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Impact of NPK and CAN fertilizers on tobacco performance and economic returns under three major soil types of Tabora, Tanzania

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Abstract

Soil fertility has become the major issue in tobacco cultivation leading to low yield, poor leaf quality and low income. This study investigated how combinations of NPK and CAN fertilizers influence tobacco yield, quality and economic benefit in three major soil types of Sikonge, Tabora, and Uyui districts identified through a study that delved into pedological characterization, shedding light to execution of this present research.

Soil analysis identified various nutrient deficiencies and characteristics that guided fertilizer application strategies. Factorial experiments in randomized complete block design (RCBD) of three replications and five treatment combinations performed. Three sites with 225 experimental plots all running together within a replicate blocks with a total of 75 experimental plots per site was designed. An individual experimental plot measured 40 m length 10 m width, with six ridges each of 37.5 m long, 0.2 m hips prepared. Seedlings transplanted 1 m between ridges, 0.5 m between holes. Application of NPK was 14 days after transplanting, CAN was applied 7 days later. Fertilization of 700 kg ha⁻¹ NPK and 175 kg ha⁻¹ CAN resulted in higher number of leaves and barn dry weight (kg) throughout the sites. Sikonge, 600 kg ha⁻¹ NPK and 175 kg ha⁻¹ CAN provided high economic returns. Similarly, Tabora 500 kg ha⁻¹ of NPK, 125 kg ha⁻¹ of CAN enhanced higher economic benefit. Uyui, highest economic return at 700 kg ha⁻¹ NPK and 175 kg ha⁻¹ CAN. The study advocates for precision in fertilizer applications tailored to address identified soil nutrient deficiencies.

Keywords: Fertilizer application; profitability analysis; yield improvement

Introduction

Tobacco (*Nicotiana tabacum*), a major global cash crop, plays a significant role in the agricultural economies of many countries (Rehman *et al.* 2019) ^[23]. The global production of tobacco is concentrated in a few leading countries, with China, Brazil, and India dominating the market (Kuboja *et al.* 2012; Mavroeidis *et al.* 2023) ^[12, 20]. China is the largest producer, accounting for approximately over 40% of the world's output, followed by Brazil and India, which contribute significantly to the global supply (Wilkinson *et al.* 2015; Sporchia *et al.* 2021) ^[30, 33]. Africa has seen a notable increase in tobacco cultivation, with countries like Zimbabwe, Malawi, and Tanzania being prominent players (Saloojee, 2004) ^[24].

In Africa, tobacco is a critical agricultural commodity, providing substantial economic benefits and employment opportunities (Larsen and Gillett, 2017) ^[13]. Tanzania, in particular, stands out as one of the key tobacco-producing countries in the region (Ilembo *et al.* 2017) ^[8]. Several regions in Tanzania known for tobacco cultivation, with the Tabora, Shinyanga, Mbeya, Katavi, kigoma and Ruvuma regions being major hubs. These regions experience suitable climatic conditions and fertile soils, which support extensive tobacco farming, in particular, contribute significantly to the country's tobacco production, which is vital for Tanzania's economy due to its export value. According to Tanzania Tobacco Board (2024), Tabora region contribute 52% of all the tobacco produce in the country. The yield of tobacco per hectare, although relatively high, often falls short of the potential yield due to suboptimal farming practices and insufficient use of modern agricultural inputs (Larsen & Gillett, 2017) ^[13].

The average yield in Tanzania ranges from 1,000 to 1,400 kg ha⁻¹, whereas the potential yield could exceed 2,000 kg ha⁻¹ with the application of advanced farming techniques and proper fertilizer management (Jew *et al.* 2017) ^[9].

Tobacco farming practices in Tanzania typically involve manual labour and traditional methods. However, the adoption of improved production practices, including the use of fertilizers containing nitrogen (N), phosphorus (P), and potassium (K) as NPK and calcium ammonium nitrate (CAN), has shown promise in enhancing tobacco growth and yield. These fertilizers supply essential nutrients that are often deficient in the soil, thereby improving plant health and productivity. The importance of tobacco to Tanzania's economy cannot be overstated. However, optimizing tobacco production to achieve higher economic returns necessitates understanding the effects of different fertilizers on crop performance across various soil types.

In Tanzania, tobacco is basal applied with NPK (10:18:24) within 14 days after planting in rates of 500 kg ha⁻¹ and top-dressed by CAN (27% N) applied at 125 kg ha⁻¹ in 21 days after planting. However, this application does not consider the individual soils types. The productivity of tobacco also determined by suitable weather conditions, like 500-1000 mm annual rainfall and 20-30 °C temperature during its growth period. Tobacco cannot stand if rainfall is more than 1000 mm (Kheawfu *et al.* 2021) ^[11].

The quantity of tobacco produced through various strategies always expected to translate into overall quality of cured leaves for the market value. Tobacco classification, quality evaluation or grading of the flue-cured tobacco leaves are other factors considered, but rely on the judgmental experience of experts, and inevitably limited by personal, physical and environmental factors (Zhang and Zhang, 2011) ^[31]. Quality in tobacco leaf expressed as the physical appearance of the cured tobacco leaf that is size, colour, leaf body, texture and cleanness (Lisuma, 2020).

The cured tobacco leaves are graded according principles, such as position of the leaf in the stalk, percentage of cleanliness, size, and colour (Zhang and Zhang, 2011) ^[31].

Materials and Methods

Description of the experimental sites

This study was conducted in Tutuo, Isikizya and Kipera villages found in Sikonge, Uyui districts and Tabora municipal, respectively in Tabora region of Tanzania. These districts lie between latitudes 05°47'775" S, 04°86'294" S and 05°14'055" S and longitudes of 032°65'686" E, 033°10'862" E, and 032°68'026" E respectively (Fig.1). The region experiences unimodal rainfall patterns, starting from November ends in March.

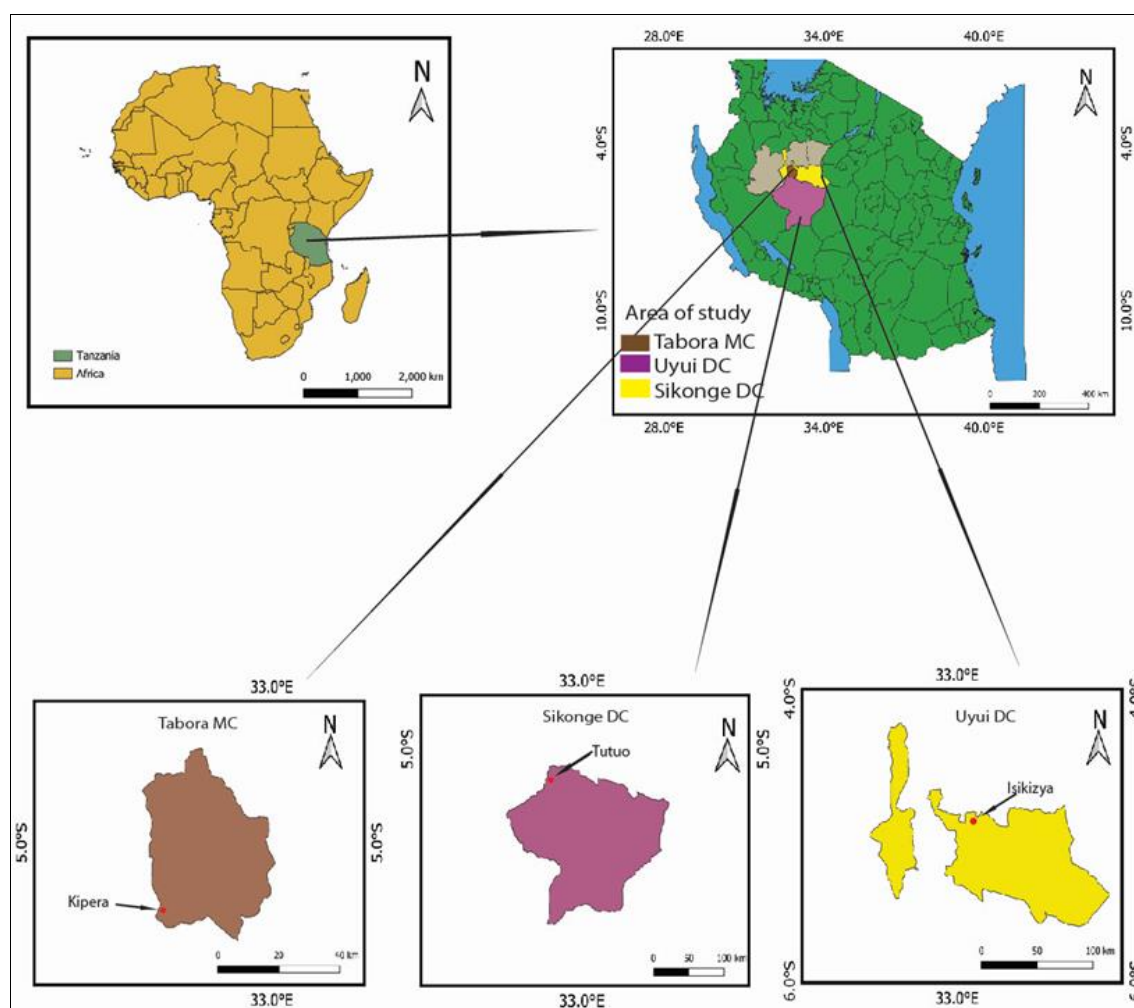


Fig 1: Map showing study site

Field experiments and laboratory analysis

A 20 m long and 1.5 m wide nursery seedbed established in each site in September 2022. A 3 g of FCV tobacco seeds (variety K326) sourced from Alliance One Tobacco Tanzania Limited was sown. This is a commonly cultivated variety, adapted in the area and attracts high market prices. At 30 days after sowing, seedlings were re-set onto secondary seedbeds of 10 m long and one wide at a spacing of ~ 3 cm by 3 cm using black-cotton soil potted polythene tubes. At 30 days after re-setting, the seedlings were ready for transplanting. Composite soil samples systematically collected in a zigzag pattern from each experimental site, reaching a depth of 0-30 cm prior to transplantation. Subsequently, these soil samples underwent laboratory analysis to determine their physical and chemical properties, adhering to established protocols.

Experimental design and treatments

Factorial experiments of N₁₀P₁₈K₂₄ and CAN (27% N) combinations were laid down in a randomized complete block design (RCBD) in three replications. There were five treatment combinations making total of 25 treatments running together within a replicate block (Table 1), which constituted 75 experimental plots. An individual experimental plot measured 40 m length and 10 m width, with six ridges each of 37.5 m long and 0.2 m hips. Seedlings transplanted at 1 m between rows (inter-row) and 0.5 m between planting holes within a row (intra-row) in each ridge, with transplanting of tobacco seedlings (Fig 2 (b)). The application of N₁₀P₁₈K₂₄ was done 14 days after transplanting, while CAN (27% N) fertilizer was applied 7 days later (21 days after transplanting). Similar experiments were conducted in three sites of Tabora region, characterized by contrasting major soil types, which are Isikizya site in Uyui district (predominantly Mollisols), Tutuo site in Sikonge district (predominantly Alfisols), and Kipera site in Tabora municipal (predominantly Oxisols). Therefore, for three sites did 225 experimental plots all constitute the same research theme.

Table 1: Fertilizer treatments and their combination strategies

(N ₁₀ P ₁₈ K ₂₄) (kg ha ⁻¹)		(CAN 27%N) (kg ha ⁻¹)				
		0	100	125	150	175
		I				
T		I0	I1	I2	I3	I4
Treatment combinations*						
0	T0	T0I0	T0I1	T0I2	T0I3	T0I4
400	T1	T1I0	T1I1	T1I2	T1I3	T1I4
500	T2	T2I0	T2I1	T2I2	T2I3	T2I4
600	T3	T3I0	T3I1	T3I2	T3I3	T3I4
700	T4	T4I0	T4I1	T4I4	T4I3	T4I4

*Symbols plots and values represent individual treatment combinations that randomly assigned to each replicate block. Each replication had 25 experimental.

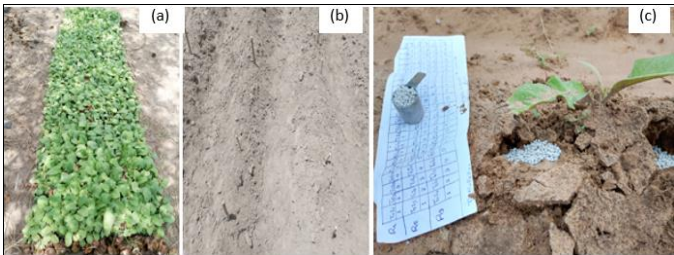


Fig 2: a) Tobacco seedlings in a nursery, b) Field lay out of an experimental plots and c) NPK fertilizer application

Data collection

One among four tobacco plants in each plot randomly selected and tagged with laminated tags at each treatment combination. Growth parameters (plant height, leaf length and width and number of leaves) recorded. The data for growth parameters collected by measuring the plant height, number of leaves, and leaf length and width in three growth phases. The first phase was 14 days after planting (before NPK basal fertilization). The second phase recorded in the 42 days after planting (21 days after top-dressing with CAN). The final growth data taken on 84 days after planting (6 days before harvesting commenced). The leaves full ripened at 90 days after transplanting, harvesting done by handpicking. The leaves were graded, labelled and tied in the sticks by using jute twine ropes. The sticks were loaded in the barns and hanged in the barn rakes, then fire was set and temperature controlled within the curing barns by using thermometer. The tobacco leaves left in the barns for 9 days until well dried. The vents of the curing barns opened to allow the dried leaves to cool by natural air. After cooling, the leaves were grouped (graded) based on their similarities (size, colour, leaf body, texture, cleanness and other factors). After grading, the authorized Tobacco Classifier from Tanzania Tobacco Board invited to assign grade names for each similar leaves. The dry leaves measured using digital weighing balance to determine the total produce (kg ha⁻¹) for each experimental plot.

Economic benefits

The partial budget analysis calculated to determine the benefits derived from costs associated with tobacco production using NPK and CAN fertilizers, following steps described by Shaaban and Kisetu (2014) [25] and Tlatlaa *et al.* (2024) [29]. Shaaban and Kisetu (2014) [25] indicated that the benefit to cost ratio (BCR) simplifies decision-making in economic profitability. Tlatlaa *et al.* (2024) [29] indicated that gross benefit alone does not provide concluding results if benefit to cost ratio is not considered. The costs for a 50 kg capacity bag of N₁₀P₁₈K₂₄ and CAN (27% N) fertilizers during the 2022/23 cropping season were USD 70.72 and USD 59.99, respectively. In this experiment, one bag of each fertilizer type was sufficient for the entire experiment. However, specific amounts of each fertilizer used in a site adjusted accordingly to reflect their actual market values for the quantities applied. Therefore, these costs converted into 1 kg of fertilizer to give USD 1.41 and USD 1.20 for NPK and CAN, respectively. Assuming that all other variable costs uniformly distributed across experimental sites, only costs for fertilizers and person-days for fertilizer applications considered (Tlatlaa *et al.*, 2024) [29]. After converting the total average yield per hectare of each fertilizer combination, the produce subjected to the 2022/23 market price matrix with an average price of USD 2 per kilogram of cured tobacco, at an exchange rate of one USD being TZS. 2344 on April 01, 2023. The gross benefit (GB) was determined by using Equation 1.

$$GB = A_{vp} \times Y$$

(1)

Where A_{vp} is average price; Y = Yield (kg ha⁻¹)

The marginal return (MR) was determined by subtracting the total variable costs (TVC) from the GB. The benefit to cost ratio (BCR) was determined by dividing GB by TVC.

Statistical data analysis

The data on growth and yield parameters subjected to a two-way

analysis of variance (ANOVA) with experimental sites forming the whole plot, fertilizer combinations forming the sub-plot and replicate blocks treated as random effect. The sites considered under whole plot during statistical analysis since the main interest, as a contributing factor is the fertilizer combination, tested across contrasting soil types. The significant treatment means among sites were compared through the least significant difference (LSD) while the significant differences due to NPK and CAN fertilizers' combinations and/or their interactions with the sites were compared using standard errors of differences of means (S.E.D.) at a 5% threshold by Tukey's Honest post hoc. Descriptive statistics engaged for data on leaf quality to compute the mean percentage quality for each fertilizer combination. On the other hand, the data on economics subjected to a one-way analysis of variance with each experimental site treated

independently and only fertilizer combinations considered a factor and replications as random effect. The significant means compared through the standard errors of differences of means (S.E.D.) at a 5% threshold by Tukey's Honest post hoc. In addition, simple linear regression analysis was performed between fertilizer combinations and economic indicators (gross benefits, marginal return/net benefit, and benefit to cost ratio) to unveil the significantly highest economic return from fertilizer combinations as described by Tlatlaa *et al.* (2024)^[29].

Results
Physical and chemical properties of the soils in the study areas
The physical and chemical soil properties for Uyui, Sikonge, and Tabora sites presented in Table 2 and Table 3.

Table 2: Soil chemical properties for the three sites

Location	pH	EC1:2.5	Ca	Mg	K	Na	BS	CEC	ESP	OC	Total N
	(H ₂ O) 1:2.5	(mS cm ⁻¹)	(cmol ⁺ kg ⁻¹)				%				
Uyui	5.28	0.032	0.57	0.73	0.21	0.02	19	8	0.3	1.3	0.022
Sikonge	4.42	0.068	0.84	1.79	0.33	0.09	22	14	0.7	1.75	0.039
Tabora	4.49	0.078	0.49	1.01	0.07	0.02	10	16	0.2	0.89	0.014

Key: BS=Base saturation; CEC=cation exchange capacity; ESP=exchange sodium percentage; OC=organic carbon

Table 3: Soil chemical and physical properties for the three sites

Location	P	Cu	Fe	Zn	Mn	S	Sand	Silt	Clay	T.C.	BD
	mg kg ⁻¹	(mg kg ⁻¹)					%				(g cm ⁻³)
Uyui	22.44	21.25	139.5	4.14	148.45	6.04	84	11	5	LS	0.93
Sikonge	33.83	4.98	520.5	0.4	167.96	8.44	76	9	15	S L	1.97
Tabora	12.74	6.36	376.5	1.44	166.35	13.87	66	11	23	SCL	1.4

Key: T.C = textural class; BD=Bulk density; S= sulphur; Mn = manganese; Zn = zinc; Fe= iron, Cu=copper; AvP= Available P

Effects of NPK and CAN fertilizer application on tobacco performance
Plant height measurements showed that Uyui achieved the highest recorded height of 119.7 cm when applying 700 kg NPK ha⁻¹ and 175 kg CAN ha⁻¹, Sikonge followed closely with a plant height of 109.9 cm under the same fertilizer application, while Tabora reached 109.0 cm with 600 kg NPK ha⁻¹ and 150 kg CAN ha⁻¹. In terms of leaf length, Uyui exhibited the longest leaves at 76.0 cm with 700 kg NPK ha⁻¹ and 175 kg CAN ha⁻¹, followed by Sikonge with 65.4 cm using 600 kg NPK ha⁻¹ and 125 kg CAN ha⁻¹ and Tabora at 63.3 cm with 700 kg NPK ha⁻¹ and 175 kg CAN ha⁻¹. Leaf width measurements showed Uyui with the widest leaves at 36.3 cm under 700 kg NPK ha⁻¹ and 175 kg CAN ha⁻¹, Sikonge with 28.7 cm using 600 kg NPK ha⁻¹

and 125 kg CAN ha⁻¹, and Tabora with 24.7 cm under 700 kg NPK ha⁻¹ and 175 kg CAN ha⁻¹. The highest number of leaves per plant observed in Uyui (19) under application of 700 kg NPK ha⁻¹ and 175 kg CAN ha⁻¹, followed by Sikonge (18) and Tabora (16) with the same fertilizer combinations
Figure 3. presents the means for tobacco barn dry weight (kg), demonstrating the effects of fertilizer treatments and sites on yield, the results demonstrated Uyui achieving the highest leaf barn dry weight (kg) of 2201 kg ha⁻¹ with 700 kg NPK ha⁻¹ and 175 kg CAN ha⁻¹, followed by Sikonge with 1916 kg ha⁻¹ under the same fertilizer regime, and Tabora with 1753 kg ha⁻¹ following the same application. The lowest yields were recorded in the absolute control, with 217 kg ha⁻¹, 163 kg ha⁻¹, and 96 kg ha⁻¹ for Sikonge, Uyui, and Tabora, respectively.

Table 4: Analysis of variance (ANOVA) for the tobacco growth parameters and leaf dry weight (yield) as affected by sites, fertilizer combinations and their interactions

Source of variation	d.f.	Plant height			Leaf length			Leaf width			Number of leaves per plant			Leaf dry weight		
		m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.	m.s.	v.r.	F pr.
Replication	2	87.6	0.4		565.2	6.6		86.6	4.6		0.284	0.15		371853	4.42	
Sites	2	953.9	4.35	0.099	1021.3	11.8	0.021	488.4	25.8	0.005	13.471	6.93	0.05	637536	7.57	0.044
Residual	4	219.2	2.64		86.3	1.5		18.9	1.2		1.944	1.14		84170	1.6	
Fertilizers	24	1466.9	17.7	<0.001	327.1	5.8	<0.001	58	3.7	<0.001	26.851	15.74	<0.001	2781032	52.75	<0.001
Sites × Fertilizers	48	75.8	0.91	0.631	59.6	1.1	0.383	22.5	1.4	0.059	2.837	1.66	0.011	59459	1.13	0.29
Residual	144	82.9			56.1			15.8			1.706			52726		
Total	224															

Key: d.f. = degree of freedom; m.s. = mean sum of square; v.r. = variance; F pr. = probability

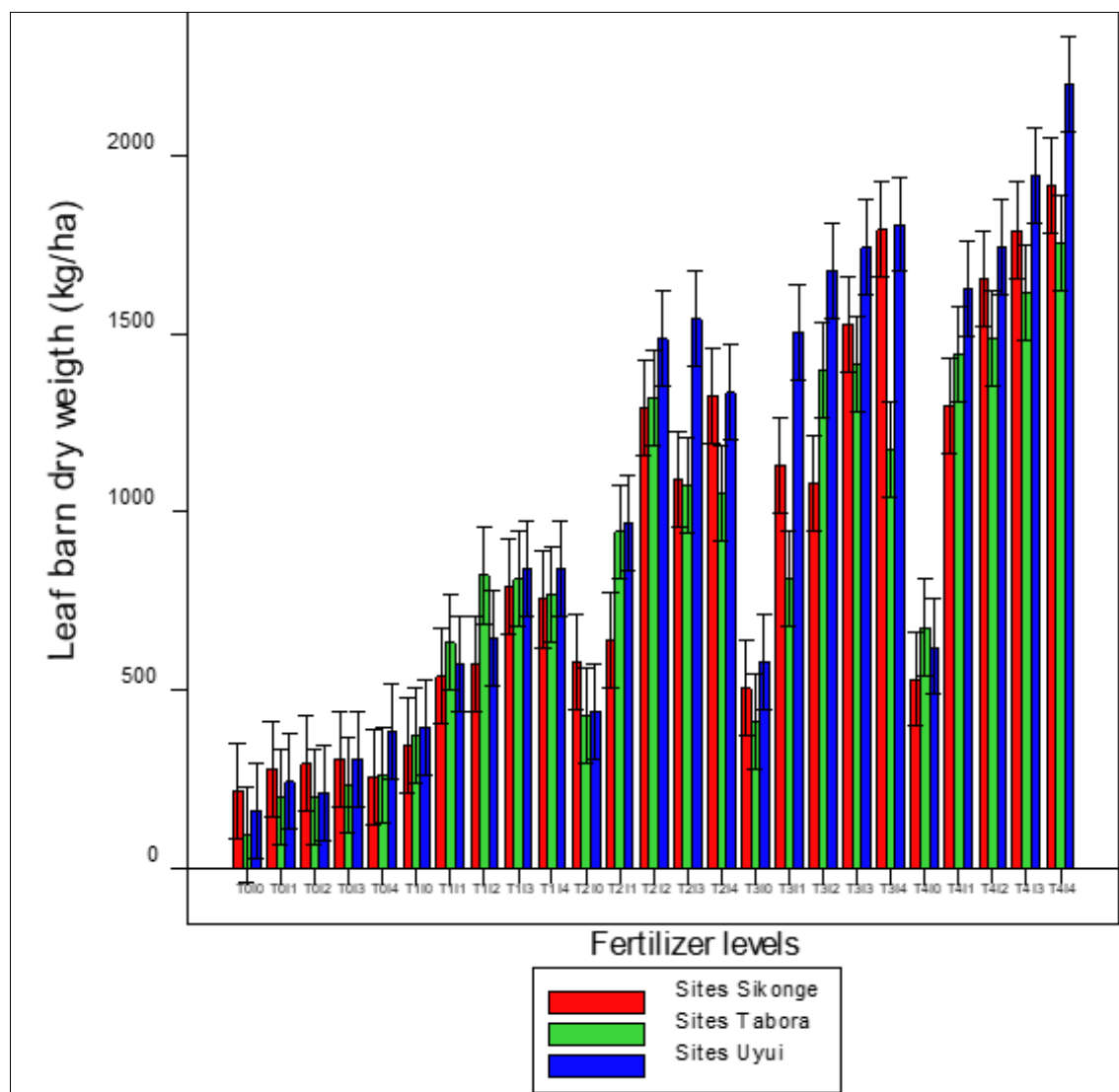


Fig 3: Means for the tobacco barn dry weight as affected by the interactions of fertilizer treatments and sites

Furthermore, the results provided a detailed breakdown of tobacco quality grades influenced by various

fertilizer combinations across Uyui, Sikonge, and Tabora sites (Figure 4).

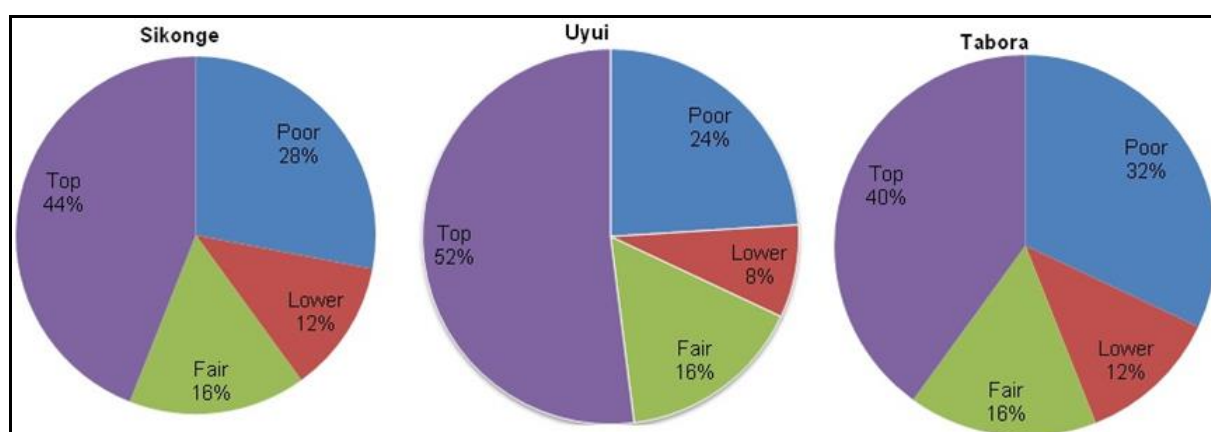


Fig 4: Percentage of total grades for tobacco quality recorded in Sikonge, Uyui and Tabora sites

Economic feedbacks from NPK and CAN fertilization on tobacco

The data in Table 5, tells the economic benefits of various fertilizer combinations on tobacco crop across Sikonge, Tabora, and Uyui. Economic analysis revealed that the gross benefit (GB) increased significantly with varying rates of NPK and

CAN application. For instance, in Sikonge, the GB ranged from \$434 with no fertilizer to \$3,588 with the combination of 600 kg ha⁻¹ NPK and 175 kg ha⁻¹ CAN. Marginal returns (MR) and BCR for Sikonge were \$2529.4 and 3.4, respectively at the same level of fertilizer combinations. In Tabora, the GB and MR increased from \$192 with no fertilizer to \$2,642 and \$1785,

respectively while the BCR was 3.1 with the combination of 500 kg ha⁻¹ NPK and 125 kg ha⁻¹ CAN fertilizers. In Uyui, the GB and MR increased from \$326 with no fertilizer to \$4,407 and \$3202, respectively while the BCR was 3.7 with the combination of 700 kg ha⁻¹ NPK and 175 kg ha⁻¹ CAN fertilizers.

The benefit-cost ratios observed in varying NPK and CAN doses, demonstrating that more intensive fertilizer use can significantly improve economic outcomes. However, the optimal fertilizer combination varied by location, with Uyui showing the highest profit from the highest fertilizer combinations.

Table 5: Gross benefit, marginal return and benefit to cost ratio of tobacco following strategic application of NPK and CAN fertilizers

Fertilizers			Sikonge			Tabora			Uyui		
	NPK (kg ha ⁻¹)	CAN (kg ha ⁻¹)	GB (USD)	MR (USD)	BCR	GB (USD)	MR (USD)	BCR (USD)	GB (USD)	MR (USD)	BCR (USD)
ToI ₀	0	0	434g	434efg	0	192i	192cde	0	326g	326ef	0
ToI ₁	0	100	558g	438efg	4.7a	398hi	2778ade	3.3a	486fg	366ef	4.1a
ToI ₂	0	125	588g	438efg	3.9ab	400hi	250cde	2.7a	426g	276f	2.8a-d
ToI ₃	0	150	614g	434efg	3.4abc	468ghi	288cde	2.6a	614fg	434ef	3.4abc
ToI ₄	0	175	514g	304fg	2.4abc	528f-i	318cde	2.5ab	772fg	562ef	3.7ab
TiI ₀	400	0	688g	122.2fg	1.2cd	746e-i	180.2cde	1.3ab	794fg	228.2f	1.4cde
TiI ₁	400	100	1076fg	390.3efg	1.6bcd	1268d-i	582.3b-e	1.9ab	1148fg	462.3ef	1.7b-e
TiI ₂	400	125	1146efg	430.3efg	1.6bcd	1644b-i	928.3a-e	2.3ab	1290efg	574.3ef	1.8b-e
TiI ₃	400	150	1586d-g	840.3d-g	2.1bcd	1624b-i	878.3a-e	2.2ab	1682d-g	936.3c-f	2.3a-d
TiI ₄	400	175	1510d-g	734.3d-g	1.9bcd	1538c-i	762.3a-e	2.0ab	1680d-g	904.3def	2.2a-d
T2I ₀	500	0	1156efg	448.8efg	1.6bcd	856e-i	148.8de	1.2ab	880fg	172.8f	1.2de
T2I ₁	500	100	1284efg	456.8efg	1.6bcd	1888a-h	1061a-e	2.3ab	1938c-f	1111b-f	2.3a-d
T2I ₂	500	125	2584bcd	1726.8a-d	3.0abc	2642a-d	1785a-d	3.1a	2974a-d	2117a-d	3.5abc
T2I ₃	500	150	2188cdef	1300.8b-f	2.5abcd	2150a-f	1263a-e	2.4ab	3086a-d	2199a-d	3.5abc
T2I ₄	500	175	2656a-d	1738.8a-d	2.9cd	2102a-g	1185a-e	2.3ab	2672b-e	1755a-e	2.9a-d
T3I ₀	600	0	1008fg	159.4fg	1.2cd	828e-i	20.6e	1.0ab	1162fg	313.4ef	1.4cde
T3I ₁	600	100	2266cde	1297.4b-e	2.3abcd	1626b-i	657.4a-e	1.7ab	3010a-d	2041a-d	3.1a-d
T3I ₂	600	125	2158c-f	1159.4c-g	2.2abcd	2800a-d	1801a-d	2.8a	3360abc	2361abc	3.4abc
T3I ₃	600	150	3056abc	2027.4abc	3.0abc	2826a-d	1797a-d	2.8a	3488ab	2459ab	3.4abc
T3I ₄	600	175	3588ab	2529.4a	3.4abc	2352a-e	1293a-e	2.2ab	3616ab	2557ab	3.4abc
T4I ₀	700	0	1064fg	73.9g	1.1cd	1354c-i	363.9ade	1.4ab	1244efg	253.9f	1.3de
T4I ₁	700	100	2602bcd	1491.9a-e	2.3abcd	2884a-d	1774a-d	2.6ab	3256abc	2146a-d	2.9a-d
T4I ₂	700	125	3310abc	2169.9abc	2.9cd	2980abc	1840abc	2.6ab	3492ab	2352a-d	3.1a-d
T4I ₃	700	150	3584ab	2414ab	3.1abc	3234ab	2064ab	2.8a	3888ab	2718a	3.3a-d
T4I ₄	700	175	3832a	2632a	3.2abc	3506a	2306a	2.9a	4407a	3202a	3.7ab
S.E.D.			305	305	0.6	433.1	433.1	0.6	375.7	357.7	0.5
p-value			<0.001	<0.001	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	<0.001

Key: T_nI_n = Fertilizer combinations; GB=gross benefit; MR=marginal return; BCR = benefit cost ratio. *Means along the same column in a specific factor category bearing different letter(s) differ significantly; otherwise, they are similar according to Turkey's HSD test.

Table 6: Analysis of variance for gross benefit, marginal return and benefit to cost ratio of tobacco following application of NPK and CAN fertilizers

Sites			BCR				GB				MR			
	Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
Uyui	Replication	2	3.5	1.75	3.96		2192639	1096319	5.18		2192767	1096383	5.18	
	Fertilizers	24	74.63	3.11	7.04	<0.001	1.19E+08	4965490	23.45	<0.001	71812087	2992170	14.13	<0.001
	Residual	48	21.21	0.44			10165165	211774			10165062	211772		
	Total	74	99.34				1.32E+08				84169916			
Sikonge	Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
	Replication	2	0.43	0.22	0.35		1815956	907978	6.51		1815944	907972	6.51	
	Fertilizers	24	74.56	3.11	5.04	<0.001	86837449	3618227	25.93	<0.001	49084152	2045173	14.66	<0.001
	Residual	48	29.61	0.62			6697946	139541			6698067	139543		
	Total	74	104.6				95351351				57598163			
Tabora	Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.	s.s.	m.s.	v.r.	F pr.
	Replication	2	1.01	0.5	0.74		312937	156469	0.56		312937	156468	0.56	
	Fertilizers	24	40.97	1.71	2.49	0.004	72387664	3016153	10.72	<0.001	36344392	1514350	5.38	<0.001
	Residual	48	32.97	0.69			13506835	281392			13506940	281395		
	Total	74	74.95				86207436				50164270			

Key: BCR = benefit to cost ratio; GB = gross benefit; MR = marginal return; d.f. =degrees of freedom; s.s = sum of squares; m.s. = mean sum of squares; v.r. = variance; F pr. = F probability.

Discussion

The soil characteristics assessed in this study offer critical insights into the challenges and suitability of tobacco production across different regions. Soil pH emerged as a significant factor influencing nutrient availability. Across all study sites, pH levels found to be below 5.5, indicating acidic soils. This acidity can

limit the availability of essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients crucial for tobacco growth and development (Karuma *et al.* 2015) ^[10]. Bulk density, another crucial parameter, varied among the sites. Lower bulk density values in Sikonge and Tabora suggest looser soil structures favorable for root penetration and aeration, which are

vital for optimal plant growth (Zhang *et al.* 2016) [32]. In contrast, higher bulk density observed in Uyui indicates compacted soils that may hinder root growth and water infiltration, potentially compromising tobacco yields if not addressed through appropriate soil management practices (Cochavi *et al.* 2020) [4].

Nutrient levels in the soils assessed, revealing deficiencies in key elements such as calcium, magnesium, and potassium across different sites. Calcium is essential for cell wall formation and disease resistance in tobacco plants (Naiji and Souri, 2018) [21], while magnesium plays a crucial role in chlorophyll synthesis and enzyme activation (Li *et al.* 2023) [14]. Potassium is vital for root development and nutrient transport within plants (Subhashini 2016) [27]. Deficiencies in these nutrients highlight the need for targeted fertilization strategies tailored to specific soil conditions to optimize tobacco crop performance. Excessive soil nitrogen will negatively affect tobacco leaf curing by producing dark brown to black color, dry and chaffy and have a strong and pungent smoke (Drake *et al.* 2015) [5].

Micronutrient levels, including zinc, copper, iron, manganese, and sulfur evaluated. Excessive levels of micronutrients like copper and iron can lead to toxicity, adversely affecting plant health and productivity. Conversely, deficiencies in essential micronutrients can limit crop growth and development (Sillanpää, 1982; Fageria *et al.* 2002) [26, 6]. These findings underscore the importance of balanced fertilization practices and soil testing to ensure adequate nutrient supply while minimizing environmental impact. Spectrum Analytic Inc., (2010) reported that high amount of S has negative effects on tobacco aroma, nicotine, combustibility, ash colour and smoking characteristics. The application of fertilizers had a profound impact on tobacco growth, leaf quality, and economic returns across the study sites. Different fertilizer combinations rich in nitrogen, phosphorus, potassium, and other essential nutrients were tested to address soil nutrient deficiencies identified in the soil analyses. In Sikonge, where soils exhibited acidic pH and deficiencies in key nutrients, the combination of 600 kg ha⁻¹ of NPK and 175 kg ha⁻¹ of CAN proved highly effective. This treatment significantly improved tobacco yield and quality, enhancing economic returns for farmers. The fertilization strategy tailored to Sikonge's specific soil conditions contributed to robust plant growth and optimal leaf production, reflecting the importance of addressing soil acidity and nutrient deficiencies in maximizing crop performance.

Similarly, in Tabora, where soil conditions required a different approach, the application of 500 kg ha⁻¹ of NPK and 125 kg ha⁻¹ of CAN resulted in improved nutrient uptake and enhanced tobacco yield. This combination effectively supplemented soil fertility, supporting better root development and nutrient utilization by tobacco plants. The results underscored the importance of adapting fertilizer applications to meet specific soil nutrient demands, thereby optimizing crop productivity and economic benefits.

In Uyui, characterized by high nutrient demand and compacted soils, the highest yield and economic returns reached at the application of 700 kg ha⁻¹ of NPK and 175 kg ha⁻¹ of CAN. This intensive fertilization strategy compensated for nutrient deficiencies and improved soil structure, promoting vigorous plant growth and maximizing tobacco production. The findings highlight the critical role of balanced fertilization practices and soil management in overcoming soil challenges and enhancing agricultural sustainability.

Conclusion

This study recommends tailoring fertilizer applications to address specific soil nutrient deficiencies identified through comprehensive soil testing. Optimal fertilizer combinations (NPK and CAN) be applied to maximize nutrient uptake efficiency and minimize environmental impacts. The study also advocates for promoting sustainable agricultural practices that conserve soil biodiversity, reduce nutrient runoff, and mitigate climate impacts. Adopt integrated nutrient management strategies to improve soil health and long-term agricultural productivity. Additionally, the study recommends establishing monitoring programs to assess the long-term impacts of fertilization practices on soil health, water quality, and biodiversity. Fertilizer strategies continuously be evaluated and adjusted based on crop response and environmental sustainability criteria

Data availability statement

No publically available datasets analysed in this study.

Author contributions

Conceptualization, DSM. Implementation, All. Formal Analysis, All. Writing - Original Draft, MDS. Writing - Review and Editing, BHJM and EKN. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research conducted in the absence of any commercial or financial relationship that construed as a potential conflict of interest.

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