90	<0.001	0.10	4.18; <0.001	4.73	<0.001
Ca	6; 639	119.97	<0.001	0.53	12.16; <0.001	138.51	<0.001
CEC	6; 639	14.45	<0.001	0.14	3.14; 0.049	48.36	<0.001
Mg	6; 639	123.83	<0.001	0.54	9.91; <0.001	84.49	<0.001
Na	6; 639	58.97	<0.001	0.36	4.29; <0.001	45.48	<0.001
Sand	6; 639	35.63	<0.001	0.25	7.66; <0.001	42.72	<0.001
Silt	6; 639	53.11	<0.001	0.33	11.79; <0.001	71.48	<0.001
Clay	6; 639	19.06	<0.001	0.15	6.67; <0.001	45.87	<0.001

Note: Welch's ANOVA was used only to confirm statistical significance under unequal variances, while effect sizes (η^2) were derived exclusively from classical ANOVA to ensure comparability. CEC (cation exchange capacity)
Source: Authors' Analysis (2025)

Table 6. Mean (±SD) of soil chemical properties across altitude ranges. Based on data collected between April 2022 and December 2024

Altitude (m a.s.l.)	pH	TN	OC	P	Ca	Mg	K	Na
		(%)		(mg/kg)	cmolc/kg			
944– 1044	6.32 ± 0.24a	0.15 ± 0.05c	2.35 ± 0.91ab	11.08 ± 9.70a	15.22 ± 3.60a	3.85 ± 1.52a	0.83 ± 0.29a	0.13 ± 0.10c
1244–1344	5.73 ± 0.54b	0.22 ± 0.10bc	2.67 ± 0.97ab	9.60 ± 9.77a	11.09 ± 5.16b	2.87 ± 1.46b	0.75 ± 0.65a	0.42 ± 0.38a
1345–1444	5.74 ± 0.64b	0.29 ± 0.29a	3.08 ± 4.06a	5.84 ± 5.36b	8.16 ± 4.52c	2.23 ± 1.38c	0.33 ± 0.26b	0.31 ± 0.25b
1445–1544	5.20 ± 0.21c	0.28 ± 0.12ab	2.71 ± 0.89ab	6.46 ± 8.33ab	3.03 ± 1.16d	0.98 ± 0.61d	0.22 ± 0.09bc	0.08 ± 0.04c
1545–1644	5.05 ± 0.36c	0.20 ± 0.16bc	1.97 ± 1.62b	5.72 ± 4.23b	3.15 ± 2.21d	0.76 ± 0.61d	0.21 ± 0.18c	0.13 ± 0.05c
1645–1744	5.18 ± 0.35c	0.18 ± 0.06bc	2.24 ± 0.86ab	5.85 ± 8.49b	3.10 ± 1.68d	0.78 ± 0.47d	0.23 ± 0.13bc	0.09 ± 0.06c
1745–1900	4.92 ± 0.46c	0.21 ± 0.09bc	2.36 ± 0.98ab	9.93 ± 10.21a	3.08 ± 2.04d	0.81 ± 0.67d	0.32 ± 0.20bc	0.15 ± 0.10c
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Note: Values represent mean ± standard deviation (SD). Within each column, means followed by different lowercase letters are significantly different among agroecological zones based on one-way ANOVA followed by *post-hoc* multiple comparison tests ($p < 0.05$). N indicates the number of soil samples analysed per agroecological zone. Sand, silt, and clay are expressed as percentages (%).
Source: Authors' Analysis (2025)

Table 7. Mean (±SD) of soil texture composition and cation exchange capacity (CEC) across altitudinal ranges. Based on data collected between April 2022 and December 2024

Altitude Range (m a.s.l.)	Sand (%)	Silt (%)	Clay (%)	CEC (cmolc/kg)	Soil Textural Class
944–1044	47.55 ± 12.91bc	39.16 ± 11.83a	13.29 ± 3.46d	26.685 ± 5.41a	Silt loam
1244–1344	36.98 ± 12.17d	36.13 ± 10.99a	26.90 ± 9.87a	23.754 ± 7.99ab	Loam / Clay loam
1345–1444	52.68 ± 15.56ab	26.25 ± 12.85b	21.08 ± 6.83c	19.835 ± 19.06b	Sandy loam
1445–1544	44.40 ± 10.96c	33.95 ± 10.24a	21.65 ± 6.87bc	17.64 ± 6.87bc	Loam
1545–1644	55.14 ± 11.78ab	22.31 ± 8.49c	22.55 ± 7.49bc	13.352 ± 9.23c	Sandy loam
1645–1744	56.56 ± 7.99a	18.33 ± 4.71c	25.11 ± 8.51ab	12.592 ± 4.57c	Sandy loam
1745–1900	57.21 ± 14.56a	18.17 ± 5.73c	24.63 ± 8.33ab	14.727 ± 8.14c	Sandy clay loam
p-value	<0.001	<0.001	<0.001	<0.001	–

Note: Values represent mean ± standard deviation (SD). Within each column, means followed by different lowercase letters are significantly different among agroecological zones based on one-way ANOVA followed by post-hoc multiple comparison tests ($p < 0.05$). N indicates the number of soil samples analysed per agroecological zone. Sand, silt, and clay are expressed as percentages (%).
Source: Authors' Analysis (2025)

Soil chemical properties exhibited clear altitudinal patterns. Lower elevations (944–1044 m a.s.l.) had significantly higher pH, Ca, Mg, and Na than higher-elevation bands, reflecting greater base saturation and nutrient availability. Exchangeable K at 944–1044 m a.s.l. (0.83 cmolc/kg) was not significantly different from K at 1244–1344 m a.s.l. (0.75 cmolc/kg; Table 6), indicating that K differentiation among altitude bands was less pronounced at lower elevations. pH decreased significantly above 1345 m a.s.l., reaching minimum levels at 1745–1900 m a.s.l. (pH 4.92). TN peaked significantly at mid-elevations (1345–1544 m a.s.l., mean TN = 0.29% and 0.28%, respectively; Table 6). However, this altitude effect on TN ($\eta^2 = 0.09$) is modest, indicating that altitude accounts for only a limited proportion of total TN variability. The considerable within-altitude-band variation in TN is notable at 1345–1444 m a.s.l. (SD = 0.29) reflects the strong influence of localised management practices, organic matter inputs, and land-use history, consistent with the stronger AEZ effect on TN ($\eta^2 = 0.27$). OC showed a weakly significant altitudinal pattern ($\eta^2 = 0.10$); values were somewhat higher at mid-altitude bands but showed no consistent monotonic trend across the full gradient. P showed a nonlinear distribution, being significantly elevated at the lowest (944–1044 m a.s.l.) and highest (1745–1900 m a.s.l.) altitudes, likely reflecting hydrological retention and land-use effects at both extremes. Ca and Mg declined sharply and significantly above 1445 m a.s.l., while Na remained low across all bands, with only modest significant differences.

Soil texture and CEC vary significantly across altitudes ($p < 0.001$). Lower altitudes (944–1044 m)

Table 8. Comparison of effect sizes (η^2) for soil physicochemical parameters by agroecological zone (AEZ) and altitude

Parameter	AEZ			Altitude		
	Welch's F	Welch's p	η^2	Welch's F	Welch's p	η^2
pH	107.23	<0.001	0.33	149.87	<0.001	0.45
TN	11.35	<0.001	0.27	12.45	<0.001	0.09
P	5.10	<0.001	0.06	6.21	<0.001	0.13
K	32.80	<0.001	0.29	43.3	<0.001	0.47
OC	7.59	<0.001	0.31	4.73	<0.001	0.10
Ca	111.09	<0.001	0.49	138.51	<0.001	0.53
Mg	53.66	<0.001	0.37	84.49	<0.001	0.54
Na	33.25	<0.001	0.26	45.48	<0.001	0.36
Sand	49.13	<0.001	0.32	42.72	<0.001	0.25
Silt	62.07	<0.001	0.36	71.48	<0.001	0.33
Clay	47.03	<0.001	0.16	45.87	<0.001	0.15

Note: Welch's ANOVA was used only to confirm statistical significance under unequal variances, while effect sizes (η^2) were derived exclusively from classical ANOVA to ensure comparability.
Source: Authors' Analysis (2025).

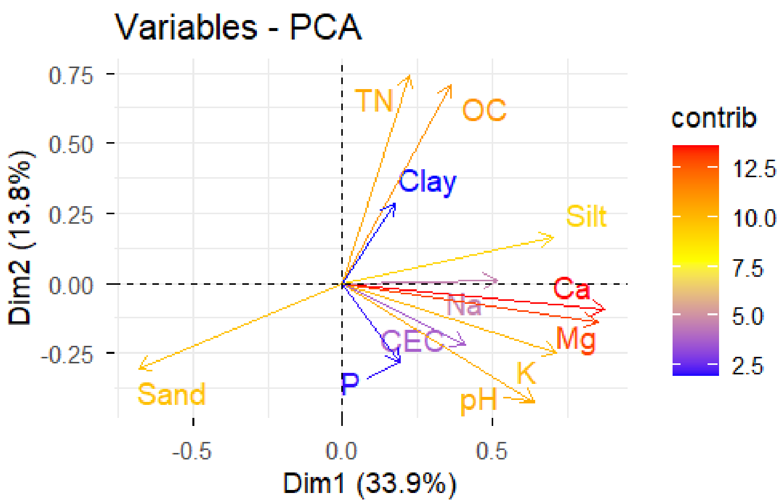

Figure 2. PCA biplot of soil properties in Rwandan marshlands
Note: PC1 represents a soil fertility gradient associated with base cations and pH, while PC2 reflects an organic matter gradient driven by OC, TN, and clay.
Source: Authors' Analysis (2025)

feature silt loam soils with the highest CEC (26.7 cmolc/kg), reflecting strong nutrient-holding capacity. With increasing altitude, sand content rises and silt declines, shifting texture toward sandy and sandy clay loam. Clay peaks at mid-altitudes (1244–1344 m). CEC drops steadily to ~12.6–14.7 cmolc/kg above 1645 m, indicating reduced nutrient retention in coarser, higher-elevation soils. Lower-altitude soils are thus more fertile, with direct implications for fertilizer management and crop productivity (Table 7).

Relative influence of agroecological zones and altitude on soil physicochemical properties: comparison of effect sizes

The comparison of effect sizes (Table 8) shows that both AEZ and altitude significantly influenced soil physicochemical properties, but the strength of their effects varied by parameter. Altitude explained a greater proportion of variation in most variables than AEZ, particularly for Ca ($\eta^2 = 0.53$), Mg ($\eta^2 = 0.54$), pH ($\eta^2 = 0.45$), and K ($\eta^2 = 0.47$), indicating that elevation-driven environmental gradients strongly shape soil nutrient availability. In contrast, AEZ had notable explanatory power for Ca ($\eta^2 = 0.49$), Mg ($\eta^2 = 0.37$), silt ($\eta^2 = 0.36$), and sand ($\eta^2 = 0.32$), reflecting the influence of regional soil-forming factors such as parent material and landscape position. Overall, altitude exerted a stronger control on soil chemistry, while AEZ classification captured broader spatial patterns of soil texture and nutrient distribution. Notably, for OC and TN, AEZs showed greater explanatory power than altitude (OC: $\eta^2 = 0.31$ vs. 0.10; TN: $\eta^2 = 0.27$ vs. 0.09; Table 8), suggesting that regional agroecological factors such as differences in organic matter inputs, land-use history, and parent material may play a stronger role in governing nitrogen and carbon dynamics than elevation alone, though this interpretation requires direct measurement of these factors in future studies.

Principal Component Analysis (PCA) of Soil Chemical and Physical Properties

PCA was performed to identify the key soil properties driving variability across the studied marshlands and to explore how these relate to nutrient availability for rice production. The first two principal components (PC1 and PC2) explained **33.9%** and **13.8%** of the total variance, respectively, accounting together for **47.7%** of the overall variability in soil fertility parameters.

PCA explained 47.7% of total variability, with Dim1 (33.9%) representing a soil fertility gradient and Dim2 (13.8%) reflecting organic matter dynamics. Dim1 separated sandy soils (negative) from silt-rich, base-saturated soils (positive), where Ca, Mg, K, Na, and pH were strongly associated, indicating higher pH in more fertile soils. Dim2 was driven by TN, OC, and clay content, highlighting the role of clay in stabilizing organic matter. Exchangeable bases clustered together, while sand showed an inverse relationship with most nutrients. Overall, variability was controlled by texture-driven fertility and organic matter–nutrient interactions.

DISCUSSION

Soil Fertility Across Agroecological Zones

The Imbo AEZ emerged as the most fertile marshland region in Rwanda, exhibiting higher concentrations of essential nutrients such as Ca, P, K, and Mg, along with a near-neutral pH. Its lower altitude is associated with warmer temperatures that enhance microbial activity, accelerating organic matter decomposition and nutrient release, particularly P and K, which are critical for rice growth (Feng et al., 2024). Exchangeable Ca in this zone exceeded 10 cmolc/kg, well above the sufficiency threshold of 5 cmolc/kg for rice, while available P levels above 8 mg/kg fall within the optimal 8–15 mg/kg range (Dobermann and Fairhurst, 2000).

In contrast, the Congo Nile Watershed Divide showed significantly lower Ca (2.54 cmolc/kg) and Mg (0.70 cmolc/kg), indicating marked nutrient limitations (Dobermann and Fairhurst, 2000); however, P in this zone (9.78 mg/kg) was among the higher values, not statistically different from the Eastern Plateau (Table 3), and was not limiting. Similarly, Mayaga had low Ca and Mg, but P (6.51 mg/kg) remained above deficiency thresholds for most criteria. The Kivu Lake Borders were limited in Mg and K, emphasising the need for localised amendments. The Eastern Plateau and Eastern Savanna zones exhibited intermediate fertility; despite numerical differences, TN and OC in these zones were not statistically different from most other AEZs (Table 3), and P was among the higher values in the Eastern Plateau (9.20 mg/kg). TN values around or below 0.2% mark the lower limit of sufficiency for rice production (Dobermann and Fairhurst, 2000).

Soil fertility variations among AEZs are partly mediated by altitude-related factors, including temperature, precipitation, and microbial activity (Tian et al., 2023; Zhang et al., 2023). Higher-altitude zones, including the Congo Nile Watershed Divide and Central Plateau, showed significantly lower pH, reduced base cation content, and higher sand content, which promotes nutrient leaching, slow organic matter turnover, and reduced microbial diversity (Kumar et al., 2019; Jeyakumar et al., 2020). These findings underscore the importance of localised soil testing and tailored fertilisation strategies to optimise nutrient use, sustain rice yields, and enhance marshland productivity in Rwanda.

Soil Fertility along Altitudinal Gradients

Altitude was a key determinant of soil chemical properties across the studied marshlands. Higher elevations are typically cooler and receive more precipitation, factors that slow decomposition and promote leaching, resulting in the accumulation of OC but lower availability of nutrients such as total nitrogen and phosphorus (Sundqvist et al., 2011). Enhanced leaching of base cations, especially Ca and Mg at higher altitudes contributes to greater soil acidity and a decline in pH (Wang et al., 2017). High-altitude soils exhibited low pH, nutrient deficiencies, and reduced salinity, while lower-altitude soils had higher pH, greater base cation retention, and more favourable chemical fertility. (Malik and Haq, 2022).

Lower elevations exhibited higher exchangeable Ca, Mg, K and CEC, reflecting improved nutrient availability and less acidic conditions. In contrast, high-altitude marshlands showed marked reductions in these cations due to increased leaching and slower microbial activity (Zhang et al., 2023). These altitude-dependent patterns highlight the necessity for differentiated soil management strategies. High-altitude soils may benefit from increased organic amendments, such as manure, to counteract acidity and improve nutrient availability. Fertilisation strategies should also consider altitude-specific deficiencies to optimise crop productivity sustainably (Kumar et al., 2019).

Declining levels of base cations at higher altitudes, particularly Ca and Mg, may negatively affect plant physiological processes because these nutrients play essential roles in membrane stability, chlorophyll synthesis, and enzymatic activation (Marschner, 2012). Such reductions are commonly associated with increased leaching, progressive soil acidification, and slower mineral weathering rates under cool, high-altitude conditions (Kewlani et al., 2021). In contrast, total nitrogen and phosphorus showed weaker altitude-related effect sizes, indicating that their spatial variability is more strongly influenced by management practices and organic matter inputs than by elevation alone. This reinforces the importance of integrating altitude-specific interventions, such as liming acidic soils and providing targeted nutrient amendments, alongside conventional AEZ-based approaches.

Integrating AEZs and Altitude for Soil Fertility Management

Effect size analyses confirmed that both AEZs and altitude meaningfully influence soil chemical and physical properties, though the strength of their effects differs by parameter. Altitude emerged as the dominant driver for key properties such as pH and exchangeable Ca, Mg, and K, exerting a stronger influence than AEZs. This underscores the dominant role of elevation, where intensified leaching, reduced microbial activity, and cooler temperatures limit base cation availability and promote soil acidity (Tan and Wang, 2016; Wang et al., 2017). Accordingly, nutrient management should be tailored to altitude, including practices like liming in acidic highland soils and supplementing base cations in higher-elevation wetlands.

Cation exchange Capacity (CEC) was relatively higher in the *Eastern Plateau*, *Eastern Savanna*, and Imbo agroecological zones; however, altitude exerted a stronger overall control on CEC variability, with values declining progressively at higher elevations due to enhanced leaching of base cations and reduced base saturation under cooler, high-rainfall conditions (Wang et al., 2017).

In contrast, AEZs had greater influence on total nitrogen, sand, and silt and clay. This reflects the importance of regional factors in determining organic matter content and soil texture, including differential organic matter inputs, geomorphology, and land-use history (Feng et al., 2024). For example, lowland marshlands generally exhibited higher OC and nitrogen, whereas more weathered zones displayed lower values. Soil texture also varied more with AEZ than with altitude, suggesting that regional geomorphology predominantly controls sand and silt distribution. Consequently, fertility management for organic matter and nitrogen should rely on AEZ-based strategies, such as zone-specific organic amendments or tailored fertiliser applications.

Some soil properties, including available phosphorus and clay content, exhibited low η^2 values, indicating that neither AEZ nor altitude fully explained their variability. This highlights the importance of localised management practices and field-specific conditions in controlling nutrient availability (Zhang et al., 2023). Hence, phosphorus management strategies should be grounded in field-level soil testing rather than generalised recommendations based solely on AEZ or altitudinal zonation.

The observed clustering of Ca, Mg, and K demonstrates the strong interrelationship among these base cations, reflecting their synergistic role in maintaining soil chemical balance and nutrient availability for rice. This is consistent with previous findings emphasising the importance of these cations in supporting root development, nutrient uptake, and overall growth in flooded rice systems (Dobermann and Fairhurst, 2000).

The integration of AEZ and altitude information offers a comprehensive framework for soil fertility management. Altitude primarily governs the availability of Ca, Mg, Na, and K as well as pH, while AEZs better capture variation in organic carbon, total nitrogen, and soil texture. Combining both factors enables targeted interventions that address variability at both regional and elevational scales, supporting improved productivity and the long-term sustainability of marshland soil fertility.

CONCLUSIONS

Soil fertility in Rwandan marshlands varies significantly among agroecological zones. The Imbo AEZ was the most fertile, while high-altitude zones such as Mayaga and the Congo Nile Watershed Divide exhibited acidic, nutrient-poor soils.

Altitude exerted a stronger influence on soil pH and base cation availability (Ca, Mg, K) than AEZ classification. Effect size analysis confirmed altitude's greater explanatory power for key chemical properties (Ca: $\eta^2 = 0.53$, Mg: $\eta^2 = 0.54$, pH: $\eta^2 = 0.45$), while AEZs better captured patterns in OC ($\eta^2 = 0.31$), TN ($\eta^2 = 0.27$), and soil texture. Integrating altitude, AEZs, and site-specific soil tests provides a more precise basis for fertiliser and lime management decisions.

Policy Implications

Altitude-informed fertiliser recommendations and targeted lime application in acidic high-altitude marshlands can enhance nutrient-use efficiency and rice yields. National fertiliser policy should explicitly incorporate altitude-stratified guidance, moving beyond uniform AEZ-based prescriptions. Strengthening soil testing services and extension support will be critical to translating these findings into practice.

Recommendations and Future Research

High-altitude marshland soils (e.g., pH 4.92 at 1745–1900 m a.s.l.) require liming to raise pH toward the optimal range (~5.5) for rice. Where liming is logistically constrained, organic amendments such as compost or farmyard manure are recommended to improve base saturation and soil biological activity.

Future research should incorporate long-term monitoring, detailed climatic and soil biological variables, crop response trials, interaction effects between altitude and AEZ, and econometric models (including panel data approaches) to explain soil quality as a function of altitude and AEZ. Assessment of the socio-economic feasibility of site-specific nutrient management among smallholder farmers is also needed. Updating AEZ classifications using current land-use and soil data would further strengthen the precision of national fertiliser recommendations.

Study Limitations

Although interaction effects between altitude and AEZs were not explicitly analysed, the extensive spatial coverage of the dataset and effect-size comparisons provide robust evidence of their independent influences. Nevertheless, results may be constrained by the absence of biological indicators, historical land and nutrient management data, and potential spatial autocorrelation.

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REFERENCES

Alivelu K., Subba-Rao A., Sanjay S., Singh K.N., Raju N.S., and Madhuri P. (2006): Prediction of optimal N application rate of rice based on soil test values. European Journal of Agronomy 25: 71–73. https://doi.org/10.1016/j.eja.2005.10.011

Bizoza A.R. (2021): Investigating the effectiveness of land use consolidation: A component of the crop intensification programme in Rwanda. Journal of Rural Studies 87: 213–225. https://doi.org/10.1016/j.jrurstud.2021.09.018

Chuma B.A., Cotter M., Kalisa A., Rajaona A., Senthilkumar K., Stuerz S., Vincent I., Asch F. (2020): Altitude temperature and nitrogen management effects on yield and yield components of contrasting lowland rice cultivars. Journal of Agronomy and Crop Science 206: 456–465. https://doi.org/10.1111/jac.12420

Cohen J. (1988): Statistical power analysis for the behavioral sciences (2nd Ed.). New York, Lawrence Erlbaum Associates Publishers. Retrieved from https://1url.cz/xeqlC

Cyamweshi A.R., Kayumba J., Nabahungu N.L. (2017): Optimising fertiliser use within the context of integrated soil fertility management in Rwanda. In C.S. Wortmann, K. Sones (Eds.): Fertiliser use optimisation in Sub-Saharan Africa (pp. 165–175). CABI. https://doi.org/10.1079/9781786392046.0164

De Vos K., Janssens C., Jacobs L., Campforts B., Boere E., Kozicka M., Havlík P., Folberth C., Balkovič J., Maertens M., Govers G. (2023): Rice availability and stability in Africa under future socio-economic development and climatic change. Nature Food 4: 518–527. https://doi.org/10.1038/s43016-023-00770-5

Diagne A., Alia D.Y., Amovin-Assagba E., Wopereis M.C.S., Saito K., Nekelsev T. (2013): Farmer perception of biophysical constraints to rice production in Sub-Saharan Africa. In M.C.S. Wopereis, D.E. Johnson, N. Ahmadi, E. Tollens (Eds.): Realizing Africa's rice promise (pp. 46–68). CABI. https://doi.org/10.1079/9781845938123.0046

Dobermann, A., Fairhurst, T.H. (2000): Nutrient disorders and nutrient management. Potash and Phosphate Institute, Potash and Phosphate Institute of Canada and International Rice Research Institute, Singapore, Oxford Graphic Printers. Retrieved from http://books.irri.org/9810427425_content.pdf

Feng W.L., Yang J.L., Xu L.G., Zhang G.L. (2024): Spatial variations and driving factors of C N P stoichiometric characteristics of plant and soil in terrestrial ecosystems. Science of the Total Environment 951: 175543. https://doi.org/10.1016/j.scitotenv.2024.175543

Flor R.J., Yuan S., Rizzo G., Agus F., Pame A.R.P., Ouk A., Then R., Keo S., Kumar V., Grassini P. (2024): Accurate measurement of field size is essential for analysis of smallholder survey data. Field Crops Research 311: 109383. https://doi.org/10.1016/j.fcr.2024.109383

Griffiths R.P., Gray A.N., Spies T.A. (2010): Soil properties in old-growth Douglas-Fir forest gaps. Northwest Science: 84 33–45. https://doi.org/10.3955/046.084.0104

He X., Hou E., Liu Y., Wen D. (2016): Altitudinal patterns of plant and soil nutrient concentrations in subtropical China. Scientific Reports, 6: 24261. https://doi.org/10.1038/srep24261

Jeyakumar S.P., Dash B., Singh A.K., Suyal D.C., Soni R. (2020): Nutrient cycling at higher altitudes. In R. Goel, R. Soni, D. Suyal (Eds.) Microbiological advancements for higher altitude agro-ecosystems & Sustainability. Rhizosphere Biology Singapore, Springer. https://doi.org/10.1007/978-981-15-1902-4_15

Kewlani P., Negi V.S., Bhatt I.D., Rawal R.S., Nandi S.K. (2021): Soil nutrient concentration along altitudinal gradients in the Himalaya. Scandinavian Journal of Forest Research 36: 98–104. https://doi.org/10.1080/02827581.2020.1871065

Kumar S., Suyal D.C., Yadav A., Shouche Y., Goel R. (2019): Microbial diversity and soil characteristics at high altitude. PLoS ONE 14: e0213844. https://doi.org/10.1371/journal.pone.0213844

Lal R. (2020): Regenerative agriculture for food and climate. Journal of Soil and Water Conservation 75: 123A–124A. https://doi.org/10.2489/jswc.2020.0620A

Malik Z.A., Haq S.M. (2022): Soil chemical properties variation with altitude. Journal of Forest and Environmental Science 38: 21–37. https://doi.org/10.7747/JFES.2022.38.1.21

Marschner P. (2012): Marschner's mineral nutrition of higher plants (3rd Ed.). London, Elsevier Ltd. Retrieved from https://1url.cz/eeqlV

Nabahungu N.L., Visser S.M. (2011): Contribution of wetland agriculture to farmers' livelihood in Rwanda. Ecological Economics 71: 4–12. https://doi.org/10.1016/j.ecolecon.2011.07.028

Nahayo A., Omondi M.O., Zhang X., Li L., Pan G., Joseph S. (2017): Factors influencing farmers' participation in Rwanda's crop intensification program. Journal of Integrative Agriculture 16: 1406–1416. https://doi.org/10.1016/S2095-3119(16)61555-1

Okalebo J.R., Gathua K.W., Woomer P.L. (2002): Laboratory methods of soil and plant analysis (2nd Ed.). Nairobi, Sacred Africa. Retrieved from https://1url.cz/1eqlk

Olejnik S., Algina J. (2003): Generalized eta and omega squared statistics. Psychological Methods 8: 434–447. https://doi.org/10.1037/1082-989X.8.4.434

R Core Team (2025): R: A language and environment for statistical computing. Retrieved from https://www.r-project.org

Senthilkumar K., Tesha B.J., Rodenburg J., Bakker R.R. (2020): On-farm performance of improved rice varieties. Field Crops Research 246: 107693. https://doi.org/10.1016/j.fcr.2019.107693

Shrestha S., Asch F., Dingkuhn M., Becker M. (2011): Cropping calendar options for rice systems. Field Crops Research 121: 158–167. https://doi.org/10.1016/j.fcr.2010.12.006

Spielman D.J., Mugabo S., Rosenbach G., Ndikumana S., Benimana G., Ingabire C. (2025): Fertiliser policy reforms in Rwanda. Food Policy 133: 102823. https://doi.org/10.1016/j.foodpol.2025.102823

Sundqvist M.K., Giesler R., Wardle D.A. (2011): Plant traits and decomposition across elevation. PLoS ONE 6: e27056. https://doi.org/10.1371/journal.pone.0027056

Tan Q., Wang G. (2016): Decoupling of nutrient element cycles in soil and plants across an altitude gradient. Scientific Reports 6: 34875. https://doi.org/10.1038/srep34875

Teron G., Bordoloi R., Paul A., Singha L.B., Tripathi O.P. (2026): Effect of altitude on soil properties. Geology, Ecology, and Landscapes 10: 1–19. https://doi.org/10.1080/24749508.2024.2430040

Tian Q., Jiang Q., Huang L., Li D., Lin Q., Tang Z., Liu F. (2023): Soil bacterial communities along elevation gradient. Microbial Ecology 85: 628–641. https://doi.org/10.1007/s00248-021-01949-8

Vanlauwe B., Coyne D., Gockowski J., Hauser S., Huising J., Masso C., Van Asten P. (2015): Sustainable intensification in Africa. Current Opinion in Environmental Sustainability 8: 15–22. https://doi.org/10.1016/j.cosust.2014.07.002

Verdoodt A., Van Ranst E. (2003): Land evaluation for agricultural production in the tropics. Ghent, Ghent University Laboratory of Soil Science. Retrieved from http://hdl.handle.net/1854/LU-212638

Wang T., Kang F., Cheng X., Han H., Bai Y., Ma J. (2017): Spatial variability of organic carbon and total nitrogen in the soils of a subalpine forested catchment at Mt. Taiyue, China. Catena 155: 41–52. https://doi.org/10.1016/j.catena.2017.03.004

World Bank (2025): Rwanda economic update: Modernizing agriculture to accelerate structural transformation. Rwanda Economic Update. Washington, World Bank Group. Retrieved from https://1url.cz/1eqlD

Yuan S., Saito K., van Oort P.A., van Ittersum M.K., Peng S., Grassini P. (2024): Intensifying rice production in Africa. Nature Communications 15: 835. https://doi.org/10.1038/s41467-024-44950-8

Zhang T., Song B., Han G., Zhao H., Hu Q., Zhao Y., Liu H. (2023): Effects of wetland reclamation on soil nutrients. Land Degradation and Development 34: 3340–3349. https://doi.org/10.1002/ldr.4687