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Research Article

Increasing rainwater use efficiency, gross return, and grain protein of rain-fed maize under nitrate and urea nitrogen forms

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Abstract

The soil's capability to adjust and mitigate the effects of water shortage due to climate change is limited in some regions such those that suffer from the low rainfall rates. This experimental field study aimed to assess the effects of two inorganic nitrogen forms on maize performance (i.e., growth, yield, grain protein content, and gross returns) and rainwater use efficiency (RUE). Treatments comprised three replicates of synthetic nitrogen forms (i.e., urea and nitrate) that were located in the main plots with four levels that were assigned to the subplots (i.e., 0, 25, 50, and 100 kg N ha^{-1}). Nitrate application resulted in a higher plant height (62 cm) at the vegetative phase with superior values (11.6%) recorded in grain protein than those obtained from other treatments. In addition, the highest grain yield was obtained in nitrate-treated plots in comparison to other N application forms. The leaf area index registered optimal values when 50 kg N ha^{-1} was applied. On the application of two nitrogen forms, nitrate resulted in a higher RUE (2.1-3.4 kg ha^{-1} mm^{-1}) than that obtained from maize treated with urea (1.3-1.9 kg ha^{-1} mm^{-1}). This translated to a 123-234% increase in RUE over the control (N0), which is the key smallholder farmers' practice. It is recommended that producing maize using nitrate nitrogen at 50 kg N ha^{-1} as opposed to urea can increase yield stability, and rain use efficiency with higher gross returns in water-scarce agro-ecologies in SSA.

Keywords: climate change; nitrogen forms; protein content; rainwater use efficiency

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Introduction

Maize is considered one of the most important sources of human food and part of the staple diet in many developing countries as well as the highest contributor to feed grain globally (FAO, 2018; Cheptoek *et al.*, 2021; 2022). It is also a potentially critical bio-energy source with an average cropped land area of 228 million ha (FAO, 2018; Battaglia *et al.*, 2020). Scholars (Alexandratos and Bruinsma, 2012) project maize production must increase by 66% by the year 2050 to meet its global demand due to the rapidly increasing world population estimated to plateau at around 9 billion in the same year (United Nations, 2015). However, the current variation in climatic conditions characterized by higher temperatures with decreasing rainfall has caused an overall drying trend that has prompted changes in precipitation patterns (IPCC, 2021; Nyawade *et al.*, 2021). This bears the result of higher demand for water by crops maize inclusive. As a consequence, the same scenario has continuously prompted alternative water sourcing to enable the maize crop to fulfil its water requirements (Saddique *et al.*, 2020; Wang *et al.*, 2020; Xiao *et al.*, 2020).

In most smallholder farms, especially in arid and semi-arid lands (ASALs) with an average annual precipitation range of 50 - 600 mm, the evapotranspiration rate often surpasses that of the annual rate of total precipitation resulting in low maize yields (Nicholson, 1994; Khattak and Ali, 2015; Khan and Hasan, 2017). Not only does water scarcity limit crop productivity by upsetting biochemical processes like mineralization, especially in N-based nutrients, but it also affects the availability of nutrients via extraction of nutrients from the soil and by influencing soil microbial activities (Ochieng' *et al.*, 2021; Raza *et al.*, 2021; Mirzapour *et al.*, 2022; Kisaka *et al.*, 2023). Moreover, soil moisture besides acting as a solvent for nutrients is also a medium of their transportation within the plant for growth as Schwingshackl *et al.* (2017) observed. During the crops' critical growth period, any threats of water stress will result in radical scarcities in soil moisture and agricultural drought which in most cases exacerbate low crop production as reported by Gitari *et al.* (2018), Cuthbert *et al.* (2019), Otieno *et al.* (2021), Seleiman *et al.* (2021). Furthermore, soil water content falling ≤ 20 % results in a rapid decline in the matric potential of the furrows and soil ridges thereby making redistribution of soil moisture slow with a penalty of irregular plant growth due to impaired nutrient uptake (Nyawade *et al.*, 2019; Rahimi *et al.*, 2022).

Crop water requirement and supply ought to be balanced against water scarcity and efficiency of nutrient use to establish an equilibrium on the right time and amount of water supplied to the crop for the realization of optimum water productivity also known as "Crop per drop" (Rockström, 2003; Chai *et al.*, 2016; Nasar *et al.*, 2021, 2022b; Nyawade *et al.*, 2020; Alhammad *et al.*, 2023a). On the other hand, nutrient uptake efficiency is viewed as the proportion of nutrients used in producing the economic yields (White *et al.*, 2018; Mugo *et al.*, 2021; Mwakidoshi *et al.*, 2021; Mirriam *et al.*, 2022; Muindi *et al.*, 2023). Therefore, RUE is often considered as the ratio of primary net productivity of the aboveground yield to the annual rainfall is equally so informative to water use efficiency (WUE) (Gitari *et al.*, 2017). The efficiency of water use is closely linked to the effectiveness of the use of precipitation since there is no other water source, especially in arid and semi-arid zones of the world where RUE had a stable value of ≈ 4 kg of dry matter ha^{-1} mm^{-1} rainfall (Varvel, 1995; Hatfield *et al.*, 2001). Understanding RUE is critical in addressing the challenges of climate change, food security, and environmental degradation (associated with indiscriminate nitrogen fertilizer use) from both socioeconomic and technological perspectives (Zhang *et al.*, 2015; Rahimi *et al.*, 2023).

Water use efficiency is the relationship between the attained marketable yield and the complete amount of water utilized during production by the plant, measured in kg m^{-3} (Kadigi *et al.*, 2004). It enables one to assess the possible rise in crop yield due to improvised water use (Angus and van Herwaarden, 2001; Nyawade *et al.*, 2021). A precise estimation of the balance between soil water and crop evapotranspiration under varied nitrogen forms and rates is significant in boosting the crop water productivity of maize in rain-fed agriculture.

Production of maize under erratic rainfall patterns, with soil moisture scarcity, therefore, requires more focus on the efficient use of water as previously documented by Pereira *et al.* (2012). Numerous interventions that farmers have adopted to promote efficient use of water under scarce moisture conditions include mulching, supplemental irrigation, and amplified indiscriminate N fertilizer use on crops (Danga *et al*., 2015; Zhang *et al*., 2017; Nduwimana *et al*., 2020; Mwadalu *et al*., 2021; Nasar *et al*., 2022a). Nonetheless, the use of organic mulches (maize stalks) as a moisture conservation strategy in maize production is untenable due to its competitive alternative uses as fodder and fuel (Gachene, 2015). Additionally, besides crop residues being prone to termite infestation under tropical ecologies, they are also subject to rapid decomposition. Careful choice of N form among smallholder maize farmers is critical in enhancing soil moisture use efficiency for optimal returns (Ochieng' *et al*., 2021).

Nitrogen nutrient is the world's most deficient in agricultural soils and a primary component of plant's nucleic acid and protein therefore, low soil nitrogen depresses plant production as well as its physiological protein content (Beeckman *et al.*, 2018; Heydarzadeh *et al*., 2021; Mwadalu *et al*., 2022). The use of synthetic nitrogen fertilizers has been on the increase since the 1960s globally (Lu and Tian, 2017; Heydarzadeh *et al*., 2023). However, most smallholder farmers who produce maize under conditions of low soil nitrogen and moisture scarcity are equally ignorant of the proper choice of the most efficient N fertilizer products to use or are constrained by economic implications associated with these acquisitions (Gitari *et al*., 2019).

This trend among farmers often leads to indiscriminate use of nitrogen (N) fertilizers with deleterious consequences of diminishing returns due to poor nutrient use efficiency (NUE) caused by wrong nitrogen species and low water use efficiency (WUE) related to ineffective use of precipitation (Hatfield *et al.,* 2001). Therefore, given the current overall scenario of scarce water and land resources, the proper choice of nitrogen form could improve both crop yields and WUE. The current study therefore sought to determine the effects of Urea and Nitrate inorganic nitrogen forms on maize growth, yield, grain protein content, and gross returns and rainwater use efficiency.

Materials and Methods

Experimental treatments and design

This field experiment was laid out as a split plot in a randomized complete block design (RCBD) with three replicates. The subplots that measured 3 × 3 m were separated using a path measuring 0.5-m within the blocks that were 1 m far from each other. Treatments comprised three replicates of synthetic nitrogen forms (i.e., Urea and Nitrate) that were located in the main plots with four levels that were assigned to the subplots (i.e., 0, 25, 50, and 100 kg N ha^{-1}). The two synthetic nitrogen forms (Urea and Nitrate) were supplied using urea and calcium nitrate fertilizers, respectively. Preparation of land to suitable tilth was done before the onset of rains. The fertilizers were applied in two splits (25% at 14 days following planting and 75% 40 days afterward) with a blanket treatment on all plots with Muriate of Potash and triple superphosphate at the rate of 10 kg P ha^{-1}. A test crop ('Haraka' maize variety) was planted at an intra-row spacing of 0.3 m and inter-row spacing of 0.75 m. Planting of two seeds per hole was done and thinning to a seedling per hole was performed 14 days after emergence leaving a population density of 44,289 plants ha^{-1}. Agronomic activities like weed and pest control were duly conducted.

Study site description

A consecutive two-year (Short 2019 and 2020 long rain seasons) study was conducted at the main campus, Kenyatta University, Kenya (36°55′34″E, 1°10′59″S, and altitude of 1580 m) research and demonstration farm. The site has a bimodal pattern of rainfall where the months of mid-march and June experience long rains while those of October and December receive short rains. During the 2019 short rain season, a cumulative rainfall amount of 427 mm was received. This was, however, higher by a value of 18% than the 346 mm average value recorded in a 20-year (2000-2019) period. On the other hand, in the 2020 long rain season, a 224 mm quantity of rainfall was registered although this was lower than the 20-year (long-term) average by 84 mm. The months of November and March (2019 and 2020, respectively) recorded the highest (147 and 89 mm) rainfall in the corresponding order (Ochieng' *et al.*, 2021). The soil was loamy sand, with a bulk density of 1.6 g cm^{-3}, organic carbon of 2.4 g kg^{-1}, 4.8 mg kg^{-1} of available P, 0.3 g kg^{-1} of total N, and pH of 6.1. Rainfall amount and average air temperature during the study years are captured in Figure 1.

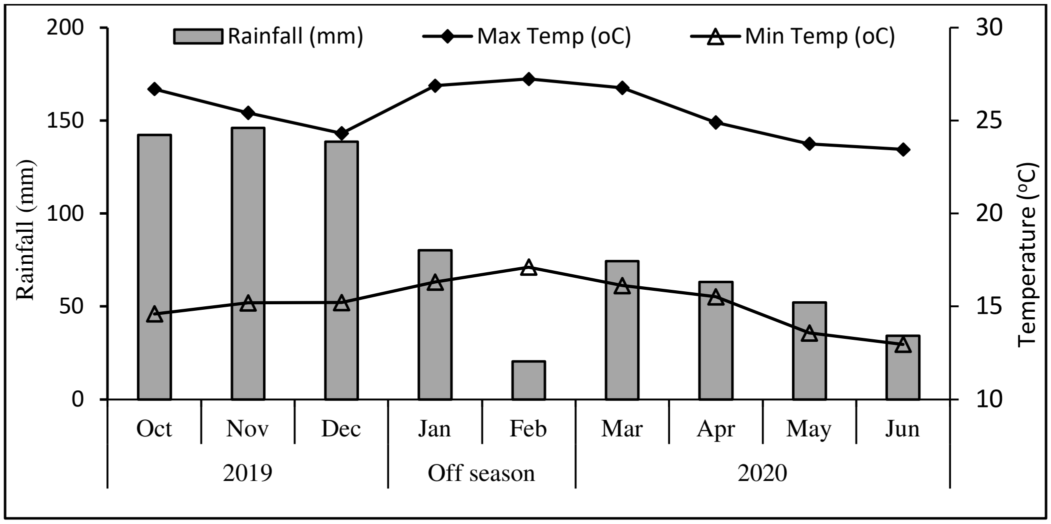

Figure 1. Rainfall and temperature as observed during the experimental seasons (2019 short rains and 2020 long rains)

Sampling, measurements, and analyses

A net area measuring 2 x 2 m at the center of each plot was used for data collection. Random selection and tagging of three plants from this net area were done and measurement of various parameters of growth was done at vegetative, tasseling, and harvesting (V-10, VT, and R6 respectively) phenological stages (Stevens *et al.,* 1986). Data collected were plant height, number of leaves, leaf area index, and leaf area. Determination of plant height was done using a graduated tape measure where the length from the ground to the tip of the youngest leaf collar was measured. The number of leaves was physically counted from the first visible plant leaf from the base to the fully opened, youngest leaf collar. Plant leaf area was calculated as a product of the width (broadest mid-portion breadth of the leaf) and that of the total length of the leaf multiplied by a correction factor (0.75 for maize) as prescribed by Rajeshwari *et al.* (2007). Estimation of plant leaf area index (LAI) was done by multiplying the number of leaves plant^{-1} by the corresponding plant leaf area to result in the total leaf area, which was in turn divided by the respective land area accordingly (Ochieng' *et al.*, 2021) (Eq. 1).

$$LAI = \frac{\text{Total leaf area } (cm^2/\text{plant}) \times \text{leaf number}}{\text{Land area } (cm^2/\text{plant})} \qquad (1)$$

At each of the phenological phases, three plants per plot were randomly picked for additional destructive sampling by cutting, chopping, and recording biomass weights. Mixing of the chopped samples was done and a 1 kg composite sample was drawn, packed in zip lock sampling bags, and transported to the lab for analysis of total N uptake. Moreover, samples of grains obtained from manually threshed cobs and dried to a moisture content of 12.5% at harvesting were taken. The samples were oven-dried at 60 °C to constant dry weight and the recorded weights were used to calculate the yield on a dry weight basis. The samples were then Wiley milled and analyzed for total N using micro-Kjeldahl procedures (Kirk, 1950). Uptake of N in the plants was obtained as a product of total dry biomass and that of total N while the protein content of the grain was obtained as a product of total N (%) and a conversion factor of 6.25 as prescribed by Mosse (1990).

Determination of water use efficiency

In this experiment, since direct measurement of evapotranspiration was not undertaken in both years, rainwater use efficiency (RUE) was calculated in lieu of water use efficiency (WUE). This is because RUE provides similar information to that of WUE by diagnosing the level of effectiveness of precipitation to the treatments independently and can be considered as the quantity of grain produced (weight kg^{-1}) per mm of rainfall received (Le Houérou 1984; Varvel, 1995) (Eq. 2).

$$\text{RUE} = \frac{\text{Grain yield)}}{\text{Rainfall (mm)}} \tag{2}$$

Gross returns analysis

Calculation of maize yield was done by obtaining an average per treatment for the two seasons and revenue accrued from maize was calculated using prices (0.9 US$ kg^{-1}) at the farm gate. The prevailing retail prices during the study period informed the unit costs. Hence, the gross economic return (revenue) of maize was computed as illustrated in Equation 3 (Soratto *et al.*, 2022).

$$\text{Revenue} = \text{Grain yield x Market price} \tag{3}$$

Statistical analysis of data

The data on RUE and N forms on maize growth parameters and yield were collected, cleaned, computed, arranged, and designed for analysis of variance (ANOVA) in the R environment (R, Development Core Team 2016) version 3.4.2. Means separation was done using Tukey's LSD test at a 5% significance level.

Results

Plants growth parameters

Urea application depressed plants' height at both phenological stages V10 and VT (vegetative and tasseling) by 14 and 19% respectively compared to the peak heights (62 and 214 cm) recorded in nitrate-treated plots at vegetative and tasseling stages respectively (Table 1). On the contrary, unfertilized plots (control) registered the least values (46 and 146 cm) on plant height at the respective V10 and VT stages. Application of nitrogen to the plants significantly ($p \leq 0.05$) enhanced their heights with increasing levels where optimal heights of 65 and 240 cm were recorded in plants that received 50 kg N ha^{-1}. Nonetheless, there was no significant improvement in plant height (61 and 236 cm) with a further increase in N fertilizer rate to 100 kg N ha^{-1} in relation to the 50 kg N ha^{-1} rate.

Treatment with nitrate had a significant ($p < 0.001$) higher leaf area and leaf area index (Table 2). Plants supplied with nitrate exhibited a larger leaf area (LA) at both growth stages as compared to those that received urea. Urea decreased the variable by 32% at the vegetative stage. Irrespective of the nitrogen forms, control plots recorded the lowest LA with a cumulative increase to a plateau at the rate of 50 kg N ha^{-1}. A similar trend was observed in plant height with increased fertilizer (N) levels to 100 kg N ha^{-1}.

Leaf area index (LAI) diminished at the vegetative stage in the order of nitrate (1.8) > urea (1.0), while plants treated with nitrate recorded greater LAI (6.3) than those that received urea (4.8) nutrition. Based on N levels, the same trend reported for LA was observed with unfertilized plots registering the least (0.7 and 3.6) LAI at vegetative and tasseling phenological phases, respectively.

Table 1. Plant height (cm) at vegetative (V10) and tasseling (VT) growth phases (means ± standard error) as influenced by nitrogen forms at various levels during the experimental seasons (2019 short rains and 2020 long rains)

Treatment	Rate (kg N ha^{-1})	2019 Short rains		2020 Long rains	
		Plant height (cm)			
		V10	VT	V10	VT
Nitrate	0	51.04 ± 1.04^{c}	152.07 ± 1.43^{d}	52.27 ± 0.87^{d}	149.16 ± 0.58^{c}
	25	67.27 ± 1.31^{bc}	244.63 ± 1.75^{c}	59.47 ± 1.01^{c}	221.73 ± 1.15^{b}
	50	79.22 ± 1.30^{a}	258.67 ± 1.53^{a}	68.62 ± 1.20^{a}	238.50 ± 1.50^{a}
	100	78.31 ± 1.23^{b}	258.17 ± 1.43^{b}	67.31 ± 1.17^{b}	237.17 ± 0.58^{a}
Urea	0	49.48 ± 0.90^{c}	160.20 ± 1.42^{d}	48.01 ± 0.34^{c}	134.67 ± 0.76^{d}
	25	55.63 ± 1.27^{b}	222.57 ± 1.26^{c}	46.93 ± 1.07^{b}	187.00 ± 0.50^{c}
	50	68.92 ± 0.55^{a}	236.63 ± 1.26^{b}	59.82 ± 1.55^{a}	205.33 ± 1.26^{b}
	100	66.25 ± 0.67^{b}	238.47 ± 1.26^{a}	58.35 ± 0.67^{a}	207.50 ± 1.00^{a}

Summary of analyses of variance (*p* values)

Growth stages	Treatment (T)	Rate (R)	Season (S)	T x R	T x S
V10	<0.001	<0.001	<0.001	<0.001	0.200
VT	<0.001	<0.001	<0.001	<0.001	<0.001

Down the column (within the same treatment), means followed by dissimilar superscript letters differ significantly ($p \leq 0.05$) by LSD test

Table 2. Leaf area index and leaf area (m^{2}) at various phenological stages (vegetative, V10 and tasseling, VT) (means ± standard error) as affected by nitrogen forms at varied rates during the experimental seasons (2019 short rains and 2020 long rains)

Season	Treatment	Rate (kg N ha^{-1})	Leaf area (m^{2})		Leaf area index (L.A.I)	
			V10	VT	V10	VT
2019 Short rains	Nitrate	0	0.22 ± 0.11^{c}	0.98 ± 0.03^{d}	0.96 ± 0.12^{c}	3.78 ± 0.13^{c}
		25	0.47 ± 0.13^{b}	1.44 ± 0.15^{c}	2.26 ± 0.11^{b}	6.23 ± 0.24^{b}
		50	0.66 ± 0.04^{a}	2.01 ± 0.01^{a}	2.31 ± 0.63^{a}	6.76 ± 0.14^{a}
		100	0.61 ± 0.17^{b}	1.89 ± 0.06^{b}	2.28 ± 0.31^{b}	6.83 ± 0.16^{a}
	Urea	0	0.25 ± 0.03^{b}	1.15 ± 0.04^{c}	0.97 ± 0.11^{c}	4.56 ± 0.29^{c}
		25	0.26 ± 0.13^{a}	1.39 ± 0.05^{bc}	1.27 ± 0.13^{b}	5.89 ± 0.12^{bc}
		50	0.28 ± 0.12^{a}	1.41 ± 0.09^{bc}	1.30 ± 0.08^{a}	6.12 ± 0.19^{ab}
		100	0.27 ± 0.03^{a}	1.51 ± 0.09^{a}	1.28 ± 0.11^{a}	6.17 ± 0.41^{a}
2020 Long rains	Nitrate	0	0.21 ± 0.11^{c}	0.71 ± 0.04^{d}	0.78 ± 0.14^{c}	3.18 ± 0.16^{d}
		25	0.39 ± 0.12^{b}	1.34 ± 0.08^{c}	1.38 ± 0.12^{b}	5.39 ± 0.36^{c}
		50	0.43 ± 0.11^{a}	1.57 ± 0.17^{a}	1.85 ± 0.06^{a}	5.86 ± 0.30^{a}
		100	0.44 ± 0.03^{a}	1.53 ± 0.16^{b}	2.10 ± 0.11^{a}	5.69 ± 0.28^{b}
	Urea	0	0.14 ± 0.01^{c}	0.56 ± 0.03^{d}	0.58 ± 0.15^{c}	2.88 ± 0.12^{d}
		25	0.17 ± 0.01^{b}	0.79 ± 0.04^{c}	0.74 ± 0.15^{b}	3.60 ± 0.16^{c}
		50	0.22 ± 0.01^{a}	0.92 ± 0.06^{b}	0.99 ± 0.06^{a}	4.17 ± 0.35^{b}
		100	0.24 ± 0.01^{a}	0.96 ± 0.07^{a}	1.02 ± 0.15^{a}	4.61 ± 0.23^{a}

Summary of analyses of variance (*p* values)

Variable	Treatment (T)	Rate (R)	Season (S)	T x R	T x S
Leaf area	<0.001	<0.001	<0.001	<0.001	<0.001
Leaf area index	<0.001	<0.001	<0.001	<0.001	<0.001

Means followed by dissimilar superscript letters (down the column within the same treatment) differ significantly ($p \leq 0.05$) by LSD test

Grain protein content and yield, gross returns, and rain use efficiency

Nitrate and urea significantly ($p \leq 0.05$) influenced grain protein content and yield, gross returns, and rain use efficiency at varying N rates (Table 3). Treatment with urea resulted in the least (2.5 t ha^{-1}) grain yield whereas nitrate nutrition registered the highest (2.9 t ha^{-1}) value on this parameter. Furthermore, plants fertilized with Nitrate-N had their protein content more enhanced (11.6%) than those treated with urea (8.6%). The control plots however recorded the least values (1.9 t ha^{-1} and 7.4%) on grain yield and protein content respectively. Increasing fertilizer levels resulted in a proportionate rise in yield and that of grain protein content peaking at 50 kg N ha^{-1}. Conversely, increasing the fertilizer level to 100 kg N ha^{-1} did not significantly improve the aforementioned variables in relation to the 50 kg N ha^{-1} rate.

Analysis of rain use efficiency for the entire period of the experiment showed significant ($p < 0.001$) differences in the treatments (Table 3). Maize that received nitrate was the most efficient with higher RUE of 16 and 19 kg ha^{-1} mm^{-1}, followed by those that were treated with urea that registered 11 and 14 kg ha^{-1} mm^{-1} across the respective seasons. Plants in the control plots recorded the lowest RUE by 35 and 40% in relation to urea and nitrate, respectively (Table 3).

Table 3. Maize grain yield, gross returns, rainwater use efficiency (RUE), and grain protein content (means ± standard error) as influenced by N forms at varied rates during the experimental seasons (2019 short rains and 2020 long rains)

Season	Treatment	Rate (kg N ha^{-1})	Grain yield (t ha^{-1})	Gross return	RUE	Grain protein
2019 Short rains	Nitrate	0	2.07 ± 0.07^{c}	472.12 ± 9.94^{d}	1.11 ± 0.02^{c}	4.94 ± 0.32^{d}
		25	2.89 ± 0.16^{b}	1255.15 ± 49.9^{c}	2.94 ± 0.12^{b}	7.54 ± 0.22^{c}
		50	5.06 ± 0.27^{a}	1473.94 ± 65.4^{b}	3.45 ± 0.15^{a}	11.85 ± 0.41^{a}
		100	5.04 ± 0.18^{a}	1502.73 ± 34.55^{a}	3.52 ± 0.08^{a}	10.03 ± 0.12^{b}
	Urea	0	2.17 ± 0.04^{c}	316.67 ± 9.97^{c}	0.74 ± 0.02^{a}	4.90 ± 0.41^{c}
		25	2.73 ± 0.23^{b}	777.27 ± 59.83^{b}	1.82 ± 0.14^{c}	7.67 ± 0.32^{b}
		50	3.64 ± 0.22^{a}	811.8 ± 96.17^{a}	1.90 ± 0.23^{b}	8.88 ± 0.20^{a}
		100	3.65 ± 0.42^{a}	915.45 ± 79.15^{a}	2.14 ± 0.19^{a}	8.50 ± 0.11^{a}
2020 Long rains	Nitrate	0	1.85 ± 0.14^{c}	443.33 ± 9.97^{c}	1.98 ± 0.04^{c}	4.99 ± 0.62^{c}
		25	2.54 ± 0.14^{b}	990.30 ± 9.97^{b}	4.42 ± 0.04^{b}	11.14 ± 0.51^{b}
		50	2.61 ± 0.27^{a}	1065.15 ± 9.97^{a}	4.75 ± 0.04^{a}	12.09 ± 0.37^{a}
		100	2.79 ± 0.33^{a}	1053.64 ± 45.70^{a}	4.70 ± 0.20^{a}	12.06 ± 0.48^{a}
	Urea	0	1.77 ± 0.15^{d}	454.85 ± 19.94^{c}	2.03 ± 0.09^{c}	4.97 ± 0.29^{d}
		25	1.89 ± 0.13^{c}	829.09 ± 89.75^{b}	3.70 ± 0.40^{b}	9.49 ± 0.44^{c}
		50	2.40 ± 0.24^{b}	898.18 ± 17.27^{a}	4.01 ± 0.08^{a}	10.78 ± 0.61^{a}
		100	2.48 ± 0.14^{a}	886.67 ± 18.67^{a}	3.96 ± 0.63^{a}	10.15 ± 0.27^{b}

Summary of analyses of variance (p values)

Variable	Treatment (T)	Rate (R)	Season (S)	T x R	T x S
Grain yield	<0.001	<0.001	<0.001	<0.001	0.062
Gross return	<0.001	<0.001	<0.001	<0.001	<0.001
RUE	0.001	<0.001	<0.001	0.002	<0.001
Grain protein	0.001	<0.001	<0.001	0.003	<0.001

Within the same treatment (down the column), means followed by dissimilar superscript letters are significantly different at $p \leq 0.05$ by LSD test

The highest gross returns were incurred in nitrate-treated maize ranging from US$ 1176 ha^{-1} to US$ 888 ha^{-1} while urea recorded 14 and 23% lower on this parameter across the seasons. Control plots registered the least (US$ 374 ha^{-1}) on gross returns. During the short rain season, the gross return of nitrate applied at a 50 kg N ha^{-1} rate was 1.2 times higher ($p < 0.05$) than urea applied at an equivalent rate in the long rain season. The gross returns increased with an increase in N application rates, with peak values observed at 50 kg N ha^{-1}.

However, increasing the N rate to 100 kg N ha^{-1} did not conform to a consistent trend, that is, it increased with an increase in N levels in the short rain season but varied conversely with N levels during the short rain season.

Discussion

The inhibited growth in plants by urea nutrition could be accredited to the slow release of nitrogen through the mineralization process of urea to available ammonium (NH_4^+) (Ochieng' *et al.*, 2021). This consequently may have deferred the positive influence of nitrogen on plant growth such as increasing the number and length of internodes thereby enhancing the plant's height as revealed in the previous studies (Sharma, 1973; Chandler, 2015). Further, the intermediate ammonia gas (NH_3) and ammonium formed during hydrolysis of urea could have also suffered significant losses by rapid volatilization, especially under higher temperature conditions leading to depressed plants height due to deficiency of nitrogen, this is in agreement with findings from previous studies that corroborate slow dissociation of urea to a maximum two-week period (Amanullah *et al.*, 2016; Simon *et al.*, 2017). Nitrate application enhanced the plant's height probably since it was readily available for uptake compared to urea. Timely plants' N- nutrition promote rapid cell elongation, division, and differentiation in plants as observed by previous scholars (Chandler, 2015; Ochieng' *et al.*, 2021; Sousa *et al.*, 2022; Zhao *et al.*, 2023). In the present study, the application of nitrogen recorded a significant difference in plant height from those of the control with increasing levels and spike heights registered at mid-N level (50 kg N ha^{-1}). Similar results have been confirmed with barley (*Hordeum vulgare*) (Barati *et al.*, 2015) and millet (*Panicum miliceaum*) (Gong *et al.*, 2017).

Enhancement of leaf area and leaf area index with nitrate treatment could be ascribed to the stimulated synthesis of phytohormones (Zeatin) marked by biological synthesis of cytokinins that promote rapid plant cell division, growth, and differentiation (Rahayu *et al.*, 2005; Faridvand *et al.*, 2021). Administering urea and its associated mineralization process that results in the formation of ammonium nitrogen form could have further, conversely resulted in a decline in leaf area, inhibition of leaf expansion, and restriction of leaf growth as similarly documented in previous scholarly works (Guo *et al.*, 2007; Borgognone *et al.*, 2013; Raza *et al.*, 2021).

The low grain yield associated with urea at all N rates (Table 3) is an indicator of the inferiority of this N-fertilizer form as compared to nitrate. Urea may have delayed the release of N from the mineralization process during the crucial plants' demand for N thereby causing nitrogen deficiency. Moreover, low nitrogen supply due to urea nutrition could have resulted from ammonification (volatilization of ammonia) hence a trigger to low grain yields. Our results largely concur with previous studies which have implicated urea nutrition (and its formation of ammonium during mineralization) with acidification of the rhizosphere, osmotic imbalance, and antagonism in the uptake of essential cations on the soil exchange complex with an eventual decline in maize yields on a global scale (Guo *et al.*, 2016).

On the other hand, this study has established that the application of nitrate at equivalent levels to that of urea boosted grain yields and protein. This could be explained by the rhizospheric alkalization caused by nitrate which could have further enhanced the uptake of the other adsorbed essential cations. The consequence of this uptake could have been that of positive synergy with N for high grain yields and gluten (protein) primarily because the critical grain protein content is a product of the suitable amount of N supplied to a plant (Zhu *et al.*, 2001; Alloway, 2004).

The result of this study has demonstrated that the application of an appropriate form of nitrogen increased crop yield while administering higher nitrogen levels not only resulted in nutrient loss but also contrasted the final crop yield (Wang *et al.*, 2012, 2017). Similar previous studies involving wheat with high N levels have revealed an increase in the number of leaves, plant height, and other agronomic traits which consequently caused poor light penetration and ventilation as well as canopy shading, all of which predispose the crops to diseases as well as compromised photosynthesis with an eventual decline in yield (Luo *et al.*, 2021; Yasin *et al.*, 2022).

The total maize grain protein content and its components is a quality index majorly controlled by genetic makeup, but the bearing of environmental dynamics especially nitrogen can be great (Ochieng' *et al.*, 2021). Previous studies show that factors of the environment can account for over 89% of the effect on grain protein content, while differences in variety claim a paltry 8% on this parameter (Martinez *et al.*, 2010).

The high grain protein content recorded in nitrate-treated plants as opposed to those that received urea was probably due to the timely release of nitrogen (for plants uptake) by nitrate compared to urea which had to mineralize into available N. Plant's timely nitrogen physiological condition (especially at flowering) at higher rates significantly increases its final total seed protein (gliadin, albumin, and gluten) content (Kaizzi *et al.*, 2012; Han *et al.*, 2020; Alhammad *et al.*, 2023b). The results of this study were consistent with those observed by previous scholars (Ochieng' *et al.*, 2021; Ogega *et al.*, 2022). This finding suggested that varied rates of N may have some effect on grain protein content. However, this differs slightly from other former researchers (Ochieng' *et al.*, 2021).

Nitrate may have resulted in higher gross returns of maize probably due to the associated high grain yield as opposed to urea. The positive synergy of timely nitrogen supply obtained from nitrate and the available rainwater over the experimental seasons could have contributed to the greater water use efficiency witnessed with nitrate rather than urea. This is because water is the most critical limiting input factor for crop productivity followed by nitrogen element.

Conclusions

The findings of this study reveal that maize plant height, leaf area index, grain protein content, and grain yield were greatly dependent on the form of nitrogen applied. Compared with nitrate, urea delayed nitrogen release for plant uptake, thereby resulting in a significant reduction in grain yield. The high grain yield and protein content values associated with nitrate nutrition indicate an unlimited potential for improving maize productivity. Nitrogen applied at 50 kg N ha^{-1} is an effective practice for obtaining optimal gross returns and yield of maize in semi-arid agro-ecologies with similar rainwater conditions. Further studies ought to focus on quantities of N losses due to mineralization in the soil and its economics thereof.

Authors' Contributions

Conceptualization: IOO, RP, HIG, SR, SS, MFS, SRP and DW; Data curation: IOO, RP, HIG, SR, SS, and SRP; Formal analysis: IOO, and RP; Investigation: HIG, MFS and DW; Methodology: IOO, RP, HIG, SR, SS and MFS; Resources: MFS; Software: HIG, and MFS; Supervision: HIG Writing - original draft: IOO, and RP; Writing - review and editing: HIG, SR, MFS, SRP and DW. All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

References

Alexandratos N, Bruinsma J (2012). World agriculture towards 2030/2050: the 2012 Revision. ESA Working Paper No. 12-03. FAO, Rome.

Alhammad BA, Mohamed A, Raza MA, Ngie M, Maitra S, … Gitari HI (2023a). Optimizing productivity of Buffel and Sudan grasses using optimal nitrogen fertilizer application under arid conditions. Agronomy 13:2146. *https://doi.org/10.3390/agronomy13082146*

Alhammad BA, Roy DK, Ranjan S, Padhan SR, Sow S, Nath D, Seleiman M (2023b). Conservation tillage and weed management effect on weed dynamics, crop performance, soil properties, and profitability in rice-wheat-greengram system in Eastern Indo-Gangetic Plains. Agronomy 13(7):1953. *https://doi.org/10.3390/agronomy13071953*

Alloway BJ (2004). Zinc in soils and crop nutrition. Second edition, published by IZA and IFA Brussels, Belgium and Paris, France.

Amanullah H (2016). Influence of organic and inorganic nitrogen on grain yield and yield components of hybrid rice in Northwestern Pakistan. Rice Science 23:326-333. *http://dx.doi.org/10.1016/j.rsci.2016.02.007*

Angus JF, Herwaarden AF. (2001). Increasing water use and water use efficiency in dryland wheat. Agronomy Journal 93:290-298. Portico. *http://dx.doi.org/10.2134/agronj2001.932290x*

Barati V, Ghadiri H, Zand-Parsa S, Karimian N (2015). Nitrogen and water use efficiencies and yield response of barley cultivars under different irrigation and nitrogen regimes in a semi-arid Mediterranean climate. Archives of Agronomy and Soil Science 61:15-32. *http://dx.doi.org/10.1080/03650340.2014.921286*

Battaglia M, Thomason W, Fike JH, Evanylo GK, von Cossel M, Babur E, Diatta A (2020). The broad impacts of corn stover and wheat straw removal for biofuel production on crop productivity, soil health and greenhouse gas emissions: A review. Gcb Bioenergy 13(1):45-57. *https://doi.org/10.1111/gcbb.12774*

Beeckman F, Motte H, Beeckman T (2018). Nitrification in agricultural soils: impact, actors and mitigation. Current Opinion of Biotechnology 50:166-173. *http://dx.doi.org/10.1016/j.copbio.2018.01.014*

Borgognone D, Colla G, Rouphael Y, Cardarelli M, Rea CR, Schwarz D (2013). Effect of nitrogen form and nutrient solution pH on growth and mineral composition of self-grafted and grafted tomatoes. Scientia Horticulturae 149:61-69. *https://doi.org/10.1016/j.scienta.2012.02.012*

Chai Q, Gan Y, Zhao C, Xu HL, Siddique KHM (2016). Regulated deficit irrigation for crop production under drought stress. A review. Agronomy for Sustainable Development 36:3. *http://dx.doi.org/10.1007/s13593-015-0338-6*

Chandler RF (2015). Plant morphology and stand geometry in relation to nitrogen. Physiological Aspects of Crop Yield 265-285. *http://dx.doi.org/10.2135/1969*

Cheptoek RP, Gitari HI, Mochoge B, Kisaka OM, Otieno E, Maitra S, Seleiman MF (2021). Maize productivity, economic returns and phosphorus use efficiency as influenced by lime, Minjingu Rock Phosphate and NPK inorganic fertilizer. International Journal of Bioresource Science 8:47-60. *https://doi.org/10.30954/2347-9655.01.2021.7*

Cheptoek RP, Nasar J, Ochieng' IO, Maitra S, Heydarzadeh S, Gitari HI (2022). Role of Minjingu Rock Phosphate and Nitrogen Fertilizer in improving phosphorus and nitrogen use efficiency in maize: A Kenyan case study. International Journal of Bioresource Science 9:9-19. *https://doi.org/10.30954/2347-9655.01.2022.2*

Cuthbert MO, Taylor RG, Favreau G, Todd MC, Shamsudduha M, Villholth KG, Kukuric N (2019). Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. Nature 572(7768):230-234. *https://doi.org/10.1038/s41586-019-1441-7*

Danga BO. Gitari HI, Mochoge BE (2015). Effect of lime and goat manure on soil acidity and maize (*Zea mays*) growth parameters at Kavutiri, Embu County - Central Kenya. Journal of Soil Science and Environmental Management. 6:275-283. *https://academicjournals.org/journal/JSSEM/article-abstract/FA9BA8255355*

FAO-Food and Agriculture Organization. (2018). FAO Statistical Yearbook: World Food and Agriculture. *http://www.fao.org/faostat/en/#data/QC*

Faridvand S, Rezaei-Chiyaneh E, Battaglia M, Gitari H, Raza MA, Siddique KHM (2021). Application of bio and chemical fertilizers improves yield, and essential oil quantity and quality of Moldavian balm (*Dracocephalum moldavica* L.) intercropped with mung bean (*Vigna radiata* L.). Food Energy and Security 11:319. *http://dx.doi.org/10.1002/fes3.319*

Gachene CKK, Gitari HI, Karanja NN, Kamau S, Sharma K, Schulte-Geldermann E (2018). Nitrogen and phosphorous uptake by potato (*Solanum tuberosum* L.) and their use efficiency under potato-legume intercropping systems. Field Crops Research 222:78-84. *http://dx.doi.org/10.1016/j.fcr.2018.03.019*

Gitari H, Gachene C, Karanja N, Schulte-Geldermann E (2017). Evaluation of potato (*Solanum tuberosum* L.) nutrient use efficiency under legume intercropping systems. Annual conference proceedings of Tropical and Subtropical Agricultural and Natural Resource Management (TROPENTAG), organized by the University of Natural Resources and Life Sciences. (BOKU Vienna), Austria, September 18-21, 2017.

Gitari HI, Gachene CKK, Karanja NN, Kamau S, Nyawade S, Sharma K, Schulte-Geldermann E (2018). Optimizing yield and economic returns of rain-fed potato (*Solanum tuberosum* L.) through water conservation under potato-legume intercropping systems. Agricultural Water Management 208:59-66. *http://dx.doi.org/10.1016/j.agwat.2018.06.005*

Gitari HI, Nyawade SO, Kamau S, Gachene CKK, Karanja NN, Schulte-Geldermann E. (2019). Increasing potato equivalent yield increases returns to investment under potato-legume intercropping systems. Open Agriculture 4:623-629. *http://dx.doi.org/10.1515/opag-2019-0062*

Gong XW, Han HK, Zhang DZ, Li J, Wang M (2017). Effects of nitrogen fertilizers on the field microclimate and yield of broomcorn millet at grain filling stage. Journal of China Agriculture University 22:10-19. *http://dx.doi.org/10.11841/j.issn.1007-4333.2017.12.02*

Guo C, Li P, Lu J, Ren T, Cong R, Li X (2016). Application of controlled release urea in rice: Reducing environmental risk while increasing grain yield and improving nitrogen use efficiency. Communication in Soil Science and Plant Analyses 47:1761183. *http://dx.doi.org/10.1080/00103624.2016.116625*

Guo S, Zhou Y, Shen Q, Zhang F (2007). Effect of ammonium and nitrate nutrition on some physiological processes in higher plants-growth, photosynthesis, photorespiration, and water relations. Plant Biology 9(1):21-29. *https://doi.org/10.1055/s-2006-924541*

Han ZY, Guan XY, Zhao Q, Wu CY, Huang FD, Pan G, Cheng FM (2020). Individual and combined effects of air temperature at filling stage and nitrogen application on storage protein accumulation and its different components in rice grains. Acta Agronomica Sinica 46:1087-1098. *https://doi.org/10.3724/sp.j.1006.2020.92062*

Hatfield JL, Sauer TJ, Prueger JH (2001). Managing soils to achieve greater water use efficiency: a review. Agronomy Journal 93:271-280. *https://doi.org/10.2134/agronj2001.932271x*

Heydarzadeh S, Arena C, Vitale E, Rahimi A, Mirzapour M, Nasar J, … Ranjan S. (2023). Impact of different fertilizer sources under supplemental irrigation and rain-fed conditions on eco-physiological responses and yield characteristics of dragon's head (*Lallemantia iberica*). Plants 12:1693. *https://doi.org/10.3390/plants12081693*

Heydarzadeh S, Hosseinpour A, Gitari H, Maitra S, Rahimi A (2021). Improving quantitative and qualitative properties of cotton through the use of organic and chemical fertilizers under water deficit stress conditions. International Journal of Bioresource Science 8(2):69-80. *http://dx.doi.org/10.30954/2347-9655.02.2021.2*

IPCC-Intergovernmental Panel on Climate Change. (2021). Climate change: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Kadigi RMJ, Kashaigili JJ, Mdoe NS (2004). The economics of irrigated paddy in Usangu Basin in Tanzania: water utilization, productivity, income and livelihood implications. Physics and Chemistry of the Earth 29(15):1091-1100. *http://dx.doi.org/10.1016/j.pce.2004.08.010*

Kaizzi KC, Byalebeka J, Semalulu O, Alou I, Zimwanguyizza W, Nansamba A, Wortmann CS (2012). Maize response to fertilizer and nitrogen use efficiency in Uganda. Agronomy 104(1):73-82. *http://dx.doi.org/10.2134/agronj2011.0181*

Khan S, Hasan MU (2017). Evapotranspiration distribution and variation of Pakistan (1931-2015). Annals of Valahia University of Targoviste, Geographical Series 17(2):184-197. *https://doi.org/10.1515/avutgs-2017-0017*

Khattak MS, Ali S (2015). Assessment of temperature and rainfall trends in Punjab province of Pakistan for the period 1961-2014. Journal Himalayan Earth Science 48(2):42-61.

Kirk PL (1950). Kjeldahl method for total nitrogen. Analytical Chemistry 22(2):354-358. *http://dx.doi.org/10.1021/ac60038a038*

Kisaka MO, Shisanya C, Cournac L, Manlay JR, Gitari H, Muriuki J (2023). Integrating no-tillage with agroforestry augments soil quality indicators in Kenya's dry-land agroecosystems. Soil & Tillage Research 227:105586. *http://dx.doi.org/10.1016/j.still.2022.105586*

Le Houérou LHN (1984). Rain-use efficiency: a unifying concept in arid-land ecology. Journal of Arid Environments, 7:213-247. *https://doi.org/10.1016/s0140-1963(18)31362-4*

Lu C, Tian H (2017). Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: shifted hot spots and nutrient imbalance. Earth System Science Data 9(1):181-192. *https://doi.org/10.5194/essd-9-181-2017*

Luo CS, Ma LK, Zhu JH, Guo ZP, Dong K, Dong Y (2021). Effects of nitrogen and intercropping on the occurrence of wheat powdery mildew and stripe rust and the relationship with crop yield. Frontiers in Plant Science 12:637393. *https://doi.org/10.3389/fpls.2021.637393*

Martinez MF, Arelovich HM, Wehrhahne LN (2010). Grain yield, nutrient content and lipid profile of oat genotypes grown in a semiarid environment. Field Crops Research. 116:92-100. *https://doi.org/10.1016/j.fcr.2009.11.018*

Mirriam A, Mugwe J, Raza, MF, Seleiman MA, Maitra S, Gitari HI (2022). Aggrandizing soybean yield, phosphorus use efficiency and economic returns under phosphatic fertilizer application and inoculation with *Bradyrhizobium*. Journal of Soil Science and Plant Nutrition. *http://dx.doi.org/10.1007/s42729-022-00985-8*

Mirzapour M, Valizadeh N, Heydarzadeh S, Rahimi A, Gitari H (2022). Factors affecting the production of secondary metabolites in medicinal plants. In: Ozyazici G (Ed). New Development on Medicinal and Aromatic Plants-II, Iksad publishing house, Turkey, pp 3-32. *https://iksadyayinevi.com/home/new-development-on-medicinal-and-aromatic-plants-ii*

Mosse J (1990). Nitrogen to protein conversion factors for 10 cereals and 6 legumes or oilseeds– a reappraisal of its definition and determination – variation according to species and to seed protein-content. Journal of Agricultural and Food Chemistry 38:18-24. *https://doi.org/10.1021/jf00091a004*

Mugo NJ, Karanja NN, Gachene CK, Dittert K, Gitari HI, Schulte-Geldermann E (2021). Response of potato crop to selected nutrients in Central and Eastern highlands of Kenya. Cogent Food & Agriculture 7:1898762. *https://doi.org/10.1080/23311932.2021.1898762*

Muindi E. M, Mwakidoshi ER, Gitari HI, Wamukota AW, Seleiman MF, Maitra S (2023). Smallholder farmers' knowledge of the use of bioslurry as a soil fertility amendment for potato production in Kenya. Land Degradation & Development 34(8):2214-2227. *http://dx.doi.org/10.1002/ldr.4601*

Mwadalu R, Mochoge B, Mwangi M, Gitari H (2021). Heightening sorghum nitrogen uptake while maintaining optimal soil nutrient levels through mineral fertiliser application. Journal of Applied Life Sciences and Environment 54:458-472. *http://dx.doi.org/10.46909/journalalse-2021-033*

Mwadalu R, Mochoge B, Mwangi M, Maitra S, Gitari H (2022). Response of Gadam sorghum (*Sorghum bicolor*) to farmyard manure and inorganic fertilizer application. International Journal of Agriculture, Environment and Biotechnology 15:51-60. *http://dx.doi.org/10.30954/0974-1712.01.2022.6*

Mwakidoshi ER, Gitari HI, Muindi EM (2021). Economic importance, ecological requirements, and production constraints of potato (*Solanum tuberosum* L.) in Kenya. International Journal of Bioresource Science 8(2):61-68. *https://doi.org/10.30954/2347-9655.02.2021.1*

Nasar J, Khan W, Khan MZ, Gitari HI, Gbolayori JF, Moussa AA, … Maroof SM (2021). Photosynthetic activities and photosynthetic nitrogen use efficiency of maize crop under different planting patterns and nitrogen fertilization. Journal of Soil Science and Plant Nutrition. *http://dx.doi.org/10.1007/s42729-021-00520-1*

Nasar J, Wang GY, Ahmad S, Muhammad I, Zeeshan M, Gitari H, Hasan ME (2022a). Nitrogen fertilization coupled with iron foliar application improves the photosynthetic characteristics, photosynthetic nitrogen use efficiency, and the related enzymes of maize crops under different planting patterns. Frontiers in Plant Science 13:988055. *http://dx.doi.org/10.3389/fpls.2022.988055*

Nasar J, Wang GY, Zhou FJ, Gitari H, Zhou XB, Karim M, … Jahan MS (2022b). Nitrogen fertilization coupled with foliar application of iron and molybdenum improves shade tolerance of soybean under maize soybean intercropping. Frontiers in Plant Science 13:1014640. *http://dx.doi.org/10.3389/fpls.2022.1014640*

Nduwimana D, Mochoge B, Danga B, Masso C, Maitra S, Gitari H (2020). Optimizing nitrogen use efficiency and maize yield under varying fertilizer rates in Kenya. International Journal of Bioresource Science 7(2):63-73. *https://doi.org/10.30954/2347-9655.02.2020.4*

Nicholson SE (1994). Recent rainfall fluctuations in Africa and their relationships to past conditions over the continent. Holocene 4:121-131 *http://dx.doi.org/10.1177/095968369400400202*

Nyawade S, Gitari H I, Karanja NN, Gachene CKK, Schulte-Geldermann E, Sharma K, Parker ML (2020). Enhancing climate resilience of rain-fed potato through legume intercropping and silicon application. Frontiers in Sustainable Food Systems 4:566345. *http://dx.doi.org/10.3389/fsufs.2020.566345*

Nyawade S, Gitari HI, Karanja NN, Gachene CKK, Schulte-Geldermann E, Parker M (2021). Yield and evapotranspiration characteristics of potato-legume intercropping simulated using a dual coefficient approach in a tropical highland. Field Crops Research 274. *http://dx.doi.org/10.1016/j.fcr.2021.108327*

Nyawade SO, Karanja NN, Gachene CKK, Gitari HI, Schulte-Geldermann E, Parker M (2019). Intercropping optimizes soil temperature and increases crop water productivity and radiation use efficiency of rainfed potato. American Journal of Potato Research 96(5):457-471. *http://dx.doi.org/10.1007/s12230-019-09737-4*

Ochieng' IO, Gitari HI, Mochoge B, Rezaei-Chiyaneh E, Gweyi-Onyango JP (2021). Optimizing maize yield, nitrogen efficacy and grain protein content under different N forms and rates. Journal of Soil Science and Plant Nutrition 21(2):297-306. *https://doi.org/10.1007/s42729-021-00486-0*

Ogega S, Mugwe J, Michen A. (2022). Tillage methods and inorganic nutrients source's interactive effects in maize and beans performance. Annals of Reviews and Research 7:555717. *http://dx.doi.org/10.19080/ARR.2022.07.555717*

Otieno MA, Gitari HI, Danga B, Karuma AN (2021). Soil properties and fertility management with respect to Capsicum (*Capsicum annuum* L.) production in Nairobi Peri-urban Counties. Journal of Soil Science and Plant Nutrition 22:374-392. *http://dx.doi.org/10.1007/s42729-021-00655-1*

Pereira LS, Cordery I, Iacovides I (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agricultural Water Management 108:39-51. *https://doi.org/10.1016/j.agwat.2011.08.022*

Rahayu YS, Walch-Liu P, Neumann G, Römheld V, Von Wirén N, Bangerth F (2005). Root-derived cytokinins as long-distance signals for NO_3^- -induced stimulation of leaf growth. Journal of Experimental Botany 56:1143-1152. *https://doi.org/10.1093/jxb/eri107*

Rahimi A, Lyons G, Heydarzadeh S, Tuncturk M, Tuncturk R (2023). Effects of vermicompost, compost and animal manure on vegetative growth, physiological and antioxidant activity characteristics of *Thymus vulgaris* L. under water stress. (2022). Yuzuncu Yil University Journal of Agricultural Science*s* 32(1):40-53. *https://doi.org/10.29133/yyutbd.1124458*

Rahimi A, Mohammadi MM, Moghadam SS, Heydarzadeh S, Gitari H (2022). Effects of stress modifier biostimulants on vegetative growth, nutrients and antioxidants contents of garden thyme (*Thymus vulgaris* L.) under water stress. Journal of Plant Growth Regulation 41:2059-2072. *http://dx.doi.org/10.1007/s00344-022-10604-6*

Rajeshwari RS, Hebsur S, Pradeep HM, Bharamagoudar, TD (2007). Effect of integrated nutrient management on growth and yield of maize. Agricultural Science 20:399-400.

Raza MA, Gul H, Wang J, Yasin HS, Qin R, Khalid MHB, Naeem M, …Yang W (2021). Land productivity and water use efficiency of maize-soybean strip intercropping systems in semi-arid areas: A case study in Punjab Province, Pakistan. Journal of Cleaner Production 308:127282. *http://dx.doi.org/10.1016/j.jclepro.2021.127282*

Rockström J (2003). Water for food and nature in drought-prone tropics: vapour shift in rain-fed agriculture. Philosophical Transactions of the Royal Society 358:1997-2009. *https://doi.org/10.1098/rstb.2003.1400*

Saddique Q, Liu DL, Wang B, Feng P, He J, Ajaz A, … Cai H (2020). Modelling future climate change impacts on winter wheat yield and water use: a case study in Guanzhong Plain, Northwestern China. European Journal of Agronomy 119:126113. *https://doi.org/10.1016/j.eja.2020.126113*

Schwingshackl C, Hirschi M, Seneviratne SI (2017). Quantifying spatiotemporal variations of soil moisture control on surface energy balance and near-surface air temperature. Journal of Climate 30(18):7105-7124. *https://doi.org/10.1175/jcli-d-16-0727.1*

Seleiman MF, Aslam MT, Alhammad BA, Hassan MU, Maqbool R., Chattha MU, … Battaglia ML (2021). Salinity Stress in Wheat: Effects, Mechanisms and Management Strategies. Phyton-International Journal of Experimental Botany 91(4):667-694. *http://dx.doi.org/10.32604/phyton.2022.017365*

Sharma RK (1973). Response of maize to nitrogen fertilization. Madras Agricultural Journal 60:399440.

Simon J, Dannenmann M, Pena R, Gessler A, Rennenberg H (2017). Nitrogen nutrition of beech forests in a changing climate: importance of plant-soil-microbe water, carbon, and nitrogen interactions. Plant Soil 418:89-114. *https://doi.org/10.1007/s11104-017-3293-y*

Soratto RP, Perdoná MJ, Parecido RJ, Pinotti RN, Gitari HI (2022). Turning biennial into biannual harvest: Long-term assessment of Arabica coffee–macadamia intercropping and irrigation synergism by biological and economic indices. Food Energy and Security 11(2):365. *http://dx.doi.org/10.1002/fes3.365*

Sousa WS, Soratto RP, Peixoto DS, Campos TS, da Silva MB, Souza AGV, … Gitari HI (2022). Effects of *Rhizobium* inoculum compared with mineral nitrogen fertilizer on nodulation and seed yield of common bean. A meta-analysis. Agronomy for Sustainable Development 42:52. *http://dx.doi.org/10.1007/s13593-022-00784-6*

Stevens EJ, Stevens SJ, Flower Day AD, Gardner CO, Eskridge KM (1986). Developmental morphology of dent corn and popcorn with respect to growth staging and crop growth models. Agronomy 78(5):867-874. *https://doi.org/10.2134/agronj1986.00021962007800050025x*

United Nations (2015). Key Findings and Advance Tables. In World Population Prospects: The Revision, ESA/P/WP.241; United Nations: New York, NY, USA

Varvel GE (1995). Precipitation use efficiency of soybean and grain sorghum in monoculture and rotation. Soil Science Society America Journal 59:527-531. *https://doi.org/10.2136/sssaj1995.03615995005900020036x*

Wang XY, Zhou XB, Zhong WW, Chen YH, Han K (2017). Planting pattern and nitrogen rate on farmland microclimate and yield of winter wheat. Agricultural Resource of Arid Areas 35:14-21. *https://doi.org/10.7606/j.issn.1000-7601.2017.01.03*

Wang Y, Kong Y, Chen H, Ding Y (2020). Spatial-temporal characteristics of drought detected from meteorological data with high resolution in Shaanxi Province, China Journal Arid Land 12:561-579. *https://doi.org/10.1007/s40333-020-0066-x*

Wang YX, Li QQ, Liu YT, Lian YL, Yang H. Y, Bo M (2012). Effect of planting density and nitrogen fertilizer topdressing on yield character of broomcorn millet. Chinese Agricultural Science Bulletin 28:188-194. *https://doi.org/10.3969/j.issn.1000-6850.2012.36.032*

White PJ, Bradshaw JE, Brown LK, Dale MFB, Dupuy LX, George TS, Wright G. (2018). Juvenile root vigour improves phosphorus use efficiency of potato. Plant and Soil 432(1-2): 45-63. *http://dx.doi.org/10.1007/s11104-018-3776-5*

Xiao D, Liu DL, Wang B, Feng P, Bai H, Tang J (2020). Climate change impact on yields and water use of wheat and maize in the North China Plain under future climate change scenarios. Agricultural Water Management 238:106238. *https://doi.org/10.1016/j.agwat.2020.106238*

Yasin HS, Raza MA, Gul H, Qin R, Din AMU, Khalid MHB, … Yang W (2022). Maize/soybean strip intercropping produces higher crop yields and saves water under semi-arid conditions. Frontiers in Plant Science 13:1006720. *https://doi.org/10.3389/fpls.2022.1006720*

Zhang X, Davidson EA, Mauzerall DL, Searchinger TD, Dumas P, Shen Y (2015). Managing nitrogen for sustainable development. Nature 528(7580):51-59. *https://doi.org/10.1038/nature15743*

Zhang YL, Wanga F, Shock CC, Yang K, Kang S, Qin S, Li S (2017). Influence of different plastic film mulches and wetted soil percentages on potato grown under drip irrigation. Agriculture Water Management 180:160-171. *https://doi.org/10.1016/j.agwat.2016.11.018*

Zhao CJ, Nasar J, Khan R, Gul H, Gitari H, Shao Z, … Yang J (2023). Maize-soybean intercropping at optimal N fertilization increases the N uptake, N yield and N use efficiency of maize crop by regulating the N assimilatory enzymes. Frontiers in Plant Science 13:1077948. *http://dx.doi.org/10.3389/fpls.2022.1077948*

Zhu YG, Smith SE, Smith FA (2001). Plant growth and cation composition of two cultivars of spring wheat (*Triticum aestivum* L.) differing in P uptake efficiency. Experimental Botany 52(359):1277-1282. *https://doi.org/10.1093/jexbot/52.359.1277*

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