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EFFECTS OF GRADIENT, FERTILIZER APPLICATION AND PLANTING TIME ON THE GROWTH AND YIELD OF ROUND POTATOES (*Solanum tuberosum L.*) IN ANDOSOLS OF UPOROTO HIGHLANDS, SOUTHERN TANZANIA

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ABSTRACT

This study investigated the effects of topographical gradient, fertilizer application and planting time, which is days after planting, on the growth and yield of round potatoes (*Solanum tuberosum L.*) in the Uporoto Highlands of southern Tanzania. The objective was to generate site-specific agronomic evidence to enhance the productivity and profitability of smallholder potato cultivation, which is often constrained by varied terrain and declining soil fertility. Understanding the interactions between slope position, nutrient management, and the interval from days after planting is critical for optimizing yield and promoting sustainable production in highland agroecosystems. A field experiment was conducted on two different gradients (upper and lower) using a randomized complete block design (RCBD) with three replications. Three fertilizer treatments were applied: a control (no fertilizer), a farmer-based practice (TSP+), and an innovative fertilizer regime (TSP++), formulated based on soil nutrient analysis and administered at both planting and early vegetative stages. Four industrial fertilizers - Triple Super Phosphate (TSP), Muriate of Potash (MOP), Nitrobor, and Urea - were applied in defined ratios, and the '*Obama*' cultivar was used as the test crop. Results indicated that both gradient and fertilizer treatments significantly influenced most growth and yield parameters. The lower gradient consistently exhibited superior vegetative growth and higher tuber yields, which can be attributed to greater soil moisture retention and improved nutrient availability. The TSP++ treatment produced the highest total tuber yield (50.9 ± 3.7 t ha^{-1}), marketable yield (46.3 ± 3.1 tons/ha), and biological yield (54.6 ± 4.2 tons/ha). Gradient, fertilizer and days after planting significantly affected most growth variables, whereas stem number was predominantly influenced by their three-way interaction ($p = 0.031$). The study emphasizes the importance of gradient-sensitive and soil-informed fertilizer management for optimizing potato productivity in highland environments. It is recommended that smallholder farmers adopt site-specific fertilizer strategies guided by soil analysis and implement moisture conservation practices, particularly on upper slopes, to enhance yield stability, improve resource-use efficiency, and increase overall profitability in Tanzania's highlands and comparable agroecological regions.

Key words: Round potatoes yield, soil fertility, upper and lower gradients

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INTRODUCTION

Round potato (*Solanum tuberosum L.)* is the fourth most cultivated food crop in the world, followed by wheat (*Triticum aestivum*), rice (*Oryza sativa*) and maize (*Zea mays*) [1]. It is a crucial crop and food source for enhancing food security and income generation, particularly among small-scale farmers, and supports approximately 800 million people worldwide [2, 3]. The crop is characterised by a short growing cycle (about 3 to 4 months) and produces high yields of up to 30 tons/ha under ideal conditions [4, 5, 6]. Population expansion, changing dietary habits, and an expanding food processing sector contribute to the rise in global demand for potatoes [7, 8].

Potatoes have become more critical in sub-Saharan Africa (SSA) because of their substantial capacity for enhancing food security and income generation [9]. However, potato production in SSA continues to face various challenges, including low soil fertility, poor agronomic practices, pest and disease pressures and fluctuating climatic conditions [10]. In East Africa, notably Tanzania and Kenya, these challenges contribute to average yields that are consistently below regional potential, emphasising the need for location-specific agronomic interventions. Although the demand for potatoes is rising rapidly, their production in the SSA remains significantly below their potential, averaging 6-10 tons/ha, compared to 25-35 tons/ha under ideal conditions. In Tanzania, the average yield is reported at 5.9 tons/ha, while in Kenya and Uganda, the yields are approximately 9.1 and 5.8 tons/ha, respectively. These figures remain far below the global potential, underscoring the regional productivity gap [4, 6, 11]. Similar challenges face smallholder farmers in East Africa, where potato production is essential for food security and income generation [6, 11].

Eastern Africa, specifically Kenya, Uganda, and Tanzania, is a major producer of potatoes in SSA, contributing over 71% of the region's total production [4,12]. In response to the challenge of low yields, the Tanzanian government has implemented several initiatives to encourage the use of fertilizers, including financial aid to lower the price of agricultural inputs [6, 13]. Despite these efforts, a lack of understanding of optimal fertilizer application techniques based on the unique requirements of soils continues to limit potato yields [6]. Many potato-producing highlands, such as the Uporoto Highlands, lack a thorough understanding of the impacts of topographical gradients and how they interact with fertilizer applications.

The Uporoto Highlands, located in southern Tanzania, are among the country's central potato-producing areas [6, 14]. The region lies at an altitude of 1,500 - 2,500 m above sea level and experiences a unimodal rainfall pattern, with annual precipitation ranging from 850 to 1,200 mm, concentrated between November to

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April [15]. Mean temperatures range between 15°C and 20°C, providing a favourable environment for potato cultivation [16]. The soils in the highlands are predominantly fertile volcanic soils with a pH of 5.5-6.0, although fertility varies with slope position and land use [16, 17]. Despite climatic, edaphic and topographical conditions make the Uporoto Highlands highly suitable for potato production, smallholder farmers still face challenges of declining soil fertility and limited access to effective fertilizer management techniques [6].

Topographical gradients have a significant influence on soil physical and chemical properties, water retention, and nutrient availability, thereby affecting crop growth and yield patterns. Previous studies in East Africa have shown that lower slopes often yield higher yields due to higher moisture availability and reduced soil erosion. In contrast, upper slopes are prone to nutrient leaching and poor soil structure [18]. However, what remains poorly understood is how these gradient-related differences interact with fertilizer application and crop development stages.

This study is novel because it quantifies the combined effects of slope position, fertilizer management, and days after planting (DaP) on potato growth and yield in the Uporoto Highlands, through repeated observations of crop growth over time. Such an integrated approach provides site-specific evidence that has not been previously reported in this region. While fertilizer applications can enhance crop growth and yield, their efficacy is influenced by topographical position, soil heterogeneity, and the temporal development of the crop. Understanding how fertilizer performance varies across slope gradients and DaP is crucial for optimising nutrient utilization and improving potato productivity under field conditions. Despite previous studies on potato farming, there is limited empirical evidence on the combined effects of slope gradients, fertilizer treatments and DaP on potato growth, yield and quality. This knowledge gap restricts the development of site-specific recommendations and hinders efforts to close the productivity gap in smallholder farming systems.

Building upon the identified knowledge gaps, the present study evaluated the combined influence of topographical gradients, different fertilizer treatment levels, and the DaP on potato growth and yield parameters in the Uporoto Highlands of Tanzania. In this study, DaP was considered as a repeated observational variable, with crop growth and yield measured at multiple time points, rather than as a separate experimental factor. The study explicitly investigated how variations in slope position affect key vegetative attributes (plant height, canopy width, and leaf length) and yield components (total biomass, total tuber yield, and marketable tuber yield), while also assessing the interactions between fertilizer management practices and growth duration across diverse topographical settings. Based on the identified

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knowledge gaps, the study formulated three hypotheses: Hypothesis 1 (H1) lower slope gradients will produce significantly higher growth and yield parameters compared to upper slopes, Hypothesis 2 (H2) the innovative fertilizer application treatment (TSP++) will outperform the farmer's practice (TSP+) and control in improving growth and yield and Hypothesis 3 (H3) DaP will influence crop growth dynamics over time, and that a three-way interaction between slope, fertilizer, and DaP may affect structural traits such as stem number. Therefore, the study aimed to test the three hypotheses stated above. By testing these hypotheses, the study aimed to generate empirical evidence on how topography, soil fertility management and crop growth stages collectively influence potato productivity. Findings from this study are expected to support evidence-based recommendations, improve potato productivity, and promote sustainable farming practices that enhance the livelihoods of smallholder potato farmers in the Uporoto Highlands and comparable highland agro-ecologies across sub-Saharan Africa.

MATERIALS AND METHODS

Details of the study areas and criteria for selection

The experiment was conducted in the Mbeya region of Tanzania's Southern Highlands, specifically along two selected elevation gradients in the Uporoto Highlands of Rungwe district. Each gradient was represented by one village. The lower gradient was represented by Ndaga village, located in Ndanto ward (latitude -9.068180 S, longitude 33.577710 E) at an elevation of 1930 m above sea level. The upper gradient was represented by Isyonje village, located in Isongole ward (latitude -9.004960 S, longitude 33.626620 E) at an elevation of 2272 m above sea level. These elevations were used to define the study gradients. Additional details, including a map of the study area, are available from Kassian *et al.* [6]. The comparative environment provided by the sites allowed for the study of the effects of fertilizer application, gradient variation, and DaP on the growth and yields of round potato. The sites were selected due to their differences in soil fertility and gradient characteristics. The Uporoto Highlands receive 1000 - 2000 mm of annual rainfall, with temperatures fluctuating between 5°C and 18°C [6, 14]. The predominant Andosols, formed from volcanic deposits, are rich in minerals, but their fertility has diminished over time due to nutrient leaching [17, 18].

Experimental Design

The fertilizer trials were conducted using a Randomized Complete Block Design (RCBD) with three replications. The design followed a 2 × 3 factorial arrangement, which included two slope positions (upper and lower) and three (3) fertilizer treatments. Blocks were considered random effects. The fertilizer treatments included: (1) control (no fertilizer), (2) a farmer's practice based on conventional fertilizer application methods commonly used by local farmers, and (3) innovative fertilizer application derived from soil nutrient analysis, applied in two stages (at planting and early growth) as part of a single treatment protocol, not as a separate factor applied at both planting and early growth stages. Each block contained all three treatments, with three replications, making a total of nine plots per gradient (18 plots in total). The factor "DaP" mentioned elsewhere refers to repeated measurements at different DaP rather than a treatment factor. The design accounted for spatial variation and allowed for the random assignment of treatments.

Two experimental fields were established in the Uporoto highlands, one on the upper gradient and another on the lower gradient. The sites were selected to ensure comparable representation of soil fertility variation between gradients, taking into account their previous cropping history and soil type (Andosols).

Field Preparation

Field preparation was conducted using hand hoes. The field was cleared and ploughed on 26 March 2024, about three weeks before planting, allowing sufficient time for the decomposition of maize stalks and grasses incorporated into the soil, enhancing fertility. Maize, the preceding rotational crop, was among the key criteria in selecting experimental fields for the fertilization trial due to its contribution to soil organic matter. Potato (*Solanum tuberosum* L.) was planted on 19th April 2024, marking the beginning of the experimental period. All subsequent fertilizer applications, growth measurements, and yield assessments were recorded relative to this planting date (days after planting - DaP). Figure 1 shows the preparation of experimental plots in the upper gradient with assistance from field technicians.

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Figure 1: Preparation of experimental plots for fertilizer trials in potato production, with assistance from field technicians

Seed Sowing

One seed tuber of round potato weighing between 35 - 50 g were selected and planted in each hole at a depth of 10 cm in well-prepared Andosol soils in the selected gradients. Figure 2 (a and b) illustrates the process of seed sorting and planting, respectively.

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Figure 2(a): Selection of seed tubers with field assistants before planting in the study area

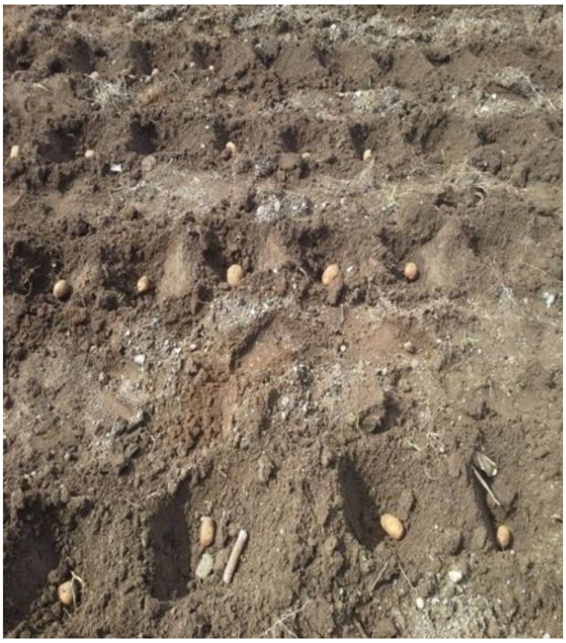

Figure 2(b): Planted potato tubers in experimental plots

Each experimental plot consisted of eight (8) rows, each containing nine (9) plants, giving a total of seventy-two (72) plants per 20 m² plot. The inter-row spacing was seventy-five centimetres (75 cm), while the intra-row spacing was twenty-five centimetres (25 cm). Figure 3 (a and b) illustrates hole preparation and plant rows, respectively.

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Figure 3: (a) Preparation of the holes by considering the recommended spacing

Figure 3: (b) Round potato plants in rows

Fertilizer Application

Fertilizers were applied based on the experimental design using a blend of four industrial fertilizers: Triple Super Phosphate (TSP), Muriate of Potash (MOP), Nitrobor and urea. In the Farmer's Practice Treatment (denoted as TSP+), fertilizers were applied once at planting in the proportions N:P: K: Ca = 62:38:17:15 kg/ha, using TSP, MOP, Nitrobor and urea. No additional fertilizers were applied afterwards. The Innovative Fertilizer Application (denoted as TSP++) involved split fertilizer applications at planting and 30 DaP, at rates of N:P: K: Ca = 100:80:90:50 kg/ha, as recommended by the soil analysis. The overall fertilizer rate in this treatment exceeded the farmer's standard practice. Control plots 0:0:0, meaning that no fertilizer was applied.

Three fertilization regimes were applied to evaluate the effects on potato growth and yield:

i) Control - no fertilizer applied.
ii) Farmer's practice (represented by TSP+) is a combination of TSP (83.5 kg ha^{-1}, supplying 38 kg P ha^{-1}), MOP (28.3 kg ha^{-1}, 17 kg K ha^{-1}), UREA (128.16 kg ha^{-1}, 62 kg N ha^{-1}), and Nitrobor (57.91 kg ha^{-1}, supplying 15 kg Ca ha^{-1}, ~0.17 kg B ha^{-1}, and 8.9 kg N ha^{-1}), applied once at planting.
iii) Innovative practice (represented by TSP++) - TSP (175.8 kg ha^{-1}, 80 kg P ha^{-1}), MOP (147.54 kg ha^{-1}, 90 kg K ha^{1}), and Nitrobor (269.73 kg ha^{-1}, 50 kg Ca ha^{-1},

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~0.8 kg B ha⁻¹, 41.5 kg N ha⁻¹) applied at planting, followed by top-dressing with UREA (127.09 kg ha⁻¹, 100 kg N ha⁻¹) at 30 days after planting. The split application at 30 DaP was adopted to improve nutrient uptake efficiency and reduce leaching losses on sloping fields [20, 21]. Nutrient rates for innovative fertilization were based on soil analysis and the recommended nutrient requirements for optimum potato tuber yield (N: 80 - 120 kg ha⁻¹, P: 50 - 120 kg ha⁻¹, K: 80 - 120 kg ha⁻¹, Ca: 56 kg ha⁻¹).

Growth and Yield Measurements

Growth Parameters: Data were collected at six distinct growth stages (28, 42, 56, 70, 84, and 98 DaP). The following parameters were recorded: leaf length and width, plant height and width (in cm), and the number of leaves and stems. The same ten (10) plants per plot were tagged and monitored throughout the season to allow repeated measurements, while an additional five (5) plants were destructively sampled at each stage.

Yield Parameters: The measures included total plant biomass, the number of harvested plants, tuber weight and the number of tubers.

Destructive Sampling: Five (4) plants were removed from each treatment plot at each growth measurement stage to conduct a detailed investigation of root growth and quantify plant biomass. Figure 4 illustrates uprooted round potato plants.

Figure 4: Potato plants uprooted for root investigation in different growth stages

Statistical Analysis

GenStat 15th Edition software was used to analyze the growth and yield parameters. Since the design was factorial (2 slopes × 3 fertilizer treatments) within RCBD, growth and yield parameters were analysed using a factorial analysis of variance (ANOVA) with block as a random effect. The experiment involved two main factors which included: (i) slope gradient (Factor A - 2 levels: upper gradient representing areas which are relatively higher elevation with lower soil moisture retention and higher erosion risk and lower gradients representing gentler slope with relatively higher soil fertility and moisture retention) and (ii) Fertilizer treatment (Factor B - 3 levels): control - no fertilizer applied, farmer's practice - TSP+ applied once at planting following local farmer practice, and innovative fertilizer application - TSP++ derived from soil analysis and applied in two splits (at planting and 30 days after planting**.** For growth traits, 10 plants per plot were measured repeatedly over multiple days after planting (DaP), while five plants per plot were destructively sampled at each time point. The repeated measurements on the same plants were analyzed using repeated measures ANOVA (RM-ANOVA) with plot nested within block as a random effect and time as the repeated factor, which accounts for correlation among observations. Destructed sampled plants were analyzed independently at each time point using standard two-way ANOVA. Treatment means were compared using Tukey's Honestly Significance Difference (HSD) at $p \leq 0.05$. Where assumptions of independence were not fully met, the results were interpreted with care.

RESULTS AND DISCUSSION

Effects of Gradients on Potato Growth Variables

The plant growth parameters varied significantly ($p < 0.05$) between the two gradient zones. In particular, the number of leaves per plant, plant height and plant breadth were all greater in the lower gradient than in the upper gradient. Potato plants in the lower gradient exhibited significantly higher growth characteristics ($p < 0.05$) compared to those in the upper gradient. For example, the average leaf length was 31.6 cm in the lower gradient, compared to 20.5 cm in the upper; plant height also reached 66.1 cm in the lower gradient, compared to 43.2 cm in the upper. Similarly, the plant width in the lower gradient (69.4 cm) was considerably greater than in the upper gradient (52.5 cm). Compared with the upper gradient, the lower gradient also had a higher average number of leaves per plant, at 72 (Table 1). This discrepancy can be attributed to the increased water retention, nutrient accumulation, and soil fertility that are present at lower elevations. The microenvironment for root development and nutrient retention is more suitable in lower gradients due to the accumulation of organic matter and finer soil particles, resulting in more vigorous vegetative growth. Conversely, erosion and nutrients washed away by runoff are more prevalent on upper gradients, which can limit plant growth and development. These observations are consistent with those reported by Merga *et al.* [19] and Masoud *et al.* [23], who found that gradient elevation and soil type significantly influence nutrient dynamics and crop performance. The results highlight the hypothesis that topographic variation influences soil-water-plant interactions, with lower elevations providing microclimatic and edaphic conditions that improve crop productivity. This indicates that targeted agronomic practices, including soil

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conservation on upper gradients and improved nutrient management, may reduce yield differences across elevation zones.

The Influence of Fertilizer Treatments on Potato Growth Variables

The application of mixed fertilizer treatments based on the innovative method (TSP++) resulted in substantially higher values ($p < 0.05$ for leaves, leaf length and plant height, Table 1) across nearly all growth parameters, including the number of leaves (74), leaf length (30.3 cm), and plant height (65.4 cm) (Table 1). In contrast, the farmer's practice (TSP+) and the control treatments did not differ significantly from each other for some traits ($p > 0.05$), and both underperformed. The balanced formulation and enhanced nutrient availability in the TSP++ treatment more effectively supported physiological processes essential for vegetative growth, including cell division, chlorophyll synthesis, and leaf expansion. The incorporation of secondary and micronutrients in TSP++ likely contributed significantly to enhanced biomass accumulation, in contrast to conventional practices that may have been deficient in essential elements. This emphasises the benefits of tailored nutrient management strategies, supported by findings from Stark et al. [24] and Zaag [20], who advocate site-specific nutrient application to maximise plant growth. These findings are consistent with the principles of integrated soil fertility management, which optimize nutrient interactions through context-specific formulations [25]. Interestingly, stem count did not differ significantly across treatments ($p > 0.05$), suggesting that the gradient and fertilizer application may have less influence on this structural trait. This may result from genetic control of stem number in potatoes, which is more closely associated with tuber size and physiological maturity than with external soil nutrient inputs.

Effects of Days After Planting (DaP) on Potato Growth Variables

Plant height increased from 20.6 cm at 28 DaP to 72.1 cm at 98 DaP (Table 1), showing statistically significant growth over time ($p < 0.05$). Leaf length and leaf number also increased significantly ($p < 0.05$), whereas stem count showed a trend toward change ($0.05 \leq p = 0.057 < 0.10$), indicating limited sensitivity to temporal variation. The observed increase in vegetative parameters aligns with the sigmoid growth curve of potato plants, which includes an initial interval phase of the DaP, succeeded by a period of rapid vegetative growth, as explained by Thangasamy [26], and Artlip *et al.* [27]. The observed growth pattern may be a result of increased cell elongation and division during the vegetative stage, influenced by adequate photosynthetic activity, water and nutrient availability. These findings align with standard potato growth patterns and emphasise the importance of monitoring crop performance across growth stages. As discussed by Gaur *et al.* [28], early-stage vigour often sets the foundation for ultimate tuber yield, making early nutrient availability crucial. The minimal variation in stem count suggests that this trait may be genetically fixed early in development, exhibiting limited sensitivity to environmental conditions throughout the growing season. This indicates that vegetative characteristics, including height and leaf area, exhibit substantial changes and responses to management practices, whereas structural features, such as stem number, demonstrate more stability. These observations highlight the importance of stage-specific agronomic interventions, such as providing a sufficient nutrient supply during the early vegetative phase, to enhance canopy development, which is directly linked to tuber bulking capacity later in the season.

Interaction Effects of Fertilizer, Gradient and Days after Planting

The significance of taking a variety of parameters into account to maximize potato output was further supported by the two-way and three-way interactions between the gradients, fertilizer treatments and DaP. A significant three-way interaction among gradient, fertilizer treatment, and DaP was observed for stem number ($p = 0.031$; Table 3), indicating that stem development depends on slope, nutrient availability, and growth stage. Plant height showed a trend in response to the fertilizer × DaP interaction ($0.05 \leq p = 0.052 < 0.10$), suggesting that prolonged vegetative growth may enhance the effect of improved fertilizer. Specific characteristics may affect plant development overall, but their combined influence may differ depending on particular conditions, such as the DaP, as indicated by the notable interaction observed in the number of stems per plant. Stem initiation and branching behaviour are influenced by external stimuli and internal hormonal balance, like auxin-cytokinin balance, which may be adjusted by nutrient availability and growth stage [29]. These combined factors emphasise the complexity of crop development, supporting prior research findings by Digrado *et al.* [30], who observed that above-ground biomass traits can exhibit variable sensitivity to environmental and management factors. This may indicate differential vegetative growth responses to diverse nutrient inputs, with prolonged growth stages enhancing the impact of improved fertilizer application techniques.

Leaf length, leaf width, plant width, leaf count per plant, and stem count per plant did not exhibit any significant interaction effects ($p > 0.05$; Table 4). This finding emphasizes the importance of monitoring crop progress over time and modifying management strategies as necessary. This result is consistent with other studies on the temporal dynamics of crop development, such as the study by Gaur *et al.* [23], which found that fertilizer and environmental factors have different impacts on plant growth. These interaction effects indicate the necessity for integrative and adaptive agronomic planning, enabling the application of site-specific and stage-specific strategies to optimise both structural and functional characteristics of the crop.

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Impact of Gradients and Fertilizer Treatments on Potato Yield

The results in Table 5 indicate that the gradient had a pronounced effect on yield. All components of yield were significantly affected by the gradient ($p < 0.05$). Total tuber yield (TTY) ranged from 13.37 to 53.55 tons/ha across slope × treatment combinations. The CV% for all variables ranged from 3.2 to 15.3%, indicating acceptable experimental precision for field trials. The lower slope consistently produced higher yields than the upper slope, with the highest TTY observed under the same treatment, ranging from 13.02 to 48.96 tons/ha, where the lower slope outperformed the upper slope in all treatments. This highlights the agronomic importance of slope-based soil fertility, which is a micro-topographic position, and fertilizer management strongly influences potato productivity, and the lower slope with TSP++ fertilizer is the most favorable combination for maximizing tuber yield. This corroborates the findings by Gwambene [31] and Xing *et al.* [32], who demonstrated that topographical position influences water and nutrient dynamics, directly impacting crop productivity. Lower-gradient areas generally accumulate greater amounts of organic matter, retain moisture for extended periods, and exhibit reduced erosion losses, all of which promote root development and tuber expansion.

Notably, the absolute control at the lower gradient yielded more marketable tubers (48.96 tons/ha; $p = 0.043$) than fertilised treatments at the upper gradient. This reflects the favourable physical and fertility conditions of the lower-gradient soils, rather than the ineffectiveness of fertilizer. Within each gradient, fertilizer application still enhanced yield relative to the control, highlighting the importance of site-specific nutrient management. Thus, while fertilizer improves yield, the response is constrained by slope-related factors such as reduced moisture retention and higher erosion in upper gradients. This may result from the natural fertility and favourable physical properties of the low-gradient soils overcoming the deficiency of externally supplied nutrients. Conversely, in upper-gradient topographical settings with reduced fertility, fertilizer alone may be inadequate to mitigate physical soil limitations such as decreased moisture retention, increased runoff, shallow soils, and higher erosion rates. These results reinforce that the effectiveness of fertilizer is dependent upon the specific site conditions, and innovative fertilizer application practices perform best when aligned with favourable site conditions, as suggested by Arsanov *et al.* [33]. This finding supports the principle of integrated site soil input management, emphasising the necessity of considering topography together with nutrient interventions [25]. Farmers operating in such areas should prioritise nutrient-responsive strategies to enhance yield.

Slope position and fertilizer management had a significant impact on potato growth and yield. The lower slope with TSP++ fertilizer consistently produced the highest total and marketable tuber yields, suggesting that micro-topographic position should be considered when applying fertilizers to optimize productivity. The study confirms that slope gradients strongly influence soil fertility, water availability and potato productivity, with lower-gradient plots exhibiting higher yields due to improved moisture retention and enhanced nutrient accumulation. These results align with findings from Ethiopia and Kenya, where downslope positions benefit from reduced nutrient leaching and erosion, highlighting the importance of micro-topography in highland farming systems [31, 32, 33, 34].

Fertilizer management also played a critical role. The innovative TSP++ treatment, which combined higher rates with split applications, outperformed both farmers' practice and the control, supporting previous studies that show stage-specific nutrient supply enhances potato growth and yield [13, 35, 36]. Days after planting (DaP) significantly influenced vegetative growth, with rapid expansion between 42 and 84 DaP, indicating that early-stage interventions are crucial for setting the foundation for tuber bulking. The observed three-way interaction (gradient × fertilizer × DaP) for stem number suggests complex genotype -environment - nutrient interactions affecting structural development [25, 37]. Fertilizer management also played a critical role. The innovative fertilizer application techniques (TSP++ treatment), which combined higher rates with split applications, outperformed both farmers' practice and the control, supporting previous studies that show stage-specific nutrient supply enhances potato growth and yield [13, 35, 36]. Days after planting (DaP) significantly influenced vegetative growth, with rapid expansion between 42 and 84 DaP, indicating that early-stage interventions are crucial for setting the foundation for tuber bulking. The observed three-way interaction (gradient x fertilizer x DaP) for stem number suggests complex genotype -environment - nutrient interactions affecting structural development [25, 37].

Practical Implications for Uporoto Highlands on Potato Production and in Other Similar Agro-ecological Zones

This study's findings have significant implications for sustainable potato production in the Uporoto Highlands and similar agro-ecological regions. The combination of innovative fertilizer application techniques and topography-specific soil management significantly improved plant growth and tuber yield. The use of fertilizer treatments, as demonstrated by the TSP++ formulation derived from soil analysis, showed better effectiveness compared to conventional methods, presenting an achievable plan for enhancing nutrient use efficiency. The innovative fertilizer application treatment (TSP++) employed in this study was not intended as a blanket recommendation for high chemical input; instead, it was derived from site-specific soil analyses to meet identified nutrient deficiencies. This approach differs from excessive or unsustainable fertilizer use because it focuses on precision inputs rather than blanket applications. Moreover, the aim is to improve nutrient use efficiency, reduce losses through runoff or leaching, and minimise negative environmental impacts. While organic and integrated nutrient sources remain essential, the present study demonstrates that strategic and science-based application of fertilizers can be compatible with sustainable development goals.

Lower gradient zones, characterised by naturally higher soil fertility, demonstrated the most significant potential for yield enhancements via improved fertilizer application. This is especially significant given the declining soil fertility in the Uporoto Highlands, as noted by Kalinga *et al.* [19]. Site-specific nutrient management is crucial for addressing these deficiencies and maintaining agricultural productivity. Soil-based recommendations remain important for improving potato growth and yield. Specifically, the highest yields were obtained at the lower slope with TSP++, indicating that both slope position and fertilizer management should be considered to maximize profitability.

The findings apply not only to the Uporoto Highlands but also to other highland regions in Tanzania, including Mbeya, Njombe, and Iringa, as well as comparable environments across East and Central Africa, such as Kenya's Central Highlands, the Ethiopian Highlands, and the Albertine Rift in Uganda [31, 32, 33 ,34]. In these areas, where potatoes are both a staple and a key economic crop, combining landscape-level soil assessment with evidence-based nutrient management can enhance productivity and support sustainable land use. These insights highlight the value of incorporating topographic information into agricultural planning to optimize resource use and maintain long-term soil fertility. This study, therefore, offers a practical framework for planners, extension officers, and farmers to improve potato yields through informed, location-specific interventions that strengthen food security and support climate-resilient highland farming systems. The pronounced yield differences across slope positions underscore the importance of slope-specific soil fertility and moisture management. Applying such knowledge in extension programs can increase nutrient-use efficiency, reduce losses from runoff and leaching, and lower production costs while safeguarding the environment [35, 36]. The findings also may be applied to similar highland agro-ecologies in regions both regional and global. Recognizing terrain-induced variability in soil fertility and water dynamics is essential for building adaptive and sustainable agricultural systems. Aligning fertilizer recommendations, soil conservation measures, and cropping schedules with topographic position can enhance resource-use efficiency, stabilize yields under variable rainfall, and mitigate land degradation [37]. Overall, this study contributes to the broader agenda of sustainable intensification and adaptive management in fragile upland environments, providing evidence-based guidance for practitioners and policy makers seeking to balance productivity, sustainability, and resilience in potato-based farming systems.

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

The results of the study highlight the significant effects of days after planting, fertilizer treatments, and gradients on the development and production of round potatoes in the Uporoto Highlands. Compared with the upper gradient, the lower gradient, characterised by improved soil fertility, consistently exhibited greater plant growth and higher yields. Potato growth and yield parameters were significantly increased by fertilizer treatments, especially the newly developed mixed fertilizer (TSP++), which outperformed the farmers' practice (TSP+) and the absolute control. Again, the study found a substantial positive correlation between tuber production and biological yield, highlighting the importance of increasing biological yield to enhance productivity. Additionally, for most growth measures, there were no significant interactions between the gradient and fertilizer treatments. However, the three-way interaction with DaP revealed some differences in stem number across the treatments.

The study investigated the effect of slope gradients, fertilizer treatments, and their interactions on potato growth and yield. Hypothesis 1 (H1) hypothesised that lower slopes would produce higher yields; this was supported as total and marketable yields were significantly higher in the lower gradient. Hypothesis 2 (H2) proposed that TSP++ would enhance growth; results confirmed significant increases in leaf length, plant height, and tuber yield. Hypothesis 3 (H3) anticipated gradient × treatment × time interactions, which were substantial primarily for stem number but not for other growth variables.

Despite these findings, the study has several limitations. Statistically, a small sample size and repeated measures may affect precision and generalizability. Ecologically, the experiment was conducted over a single growing season in only two sites, so that results may differ under other climatic or soil conditions.

Potato yields in the Uporoto Highlands were highest on lower slopes (48.96-53.55 tons/ha), indicating that slope position should guide management decisions. Application of the fertilizers based on innovative techniques TSP++ fertiliser-175.8 kg/ha TSP, 147.5 kg/ha MOP, 269.7 kg/ha Nitrobor at planting, followed by 127.1 kg/ha UREA at 30 DaP consistently improved growth and yield across gradients, outperforming both TSP+ and the control. On upper slopes, where moisture retention is lower and erosion risk is higher, TSP++ should be combined with moisture-conservation measures to achieve optimal response. Early-stage nutrient availability (28-42 DaP) should be ensured to promote canopy development, while stem

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development should be closely monitored due to the observed three-way interaction (gradient × fertilizer × DaP). These findings support site- and stage-specific nutrient management, with priority given to lower slopes for maximum productivity, and provide actionable guidance for extension services and farmers in similar highland agro-ecologies.

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Conflict of Interest

The author declares no conflict of interest associated with this study.

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Table 1: Average Main Effects of Gradients, Fertilizer Treatments, and Days After Planting on the Examined Growth Parameters of Round Potatoes in Selected Fields

Factors	Treatment	Measured Parameters and Their Measurements					
		Leaf		Plant		Number	
		Length (cm)	Width (cm)	Height (cm)	Width (cm)	Leaves	Stems
Gradient	Upper	20.5z	10.1y	43.2^{y}	52.5^{y}	54.9^{y}	3.9^{x}
	Lower	31.6^{x}	12.0^{x}	66.1^{x}	69.4^{x}	71.8^{x}	3.5x
	F pr.	**0.005**	**0.061**	**0.037**	**0.001**	**0.023**	**0.254**
Treatment	Control	23.3^{y}	9.9^{y}	49.8^{y}	55.7^{y}	57.1^{y}	3.7^{x}
	TSP+	24.6^{y}	10.3^{y}	48.8^{y}	57.6^{y}	58.4^{y}	3.4^{x}
	TSP++	30.3^{x}	12.8^{x}	65.4^{x}	69.4^{x}	74.4^{x}	4.1^{x}
	F pr.	**<.001**	**0.102**	**<.001**	**0.011**	**0.029**	**0.087**
Days after Planting (DaP)	28	15.4^{z}	6.5^{z}	20.6^{z}	29.7^{z}	29.0^{z}	3.5^{y}
	42	26.7^{y}	10.0^{y}	43.7^{x}	54^{y}	43.5^{y}	3.7^{y}
	56	28.0^{y}	10.5y	57.1^{x}	62.5^{x}	66.1^{x}	3.9^{x}
	70	30.8^{x}	12.9^{x}	63.6^{x}	70.0^{x}	78.0^{x}	3.7^{y}
	84	28.0^{y}	15.0^{x}	70.9^{x}	73.5^{x}	79.6^{x}	3.7^{y}
	98	27.5^{y}	11.2^{y}	72.1^{x}	75.7^{x}	83.8^{x}	3.9^{x}
	F pr.	**<.001**	**0.003**	**<.001**	**<.001**	**<.001**	**0.057**

Key: Means within the same column followed by different superscript letters differ significantly ($p < 0.05$) according to the LSD test; means sharing the same letter are not significantly different. DaP represents the term "Days After Planting"

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Table 2: Average Measures of Growth Variables as Influenced by the Interactions between Gradients with Treatments and Gradients with Days After Planting Potatoes in the Selected Fields

Gradients	Treatment	Measured Parameters and Their Measurements					
		Leaf		Plant		Number of	
		Length (cm)	Width (cm)	Height (cm)	Width (cm)	Leaves	Stems
Upper	Control	17^{z}	8.2^{y}	39.3^{y}	46.5^{y}	49.5^{y}	4.0^{x}
	TSP+	19.3^{y}	9.3^{y}	37.4^{y}	49.5^{y}	55.1^{y}	3.6^{x}
	TSP++	25.2^{x}	12.7^{x}	53^{x}	61.4^{x}	60.0^{x}	4.1^{x}
Lower	Control	29.6^{y}	11.6^{x}	60.3^{x}	64.9^{x}	64.7^{x}	3.4^{y}
	TSP+	29.8^{y}	11.4^{x}	60.2^{x}	65.8^{x}	61.8^{x}	3.2^{y}
	TSP++	35.5^{x}	12.9^{x}	77.9^{x}	77.3^{x}	88.8^{x}	3.9^{x}
	F pr.	**0.209**	**0.507**	**0.712**	**0.928**	**0.21**	**0.752**
Upper	28	9.8^{y}	4.5^{y}	12.8^{y}	21.3^{y}	26.9^{y}	3.7^{x}
	42	18.9^{y}	8.0^{y}	31.8^{y}	47.1^{y}	39.2^{y}	3.7^{x}
	56	21.9^{y}	9.4^{y}	43.4^{y}	52.8^{y}	48.5^{y}	4.4^{x}
	70	26.2^{x}	11.6^{x}	52.9^{x}	62.1^{x}	72.8^{x}	3.7^{x}
	84	23.0^{y}	17.9^{x}	59.7^{x}	64.6^{x}	66.3^{x}	3.8^{x}
	98	23.1^{y}	8.9^{y}	58.6^{x}	66.8^{x}	75.6^{x}	4.1^{x}
Lower	28	21.0^{y}	8.5^{y}	28.5^{y}	38^{y}	31.1^{x}	3.3^{y}
	42	34.3^{x}	11.9^{x}	55.5^{x}	60.9^{x}	47.8^{y}	3.6^{x}
	56	34.1^{x}	11.7^{x}	70.8^{x}	72.2^{x}	83.6^{x}	3.4^{x}
	70	35.4^{x}	14.1^{x}	74.2^{x}	78^{x}	83.3^{x}	3.6^{x}
	84	32.9^{x}	12.2^{x}	82.1^{x}	82.5^{x}	92.9^{x}	3.6^{x}
	98	31.8^{x}	13.5^{x}	85.6^{x}	84.6^{x}	91.9^{x}	3.7^{x}
	F pr.	**0.004**	**0.127**	**0.034**	**0.749**	**0.005**	**0.036**

Key: Means within the same column followed by different superscript letters differ significantly ($p < 0.05$) according to the LSD test; means sharing the same letter are not significantly different

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Table 3: Averages of Potato Growth Variables as Influenced by the Interactions of Gradients, Treatment Fertilizers and Days After Planting

Gradients	Treatment	Days after Planting	Measured Parameters and Their Measurements					
			Leaf		Plant		Number of	
			Length (cm)	Width (cm)	Height (cm)	Width (cm)	Leaves	Stems
Upper	Control	28	8.1^{z}	4.1^{y}	10.8z	17.3^{z}	23.8^{z}	3.4^{x}
		42	14.4^{y}	7.1^{y}	24.4^{y}	41.4^{y}	34.1^{y}	3.6^{x}
		56	18.4^{x}	8.3^{y}	45.4^{x}	46.4^{x}	42.6^{x}	5.4^{x}
		70	21.6^{x}	11.3^{x}	48.2^{x}	56.4^{x}	60.2^{x}	3.6^{x}
		84	20.8^{x}	10^{x}	53.1^{x}	56.3^{x}	68.2^{x}	3.9^{x}
		98	18.7^{x}	8.5^{y}	53.7^{x}	60.9^{x}	68.1^{x}	4.1^{x}
	TSP+	28	9.4^{z}	4.4^{y}	12^{z}	20.9^{z}	26.3^{z}	3.6^{x}
		42	17.6^{y}	8.4^{y}	30.6^{y}	48.5^{y}	38.3^{y}	3.6^{x}
		56	20.2^{x}	8.6^{y}	33.7^{x}	49.1^{x}	43.4^{x}	3.6^{x}
		70	24.8^{x}	11.6^{x}	44.1^{x}	56.6^{x}	79.5^{x}	3.3^{x}
		84	23.4^{x}	13.9^{x}	51.2^{x}	58.1^{x}	70.9^{x}	3.5^{x}
		98	20.5^{x}	8.7^{y}	52.7^{x}	63.7^{x}	72^{x}	3.8^{x}
	TSP++	28	12^{z}	5^{y}	15.5^{z}	25.7^{z}	30.7^{z}	4.1^{x}
		42	24.9^{y}	8.6^{y}	$40.4u^{y}$	51.5^{y}	45.1^{y}	4^{x}
		56	27.2^{x}	11.2^{x}	51.1^{x}	63^{x}	59.5^{x}	4.3^{x}
		70	32.2^{x}	12.1^{x}	66.7^{x}	73.3^{x}	78.6^{x}	4.2^{x}
		84	24.9^{y}	29.6^{x}	74.9^{x}	79.3^{x}	59.7x	3.9^{x}
		98	30.2^{x}	9.7^{y}	69.4^{x}	75.8^{x}	86.6^{x}	4.4^{x}
Lower	Control	28	19.3z	8.4^{y}	26.2^{z}	35^{z}	29.5^{z}	3.3^{x}
		42	31.1^{y}	11^{y}	47.9^{y}	61.5^{y}	42.6^{y}	3.2^{x}
		56	31.8^{y}	10.8^{y}	63^{x}	66.5^{x}	74.4^{x}	3.1^{x}
		70	32.8^{x}	15.3^{x}	68.8^{x}	71^{x}	73.4^{x}	3.6^{x}
		84	31.6^{x}	11^{y}	78.8^{x}	76.7^{x}	85.1^{x}	3.6^{x}
		98	30.7^{x}	13.1^{x}	77^{x}	78.9^{x}	83.1^{x}	3.9^{x}

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	TSP+	28	18.5^{z}	7.7^{y}	24.4^{z}	31.9^{z}	25.5^{z}	2.8^{x}
		42	34.1^{y}	11.9^{x}	50.5^{y}	59.9^{y}	41.3^{y}	3.5^{x}
		56	32.3^{y}	11.6^{x}	64.8^{x}	66.5^{x}	68.6^{x}	3.3^{x}
		70	34.4^{x}	14.1^{x}	67.8^{x}	77^{x}	72.5^{x}	3.2^{x}
		84	30.8^{x}	10.2^{y}	75.1^{x}	79.2^{x}	84.1^{x}	3.3^{x}
		98	28.6^{x}	12.6^{x}	78.6^{x}	80.2^{x}	78.9^{x}	3.1^{x}
	TSP++	28	25.2^{y}	9.5^{y}	34.7^{y}	47.1^{y}	38.4^{y}	3.9^{x}
		42	37.8^{x}	12.7^{x}	68.1^{x}	61.2^{x}	59.4^{x}	4^{x}
		56	38.3^{x}	12.7^{x}	84.6^{x}	83.4^{x}	107.9^{x}	3.9^{x}
		70	39^{x}	12.8^{x}	86^{x}	85.9^{x}	103.9^{x}	4^{x}
		84	36.4^{x}	15.4^{x}	92.5^{x}	91.6^{x}	109.5^{x}	3.9^{x}
		98	36^{x}	14.8^{x}	101.2^{x}	94.8^{x}	113.9^{x}	4^{x}
		F pr.	**0.593**	**0.934**	**0.363**	**0.58**	**0.936**	**0.031**

*Means within the same column followed by different superscript letters differ significantly ($p < 0.05$) according to the LSD test; means sharing the same letter are not significantly different

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Table 4: Average Potato Growth Variables as Influenced by the Interactions between Treatments (Fertilizers) and Days After Planting

Treatment	Days after Planting	Measured Parameters and Their Measurements					
		Leaf		Plant		Number of	
		Length (cm)	Width (cm)	Height (cm)	Width (cm)	Leaves	Stems
Control	28	13.7^{z}	6.2^{y}	18.5^{y}	26.2^{y}	26.6^{y}	3.3^{x}
	42	22.8^{y}	9^{y}	36.2^{y}	51.4^{y}	38.4^{x}	3.4^{x}
	56	25.1^{y}	9.5^{y}	54.2^{x}	56.4^{x}	58.5^{x}	4.3^{x}
	70	27.2^{x}	13.3^{x}	58.5^{x}	63.7^{x}	66.8^{x}	3.6^{x}
	84	26.2^{x}	10.5^{x}	65.9^{x}	66.5^{x}	76.6^{x}	3.8^{x}
	98	24.7^{x}	10.8^{x}	65.4^{x}	69.9^{x}	75.6^{x}	4^{x}
TSP+	28	13.9^{z}	6^{y}	18.2^{y}	26.4^{y}	25.9^{y}	3.2^{x}
	42	25.9^{x}	10.2^{x}	40.6^{x}	54.2^{x}	39.8^{x}	3.5x
	56	26.3^{x}	10.1^{x}	49.2^{x}	57.8^{x}	56^{x}	3.5^{x}
	70	29.6^{x}	12.8^{x}	55.9^{x}	66.8^{x}	76^{x}	3.3^{x}
	84	27.1^{x}	12.1^{x}	63.2^{x}	68.6^{x}	77.5^{x}	3.4^{x}
	98	24.6^{x}	10.7^{x}	65.7^{x}	72x^{x}	75.5^{x}	3.5^{x}
TSP++	28	18.6^{y}	7.2^{y}	25.1^{y}	36.4^{y}	34.6^{y}	4^{x}
	42	31.3^{x}	10.7^{x}	54.3^{x}	56.4^{x}	52.3^{x}	4^{x}
	56	32.8^{x}	12^{x}	67.9^{x}	73.2^{x}	83.7^{x}	4.1^{x}
	70	35.6^{x}	12.4^{x}	76.4^{x}	79.6^{x}	91.3^{x}	4.1^{x}
	84	30.6^{x}	22.5^{x}	83.7^{x}	85.5^{x}	84.6^{x}	3.9^{x}
	98	33.1^{x}	12.2^{x}	85.3^{x}	85.3^{x}	100.2^{x}	4.2^{x}
	F pr.	**0.355**	**0.444**	**0.052**	**0.097**	**0.489**	**0.375**

***NOTE:** Means within the same column followed by different superscript letters differ significantly ($p < 0.05$) according to the LSD test; means sharing the same letter are not significantly different

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Table 5: Impact of Gradients and Fertilizer Treatments on Potato Yield

Variables	**Factors and means of variables**				**Statistical parameters**			
Total Biological Yield (TBY) (tons/ ha)	**Gradient**	Upper	Lower		LSD	s.e.d	***P-value***	***CV%***
		26.3^{y}	54.6^{x}		5.58	1.30	**0.002**	**3.2**
	Treatment	TSP++	TSP+	Control				
		47^{x}	37.3^{x}	37^{x}	8.76	3.80	**0.050**	**9.4**
		Treatment						
	Gradient	TSP++	TSP+	Control				
	Upper	38.89^{yz}	23.54^{zw}	16.49^{w}	10.32	4.57	**0.034**	**11.2**
	Lower	55.13^{xy}	51.09^{xy}	57.55^{x}				
Total Tuber Yield (TTY) (tons/ ha)	**Gradient**	Upper	Lower		LSD	s.e.d	***P-value***	
		22.3^{y}	50.9^{x}		6.69	1.55	**0.003**	**4.2**
	Treatment	TSP++	TSP+	Control				
		42.5^{x}	33.9^{x}	33.5^{x}	8.6	3.73	**0.073**	**10.2**
		Treatment						
	Gradient	TSP++	TSP+	Control				
	Upper	33.95^{yz}	19.52^{zw}	13.37^{w}	10.26	4.58	**0.042**	**12.5**
	Lower	50.97^{x}	48.27^{xy}	53.55^{x}				
Marketable Tuber Yield (MTY) (tons/ ha^{-1})	**Gradient**	Upper	Lower		LSD	s.e.d	***P-value***	
		20.6^{y}	46.3^{x}		13.48	3.13	**0.015**	**9.4**
	Treatment	TSP++	TSP+	Control				
		38^{x}	31.4^{x}	31^{x}	8.24	3.57	**0.153**	**10.7**
		Treatment						
	Gradient	TSP++	TSP+	Control				
	Upper	31^{yz}	17.93^{zw}	13.02^{w}	11.82	5.18	**0.043**	**15.3**
	Lower	44.94^{xy}	44.91^{xy}	48.96^{x}				

Key: Means within the same column followed by different superscript letters differ significantly ($p < 0.05$) according to the LSD test. Yield values are expressed in tonnes per hectare (tons/ha). LSD = least significant difference; s.e.d. = standard error of difference; CV% is calculated using S.E.D ÷ mean × 100

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