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Effects of supplemental irrigation on yield, water use efficiency and nitrogen use efficiency of potato grown in mollic Andosols

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Abstract

Background: Low soil fertility and reduced seasonal rainfall contribute to low potato (*Solanum tuberosum* L.) yield in Kenya. Nitrogen (N) deficiency is the major problem facing by the smallholder farmers of Kenya due to lack of fallow. Hence an introduction of supplemental irrigation with an adequate application of this nutrient could increase potato yield. The objective of this study was to determine the effects of supplemental irrigation and N-fertilisation on potato tuber yield, water use efficiency (WUE) and nitrogen use efficiency (NUE). The experiment was conducted in Nakuru County, Kenya for two seasons. The experimental soils are classified as mollic Andosols. The treatments comprised two irrigation treatments of full supplemental irrigation (FI) and rainfed production (RF) and four N levels of four N levels of 0 (N0), 60 (N1), 90 (N2) and 130 kg N/ha (N3).

Results: The results showed that total tuber yield, marketable tuber yield and NUE were significantly ($P < 0.001$) affected by irrigation × N-fertilisation while WUE was only affected ($P < 0.001$) by N-fertilisation. The highest total tuber yield, 58.28 tonnes/hectare (t/ha), was recorded under FI combined with N3. Treatment FI significantly increased marketable tuber yield by approximately 125.58% in all N treatments compared to RF. The highest NUE of potato (236.44 kg/kg of N) was obtained under FI combined with N3 but not significantly different from the NUE of potato obtained under FI with N2. N-fertilisation N3 produced the highest WUE of 14.24 kg/m^3. Significant correlation was obtained between tuber yield and number of tubers/plant ($r = 0.75$, $P < 0.001$), NUE ($r = 0.95$, $P < 0.001$) and WUE ($r = 0.72$, $P < 0.001$).

Conclusion: High potato yield and marketable tuber yield can be achieved in mollic Andosols when water deficits of the growing season are eliminated with supplemental irrigation and an application of 130 kg N/ha.

Keywords: N-fertilisation, NUE, Potato, Supplemental irrigation, WUE, Yield

Background

Potato (*Solanum tuberosum* L.) is the second most important staple food and cash crop in Kenya, after maize (*Zea mays*) (Muthoni et al. 2017; Waaswa and Satognon 2020). Its production is predominantly rainfed (Muthoni et al. 2021). Population pressure and the need to produce more to satisfy the demand for potato have consequently led to encroachment of farming into marginal lands, forest reserves and non-traditional potato-producing areas (Muthoni et al. 2021). In Kenya, the area under production increased from 135,000 ha in 2008 to 217, 315 ha in 2018. Despite the increased area under production, a low yield of 8.6 t/ha was obtained in 2018, registering a decline of 60% from 2008 (FAOSTAT 2020; Mburu et al. 2020; Mcewan et al. 2021). Previous research attributed the low potato yield to the reduction of seasonal rainfall in the potato-growing areas of Kenya from 737 to 126 mm (Waaswa et al. 2021). Drought or dry periods between rainfall seasons and increased temperatures, which lead to high crop evapotranspiration, are experienced in 70–80% of the smallholder farms in Kenya (Bryan et al. 2013; Kimathi et al. 2021; Muthoni

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et al. 2017; Taiy et al. 2017). Soils in most potato-growing areas in Kenya are classified as mollic Andosols. These soils become dry a few days after a rainfall event due to their high infiltration rates. Potato is sensitive to water deficit and slight water stress causes a reduction in leaf number and size, canopy radiation interception and photosynthesis, which consequently affects the tuber number/plant, size and yield (Li et al. 2016). Supplemental irrigation is a perfect technique to cope with the effect of climate variability in Kenya. Supplemental irrigation is when water is supplied to essentially rainfed crops during the period when precipitation fails to uniformly provide sufficient amounts of water required by the crop to fully produce its potential yield. This method helps to maintain the soil moisture at a high level and eliminate the water deficit in the plant root zone. Research conducted in China showed that 55 mm of supplemental irrigation could increase potato yield up to 50.8% (Tang et al. 2018).

Nitrogen deficiency is another major problem facing by the smallholder farmers of potato in Kenya due to a lack of fallow (Satognon et al. 2021). Nitrogen deficiency is manifested by reduced growth and tuber yield in terms of tuber number/plant and size (Koch et al. 2020). It is well known that soil water affects nutrient transport to the root surface in the water flux created by transpiration (mass flow) (Smethurst 2004) and high water uptake by plant roots considerably enhances root N acquisition by mass flow (Mcmurtrie and Näsholm 2018). Water stress reduces N uptake as a result of the decrease in water uptake and transpiration rate (Koch et al. 2020). Hence a suppression of water stress in the root zone during the growing season can improve N uptake by potato crops. The objective of this study was to determine the effects of supplemental irrigation and N-fertilisation rates on tuber yield, NUE and WUE of potato grown in mollic Andosols in Kenya.

Materials and methods

Experimental site description

A two-season field experiment was conducted between July 2020 and January 2021 at the experimental farm of Agro-Science Park of Egerton University in Nakuru County, Kenya. The experimental site is located in agro-ecological zone III of Kenya (0.3031°S, 36.0800°E) at an altitude of 2670 m above sea level. Climatic factors including precipitation (Fig. 1), maximum and minimum temperature and humidity of the growing seasons (Table 1) were obtained from the weather station of Egerton University located 1 km away from the experimental site. Maize, wheat (*Triticum aestivum*), beans (*Phaseolus vulgaris*) and potato are the most common crops grown in the study area. The soils at the experimental site are well-drained, dark reddish clays, slightly acidic and contain medium levels of organic carbon and low levels of phosphorus, and they are classified as mollic Andosols (Jaetzold et al. 2007).

Experimental procedure

Determination of chemical properties of experimental soils

To determine the initial soil properties, soil samples were randomly taken from six locations at two different depths (0–0.15 m and 0.15–0.45 m) since the potato root zone falls in 0 and 0.4 m. The collected samples were mixed to obtain one composite sample per depth. The composite samples were air-dried at room temperature (22–25 °C) for a week, crushed and sieved through a 2-mm sieve. The baseline soil chemical analyses were performed at the soil testing laboratories of Kenya Agricultural and Livestock Research Organisation (KALRO), Nairobi. Soil pH was measured in a 1:1 (w/v) water extract. The *Kjeldahl* digestion method was used to analyse the total N content of the composite samples (Okalebo et al. 2002). In this method, the N is initially converted to ammonia using metal-catalysed acid digestion (Motsara and Roy 2008). Soil elements such as phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), manganese (Mn) and sodium (Na) were extracted using the Mehlich double acid method. In this method elements such as Na and K were determined with a flame photometer while Ca, Mg and Mn were measured using atomic absorption spectrophotometer (AAS). P was determined spectrophotometrically. Total organic carbon was analyzed using the colourimetric method (Anderson and Ingram 1993). Exchangeable acidity was measured at $pH < 5.5$ (Okalebo et al. 2002). Available iron (Fe), zinc (Zn) and copper (Cu) were extracted in a 1:10 (w/v) ratio with 0.1 M HCL followed by AAS readings. For the quality control of the analyses, samples were analysed with the reference soil sample (with known values). Samples were also duplicated during the analyses. The initial chemical soil properties are shown in Table 2.

Determination of physical properties of experimental soil

To determine the physical properties of the experimental soils, soil texture with the percentage of each primary soil (sand, silt and clay) was determined using the hydrometer method (Bouyoucos 1962). Soil bulk density (ρb) of samples collected at different depths with core rings was determined using the gravimetric method followed by the oven drying method (Blake 1965). Field capacity (FC) was assessed by subjecting the composite samples to pF2.5 followed by the oven drying method (at 105 °C for 24 h) (Aschonitis et al. 2013). Permanent wilting point (PWP) was measured by subjecting the samples to

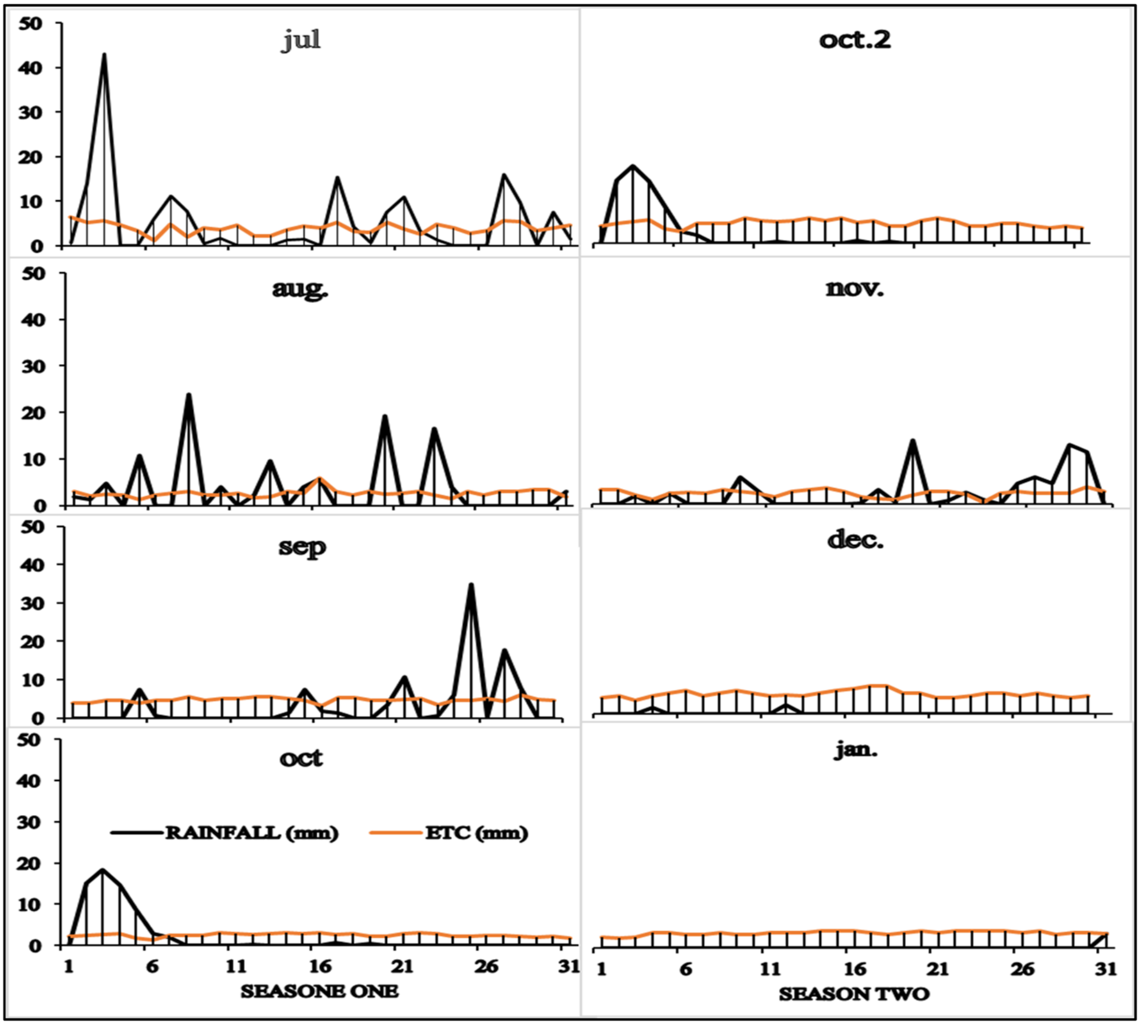

Fig. 1 Daily precipitation and ET_c of the growing seasons

Table. 1 Meteorological data from weather station of Egerton University

Parameters	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Average of maximum temperature (°C)	23.2	23.8	24.1	25.2	23.4	27.2	26.1
Average of minimum temperature (°C)	10.5	10.7	9.5	10.1	10.2	9.9	10.0
Average of humidity (%)	49.0	48.0	51.0	49.0	49.0	53.0	57.0

a pressure of pF4.2 followed by the drying oven method. Available water (AW) was then computed by subtracting PWP from FC using Eq. 82 of FAO 56 (Allen et al. 1998).

$$AW = 1000(\theta_{FC} - \theta_{WP})Zr,$$

where; AW = total available soil water in the plant root zone depth (m^3), θ_{FC} = water content at field capacity (m^3/m^3), θ_{WP} = water content at wilting point (m^3/m^3), and Z_r = rooting depth (m).

The readily available water (RAW) which is the fraction of AW that a crop can deplete from the root zone without experiencing water stress was estimated using Eq. 83 of FAO (Allen et al. 1998).

Table. 2 Soil chemical analyses of the experimental soils

Soil depth (m)	0–0.15		0.15–0.45	
Soil parameters	Value	Class	Value	Class
Soil pH	5.43	Medium acid	5.46	Medium acid
Exch. acidity meq%	0.20	Adequate	0.21	Adequate
Total nitrogen (N) %	0.16	Low	0.14	Low
Total Org. carbon %	1.69	Moderate	1.61	Moderate
P ppm	21	Low	19.1	Low
K meq%	1.14	Adequate	1.11	Adequate
Ca meq%	5.6	Adequate	5.4	Adequate
Mg meq%	1.61	Adequate	1.43	Adequate
Mn meq%	1.37	Adequate	1.25	Adequate
Cu ppm	1.80	Adequate	1.71	Adequate
Fe ppm	12.2	Adequate	12.2	Adequate
Zn ppm	2.45	Low	2.42	Low
Na meq%	0.18	Adequate	0.17	Adequate

$$RAW = pAW,$$

where; RAW = readily available soil water in the plant root zone (mm) and p = average fraction of AW that can be extracted from the root zone before water stress (reduction in ET_c) occurs. Its values range from 0 to 1 for various crops. The average fraction of potato is 0.35. This value was taken from table 83 of FAO 56 (Allen et al. 1998). The physical soil properties of the experimental site are shown in Table 3.

Water analysis for its suitability for irrigation

To check the water suitability for irrigation, an aliquot of water was analysed at KALRO, Nairobi. The pH and electrical conductivity (EC) were measured with a pH–meter. Na and K concentrations were measured with a flame photometer while Ca and Mg were determined using AAS. The chloride concentration of the water was determined by titrating an aliquot of water with silver nitrate and potassium chromate while carbonates were analysed as bicarbonates by titrating an aliquot of water with hydrochloric acid and phenolphthalein. The sulphate content of the sample was analysed using the turbidmetric method. The sodium absorption ratio was estimated using Na, Ca and Mg concentrations. The irrigation water used had a medium salinity level and high sulphate (Table 4). This indicated that the quality of water used for this study was suitable for irrigation. This interpretation was based on the USDA classification of irrigation water (Bauder et al. 2011; Scherer et al. 1996; Wilcox 1955). The soil of the experimental site was permeable with adequate drainage.

Table. 4 Composition of irrigation water used

Parameters	Values
pH	8.09
Conductivity (EC) mS/cm	0.27
Na meq%	0.37
K meq%	0.12
Ca meq%	0.04
Mg meq%	0.05
Carbonates meq%	ND[a]
Bicarbonates meq%	0.75
Chlorides meq%	1.92
Sulphates meq%	49.9
Sodium adsorption ratio	1.74

[a] *ND* not detected

Experimental design and treatments

Before the experiment setup, the land was ploughed at 0.3 m depth after which plots were prepared by raising the soils. The treatments comprised two irrigation treatments of full supplemental irrigation (FI) and rainfed production (RF) and four N levels of 0 (N0), 60 (N1), 90 (N2) and 130 kg N/ha (N3). Full supplemental irrigation (FI) was supplied using the drip irrigation method. Lateral driplines with 1.6 Lh^{-1} at 100 kPa inline drippers spaced at 30 cm were placed for each row. All plots received the same irrigation amount during the first two weeks to encourage crop establishment. The drip irrigation was then atomized in terms of minutes for FI plots after the two first weeks to deliver the calculated quantity of water based on daily crop evapotranspiration collected from the weather station of Egerton University. For FI treatment, irrigation was applied after the rain once 40% of soil available water was depleted. Soil available water was monitored using a time domain reflectometry

Table. 3 Physical properties of the experimental soils

Depth (m)	Soil texture				Moisture retention %				Bulk density (g/cm^3)
	Sand %	Silt %	Clay %	Class	FC	PWP	AW	RAW	
0.00–0.15	63.7	26.2	10.1	SL	19.9	12.3	7.6	2.66	1.26
0.15–0.45	57.6	30.2	12.2	SL	20.3	11.8	8.5	2.98	1.34

SL = Sandy Loam

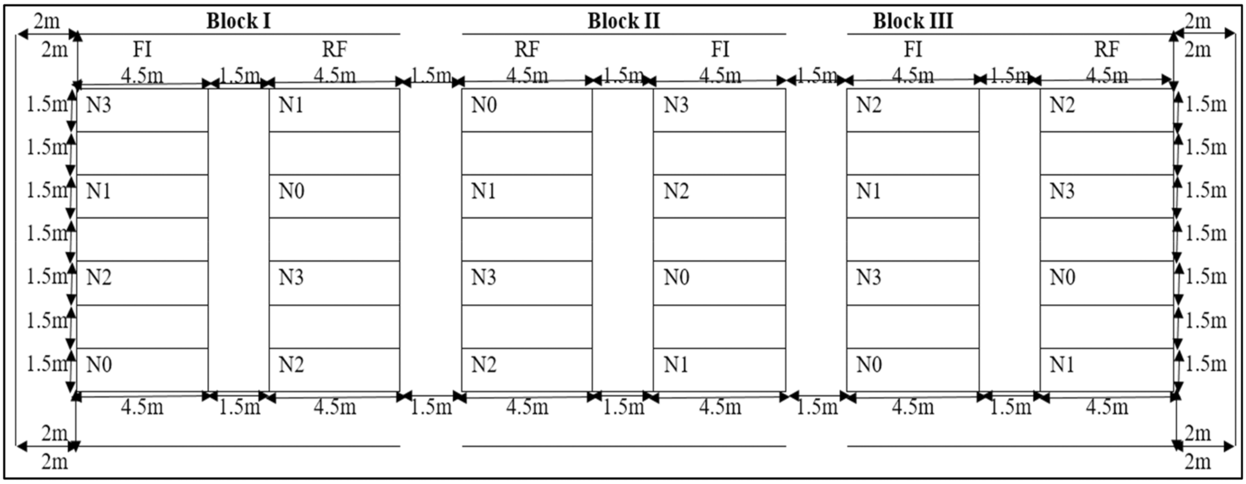

Fig. 2 Field layout

(TDR) moisture meter. All the N-fertilisation treatments were split applied at 10 (40%), 30 (40%) and 50 (20%) days after planting. Urea fertiliser was used as a source of N.

A split-plot in a randomised complete block design was used (Fig. 2). Irrigation and N treatments were randomly assigned to the main plots and subplots, respectively. This is because irrigation required a large plot. Each treatment was replicated in three different blocks. The different blocks, main plots and subplots were separated by a 1.5 m buffer. Each experimental plot measured 7.5 m^2 (5 m × 1.5 m) and 0.4 m depth. Each plot received 20 apical rooted cuttings of *Shangi* potato variety. They were planted at a spacing of 0.3 m and 0.70 m between plants and rows, respectively in a set of five rows. This gave a density of 47,617 plants/ha. Apical rooted cuttings were planted on 7 Jul. 2020 and 26 Oct. 2020 and tubers were manually harvested from the six plants in the middle rows of each subplot on 8 Oct. 2020 and 20 Jan. 2021, respectively. During planting, 90 kg/ha of potassium sulphate (SOP) and 50 kg/ha of triple superphosphate (TSP) fertilisers were added to each plot based on the universal recommendations of the area. Ridomil Gold MZ 68 WG (1 kg/ha) combined with mancozeb (1 kg/ha) fungicides were used to control the prevailing diseases especially the early and late blight diseases whereas VOLTAGE 5EC (350 ml/ha) was used to control potato pests. Plots were manually weeded using a hand hoe and earthing up was manually done one month after planting.

Crop water requirements

Reference crop evapotranspiration (ET_0) was estimated based on daily data collected from the weather station of Egerton University using Penman–Monteith's (Allen et al. 1998; Jensen and Allen 2016).

$$ET_0 = \frac{\Delta(Rn - G) + \rho_a c_p(\frac{es-ea}{ra})}{\Delta + \gamma(1 + \frac{rs}{ra})},$$

where; ETo = reference crop evapotranspiration, Δ = slope of vapor saturation pressure, Rn = net radiation, G = soil heat flux; $\rho_a =$ mean air density at the constant air pressure, cp = specific heat of the air, es − ea = vapour pressure deficit, γ = psychrometric constant, rs = surface resistance and ra = aerodynamic resistance.

The actual crop evapotranspiration (ET_c) was computed as the product of ET_0 and the crop coefficient (K_c).

$$ET_C = K_C \times ET_0.$$

The crop coefficient at different crop stages was calculated using the formulae 59, 62 and 65 of FAO (Allen

Table. 5 Monthly average of K_c, ET_0 and ET_c

Months	Season 1				Season 2			
	Jul	Aug	Sep	Oct	Oct	Nov	Dec	Jan
K_c	1.14	0.75	1.12	0.63	1.18	0.78	1.14	0.65
ET_0 (mm)	3.49	3.57	4.2	4.3	3.08	3.08	4.32	4.5
ET_c (mm)	4.63	4.32	5.32	4.93	4.26	3.86	5.46	5.15

et al. 1998). The average values of Kc at different crop stages were 1.14 and 1.18 for the initial stage, 0.75 and 0.78 for the growth stage, 1.12 and 1.14 for the middle stage and 0.63 and 0.65 for the maturation stage for seasons one and two, respectively (Table 5). The equivalence period of different stages of potato corresponded to 25, 30, 30 and 30 days for initial, growth, middle and tuber maturity stages.

The cumulative actual crop evapotranspiration (ETa) was computed over the growing season using a soil water balance equation (Steele et al. 1997; Jensen and Allen 2016).

$$ETa = P + I \pm \Delta s - R - D,$$

where; P = amount of precipitation throughout the potato-growing season, I = total amount of additional irrigation supplied during the growing season of potato (mm), ΔS = change in soil water content in the root zone during the growing season of potato (mm), R = runoff loss (mm) and D = loss due to deep drainage during the growth period (mm). R is ignored since the slope of the experimental site is relatively small with adequate soil infiltration and irrigation was supplied through drip irrigation. Loss due to deep drainage (D) was expected to occur when rainfall surpassed the soil water deficit (which was estimated as field capacity minus soil water content before a rain) in the root zone before precipitation. Irrigation never surpassed the soil water deficit level and thus, was considered to cause no loss due to deep drainage.

Yield components

Plant height, number of branches/plant, biomass, tuber number/plant, total tuber yield and marketable yield were collected as yield components on six plants from the middle rows of each subplot. The harvest index (HI) was expressed as the percentage of tuber yield in the total biomass at harvest (aboveground biomass plus tuber yield at harvest).

$$HI(\%) = \frac{Tuber\ Yield\left(\frac{t}{ha}\right)}{Total\ biomass\ at\ harvest\left(\frac{t}{ha}\right)} \times 100.$$

Water use efficiency and irrigation water use efficiency

Water use efficiency (WUE) and irrigation water use efficiency (IWUE) were computed using the following equations (Erdem et al. 2006).

$$WUE\left(\frac{kg}{m^3}\right) = \frac{Total\ tuber\ Yield\left(\frac{kg}{ha}\right)}{ETa\left(m^3\right)},$$

$$IWUE\left(\frac{kg}{m^3}\right) = \frac{TYI\left(\frac{kg}{ha}\right) - TYNI\left(\frac{kg}{ha}\right)}{I\left(m^3\right)},$$

where; TYI = total tuber yield of an irrigated plot, TYNI = total tuber yield in of a non-irrigated plot and I = amount of irrigation supplied during the growing season of potato.

Nitrogen use efficiency

Nitrogen use efficiency (NUE) was computed using the following formula (Leal Filho et al. 2015).

$$NUE\left(\frac{kg}{kg}\right) = \frac{Tyfp\left(\frac{kg}{ha}\right) - Tyufp\left(\frac{kg}{ha}\right)}{Quantity\ of\ N\ applied\left(\frac{kg}{ha}\right)},$$

where Tyfp = total tuber yield of a fertilised plot and Tyufp = total tuber yield of an unfertilised plot.

Data analysis

Before analysis, the Shapiro Wilk test at 0.05 was conducted using R software (version 3.6.3) to test the normality of the data. For any data that was not normally distributed, fitting data transformation was performed. Analysis of variance (ANOVA) was also run using the same software. The least significant difference (LSD) test was used to separate the treatment means at 0.05. Regression analyses were carried out at 0.05 to determine total tuber yield, WUE and NUE responses to N levels in mollic Andosols. Pearson correlation coefficient was carried out to test the significance of the relationship between tuber number/plant, WUE and NUE as well as total tuber yield. During the analysis, outlier data were identified using the control chart technique (Bakar et al. 2006) and any outlier data and not due to the treatment effect was deleted from the model and replaced by the nearest after confirming data entry error.

Results and discussion

Crop water requirements

During the first two weeks, 6.4 and 4.2 mm of water were supplied at the beginning of the first and the second seasons, respectively to encourage plant root establishment. The cumulative actual crop evapotranspiration (ET_a) was 268.09 and 237.7 mm for RF and 359.47 and 381.89 mm for FI during the first and the second growing seasons, respectively. This showed that the crop water requirement was higher during the second season. This agreed with the previous studies that reported that ET_a varied from 350 to 800 mm for various climates and environments (Adavi et al. 2018; Afzaal et al. 2020; Ati et al. 2010; Ati et al. 2012; Djaman et al. 2021; Ierna and

Mauromicale 2018; Meligy et al. 2020; Nowacki 2018; Paredes et al. 2018). The amount of supplemental irrigation water applied was 91.38 and 144.19 mm for seasons one and two, respectively. This indicated a reduction in seasonal rainfall patterns due to low and erratic rainfall and high temperatures recorded during the second season. Muthoni et al. (2017) and Waaswa et al. (2021) reported a significant reduction in in-season rainfall followed by an uneven distribution of rainfall in Nakuru County, Kenya. This demonstrated the need for supplemental irrigation in the potato growing area of Nakuru county.

Plant growth

The effects of supplemental irrigation and N-fertilisation on plant height and number of branches/plant are presented in Tables 6 and 7. The results showed that plant height and number of branches/plant of potato were not significantly affected by supplemental irrigation and the interaction effects of the two factors ($P > 0.05$). The average plant height during the two growing seasons in FI was higher than that in RF but did not differ significantly and this is in line with the previous research of Darabad (2014). However, many studies reported that potato crop height increases with an increase in the amount of irrigation water applied (Farrag et al. 2016; Metwaly and El-Shatoury 2017; Zhang et al. 2017). This difference in result can be attributed to the potato variety used in this study. However, a significant increase in plant height and number of branches/plant was observed as the amount of applied N increased ($P < 0.001$). The highest plant height, 76.82 cm, was recorded under N3. This increase of plant height with N dosage was also reported in previous research (Godebo and Belay 2020; Setu and Mitiku 2020; Tolessa et al. 2017). Sebnie et al. (2021) indicated that an application of mineral N fertiliser increased potato plant height compared to unfertilised plots.

Table. 7 Means separation of plant height, number of branches per plant and HI (%)

	Plant height (cm)	Number of branches/plant	HI (%)
Irrigation effect			
FI	72.58	17	56.29
RF	63.85	16	45.41
LSD	ns	ns	ns
Nitrogen effect			
N3	76.82a	19a	54.69a
N2	69.35b	18a	51.69ab
N1	67.36b	17a	49.12b
N0	59.35c	14b	47.91b
LSD	5.51	2.27	5.29

ns not significant, alpha = 0.05. The same letters within the same column indicate that there is no significant difference while different letters within the same column indicate there is a significant difference at 0.05

Yield components

The effects of supplemental irrigation and N-fertilisation on yield components (tuber number/plant, total tuber yield, marketable yield and HI) during the growing seasons are presented in Tables 6 and 7. The results indicated that irrigation, N-fertilisation and irrigation × N-fertilisation exhibited a significant effect on tuber number/plant, total tuber yield and marketable yield of potato. Conversely, HI was only significantly affected by N-fertilisation ($P < 0.001$). The FI significantly increased tuber number/plant, tuber yield and marketable yield compared to RF, regardless of N-fertilisation. For different irrigation treatments, the tuber number/plant, total tuber yield and marketable yield ranged from 16 to 20, 20.86 to 44.11 t/ha, and 15.23 to 38.83 t/ha, respectively. The tuber yield and marketable yield were higher during the second growing season. This increase in potato yield in the second season can be attributed to the high ET_a recorded during the season. This is in line

Table. 6 Mean squares plant height, branch number/plant, tuber number/plant, yield, HI and marketable yield

Source of variation	Df	Plant height	Number of branches/plant	Tuber number/plant	Total tuber yield	Marketable yield	HI
Season	1	226.03	455.53	107.97	42.84	131.50	268.94
Replicate (season)	4	140.23	41.74	10.04	11.08	4.45	36.49
Irrigation	1	914.73	6.89	225.37*	5172.76*	4942.84*	1422.01
Season × irrigation (main plot error)	1	349.27	6.40	2.36	74.12	33.05	96.84
Nitrogen	3	618.75***	44.85**	134.62***	1005.90***	993.62***	108.54*
Irrigation × nitrogen	3	54.47	17.83	23.72**	249.89***	200.94***	49.90
Error	34	44.12	7.51	4.11	9.50	6.33	40.56*
CV		9.73	16.02	12.10	9.77	0.97	12.55
R^2		0.73	0.76	0.85	0.97	9.60	0.63

HI= Harvest Index, '***', '**' and '*' are significance codes at 0.001, 0.01 and 0.05, respectively with the previous research which reported that potato is very susceptible or sensitive to water stress compared to many other crops and full irrigation without water deficit throughout the potato cycle always leads to high yield (Darabad 2014; Mattar et al. 2021). Tuber initiation to maturity growth period forms the critical water requirement period where water deficits negatively affect potato productivity (Ahmadi et al. 2010; Salter and Goode 1967; Sasani et al. 2006). Begum et al. (2018) found that supplemental irrigation is very important for potato in the areas with a high drought frequency due to the high yield of potato in a short time and if shortage of readily available water in the soil is eliminated it is possible to achieve high and stable potato yield of 40–50 t/ha or more. Previous studies found an increase in tuber number/plant and marketable potato yield of irrigated potato compared to rain-fed production (Abu El-Fotoh et al. 2019; Djaman et al. 2021; Waqas et al. 2021). Djaman et al. (2021) also reported the highest tuber number/plant under full irrigation.

The tuber number/plant, tuber yield and marketable yield across N-fertilisation varied from 13 to 23, 22.75 to 45.06 t/ha, and 16.12 to 39.84 t/ha, respectively. The maximum tuber number/plant, tuber yield and marketable yield were observed with N3. Earlier works found that potato yield, regardless of irrigation, statistically increases with an increase in N rate up to 280 kg N/ha, then tend to increase faintly as N dosage increases further (Badr et al. 2012; Ospina et al. 2014; Shunka et al. 2017). Further research needs to be conducted to determine the optimal nitrogen level for potato production in mollic Andosols since this study did not find out the point at which an increase in N dosage might lead to a decrease in potato yield.

For irrigation × N-fertilisation effects, the highest tuber number/plant, 27, was obtained in FI with N3 treatment during the first season while the lowest value, 11, was found under RF with N0 during the second growing season (Fig. 3a, b). A significant increase in the total yield and marketable yield of all N treatments under FI compared to RF was also observed. Besides, the maximum total tuber yield, 62.12 t/ha, and marketable yield, 55.79 t/ha, were found in FI with N3 during the second season whereas the smallest total tuber yield, 15.21 t/ha, and marketable yield, 9.99 t/ha, were found under RF with N0 during the second season and the first season, respectively (Fig. 3c–f). It was also found that FI enhanced marketable tuber yield by 129.84, 94.63, 151.21 and 126.63%

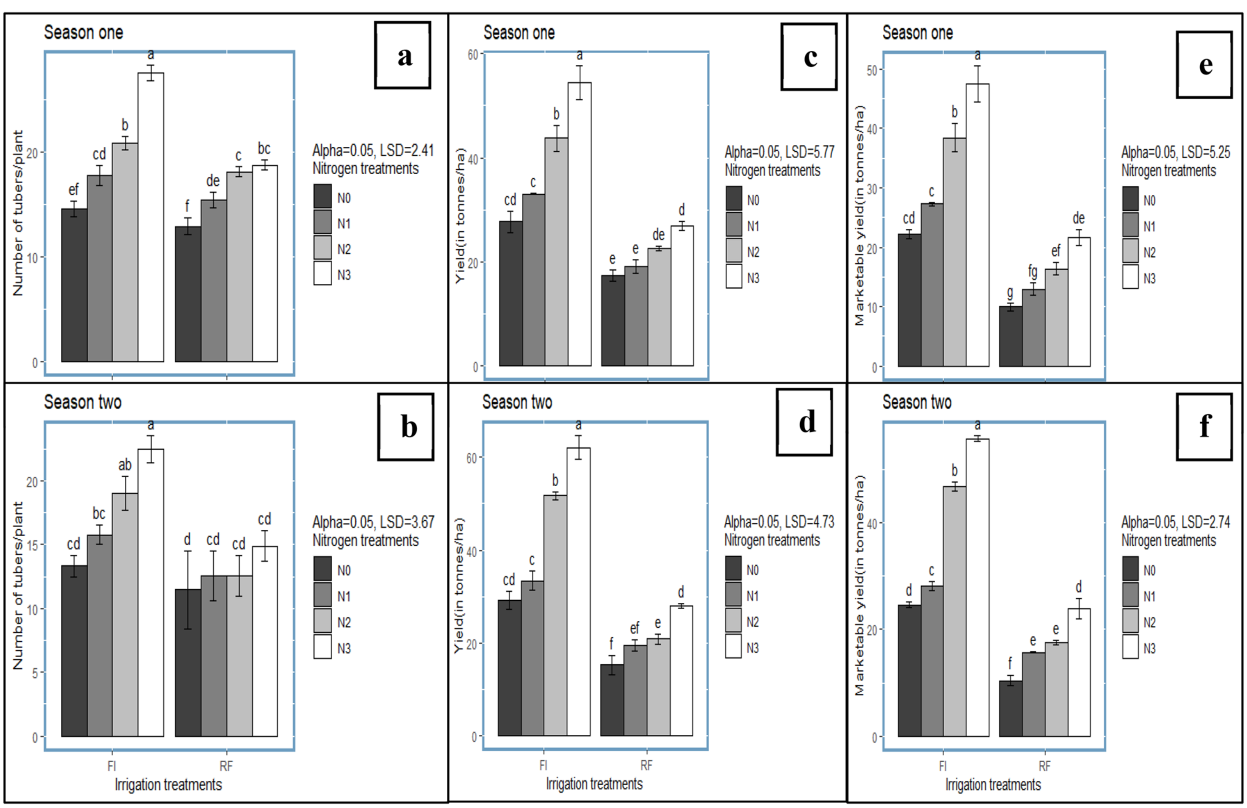

Fig. 3 Means separation of tuber number per plant, total tuber yield and marketable tuber yield of different growing seasons. Different letters indicate significant difference

for N0, N1, N2 and N3, respectively compared to rain-fed N-fertilisation. A significant effect of irrigation × N-fertilisation on tuber yield was reported by Badr et al. (2012) and Tolessa (2019).

An increment of HI with N level was found with the maximum value of HI, 54.69%, recorded in N3. However, the HI obtained with N3 did not differ significantly from the HI observed with N2. It was also found that supplemental irrigation did not affect HI. This disagreed with the early studies that reported a significant effect of irrigation for HI of potato with a reduction in HI as water stress becomes more severe (Ruttanaprasert et al. 2016; Sobhani and Hamidi 2015). This could be explained by the fact that the water deficit under RF was not so severe to affect HI during the growing seasons. To achieve an optimum marketable yield of potato grown on mollic Andosols of Kenya, supplemental irrigation with a high N rate of 130 kg N/ha is required.

Water use efficiency (WUE) and irrigation water use efficiency (IWUE)

Data collected on potato WUE and IWUE for all treatments are presented in Table 8. It was found that irrigation and irrigation × N-fertilisation did not interact with WUE. However, N-fertilisation statistically increased the WUE of potato. N-fertilisation N3 produced higher potato WUE (14.24 kg/m^3) followed by N2 (11.69 kg/m3), N1 (9.64 kg/m^3) and N0 (7.47 kg/m^3) (Fig. 4a, b). Previous studies found an increase in potato WUE with an increase in N rate (Badr et al. 2012; Tolessa 2019). IWUE indicated how the additional applied water was used by the crop in different N-treatments. It was observed that N-fertilisation considerably ($P < 0.001$) interacted with potato IWUE in mollic Andosols. IWUE obtained with N-fertilisation N3 and N2 were high but did not differ from each other. The lowermost IWUE, 10.10 kg/m^3, was recorded with N0 (Fig. 4c, d). This indicated that the additional water applied was more significantly used by the crop when applying N3 and N2 than when applying N1 and N0.

Table. 8 Mean squares of WUE and IWUE

Source of variation	Df	WUE	Source of variation	Df	IWUE
Season	1	23.41	Season	1	100.21
Replicate (season)	4	4.36	Replicate	2	2.42
Irrigation	1	48.72	Nitrogen	3	386.72***
Season × irrigation (main plot error)	1	40.04	Error	17	17.18
Nitrogen	3	100.20***	CV		23.08
Irrigation × nitrogen	3	2.16	R^2		0.82
Error	34	1.45			
CV		11.22			
R^2		0.90			

*** is a significance code at 0.001

Nitrogen use efficiency (NUE)

Irrigation, N-fertilisation and irrigation × N-fertilisation exhibited a significant effect on NUE (Table 9). The maximum potato NUE, 197.22 kg/N of kg, was observed under FI. It was observed that the NUE of potato increased as the NUE of potato increased as the N level increased, with the maximum NUE obtained with N3, but it was not significantly different from potato NUE found with N2. The smallest NUE was obtained with N1. This is in line with the study of Badr et al. (2012). On the contrary, Banerjee et al. (2015) found that NUE decreased with an increase in N rate. For irrigation × N-fertilisation effects for NUE, it was observed a significant increase of potato NUE under FI during the two seasons compared to RF with the maximum NUE, 236.44 kg/N of kg, obtained under FI with N3 but not significantly different from the NUE of potato obtained under FI with N2 (Fig. 5a, b). This implied that for an improvement of NUE in potato grown in mollic Andosols, the amount of water and N dosage should be applied at their optimum levels. The optimum level of NUE in mollic Andosols can be achieved with 90 kg N/ha since the NUE obtained with 130 kg N/ha did not differ from NUE recorded with 90 kg N/ha.

Relationship between potato yield, WUE, NUE and N-rate under different irrigation treatments

The production functions of tuber yield, WUE and NUE were evaluated in different irrigation treatments to show their responses to N level in mollic Andosols (Figs. 6, 7, 8). As expected, the relationships between tuber yield, WUE and NUE and N applied were linear (all F-values were significant at $P < 0.05$). The regression equations and determination coefficients between N-fertilisation and tuber yield obtained were the following.

$$FI : Y = 0.2368X + 25.343, R^2 = 0.90 \text{ and}$$

$$RF : Y = 0.0835X + 15.313, R^2 = 0.92.$$

These equations indicated that total potato tuber yield increased by about 236 and 83 kg/ha for each kg of N applied under FI and RF, respectively. This showed that an increase in a unit of N greatly increased total potato tuber yield under FI compared to RF. The following

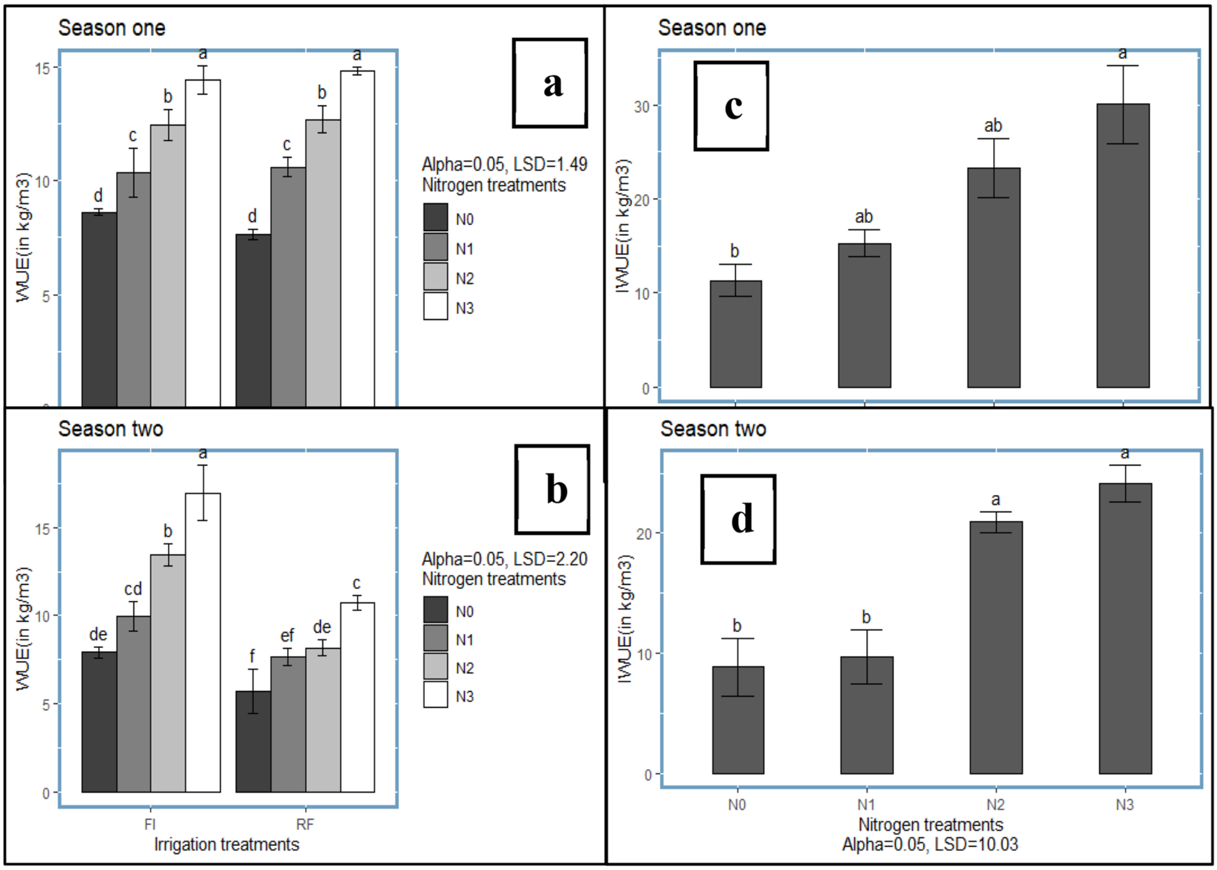

Fig. 4 Means separation of WUE and IWUE of different growing seasons. Different letters indicated significant difference

regression equations and determination coefficients were obtained between WUE and N-fertilisation.

$$FI : Y = 0.0578X + 7.7192, R^2 = 0.95 \text{ and}$$
$$RF : Y = 0.0464X + 6.5086, R^2 = 0.99.$$

Table. 9 Mean squares of NUE

Source of variation	Df	NUE
Season	1	5709.06
Replicate (season)	4	752.66
Irrigation	1	139,578.21*
Season × irrigation (main plot error)	1	604.58
Nitrogen	2	17,466.54***
Nitrogen × irrigation	2	6650.21***
Error	24	388.83
CV		14.61
R^2		0.95

***, ** and * are significance codes at 0.001, 0.01 and 0.05, respectively

This indicated that an increment of each kg of N applied respectively in FI and RF increased the WUE of potato by approximately 0.057 and 0.04 kg/m^3. The highest slope of the regression between WUE vs N-fertilisation corresponded to FI. Between NUE and N-fertilisation, the following equations and determination coefficients were also performed.

$$FI : Y = 1.4931X + 57.868, R^2 = 0.73 \text{ and}$$
$$RF : Y = 0.4753X + 28.325, R^2 = 0.99.$$

The slopes of this equation showed that an increase of each kg of N applied enhanced the NUE of potato by approximately 1.49 and 0.47 kg/kg of N under FI and RF, respectively. These results demonstrated the importance of supplemental irrigation in the growing area for a high NUE of potato. It was found that a significant positive correlation existed between tuber yield and both NUE ($r = 0.95$, $P < 0.001$) and WUE ($r = 0.72$, $P < 0.001$) (Fig. 9). The strong positive

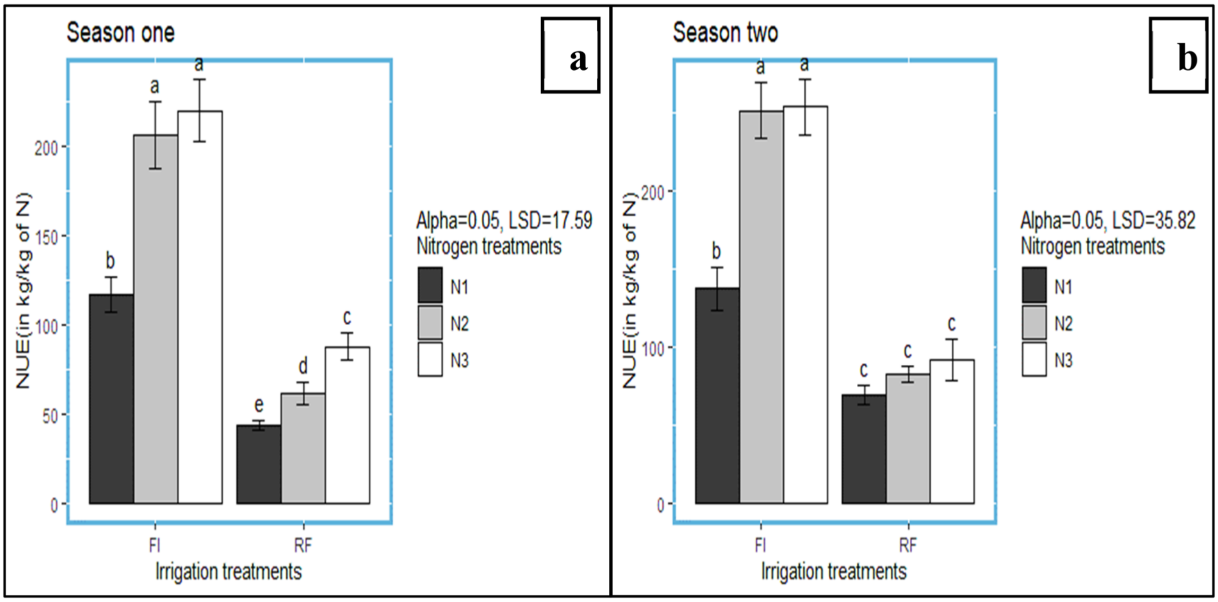

Fig. 5 Means separation of NUE of different growing seasons. Different letters indicate significant difference.

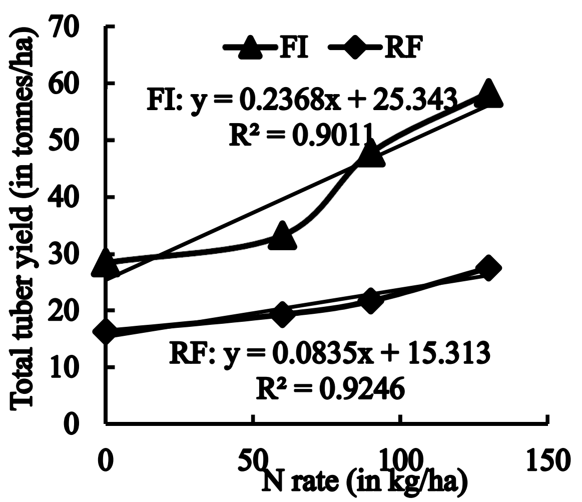

Fig. 6 Relationship between total tuber yield and N-rates under different irrigation treatments

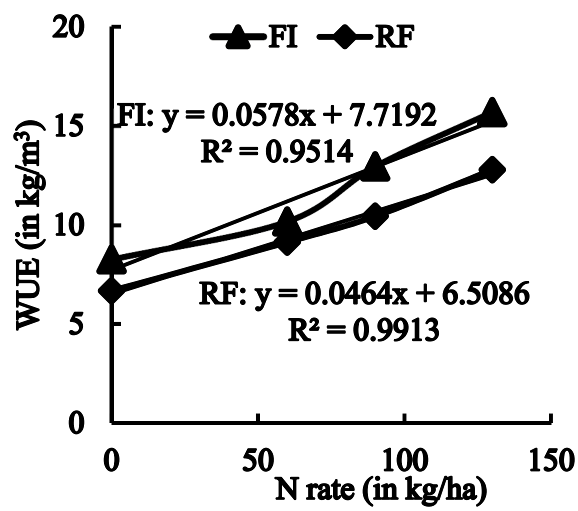

Fig. 7 Relationship between WUE and N-rates under different irrigation treatments

correlation between total tuber yield and tuber number per plant ($r=0.75$, $P<0.001$) showed that the increase in total tuber yield observed in this study depended on the tuber number/plant. On the contrary, a previous study reported that there is no correlation between tuber number/plant and potato yield (Badr et al. 2012). This difference can be attributed to the potato variety used as plant material in this study as well as the soil type.

Conclusion

Yield components of potato were largely more responsive to the interaction effect of irrigation × N-fertilisation than a single effect of irrigation and N-fertilisation. The highest total tuber yield and marketable were obtained under FI with an application of 130 kg N/ha. In this study, WUE was high when applying 130 kg N/ha. The NUE consistently increased with the increase in N rate up to

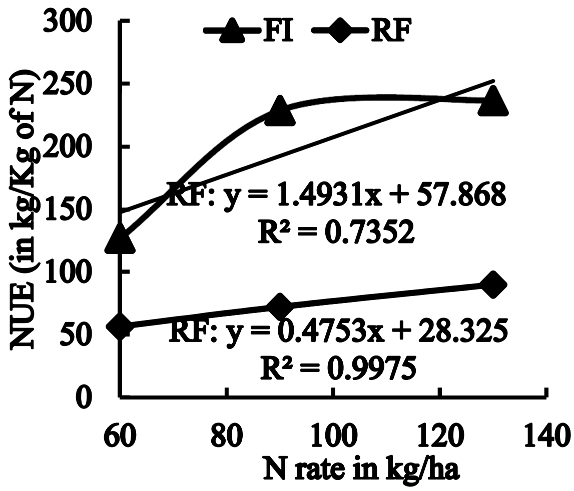

Fig. 8 Relationship between WUE and N-rates under different irrigation treatments

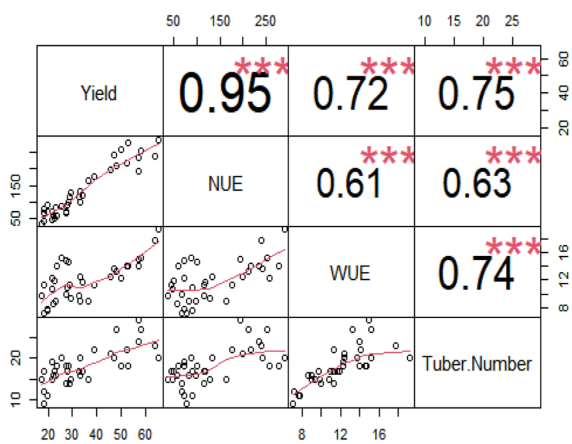

Fig. 9 Correlation between tuber number/plant, tuber yield, WUE and NUE

90 kg/ha in the two irrigation treatments. There was a high positive correlation between tuber number/plant, tuber yield, WUE and NUE. This study highlights the importance of introducing supplemental irrigation in the potato production area in Kenya. Farmers can achieve a high potato yield and marketable tuber yield in mollic Andosols when water deficits of the growing season are eliminated with supplemental irrigation and an application of 130 kg N/ha. This study also recommends further research on water regimes and irrigation methods that can lead to high potato yield with water-saving in mollic Andosols.

Abbreviations
NUE: Nitrogen use efficiency; HI: Harvest index; WUE: Water use efficiency; IWUE: Irrigation water use efficiency; FI: Full irrigation; RF: Rain-fed; KALRO: Kenya Agricultural and Livestock Research Organization.

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Authors' contributions
FS contributed to the proposal writing, experiment design, fieldwork, data collection, data analysis and interpretation using (R software version 3.6.3) and writing the manuscript. Seth F.O. Owido and Dr. Joyce J. Lelei are my supervisors. They assisted in the proposal writing, experiment design fieldwork, data collection, data analysis and interpretation using (R software version 3.6.3) and writing the manuscript. All authors read and approved the final manuscript.

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