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Research Article

Influence of combined manure and inorganic fertilizer on nutrient-use efficiency and soil balance in sweetpotato in middleveld of Eswatini

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Abstract

The cultivation of sweetpotato has always been assumed to be without nutrient amendments. This has led to a non-concerted effort to develop nutrient recommendations for different soils. This study investigated tahe nutrient use efficiency and soil balance in sweetpotato varieties under different nutrient amendments. The study was located at moist (Malkerns) and dry (Luve) agroecological zones of Eswatini. The treatments were: three sweetpotato varieties, Ligwalagwala, Kenya white and Lamngititi, and five nutrient amendments: (1) no amendment, (2) 450 kg/ha NPK fertilizer, (3) 6 t/ha manure, (4) 3 t/ha manure + 225 kg/ha fertilizer, and (5) 4.5 t/ha manure + 112.5 kg/ha fertilizer. Data were analysed using SAS software to detect significant variations among treatments at $p<0.05$. The results indicated that the highest ($p \leq 0.05$) storage root yields of 58.38 t/ha and 40.20 t/ha were recorded on Kenya white under treatments 4 and 5 at the respective sites. Uptake, agronomic, and physiological efficiencies of K were the only significant variables for the regression model on yield. Positive soil N balances were obtained in Treatments 3 and 4, whereas K exhibited a negative balance across treatments and sites. Positive P balances were obtained only at Luve in the fertilizer treatments. The response of varieties to nutrient amendment was largely affected by differences in efficiency of acquisition rather than utilisation, partly explained by environmental and soil quality constraints. It is concluded that, the combined use of manure and mineral fertilizers will avert the unavailability and-imbalance of nutrients in sweetpotatoes under marginal conditions in small-scale agriculture while significantly improving yields.

1. Introduction

Soil nutrient budgets in Sub-Saharan Africa (SSA) show a net annual depletion of nitrogen (N), phosphorus (P), and potassium (K) as a result of long-term cultivation of crops with little or no external nutrient amendment, through harvested crops and crop residues, overgrazing, leaching, erosion and volatilization [1]. Cobo et al. [2] reported recent nutrient balance results from 57 selected studies across SSA that showed negative N, P, and K balances (i.e., 85, 76, and 56% of studies, respectively). These observations were broadly consistent with the general claim of nutrient mining across the continent [3]. For instance, in the late 90s, nutrient mining was estimated to average 660 kg of N, 75 kg of P, and 450 kg of K per hectare from about 200 million hectares of cultivated land in 37 countries in Africa [4].

Farmers do not return nutrients to the soil because they are either unaware of the change in nutrient dynamics caused by crop and residue harvests or how to integrate organic and mineral nutrient sources. In Eswatini, like elsewhere in the region, cultivation of sweetpotato has been assumed to be without nutrient amendment as it is considered to thrive on marginal soils. Recently, due to the commercialisation of sweetpotato in health, nutrition, confectionery, and other industries, sweetpotato is now cultivated in prime soils [5]. Thus the lack of nutrient enrichment of soils remains a recipe for nutrient mining.

The cultivation of sweetpotato often involves the soil incorporation of crop residues and other plant materials. This practice is lacking in Eswatini owing to complete biomass removal for stall feeding or *in situ* communal grazing practices. Furthermore, there has been a lack of concerted effort to develop fertilizer or manure recommendations for crops grown in different soils. Farmers may thus apply higher or lower rates of manure or fertilizer, which may be ineffective or detrimental to crop development, soil, and environmental health.

The concern for soil nutrient depletion and low soil fertility has led to the development of several integrated soil fertility management technologies that offer the potential to improve soil fertility management for resource-limited small-scale farmers [6]. To provide the necessary nutrients for plant production, management strategies should focus on building the organic matter (OM) content of soils, such as through manure application, which leads to improved nutrient dynamics [7]. The required amount of manure needed to be applied for a specific crop depends on the soil type, soil texture, soil structure, and OM content of the soil [8]. Although genotype and environment effects vary with season, understanding such effects can be used to establish references for areas of optimal cultivar adaptation and concomitant magnitudes of soil fertility amelioration.

Variable rates of singular manure applications that gave the highest sweetpotato yield have been reported in Eswatini. For instance, disparate rates of 10 t/ha up to 40 t/ha of cattle manure were considered optimal [8, 9]. Elsewhere, [10] recommended 5 t/ha to 10 t/ha of organic manure to be applied to soils with low OM content to improve storage root development and yield of sweetpotato. In Ethiopia, [11] achieved the highest marketable storage root yield of 33.97 t/ha with the application of 7.5 t/ha farm yard manure (FYM). Nonetheless, the sole application of manure may not be feasible due to the use of biomass as energy sources, high labour demand for their preparation, and low content and slow release of nutrients [12]. To this effect, the positive effects of the combined application of organic and inorganic fertilizers on vegetative growth and yield of sweetpotato have been demonstrated, notwithstanding the varying rates. Application of 46 kg N/ha and 5 t/ha farm yard manure (FYM) increased the marketable storage root yield of sweetpotato by 49% compared to the non-fertilised plots [13] whereas [14] obtained 23.65 t/ha with a combination of 15 t/ha FYM and 69 kg/ha P_2O_5. Similar trends have been reported in West Africa [15] and India [16].

Sustainable use of fertilizers such as NPK and manure, sourced from plant and animal residues, including animal dung and faeces, must aim to maximize both the amount of nutrients taken up and utilised by the crop and soil replenishment rather than the absolute quantities applied [17]. Thus, applications of fertilizers and manures should consider nutrient use efficiency (NUE) and soil nutrient flow to guard against short- and long-term unbalanced investments. In sweetpotato, [5] reported the highest agronomic efficiency (138.5 – 171.8) with the sole application of farmyard manure at 2.5–7.5 t/ha. However, it is considered important to use more than one NUE term and account for different nutrient inputs, thereby addressing many aspects of soil-plant nutrition [18].

The nutrient balance of a cropping system is determined by the difference between the removal of nutrients by the crop and the addition of nutrients to the soil as fertilizer or manure. Although nutrient inputs cannot exactly match outputs, nutrient budgets contribute to the understanding of efficient nutrient

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management in agro-ecosystems [19]. In East and Southern Africa, they have been prepared for agroecological zones [20], crop-animal farming systems [21], cereal-legume intercropping systems [22], or banana-based farming systems [23]. Although most studies show negative nutrient stocks, the results provide scope for possible interventions towards improved soil management and NUE.

The objectives of this study aimed to measure and compare the influence of elite sweetpotato varieties, which are mostly grown in Eswatini, in contrasting environments, on the uptake of N, P, and K, efficiency and partial soil balance after combined application of manure and inorganic fertilizers. The study did not intend to increase nutrient rates from combined sources towards an optimum; rather, it assessed the singular practice of integrated nutrient management in resource-constrained environments. The study hypothesised that because of the slow release of nutrients in manure, the benefits of combined application of manure and inorganic fertilizers would not show enhanced plant nutrient uptake, efficiency, soil balance, or storage root yield in one season of application. The findings of this study will provide further theoretical and practical bases for optimising sweetpotato nutrient management in Eswatini and similar zones in the region.

2. Materials and methods

2.1. Description of experimental locations

The field experiment was carried out from November 2019 to April 2020 at the Malkerns Research Station (Malkerns) and at the Luve Experimental Station (Luve) in the Middleveld of Eswatini (Fig. 1). Malkerns is located in the moist (upper) Middleveld at 26° 56′ S, 31° 17′ E, 734 metres above sea level (m.a.s.l.) and experiences an annual rainfall of 960 mm and a mean temperature of 19 °C. Luve is in the dry (lower) Middleveld at 26° 28′ S, 31° 51′ E, 463 m.a.s.l. with an annual rainfall of 783 mm and a mean temperature of 20.9 °C.

The rainfall and temperature during the experimental season are shown in Table 1. Seasonal rainfall for Malkerns was higher than the long-term average of 400 mm, whereas Luve recorded a rainfall amount below the long-term average of 326.3 mm. A higher

Figure 1. Map of Eswatini showing study locations at Malkerns and Luve.

mean temperature of 29.5 °C was recorded at Luve compared to 21.96 °C at Malkerns. The seasonal rainfall and temperature characteristics thus confirmed long-term climate inferences that predominantly show low rainfall and higher temperature regimes for Luve, contrary to Malkerns. Soils in Malkerns are the deep red loam, Ferralsols, or the Mdutjane soil series and strongly weathered with oxic horizons [25, 26]. At Luve, grey sandy loams, Lithosols predominate and are shallow in nature with less than 10 cm depth over hard rock [25–27].

2.2. Selected properties of soil and cattle manure at establishment

Prior to planting, soil analysis was performed to obtain the particle size distribution using the hydrometer procedure [28], pH (H_2O) by the method of [29], organic carbon (OC) by the Walkley and Black method [30], total nitrogen using the modified Kjedhal method [31], available phosphorus using the ammonium molybdenum blue method [32], and exchangeable potassium, calcium and magnesium by the method of [33].

Table 2 shows the soil physical and chemical properties at the start of the experiment. The soil texture was sandy clay at Malkerns and loamy sand at Luve (Table 5). Soils at Luve were slightly acidic (pH < 6.5), whereas while at Malkerns, they were strongly acidic (pH <5.5). Cattle manure was relatively high in OC with fair amounts of nutrients with critical values

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Table 1. Rainfall and temperature at Malkerns and Luve for the 2019-2020 growing season.

Month	Rainfall (mm)		Temperature (°C)	
	Malkerns	Luve	Malkerns	Luve
November 2019	154.4	86.3	22.2	30.1
December 2019	57.8	15.6	21.7	28.4
January 2020	159.2	111.4	23.2	32.9
February 2020	119.8	48.0	22.8	29.7
March 2020	57.8	33.4	20.0	26.5
Total rainfall (mm)	549.0	294.7	-	-
Mean temperature	-	-	22.0	29.5

Table 2. Selected chemical properties of cow dung and initial physico-chemical properties of the soils of the study locations and range of crop.

Soil property	Units	Cattle manure	Malkerns	Luve	Range for soil/ crop nutrition§
Particle size distribution					-
Clay	%		41	9	-
Silt	%		7	5	-
Sand	%		52	86	-
Textural class			Sandy clay	Loamy sand	-
Chemical properties					
pH (H_2O)		8.60	5.42	6.08	5.8 – 6.2
Nitrogen	%	2.49	0.06	0.02	4.2-5.0
Organic carbon	%	25.2	0.82	0.26	0.7 - 4
Organic matter	%	43.3	1.41	0.44	-
C:N ratio	-	10.1	13.7	13.0	-
Phosphorus	mg kg^{-1}	2500	40.13	28.03	20 -100
Potassium	mg kg^{-1}	12800	118.29	68.49	150 - 800
Calcium	mg kg^{-1}	2600	306.85	217.31	> 150
Magnesium	mg kg^{-1}	3300	119.67	68.08	60 - 300
Copper	mg kg^{-1}	6.47	3.51	1.50	5-14
Iron	mg kg^{-1}	99.76	178.97	133.80	45-80
Manganese	mg kg^{-1}	31.82	9.22	22.93	26-500
Zinc	mg kg^{-1}	22.45	5.73	4.67	30-60
Exchangeable acidity	cmol kg^{-1}	0.15	0.25	0.15	-

§O'Sullivan et al. [34]; Horneck et al. [36].

for sweetpotato production [34]. The soils at either site were inherently infertile with low N contents (<0.2%). Henry et al. [35] identified K critical levels of 0.38 cmol/kg soil for intermediate-textured (30–40% clay) soils and 0.58 cmol/kg soil for heavy-textured (> 40% clay) soils in Eswatini. In addition, based on the critical P requirements for sweetpotato of 0.22% and 2.6% for K [34], both initial K and P contents were very low.

2.3. Experimental establishment

The experiment was established as a 3 x 5 factorial laid out in a randomised complete block design with three replications per treatment each, measuring 12.6 m^2. The first factor comprised three commonly grown sweetpotato varieties; Ligwalagwala (100–120 DAP), Kenya white (120–150 DAP), and Lamngititi (120–180 DAP), whose maturity periods in days after planting (DAP) are shown in brackets. The second factor consisted of four manure and/or fertilizer [NPK 2:3:4 (39)] amendments whose levels were: (1) control (no amendment), (2) 450 kg/ha NPK fertilizer, (3) 6 t/ha manure, (4) 3 t/ha manure + 225 kg/ha fertilizer, and (5) 4.5 t/ha manure + 112.5 kg/ha fertilizer. Edje and Ossom [37] recommended the application of 450

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kg/ha 2:3:4 (39) followed by side dressing with urea (45% N) and KCl (60% K) in a 10:50 ratio at 120 kg/ha for sweetpotato production in Eswatini. Only the rate of basal dressing was adopted in this study as a representation of rare cases where farmers may apply fertilizer in sweetpotato crops and would unlikely to dress. Manure was incorporated into the ridges two weeks before planting, whereas inorganic fertilizer was applied two weeks after planting. Vine cuttings of 30 cm long were planted at 0.3 m intra-row spacing with ridges spaced at 0.9 m. All weeding was done by hand-hoe.

2.4. Data collection and analysis

The uptake of NPK was determined separately for shoot and storage roots, whereas the use efficiency was determined for storage roots only. Nutrient uptake was calculated using the following formula [38]:

Nutrient uptake (kg/ha) =
(Dry matter of plant part) × (Tissue nutrient concentration)

Agronomic efficiency (AE) is described as the product of nutrient recovery from the fertilizer and denotes the efficiency with which the plant uses each additional unit of nutrient. The index determines the productivity gained using nutrient input and was calculated using the following formula [39]:

$$\text{Agronomic efficiency (AE)} = \frac{\text{Gf} - \text{Gu}}{\text{Na}} \times 100$$

Where,
Gf = Dry storage root yield from fertilised plots (kg).
Gu = Dry storage root yield from unfertilised plots (kg).
Na = Quantity of nutrient applied (kg).

Physiological efficiency (PE) is the ability of a plant to transform nutrients acquired from fertilizer into economic yield. PE was calculated using the following formula [39]:

$$\text{Physiological efficiency (PE)} = \frac{\text{Gf} - \text{Gu}}{\text{Ntf} - \text{Ntu}} \times 100$$

Where,
Ntf = Nutrient uptake by shoots and storage roots in fertilised plot (kg).
Ntu = Nutrient uptake by shoots and storage roots in an unfertilised plot (kg).

Partial nutrient balance was calculated by subtracting the total amount of N, P, or K taken up by vines, true roots, and storage roots from the total amount of N, P, or K added through manure and/or fertilizer [20]. Data were subjected to analysis of variance and regression analysis using GenStat version 18 computer software to detect significant variations and associations among treatments at a 5% probability level ($p \leq 0.05$). Means were separated using Fisher's LSD test.

3. Results

3.1. Rainfall and temperature at Malkerns and Luve for the 2019-2020 growing season

From Table 1, Higher amounts of rainfall at Malkerns and Luve were recorded in the months of November, January and February. Generally, Malkerns recorded higher and evenly distributed rainfall than Luve. Air monthly mean temperatures at Malkerns ranged between 20.04 °C and 23.17 °C whilst at Luve it ranged between 26.50 °C and 32.91 °C. Highest temperatures were recorded in January whilst lowest temperatures were recorded in March at both locations.

3.2. Some selected chemical properties of cow dung and the initial physico-chemical properties of the soils at the study locations.

The cow dung was relatively high in organic carbon, organic matter and had fair amounts of nutrients required for crop growth (Table 2). The pH of the soils, 5.42 and 6.08 for Malkerns and Luve, respectively, indicated that the soils at both study locations were slightly acidic. The results of the soil analysis also show that the total nitrogen, available phosphorus, exchangeable potassium and organic carbon contents were low. The textures of the soils were sandy clay at Malkerns, and loamy sand at Luve.

3.3. Storage root fresh yield, shoot fresh yield, and harvest index

Kenya white exhibited the highest fresh root yield and shoot yield, but exhibited the least harvest index (HI) based on the main effects of combined location analysis (Table 3). The application of 3 t/ha manure (M) + 225 kg/ha NPK produced the highest root yield,

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Table 3. Combined location effects on storage root fresh yield, shoot fresh yield, and harvest index.

Treatments	Total fresh yield (t/ha)		Harvest index (HI)
	Storage root yield	Shoot yield	
Variety (V)			
Ligwalagwala	31.67[b]	18.0[b]	79.63[a]
Kenya white	36.23[a]	36.9[a]	65.86[c]
Lamngititi	30.50[b]	20.3[b]	76.02[b]
Amendment (A)			
Control (no amendment)	20.93[d]	15.5[b]	77.08[a]
NPK 450 kg/ha	31.53[c]	29.6[a]	70.16[b]
6 t/ha manure (M)	29.32[c]	24.7[a]	71.41[b]
3 t/ha M + NPK 225 kg/ha	42.70[a]	29.2[a]	76.14[a]
4.5 t/ha M + NPK 112.5 kg/ha	39.51[b]	26.3[a]	74.38[ab]
Location (L)			
Malkerns	37.03[a]	36.4[a]	69.03[b]
Luve	28.57[b]	13.7[b]	78.65[a]
Interaction (LSD $_{(0.05)}$)			
V × A	5.21	ns	ns
V × L	3.30	9.13	ns
A × L	4.25	ns	ns
V × A × L	ns	ns	ns
CV (%)	13.2	40.5	14.2

[abc] Means with the same letters in a column for each treatment effect are not significantly different from each other (LSD $_{(0.05)}$).

Table 4. Interaction effects of variety, amendment, and location on storage root fresh yield (t/ha) at Malkerns and Luve.

Amendment[ǂ]	Malkerns				Luve			
	Lg[†]	Kw	Lm	A x L	Lg	Kw	Lm	A x L
F1	24.48[fg]	24.27[fg]	17.50[g]	22.08[DE]	18.95	20.69	19.71	19.79[E]
F2	38.84[cd]	39.83[cd]	28.71[ef]	35.80[C]	25.65	29.97	26.17	27.27[D]
F3	35.57[de]	38.07[cd]	26.57[fg]	33.40[C]	25.25	25.14	25.35	25.25[D]
F4	40.75[cd]	58.38[a]	51.70[b]	50.94[A]	31.56	37.63	34.16	34.45[C]
F5	41.97[cd]	47.01[bc]	39.75[cd]	42.91[B]	33.68	40.20	35.36	36.10[C]
V x L	*36.32[B]*	*41.91[A]*	*32.85[C]*		*27.02[E]*	*30.54[CD]*	*28.15[DE]*	

[†]Lg= Ligwalagwala, Kw= Kenya white, Lm= Lamngititi.

[ǂ]F1= Control, F2= 450 kg/ha NPK, F3= 6 t/ha manure, F4= 3 t/ha manure + 225 kg/ha NPK, F5= 4.5 t/ha manure + 112.5 kg/ha NPK.

[abc] Means with the same letters for interaction effects (uppercase A x L and V x L) across locations are not significantly different from each other (LSD $_{(0.05)}$).

whereas soil amendments were less definable for shoot yield and HI. Root yield and shoot yield were higher at Malkerns, while HI was higher at Luve. Interactions were largely significant for root yield. In the V x L interaction, Kenya white was superior to other varieties at Malkerns but Lamngititi equally performed well at Luve (Table 4). In terms of the A x L effect, 3 t/ha manure + 225 kg/ha NPK produced the highest overall yield but was matched by 4.5 t/ha manure + 112.5 kg/ha NPK at Luve.

3.4. Uptake efficiency of N, P, and K in shoots and roots

In Table 5, Kenya white had the highest N and K uptake efficiencies in both shoots and roots across all locations. Whereas N and P uptake efficiencies for nutrient amendment in shoots and roots were variable, K uptake was consistently significant at 3 t/ha manure + 225 kg/ha NPK, and 4.5 t/ha manure + 112.5 kg/ha NPK. Except for P uptake in shoots, there were no significant differences in the mean uptake efficiencies for N and K between locations in both shoots and roots.

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Table 5. Combined location effects on uptake of N, P, and K by shoots and storage roots.

Treatments	Uptake in shoots (kg/ha)			Uptake in roots (kg/ha)		
	N†	P	K	N	P	K
Variety (V)						
Ligwalagwala	13.5[c]	2.8[b]	25.9[c]	54.2[c]	29.9	105.0[c]
Kenya white	24.9[a]	3.9[a]	43.5[a]	62.9[a]	41.4	125.7[a]
Lamngititi	19.1[b]	3.6[a]	35.2[b]	57.0[b]	38.2	117.4[b]
Amendment (A)						
Control	8.0[e]	2.2[c]	12.4[d]	25.1[d]	22.3[c]	61.3[d]
NPK 450 kg/ha	14.0[d]	4.3[a]	25.1[c]	31.9[c]	50.3[a]	103.4[b]
6 t ha^{-1} manure (M)	19.1[c]	3.1[b]	33.6[b]	79.7[a]	27.8[b]	96.7[c]
3 t ha^{-1} M + NPK 225 kg/ha	28.2[a]	4.0[a]	50.5[a]	76.3[b]	46.8[a]	160.2[a]
4.5 t ha^{-1} M + NPK 112.5 kg/ha	26.5[b]	3.9[a]	52.6[a]	77.1[b]	46.5[a]	158.6[a]
Location (L)						
Malkerns	19.3[a]	4.2[a]	36.0[a]	58.9[a]	52.5[a]	117.1[a]
Luve	19.1[a]	2.8[b]	33.7[a]	57.2[a]	20.6[a]	115.0[a]
Interaction (LSD $_{(0.05)}$**)**						
V × A	2.04	ns	3.58	2.28	ns	4.63
V × L	1.29	0.85	2.27	1.44	ns	2.93
A × L	1.67	1.10	2.93	1.86	ns	3.78
V × A × L	2.89	ns	ns	3.22	ns	6.54
CV (%)	9.1	24.0	8.6	3.4	42.0	3.1

[abc] Means with the same letters in a column for each treatment effect are not significantly different from each other (LSD $_{(0.05)}$).

Based on the interaction effects (Table 6), the highest significant uptake values were attained with Kenya white and at 3 t/ha manure + 225 kg/ha NPK, although application of 4.5 t/ha manure + 112.5 kg/ha NPK performed equally well at Luve. The V x A interaction effects on P uptake efficiency were not significant, whereas those for A x L and V x L were significant, but the effects were barely distinguishable.

In Table 7, the interaction effects revealed that higher values for N uptake in roots were obtained with 6 t/ha manure at both locations as well as 4.5 t/ha manure + 112.5 kg/ha NPK at Malkerns. K uptake was higher at 3 t/ha manure + 225 kg/ha NPK and 4.5 t/ha manure + 112.5 kg/ha NPK at Luve. Interaction effects were not significant for P uptake.

3.5. Agronomic and physiological efficiency of N, P, and K

In Table 8, the varieties were not significantly different in terms of agronomic efficiency (AE_P) and physiological efficiency (PE_P) of phosphorous. Kenya white had higher PE_N but was not significantly different from Ligwalagwala for PE_K. The highest AE_N and PE_N were obtained with inorganic fertilizer whereas singular application of manure (6 t/ha) showed the least AE_N and PE_N at either location. Inorganic fertilizer treatment resulted in the lowest AE_P and PE_P, whereas manure amendment significantly improved AE_P, three to four times at Malkerns and up to five times at Luve. Similarly, soil amendment with manure doubled the values of PE_P compared to inorganic fertilizer. In terms of K, 3 t/ha manure + 225 kg/ha NPK showed the highest AE_K and PE_K at either location, but the latter did not significantly differ from those obtained with 4.5 t/ha manure + 112.5 kg/ha NPK at Luve. Interaction effects were not significant for AE, whereas significant effects on PE were associated with N and K inputs.

Uptake efficiency, AEK, and PE_K were the only significant variables to enter the regression model between yield and NPK uptake and efficiency indices at both locations (Table 9). K uptake contributed 11.1% and 24.9% to the model at Malkerns and Luve, respectively. AE_K contributed 3.6% and 3.2% to the model at Malkerns and Luve, respectively. PE_K contributed 36.4% and 25.3% to the model at Malkerns and Luve, respectively.

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Table 6. Interaction effects of variety, amendment and location on the uptake efficiency of N, P, and K in shoots from Malkerns and Luve.

Amendment[ǂ]	Malkerns				Luve			
	Lg[†]	Kw	Lm	A x L	Lg	Kw	Lm	A x L
N uptake								
F1	10.04[k]	12.50[i]	10.82[j]	11.12[E]	4.72[j]	6.19[ij]	3.70[j]	4.87[F]
F2	12.85[i]	19.97[e]	13.00[i]	19.56[D]	9.42[hi]	23.03[de]	5.41[ij]	9.48[E]
F3	14.57[h]	22.22[d]	18.50[f]	18.43[D]	12.08[gh]	26.01[cd]	21.37[e]	19.82[D]
F4	19.79[e]	34.90[a]	26.99[c]	27.23[B]	19.42[ef]	40.56[a]	27.71[c]	29.23[A]
F5	15.91[g]	27.59[c]	29.45[b]	24.32[C]	15.97[fg]	35.68[b]	34.39[b]	28.68[AB]
V x L	14.63[D]	23.44[B]	19.75[C]		12.32[D]	26.29[A]	18.52[C]	
P uptake								
F1	1.83	2.16	2.00	2.00[C]	1.32	2.98	2.58	2.29[C]
F2	4.15	5.52	5.28	4.98[A]	2.89	3.91	2.09	2.96[BC]
F3	2.20	4.16	4.03	3.46[B]	3.32	1.43	3.18	2.64[BC]
F4	4.09	5.80	6.78	5.56[A]	1.01	4.12	3.21	2.78[BC]
F5	4.73	5.26	4.29	4.76[A]	2.88	3.68	2.61	3.06[BC]
V x L	3.40[B]	4.58[A]	4.48[A]		2.28[C]	3.22[B]	2.73[BC]	
K uptake								
F1	12.55[e]	14.48[e]	15.11[e]	14.05[G]	10.77[kl]	12.72[jk]	9.02[l]	10.84[H]
F2	18.32[e]	35.27[cd]	18.23[e]	23.94[F]	18.80[i]	44.27[e]	15.89[ij]	26.32[EF]
F3	18.57[e]	35.08[cd]	33.93[cd]	29.19[E]	30.61[h]	43.81[e]	39.34[fg]	37.92[D]
F4	40.55[c]	63.15[a]	52.66[b]	52.12[B]	41.63[ef]	55.29[c]	49.62[d]	48.85[C]
F5	29.41[d]	61.10[a]	57.08[ab]	49.20[BC]	37.58[g]	69.68[a]	60.70[b]	55.99[A]
V x L	*23.88[E]*	*41.82[B]*	*35.4[C]*		*27.88[D]*	*45.15[A]*	*34.91[C]*	

[†]Lg= Ligwalagwala, Kw= Kenya white, Lm= Lamngititi.

[ǂ]F1= Control, F2= 450 kg/ha NPK, F3= 6 t/ha manure, F4= 3 t/ha manure + 225 kg/ha NPK, F5= 4.5 t/ha manure + 112.5 kg/ha NPK.

[ABC] Means with the same letters for interaction effects (uppercase A x L and V x L) across locations are not significantly different from each other (LSD $_{(0.05)}$).

Table 7. Interaction effects of variety, amendment and location on uptake efficiency of N, P, and K in roots at Malkerns and Luve.

Amendment	Malkerns				Luve			
	Lg	Kw	Lm	A x L	Lg	Kw	Lm	A x L
N uptake								
F1	23.04[h]	30.03[g]	23.03[h]	25.37[E]	23.48[i]	27.48[h]	23.68[i]	24.88[E]
F2	33.83[f]	32.80[fg]	30.56[g]	32.40[D]	31.00[h]	35.22[g]	28.06[h]	31.43[D]
F3	70.48[e]	88.57[a]	79.97[c]	79.67[A]	70.14[ef]	89.37[a]	79.69[bc]	79.73[A]
F4	73.39[d]	84.83[b]	73.73[d]	77.32[B]	69.21[f]	83.16[b]	73.23[de]	75.20[C]
F5	78.52[c]	80.63[c]	79.49[c]	79.55[A]	69.06[f]	76.63[cd]	78.51[c]	74.73[C]
V x L	55.85[C]	63.37[A]	57.36[B]		52.58[D]	62.37[A]	56.63[BC]	
P uptake								
F1	10.59	17.13	11.46	13.06	28.50	35.02	31.00	31.51
F2	21.23	31.46	30.90	27.86	50.22	55.80	52.23	52.75
F3	12.30	18.78	15.22	15.43	21.74	54.04	44.71	40.16
F4	13.78	31.41	26.55	23.91	61.23	73.41	68.42	47.02
F5	14.68	25.29	28.13	22.70	64.93	72.24	73.72	7030
V x L	14.52	24.81	27.77		45.32	58.10	54.02	
K uptake								
F1	50.99[h]	59.62[g]	51.12[h]	53.91[F]	67.52[g]	72.10[g]	66.22[g]	68.61[E]

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Table 7. *(Continued).*

Amendment	Malkerns				Luve			
	Lg	Kw	Lm	A x L	Lg	Kw	Lm	A x L
K uptake								
F2	98.32[f]	105.02[e]	95.81[f]	99.72[D]	105.54[ef]	114.86[cd]	100.86[f]	107.09[C]
F3	99.65[f]	112.26[d]	100.33[ef]	104.08[C]	38.49[h]	119.93[c]	109.26[de]	89.23[D]
F4	145.67[c]	176.52[a]	159.52[b]	160.57[A]	151.36[b]	166.43[a]	161.75[a]	159.85[AB]
F5	143.58[c]	163.78[b]	162.84[b]	156.73[B]	148.93[b]	166.36[a]	166.29[a]	160.53[A]
V x L	107.64[D]	123.44[B]	113.92[C]		102.37[E]	127.94[A]	120.88[B]	

[†]Lg= Ligwalagwala, Kw= Kenya white, Lm= Lamngititi. [ɫ]F1= Control (Unamended), F2= 450 kg/ha NPK, F3= 6 t/ha manure, F4= 3 t/ha manure + 225 kg/ha NPK, F5= 4.5 t/ha manure + 112.5 kg/ha NPK. [abc] Means with the same letters (uppercase for A x L and V x L) the interaction effects across locations are not significantly different from each other (LSD $_{(0.05)}$).

Table 8. Combined location effect on the agronomic and physiological efficiency of N, P, and K.

Treatments	Agronomic efficiency			Physiological efficiency		
	N[ɫ]	P	K	N	P	K
Variety (V)						
Ligwalagwala	49.7	141.6	48.8	84.0[b]	274.8	47.9[a]
Kenya white	63.2	177.1	63.0	105.6[a]	283.4	45.5[a]
Lamngititi	48.8	148.1	52.2	67.0[b]	214.4	38.5[b]
Amendment (A)						
Control	-	-	-	-	-	-
NPK 450 kg/ha	98.7[a]	65.8[c]	49.4[c]	166.6[a]	173.7[b]	49.6[b]
6 t ha^{-1} cow dung (CD)	20.3[c]	201.9[b]	39.4[c]	56.7[c]	397.9[a]	50.6[b]
3 t ha^{-1} CD + NPK 225 kg/ha	86.9[a]	219.5[b]	105.0[a]	105.2[b]	369.6[a]	62.4[a]
4.5 t ha^{-1} CD + NPK 112.5 kg/ha	63.6[b]	290.7[a]	79.6[b]	99.0[b]	346.3[a]	57.1[a]
Location (L)						
Malkerns	65.2[a]	187.9[a]	66.2[a]	90.0[a]	274.2[a]	47.0[a]
Luve	42.7[a]	123.3[a]	43.1[a]	81.1[a]	241.1[a]	40.9[a]
Interactions (LSD$_{(0.05)}$)						
V × A	ns[†]	Ns	ns	ns	ns	9.3
V × L	ns	Ns	ns	26.6	ns	ns
A × L	ns	Ns	ns	ns	ns	7.6
V × A × L	ns	Ns	ns	59.5	ns	13.2
CV (%)	55.9	46.4	51.8	43.3	58.7	18.4

[abc] Means with the same letters in a column for each treatment effect are not significantly different from each other (LSD $_{(0.05)}$).

Table 9. Regression analysis between storage root yield and uptake, AE_K and PE_K at Malkerns and Luve.

Index	Partial R^2	Model R^2	F value	Pr>F	Effect size
Model parameters at Malkerns[ɫ]					
Uptake	0.111	0.718	4.020	<0.0001	0.705
AE_K	0.036	0.684	2.173	0.036	0.688
PE_K	0.364	0.678	6.806	<0.0001	0.774
Model parameters at Luve[ɫɫ]					
Uptake	0.249	0.693	5.767	<0.0001	0.661
AE_K	0.032	0.765	2.353	0.024	0.595
PE_K	0.253	0.434	4.280	<0.0001	0.721

[ɫ]Regression equations at Malkerns: K uptake y= 6.435 + 0.207x, where, y= yield, x= K uptake. AE_K y= 25.285 + 0.143x, where, x= AE_K. PE_K y= 21.232 + 0.312x, where, x= PE_K.

[ɫɫ]Regression equations at Luve: K uptake y= 11.800 + 0.112x, where, y= yield, x= K uptake. AE_K y= 19.875 + 0.133x, where, x= AE_K. PE_K y= 20.484 + 0.217x, where, x= PE_K.

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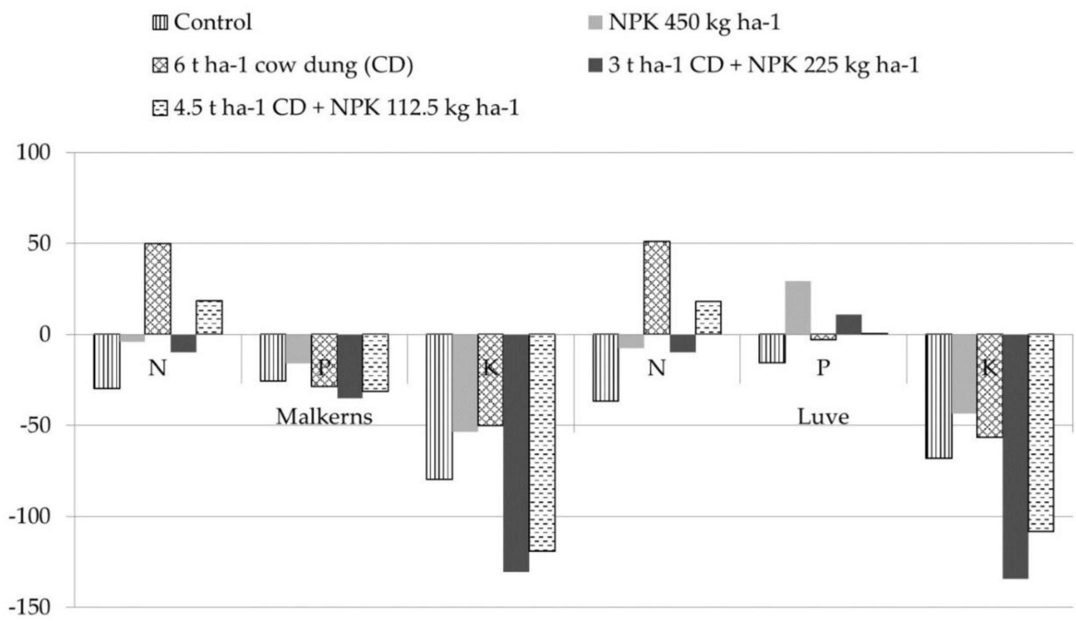

Figure 2. Partial soil nutrient balance at harvest at Malkerns and Luve.

3.6. Partial nutrient budget at harvest

As shown in Fig. 2, a positive nutrient balance indicated potential gains (soil storage), while a negative balance indicated the mining of soil reserves. Net positive N balances were obtained with 6 t/ha manure and 4.5 t/ha manure +112.5 kg/ha NPK at both locations. Net positive P balances were obtained only at Luve with 450 kg/ha NPK fertilizer, 3 t/ha manure + 225 kg/ha NPK and 4.5 t/ha manure +112.5 kg/ha NPK, respectively. The highest negative balances across treatments were for K at either location.

4. Discussion

The present study was undertaken to evaluate the performance of elite sweetpotato cultivars in two environments in terms of nutrient absorption, use efficiency, and partial soil balance after applying manure and inorganic fertilizers together. The highest yield of sweetpotato storage roots across varieties at Malkerns was 50.9 t/ha, obtained with 3 t/ha manure + 225 kg/ha NPK, which represented a yield improvement of 57% and 30%, in comparison to the yield obtained without any soil amendment and inorganic fertilizer application, respectively. At Luve, the highest yield of 36.1 t/ha was obtained with 4.5 t/ha manure + 112.5 kg/ha NPK and represented a yield improvement of 45% and 24%, compared to the yield obtained without any soil amendment and inorganic fertilizer application, respectively. The yield improvement over NPK fertilizer suggests that it is possible to reduce the mineral N fertilization in sweetpotato when combined with manure. The combined application enhances uptake and use efficiencies evidently untenable with singular application of either.

The soil nutrient status was low for sweetpotato production at both sites. There was a 68% difference in soil OC between the two sites and over 97% difference between the sites and OC in manure. Soil OM (and the carbon it contains) significantly influences on the physicochemical and hydraulic properties of highly weathered soils [40]. Given the below- average and poorly distributed rainfall at Luve, coupled with 87% sand content that contributes to low water holding capacity, the influence of soil moisture stress on plant nutrient response cannot be discounted for a 23% less yield compared to Malkerns.

The higher yield obtained through the combined application of fertilizer and manure to the soil can also be related to not only the rates applied, but additionally to optimal nutrient ratios. The yield obtained with 3 t/ha manure + 225 kg/ha NPK at Malkerns or 4.5 t/ha manure + 112.5 kg/ha NPK were where the ratio of N to K approximated 1:1. Byju and George [41] reported that the greatest tuber

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enlargement occurs when the fertilizer N:K ratio is low, preferably less than 1:3, with the optimum being influenced by the soil C:N ratio (on par between sites in the present study). In addition, even given the cited ratios, application of 6 t/ha manure or 4.5 t/ha manure + 112.5 kg/ha elevated N levels to the detriment of the agronomic efficiency of N, similar to other studies [42]. Enhanced N levels adversely affect the development of storage root numbers through increased shoot competition for photosynthates [43].

Combined manure and fertilizer application generally showed greater uptake efficiency for N and K than the sole treatment of either amendment. At Malkerns and Luve, the combined treatments represented about 42% and 46% uptake enhancement for N, and 64% and 58% for K, respectively, over the sole inorganic fertilizer application. O'Sullivan et al. [34] estimated that a crop yielding 12 t/ha would remove 52 kg N/ha, 90 kg K/ha, and 9 kg P/ha, of which 50% (N) and 33% (P and K), respectively, would be in the foliage. In the present study, across the two sites, 26 – 32% of N and 20 – 25% of K were found in the shoots, showing a measure of constancy in nutrient partitioning with soil nutrient levels. This despite removal of about 104 kg N/ha and 209 – 213 kg K/ha in combined soil amendment versus removal of 44 – 47.7 kg N/ha and 133.4 – 123.6 kg K/ha in sole fertilizer application. The importance of the need for elevated levels of K nutrition is supported by regression analysis that showed uptake, AE_K and PE_K as the primary significant variables influencing yield. This also suggests that K levels applied were insufficient to optimise crop productivity. Potassium deficiency is reported to have a greater effect on storage root yield than on the plant canopy, unlike N and P deficiency [41]. Root yield response to the addition of K has been shown to be linear, with approximately 1.2 t/ha per 28 kg/ha of applied K [44]. Animal manures have been reported to yield low levels of K compared to compost of plant materials which contain high K relative to N [45]. Therefore, wholesale recommendations for the use of manure in sweetpotato or other crops in small-scale agriculture should take cognisance of the type of manure with respect to nutrient concentration and ratios.

Various work claims a very low response of sweetpotato to P amendments [46]. The three varieties were not consistently distinguished in terms of shoot uptake, AEP, and PE_P. The PE_P was twofold significantly greater where inorganic fertilizer was used against the control. However, the AE_P for all combined fertilizer and manure treatments were four- to five-fold greater than for sole inorganic fertilizer application, even though the combined treatments had two to four times less P applied. It is noted that sole manure application or mixing manure with fertilizer had a substantive impact on AE_P and PE_P. This performance may have resulted from the alleviation of soil or crop growth constraints associated with these low OM and acidic soils that exhibit elevated levels of iron [47]. These properties are a precursor to the binding of P to aluminium and iron hydrous oxides, rendering it unavailable to plant roots. Sweetpotato is known to form vesicular arbuscular mycorrhizae, increasing plants' ability to take up P in low P soils [48]. Organic matter decomposition purportedly yields a steady source of plant-available P even in exceedingly P-fixing soils [34]. It is unlikely that soils in the study benefited from this source of P owing to their state of OM impoverishment.

A soil nutrient budget, based on the soil-plant system, was adopted and consisted of synthetic fertilizer and manure as inputs, whereas the harvested crop product and residues comprised the output. The dynamic nutrient exchanges within the soil and between the soil and plants are considered as internal processes [49] and were not accounted for in the input/output budget. A net positive soil N balance was obtained with higher levels of manure at 6 t/ha and 4.5 t/ha manure +112.5 kg/ha NPK at both locations, notwithstanding compromised crop uptake and use efficiency. Lower manure rates (3 t/ha), although combined with an elevated level of NPK fertilizer (225 kg/ha), were insufficient to yield a soil N balance. Net positive P balances were obtained at Luve. The positive P balance may have been derived from inorganic fertilizer amendment, as it declined with lower rates of P fertilizer input. The positive balance at Luve could be attributed to the impact of the poor rainfall regime on the yield response to P, whose uptake relies on a judicious soil moisture regime for solubility and mobility. Potential

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accumulation or depletion of nutrients and P within the soil environment and possible outflows from cropland into the environment necessitate balanced P inputs and outputs.

Compared to N and P, K showed the highest negative soil balance across treatments and sites. Soil and crop management factors are known to contribute to the occurrence of K deficiency. For example, removal of crop stover from the field, a typical practice in Eswatini, potentially hastens the depletion of K. It is often argued that organic materials are less of a source of nutrients than soil conditioners owing to their large contribution to soil OM content [50]. Nonetheless, the impact of their contribution to positive nutrient flow (such as K, unlike animal manure) and stemming negative flows in cropping systems provide a context in support of appropriate technologies for their retention in or transfer to cropping environments. This potential remains portrayed as a challenge to their use towards enhancing long-term soil and crop productivity in low-resourced farming environments [2].

This study focused on the uptake and utilisation efficiencies of N and P that constitute the most common nutrients in fertilizers and manure. However, numerous studies have shown crosstalk between these and other nutrient elements [51]. For example, Cl^- enhances N use efficiency, Mg^{2+} enhances remobilisation of other mineral nutrients within the plant and biomass productivity, or increases in plant performance under limited moisture regimes from adequate zinc nutrition. Yield limitation is perverse under nutrient or moisture-constrained environments, such as Luve, and therefore, could occur not only as a consequence of intrinsically low levels of NPK but also excess or low availability of other nutrients that influence metabolism.

The individual performances of the three varieties were neither consistently nor significantly distinguished from each other in terms of yield between the two sites and nutrient utilisation efficiency indices. The variety x location interaction effects were not significant for AE and PE but were significantly and consistently ranked between locations. In addition, varieties showed similar lowest PE under elevated N at 6 t/ha manure or 4.5 t/ha manure +112.5 kg/ha NPK at both locations. The shorter crop duration for Ligwalagwala could have suggested a faster nutrient accumulation rate that nonetheless does not connote the ability to convert the nutrients absorbed by the crop into storage utilisation. Similar to other local studies [52], Kenya white variety produced higher yield than the other two varieties at either location, suggesting a high resilience to environmental constraints. In general, at different levels of nutrient application, the three varieties invariably showed comparable values for the different NUE indices. Thus, the results did not establish the suggestion that varietal traits associated with the acquisition and uptake of nutrients become important under low-resourced environments, whereas traits related to utilisation become important under less limiting nutrient availability [53]. Minemba et al. [46] also reported limited genetic and phenotypic variation in P efficiency in sweetpotato. They sought other morpho-physiological traits among cultivars conferring adaptation to low P.

The implications of inconsistent varietal nutrient efficiency also suggest that while the application of mineral and/or organic inputs to improve sweetpotato varieties will boost yield, cropping systems where such inputs are inappropriately managed will yield unpredictable dividends to extant or improved germplasm. Additionally, the elevated levels of N in 6 t/ha of manure that depressed agronomic efficiency, elevated levels of soil residual P at Luve, or the inability to satisfy crop demand for K, showed that adapting manure and fertilizer types and rates used elsewhere or in other crops may be inappropriate for sweetpotato unless founded on critical research in different cropping environments.

5. Conclusions

This study demonstrated that the combined application of manure and inorganic fertilizer, even at lower rates, doubled the uptake efficiencies of nitrogen and potassium and significantly improved the yield of sweetpotato crops over unamended or fertilised. The practice improved nutrient use efficiency without reducing productivity. To deter the use of unaffordable inorganic fertilizers and improve practices reliant on the sole application of manure,

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studies that optimise nutrient ratios by combining different sources or types of manure are suggested.

This study also suggests the importance of organic matter or manure to avert the P-fixing capacity of tropical soils or degraded soils with low P availability. Unlike for nitrogen and potassium, AE_P was improved three to fivefold, while PE_P was doubled with the combined application of manure and inorganic fertilizer compared to the sole application of the later. Uptake, AE_K and PE_K were the only significant variables to enter the regression yield model at both locations. This suggests the need to address the deficiency or imbalance of potash amendments to enhance nutrient synergy in sweetpotato cultivation.

Through a partial nutrient budget, the study showed that the application of manure and/or fertilizer did not consistently abate the negative balance of soil nutrients. The notion that sweetpotato thrives on marginal soils or is not subject to fertilizer investment may continue to exacerbate the mining of major nutrients from already impoverished soils. However, sweetpotato is an important cash and food security crop given the incessant climate variability and the advent of climate change in the region. Noting that inorganic fertilizer is an expensive commodity, the study suggests that a modest combination of inorganic fertilizer and manure will enhance crop and soil productivity through enhancing uptake or use efficiency in soils with poor nutrient regimes, as encountered in this study.

The three varieties studied, Kenya white, Ligwalagwala, and Lamngititi, showed significant overlap in terms of yield and nutrient use efficiency, although the Kenya white exhibited overall superior performance. There is a need to identify and exploit extant variability in nutrient use, among other crop improvement attributes, as this crop is considered to be adapted to marginal environments.

Disclaimer (artificial intelligence)

Authors hereby state that no generative AI tools such as Large Language Models (ChatGPT, Copilot, etc.) and text-to-image generators were utilized in the preparation or editing of this manuscript.

Authors' contributions

Conceptualization, data curation, formal analysis, funding acquisition, investigation, and methodology, S.K.T., H.R.M.B., C.T.; project administration, resources, and software were taken care of by H.R.M.B., O.A.O.; project supervision, validation and visualization were done by H.R.M.B., C.T.; written by the first draft, S.K.T., review the drafted manuscript and editing, H.R.M.B., C.T., O.A.O.

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Availability of data and materials

All data will be made available on request according to the journal policy.

Conflicts of interest

The authors declare no conflict of interest.

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