Effect of Supplemental Irrigation on Tuber Yield, Water Use Efficiency and Nitrogen Use Efficiency of Potato (Solanum Tuberosum L.) Grown in a Mollic Andosol

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Effect of supplemental irrigation on tuber yield, water use efficiency and nitrogen use efficiency of potato (*Solanum tuberosum* L.) grown in a mollic Andosol

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Abstract
Background
The yield of potato (8.86 tonnes/ha), the second staple food and cash crop in Kenya is remained low due to a reduction in seasonal precipitation and low soil fertility. Drought or dry periods between rainfall seasons and increased temperatures, which leads to high crop evapotranspiration, are experienced in 70-80% of the smallholder farms. Among major elements require by potato, nitrogen is the most important influential element but it is deficient in most potato-growing soils in Kenya because of nutrient depletion with inadequate nutrient replenishment results from continuous production. Hence the introduction of supplemental irrigation with an adequate application of this nutrient could increase crop yields. Therefore, this study was conducted in Nakuru, one of the major potato growing areas in Kenya, to determine the effects of full supplemental irrigation (FI) and four nitrogen levels, N0(0), N1(60), N2(90) and N3(130 kg N/ha) on tuber yield, water use efficiency (WUE) and nitrogen use efficiency (NUE) of potato grown in a mollic Andosol in Kenya compared to conventionnel rain-fed potato production.

Results
The results showed that tuber yield, marketable tuber yield and NUE significantly differed due to the interaction effect between irrigation and N-fertilization rate ($P<0.001$) whereas the WUE was statistically different due to the N-fertilization rate ($P<0.001$). The highest tuber yield 58.28 tonnes/ha was found in supplemental irrigation with an application of 130kg N/ha treatment. Full supplemental irrigation treatment increased marketable yield by 129.84, 94.63, 151.21 and 126.63% for 0, 60, 90 and 130 kg N/ha, respectively compared to rain-fed N-fertilization treatments. NUE increased statistically with an increase in N rate up to 90 kg N/ha, then tended to increase slightly as nitrogen rate increased further. An increase in potato tuber yield was positively correlated with number of tubers/plant ($r=0.75$), NUE ($r=0.95$), WUE ($r=0.72$) ($P < 0.001$).

Conclusions
The high potato yield and marketable tuber yield in mollic Andosol can be obtained when all water deficits of the growing season are eliminated with supplemental irrigation and an application of 130kg N/ha but it is essential to exploit water regimes for acceptable yield with water-saving.

Keywords: Potato, Irrigation, N-fertilisation, Yield, WUE, NUE

Background

Potato (*Solanum tuberosum* L.) is the second most important staple food in Kenya, after maize, and the production is predominantly rainfed (Muthoni *et al.,* 2017). The area under production increased from 135,000 ha in 2008 to 217, 315 ha in 2018. An estimated yield of 8.6 tonnes/ha was obtained in 2018, which was 60% of yields achieved in 2008 (FAOSTAT, 2020; Mburu *et al.*, 2020; McEwan *et al.*, 2021). Research done to improve potato yield has generally focused on enhancing soil fertility, managing pests and introducing drought-resistant varieties and little attention have been given to optimizing nitrogen and water use efficiency for increased potato yields. Potato is sensitive to water deficit. Slight water stress causes a reduction in potato leaf number and size, canopy radiation interception and photosynthesis, which consequently affects the tuber number, size and yield (Li *et al.*, 2016). Drought or dry periods between rainfall seasons and increased temperatures, which leads to high crop evapotranspiration, are experienced in 70-80% of the smallholder farms (Bryan *et al.*, 2013; Muthoni *et al.*, 2017; Taiy *et al.*, 2017; Kimathi *et al.*, 2021). Previous research attributed the declining yield to the reduction of seasonal mean rainfall from 737 mm to 126 mm in the potato growing areas (Waaswa *et al.*, 2021). Soils in most potato growing areas in Kenya are mollic Andosols. These soils become dry a few days after a rainfall event due to their high infiltration rates. Supplemental irrigation of 55 mm could increase potato yield up to 50.8% (Tang *et al.,* 2018). Nitrogen and water management are critical in potato production in Kenya.

Water stress reduces nitrogen uptake as a result of the decreased water uptake and transpiration rate (Koch et al., 2020). Nitrogen deficiency is manifested by reduced growth and tuber yield in terms of tuber number and size (Koch et al. 2019). Integrating nitrogen with irrigation water significantly affects NUE. NUE of potato increases with irrigation water and nitrogen rates and high irrigation water application results in better NUE compared to low irrigation water (Badr *et al.*, 2012). WUE increases with nitrogen level but decreases with an increase in the amount of irrigation water (Badr *et al.*, 2012; Tolessa, 2019). The objective of the study was to determine the effects of supplementary irrigation and N-fertilization rates on tuber yield, water use efficiency and nitrogen use efficiency of potato grown in a mollic Andosols in Kenya.

Methods and Materials

Experimental site description

A two-season field experiment was conducted between July and October 2020 and November and 2020 and January 2021 at the Agro-Science Park experimental farm 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 (figure 1), maximum and minimum temperature and humidity of the growing seasons (Table 1) were collected from the weather station of Egerton University located 1 km away from the experimental site.

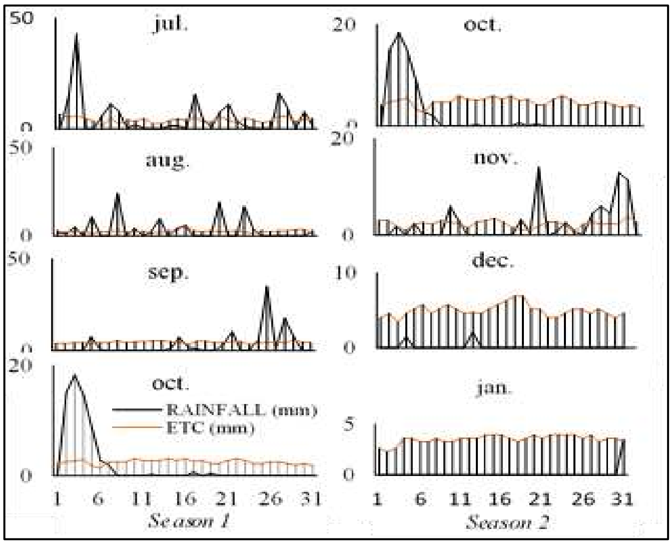

Figure 1: Daily precipitation and ET_C of the growing seasons

Table 1: Meteorological data from weather station of Egerton University

Parameters	Jul	Aug	Sep	Oct	Nov	Dec	Jan
Average of maximum temperature (ºC)	23.2	23.8	24.1	25.2	23.4	24.2	25.1
Average of minimum temperature (ºC)	10.5	10.7	9.5	10.1	10.2	9.9	10.0
Average of humidity (%)	49	48	51	49	49	53	57

To determine initial properties, soil samples were randomly taken at two different depths (from 0-0.15, and 0.15-0.45 m) because potato rooting falls between (0-0.4m). The samples were collected from six locations and mixed to obtain one composite sample per depth. The composite soil samples were dried at a constant temperature of 50°C, crushed and sieved through a 2-mm sieve in preparation for baseline soil fertility analyses at the laboratory of Kenya Agricultural and Livestock Research Organisation (KALRO). Soil pH was determined in a 1:1 (w/v) water extract. The total nitrogen content was determined using the Kjeldahl digestion method as described by Okalebo *et al.* (2002). In this method, the nitrogen of the sample is initially converted to ammonia by metal-catalyzed acid digestion (Motsara and Roy, 2008). The Cornell Morgan soil test was used to extract P, K, Mg, Ca, Mn, and Zn by shaking dried samples in a 1:5 (v/v) ratio for 30 min in Morgan solution (1 M sodium acetate buffered at pH 4.8; Morgan, 1941). The initial chemical properties are shown in table 2.

Table 2: Soil chemical analyses

Soil depth cm	0-0.15 m		0.15-0.45	
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 %	0.16	low	0.14	Low
Total Org. Carbon %	1.69	moderate	1.61	Moderate
Phosphorus ppm	21	low	19.1	Low
Potassium meq%	1.14	adequate	1.11	Adequate
Calcium meq%	5.6	adequate	5.4	Adequate
Magnesium meq%	1.61	adequate	1.43	Adequate
Manganese meq%	1.37	adequate	1.25	Adequate
Copper ppm	1.80	adequate	1.71	Adequate
Iron ppm	12.2	adequate	12.2	Adequate
Zinc ppm	2.45	low	2.42	Low
Sodium meq%	0.18	adequate	0.17	Adequate

For water suitability for irrigation, water pH and conductivity (EC) were determined from a water sample with pH–meter and electrical conductivity meter respectively. Na and K were measured with a flame photometer while Ca and Mg were determined using AAS (Atomic Absorption Spectrophotometer). Chlorides were determined by titration with silver nitrate and potassium chromate while carbonates were measured as bicarbonates determined by titration with hydrochloric acid and phenolphthalein. Sulphates were determined using the turbid metric method. In this method, an aliquot of water sample mixed with gum acacia and barium chloride crystals was taken and the turbidity was measured with the spectrophotometer at 440 nm. Sodium absorption ratio was computed using sodium, calcium and magnesium concentrations. Water had a medium salinity level and sulphates content was at a high level (table 3). The quality of water used was suitable for irrigation since the soil is permeable with adequate drainage (this interpretation was based on USDA classification of irrigation water) (Wilcox, 1955; Scherer *et al.*, 1996; Bauder *et al.*, 2011)

Table 3: Suitability of irrigation water

pH	8.09
Conductivity (EC) mS/cm	0.27
Sodium, meq/litre	0.37
Potassium, meq/litre	0.12
Calcium, meq/litre	0.04
Magnesium, meq/litre	0.05
Carbonates, meq/litre	ND*
Bicarbonates, meq/litre	0.75
Chlorides, meq/litre	1.92
Sulphates, meq/litre	49.9
Sodium Adsorption Ratio	1.74

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) was determined using the gravimetric method followed by oven-dry (Blake, 1965). Field Capacity (FC) was measured using oven-dry method (at 105 °C for 24 hours) (Aschonitis *et al.*, 2013). Permanent Wilting Point (PWP) was measured after subjecting the samples to a pressure of 1.5 bar**.** Available Water (AW) was computed by subtracting the permanent wilting point from the field capacity using equation 82 of FAO 56 (Allen *et al.*, 1998).

$$AW = 1000(\theta\,FC - \theta WP)$$

where AW is the total available soil water in the plant root zone [mm], θ_{FC} is the water content at field capacity [$m^3\ m^{-3}$], θ_{WP} is the water content at wilting point [$m^3\ m^{-3}$], Z_r is the 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 equation 83 of FAO 56 (Allen *et al.*, 1998).

RAW = p AW

where RAW the readily available soil water in the plant root zone [mm], p average fraction of AW that can be extracted from the root zone before water stress (reduction in ET) occurs [0-1]. The p average fraction of potato is 0.35 taken from table…83 of FAO 56 (Allen *et al.*, 1998). The physical soil properties of the experimental site are shown in table 4.

Table 4: Physical properties of the experimental soil

Depth (m)	Soil texture				Moisture Retention %				Bulk Density (g/cm^3)
	Sand%	Silt %	Clay %	Class	FC	PWP	AW	RAW	
0-0.15	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= Sand Loam

Experimental design and treatments

Soil was ploughed at 0.2 m depth after which the plots were prepared by raising the soil. The experiment was laid out in a split-plot within a randomized complete block design with the irrigation treatments as the main plots and the four nitrogen levels as subplots since irrigation required a large plot. Each treatment was replicated in three different blocks. Each block was separated by 1.5 m and irrigation plots in each block were separated by 1.5 m. Subplots within the main plots 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 at a spacing of 0.3 m and 0.70 m between rows and lines, respectively in set of five rows. This gave a density of 47,617 plants/hectare. Apical rooted cuttings of Shangi potato variety were planted on 7 Jul. 2020 and 9 Oct. 2020 and tubers were manually harvested from the six plants in the centre on 8 Oct. 2020 and 20 Jan. 2021. During planting, 90kg/ha of potassium sulphate (SOP) and 50kg/ha of triple superphosphate (TSP) fertilizers were added to each plot based on the universal recommendations of the area.
Irrigation treatments included FI (100%ETC) and RF. Supplementary irrigation was made through drip irrigation method. Lateral driplines with 1.6 L h^{-1} at 100 kPa inline drippers spaced at 30 cm were placed for each row. All plots were irrigated at the same level of water (during the first two weeks to encourage the crop establishment) but thereafter irrigation was daily scheduled to deliver the calculated quantity of water. For FI treatment, irrigation was made after the rain once 40% of available water was depleted. Available water was monitored using a TDR moisture meter and irrigation was applied daily based on crop evapotranspiration.

The N-fertilization treatments comprised N0(0), N1(60), N2(90) and N3(130 kg N/ha). All the N-fertilization treatments were split applied at 10 (40%), 30 (40%) and 50 (20%) days after planting. Urea fertilizer was used as a source of Nitrogen. 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. Weeding and earthing up were manually done one month after planting.

Crop Water Requirements
Reference crop evapotranspiration (ET_0) was estimated daily using Penman–Monteith's (Allen *et al.*, 1998; Jensen and Allen, 2016)

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

where ETo = reference evapotranspiration; Δ = slope of vapor saturation pressure; Rn = net radiation; G= soil heat flux; ρ_a= mean air density at constant air pressure; cp = specific heat of the air; es – ea = vapour pressure deficit; = psychrometric constant; rs = surface resistance; ra = aerodynamic resistance. The actual crop evapotranspiration (ETc) was computed as the product of ET_0 and crop coefficient (Kc).

$$ET_C = K_C \times ET_0$$

The crop coefficient at different crop stages was calculated using the formulae 59, 62 and 65 of FAO (Allen *et al.*, 1998). The average values of Kc at different crops stage are Kc initial = 1.14 and 1.18, Kc developmental = 0.75 and 0.78, Kc middle = 1.12 and 1.14, Kc maturity = 0.63 and 0.65 for the first and second season, respectively (table 5). The different stages of potato are initial stage, 25 days; growth stage, 30 days; middle stage, 30 days; and tuber maturity stage, 30 days.

Soil moisture content was computed over the growing season using a soil water balance equation (Steele *et al.*, 1997 and Jensen and Allen, 2016). Seasonal actual potato evapotranspiration (ETa) was estimated using a water balance equation (Sharma *et al.*, 2017):

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

Where P is the amount of precipitation throughout the potato growing season, I is the amount of 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 is 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 supplied through drip irrigation. Loss due to deep drainage (D) was expected to occur when rainfall surpassed the soil water deficit (which is 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.

Table 5: Monthly average of K_c, ET_0 and ET_c

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

Yield components

Plant height, number of branches, biomass, number of tubers per plant, total tuber yield and marketable yield were collected as yield components from six plants from the centre of each subplot. Harvest index was expressed as the percentage of tuber yield in tonnes/ hectare.

$$\mathrm{HI}(\%) = \frac{\text{Tuber Yield (tonnes/ha)}}{\mathit{total\ biomass\ at\ harves}\ \text{(tonnes/ha)}} \times 100$$

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).

$$\text{WUE (kg } m^{-3}) = \frac{\text{Tuber Yield (kg/ha)}}{ETa\ (m^3)}$$

$$\text{IWUE (kg } m^{-3}) = \frac{\text{TYI (tonnes/ha)} - \text{TYNI (kg/ha)}}{\mathrm{I}(m^3)}$$

Where TYI is the tuber yield in kg/ha of an irrigated plot, TYNI is the tuber yield in kg/ha of a non-irrigated plot and I is the amount of irrigation supplied during the growing season of potato (m^3).

Nitrogen Use Efficiency

Nitrogen Use Efficiency (NUE) was determined using the following formula: (Leal Filho *et al.*, 2015).

$$NUE(\text{kg kg}^{-1}) = \frac{\text{Yield of N fertilized plot in kg } - \text{Yield of unfertilized plot in kg}}{\text{Quantity of N applied in kg}}$$

Data analysis

Before analysis, the Shapiro Wilk test at the probability of ≤0.05 was run in R software to test the normality of the data. For any data that was not normally distributed, fitting data transformation was done. Analysis of variance (ANOVA) was run using R software (version 3.6.3). The least Significant Difference (LSD) test was used to separate the means of each treatment at a probability level of < 0.05. Regression analyses at 5% were carried out to determine the potato growth and yield response to the nitrogen levels in mollic Andosols. During the analysis, any outlier data and not due to the treatment effect was deleted from the model.

Results and Discussion

Crop water requirement and Crop evapotranspiration

For the first two weeks, 6.4 mm and 0 mm (because plots were not irrigated at the beginning of the second season due to the uniform rainfall) of water was used to encourage root establishment at the beginning of the first and the second season, respectively. The cumulative actual crop evapotranspiration was 268.09 and 237.7 mm; for RF; and 359.47 and 381.89 mm for FI treatment; during the first and the second growing season, respectively. The amount of supplemental irrigation was 91.38 and 144.19 mm for seasons one and two, respectively. This showed that the crop water requirement was higher during the second season than the first season. This was due to the variation of rainfall patterns in the growing season (low and erratic rainfall with high temperatures) with a consequence of increasing crop evapotranspiration (Muthoni *et al.*, 2017). Previous studies reported that the total seasonal potato ETa varied from 350 to 800 mm for various climates and environment (Ati *et al.*, 2010; Ati *et al.*, 2012; Paredes *et al.*, 2018; Nowacki, 2018; Ierna and Mauromicale, 2018; Adavi *et al.*, 2018; Afzaal *et al.*, 2020; Meligy *et al.*, 2020; Djaman *et al.*, 2021).

Yield components

The effects of supplemental irrigation and N-fertilization on yield components (plant height, number of branches and tubers/plant, yield, HI and the marketable yield) during the growing seasons are presented in table 6. The irrigation treatments had a significant effect on the number of tubers/plant (P <0.05), yield (P <0.001), and the marketable yield (P <0.001) but no effect on plant height, number of branches/plant and HI (P >0.05). However, the yield components plant height (P <0.001), number of branches (P <0.01), tubers/plant (P <0.001), yield (P <0.001), HI (P <0.05) and the marketable yield (P <0.001)) were significantly affected by N-fertilization treatments. Irrigation×N-fertilization interaction was significant for the tuber yield, number of tuber/plant, and the marketable yield (P <0.001) but was not significant for plant height, number of branches/plant, and HI (P >0.05).

Table 6: ANOVA table for plant height, number of branches/plant, number of tubers/plant, yield, HI and marketable yield

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

HI= Harvest Index, Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

Table 7: Means separation of plant height, number of branches/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 average plant heights during the two growing seasons in FI was higher than RF but did not differ significantly and this is in line with previous research of Darabad (2014). However, the early studies found out that potato crop height increased with an increased amount of irrigation water (Farrag *et al.*, 2016; Zhang *et al.*, 2017; Metwaly and El-Shatoury, 2017). The same comparison across the N fertilization treatments showed an increase in plant height with an increase in nitrogen rate. The same result was found by previous research (Tolessa *et al.*, 2017; Godebo and Belay, 2020; Setu and Mitiku, 2020). The number of branches/plant and HI significantly increased with an increase in nitrogen rate (table 7).

The FI significantly increased ($P < 0.001$) the number of tubers/plant, tuber yield and marketable yield compared with RF, regardless of N-fertilization treatments. For different irrigation treatments, the number of tubers/plant, tuber yield and marketable yield ranged from 16 to 20 and 13 to 18, 21.45 to 39.73 and 20.86 to 44.11 tonnes/ha, and 15.23 to 33.87 and 16.83 to 38.83 tonnes/ha for the first and the second season, respectively and the tuber yield and marketable yield were higher during the second growing season. The previous research found that the potato is very susceptible or sensitive to water stress compared to many other crops and FI leads to high potato yield (Darabad, 2014; Mattar *et al.*, 2021). Tuber initiation to maturity growth period forms the critical water requirement period where water deficits affect potato productivity (Salter and Goode, 1967; Sasani *et al.*, 2006; Ahmadi *et al.*, 2010). Begum *et al.* (2018) found out that irrigation water is very important for potato production due to the high yield of potato in a short time and if shortage of readily available water in the soil is eliminated by irrigation it is possible to achieve high and stable yields of potatoes, at the level of 40-50 tonnes/ ha or more. Previous studies found an increase in number of tubers/plant and marketable potato yield of irrigated potato compared to rain-fed production (Abu El-Fotoh *et al.*, 2019; Waqas *et al.*, 2021; Djaman *et al.*, 2021). Djaman *et al.* (2021) also reported that the highest number of tubers per plant is obtained in FI.

It was also reported that N-fertilization significantly increased number of tubers/plant, tuber yield and marketable yield (Badr *et al.*, 2012). Number of tubers/plant, tuber yield and marketable yield across N-fertilization treatments varied from 13 to 23 and 13 to 19, 22.75 to 40.69 and 22.18 to 45.06 tonnes/ha, and 16.12 to 34.53 and 17.50 to 39.84 tonnes/ha for season one and two, respectively. Early works found that potato yield and marketable potato yield, regardless of irrigation treatment, increased statistically with an increase in N rate up to 280 kg N/ha, then tended to increase faintly as nitrogen rate increased further (Badr *et al.*, 2012; Ospina *et al.*, 2014; Shunka *et al.*, 2017). Further research needs to be done to determine the optimal nitrogen level for potato production in mollic Andosols.

An interaction effect of Irrigation×Nitrogen was found for number of tubers/plant, tuber yield and marketable yield ($P < 0.001$). The highest number of tuber/plant (27) was obtained in FI×N3 treatment during the first season. In contrast, the lowest value of number of tubers/plant (11) was found in RF×N0 treatment of the second growing season (figure 2a and b). Besides, the highest tuber yield (62.12 tonnes/ha) and marketable yield (55.79 tonnes/ha) were found in FI×N3 treatment during the second season whereas the lowest tuber yield (15.21 tonnes/ha) and marketable yield (9.99 tonnes/ha) were found in FI×N3 treatment during the second season and the first season, respectively (figure 2c, d, e, and f). FI treatment increased marketable yield by 129.84, 94.63, 151.21 and 126.63% for N0, N1, N2 and N3, respectively compared to rain-fed N-fertilization treatments. An interaction effect of irrigation×N-fertilization was also reported by (Badr *et al.*, 2012). Nitrogen and irrigation have significant interactive effects on potato yield and quality (Tolessa, 2019). Tang *et al.* (2018) reported that supplemental irrigation of 55 mm could increase potato yield up to 50.8% compared to the rain-fed production.

Water use efficiency and irrigation water use efficiency

Data on irrigation water use efficiency (WUE) and water use efficiency (IWUE) for all treatments are presented in table 8 and 9. The ANOVA table on WUE showed that the N-fertilization treatments ($P < 0.001$) effect was significant in WUE and tuber yield whereas the irrigation and interaction effect was not significant. Comparison across irrigation treatments showed that FI produced the higher WUE (11.77 kg/m3) in comparison to RF (9.75 kg/m3) but they did not differ significantly. Different N-fertilization treatments resulted in a significant increase in water use efficiency (WUE) compared with the control treatment. Moreover, N-fertilization treatments N3 (14.24 kg/m3) produced higher WUE followed by N2 (11.69 kg/m3), N1 (9.64 kg/m^3) and N0 (7.47 kg/m^3) (figure 2 g and h). Previous studies found an increase in WUE with an increase nitrogen rate (Badr *et al.*, 2012; Tolessa, 2019). N-fertilization significantly affected IWUE ($P < 0.001$). IWUE of N-fertilization treatments N3 and N2 were high but did not differ from each other. However, N-fertilization treatments N3 and N2 significantly differed from N1 and N0. The highest value of IWUE was obtained in N3 (27.13 kg/m^3) whereas the lowest in N0 (10.10kg/m^3) (figure 2i and j).

Table 8: ANOVA table of WUE

Source of variation	Df	WUE
Season	1	23.41
Replicate(Seasons)	4	4.36
Irrigation	1	48.72
Seasons*Irrigation (Main plot error)	1	40.04
Nitrogen	3	100.20***
Nitrogen*Irrigation	3	2.16
Error	34	1.45
CV		11.22
R^2		0.90

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05

Table 9: ANOVA table of IWUE

Source of variation	df	IWUE
Season	1	100.21
Replicate	2	2.42
Nitrogen	3	386.72***
Error	17	17.18
CV		23.08
R^2		0.82

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05

Nitrogen use efficiency

Irrigation, N-fertilization and interaction between N-fertilization×Irrigation significantly affected the nitrogen use efficiency (table 10). Significantly the highest and lowest NUE were obtained from FI treatment (197.22 kg/N kg) and RF treatment (72.69 kg/N kg), respectively. The same trend was found by previous works (Badr *et al.*, 2012; Tolessa *et al.*, 2017). NUE was greatly affected by the N rate and increased as the N level was increased. Significantly the highest NUE was recorded N-fertilization N3. However, it was not significantly different from that of N2. The lowest was obtained at N1. This is in line with the study of (Badr *et al.*, 2012). On the contrary, Banerjee *et al.* (2015) found out that NUE decreased with an increase in N rate. For the interaction, the highest value of NUE was recorded at FI×N3 (236.44 kg/N kg) whereas the latest was obtained from RF×N1(56.30 kg/N kg) (figure 2k and l).

Table: 10 ANOVA table of NUE

Source of variation	df	NUE
Season	1	5709.06
Replicate(Seasons)	4	752.66
Irrigation	1	139578.21*
Seasons*Irrigation (Main plot error)	1	604.58
Nitrogen	2	17466.54***
Nitrogen*Irrigation	2	6650.21***
Error	24	388.83
CV		14.61
R^2		0.95

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05

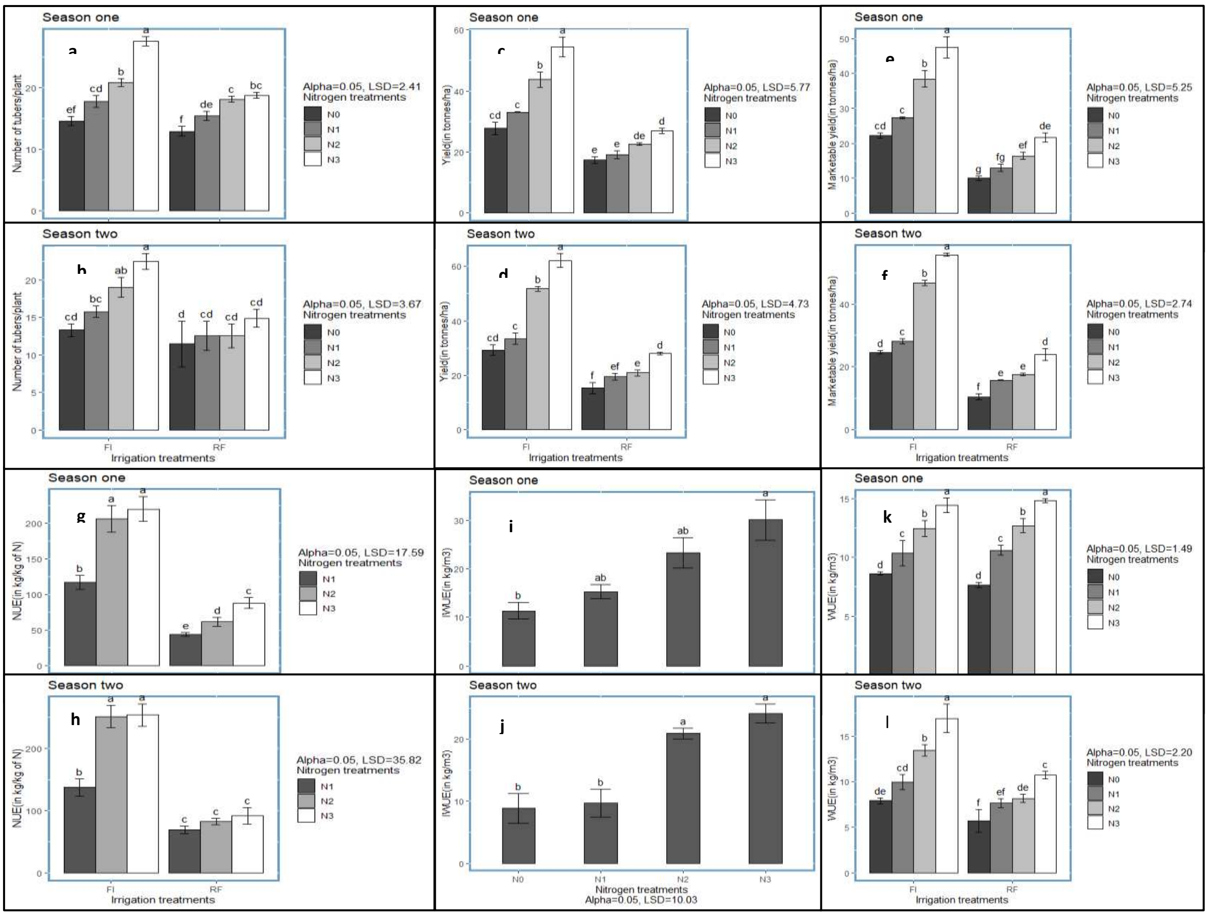

Figure 2: Means separation of number of tubers/plant, tuber yield, marketable yield WUE IWUE and NUE per season at 0.05

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

The regression equations and determination coefficients between N-fertilization and tuber yield obtained were, FI: $Y = 0.2033X + 25.517$, $R2= 0.91$ and $Y = 0.2667X + 25.33$, $R2 = 0.92$; and RF: $Y = 0.0689X + 16.178$, $R2 = 0.92$; and $Y = 0.0956X + 14.061$, $R2 = 0.92$ (all F-values were significant at $P < 0.05$) for the two seasons respectively. FI showed the highest slope during the two growing seasons (figure 3a and b). The following regression equations and determination coefficients were obtained between WUE and N-fertilization, FI: $Y = 0.0389X + 8.5278$, $R2 = 0.92$ and $Y = 0.0622X + 7.3944$, $R2 = 0.94$ and RF: $Y = 0.0544X + 7.9389$, $R2 = 0.99$ and $Y = 0.03778X + 5.8556$, $R2 = 0.99$ (all F-values analysis were significant at $P < 0.05$). The highest slope of the regression between WUE vs N-fertilization corresponded to FI during the two growing seasons (figure 3c and d). Between NUE and N-fertilization, the following equations were obtained FI: $Y = 1.4095X + 48.784$, $R2 = 0.77$ and $Y =1.5703X + 68.108$, $R2 = 0.69$ and RF: $Y = 0.6432 X + 4.2973$, $R2 = 0.99$ and $Y = 0.323 X + 51.189$, $R2 = 0.96$ (all F-values analysis were significant at $P < 0.05$). (figure 3e and f). FI had the highest slope for the two seasons but the coefficient of determinations in FI were lower compared to RF.

It was found out that a high positive correlation existed between tuber yield and NUE (r=0.95, P < 0.001), yield and WUE (r=0.72, P < 0.001) and between NUE and WUE (r=0.61, P < 0.001). All the correlations were significant (figure 4). The strong positive correlation between yield and number of tubers per plant showed that an increase in yield was related to the number of tubers/plant. on the contrary, it was reported that there is no correlation between number of tubers/plant and potato yield (Badr *et al.*, 2012).

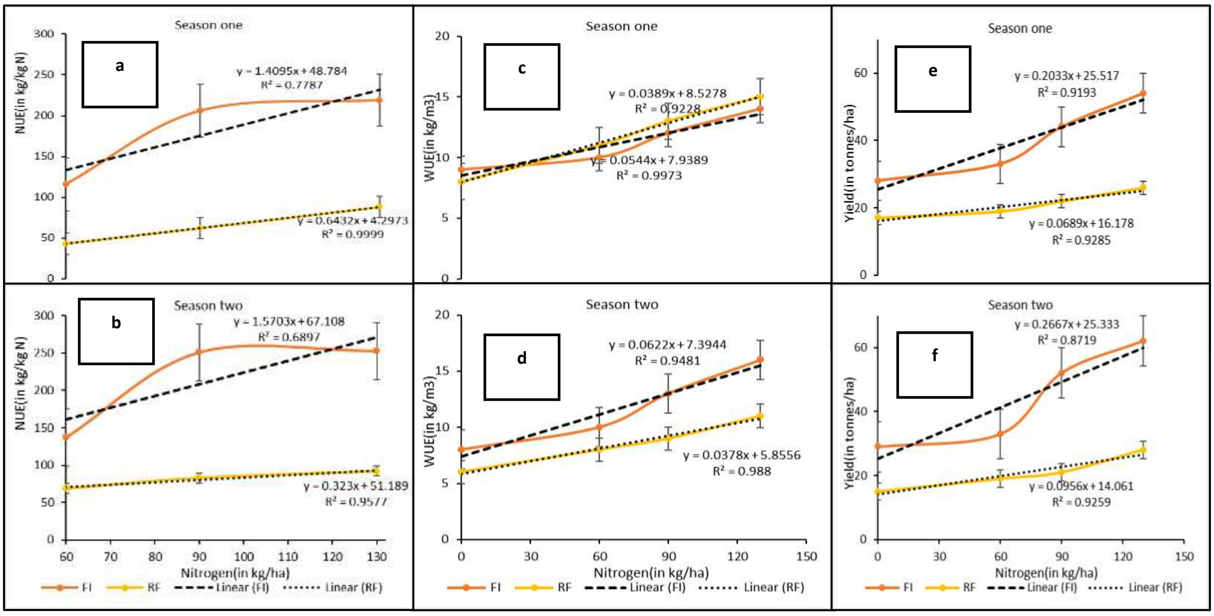

Figure 3: Relationship between potato yield, WUE, NUE and N-rate in different irrigation treatments.

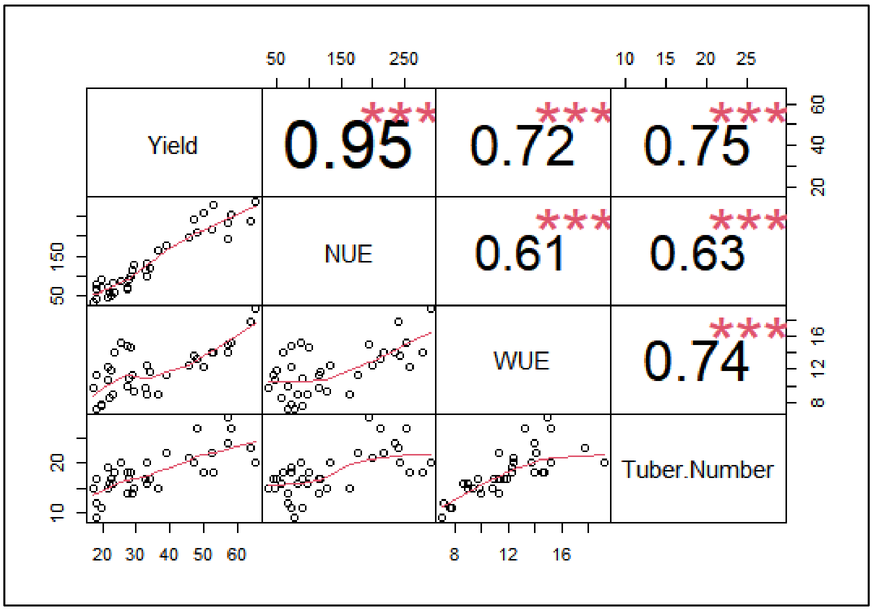

Figure 4: correlation between number of tuber/plant, tuber yield, WUE and NUE

Conclusion

Yield components of potato were largely more responsive to the interaction effect of irrigation and N-fertilization than a single effect of irrigation and N-fertilization rate. Plant growth was significantly affected by N-fertilization level whereas number of tubers/plant, tuber yield and marketable tuber yield were affected by irrigation× N-fertilization. Marketable potato tuber yield was greatly increased by supplemental irrigation. The increase of N rate produces an increase in the tuber yield and marketable yield at full irrigation, while under conventional rain-fed production, reduced N rate negatively affects tuber yield and marketable yield. The water was used efficiently in N3(130kg/ha). The NUE consistently increased with the increase in N rate up to 90kg/ha in the two irrigation treatments. There is a high positive correlation between number of tubers/plant, tuber yield, WUE, NUE and WUE. This study highlights the importance of introducing supplemental irrigation in the potato production area in Kenya to keep the soil moisture at the optimum and eliminate the effects of high infiltration rate of mollic Andosols and drought throughout the growing season for an increase in marketable potato yield.

Abbreviations
NUE: Nitrogen Use Efficiency; HI: Harvest Index; Water Use Efficiency: WUE, Irrigation Water Use Efficiency: IWUE, Full Irrigation: FI, Rain-fed: RF, Kenya Agricultural and Livestock Research Organization: KALRO.

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Authors' contributions
Satognon contributes to the proposal writing, experiment design fieldwork, data collection, data analysis and interpretation using (version 3.6.3) and writing the manuscript. Prof. 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 (version 3.6.3) and writing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
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Ethics approval and consent to participate
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Competing interests
The authors declared that there is no competing interest.

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Figures

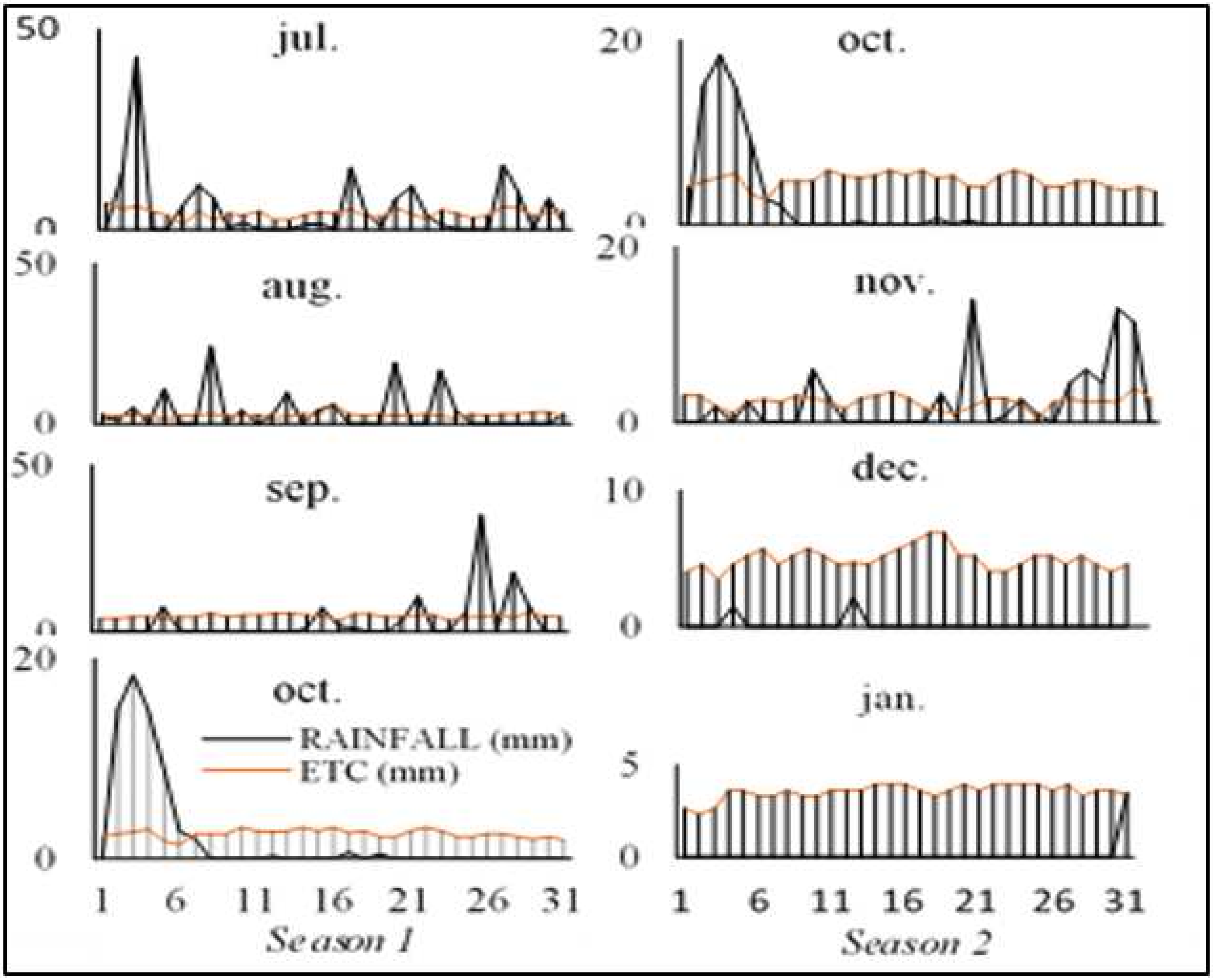

Figure 1

Daily precipitation and ETC of the growing seasons

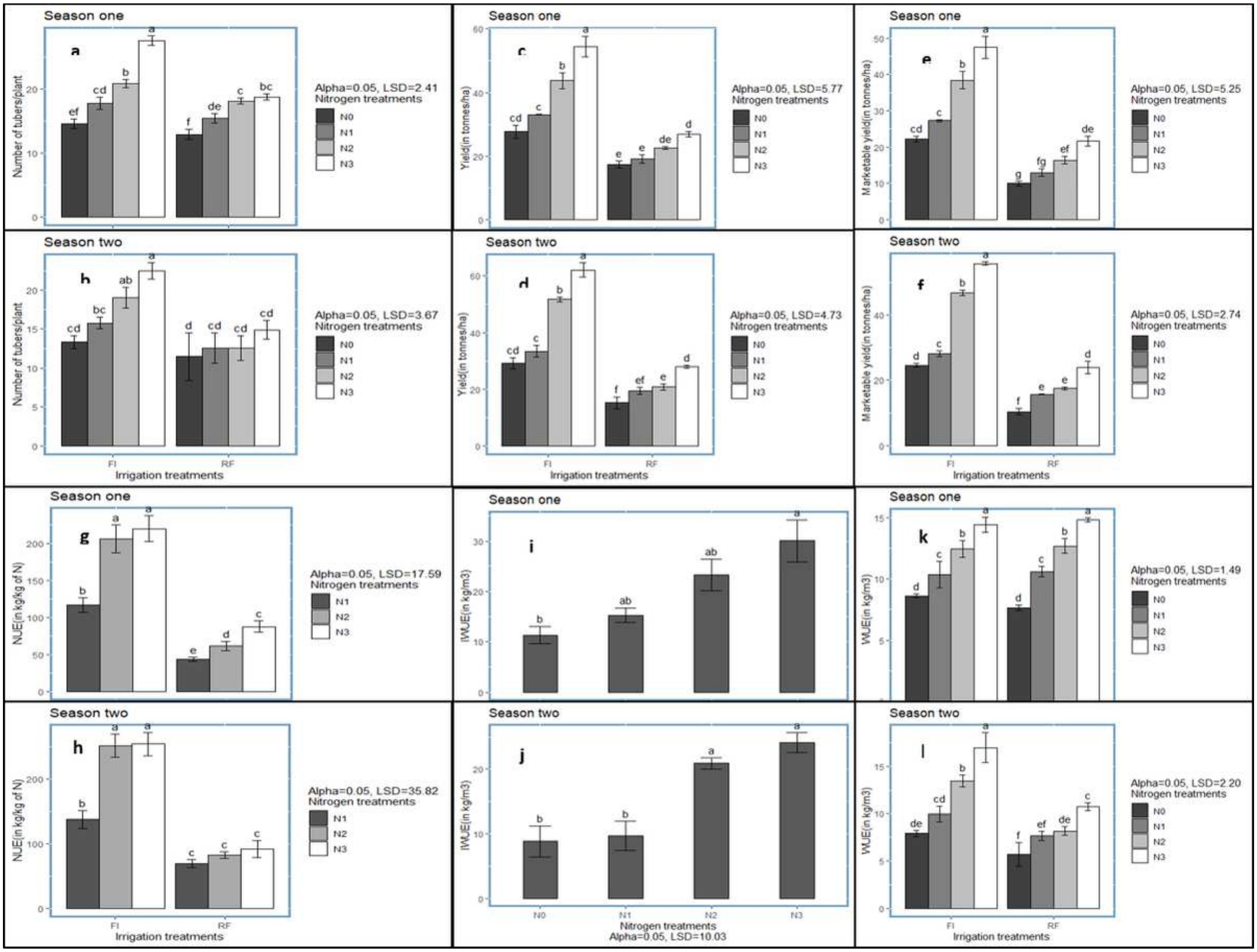

Figure 2

Means separation of number of tubers/plant, tuber yield, marketable yield WUE IWUE and NUE per season at 0.05

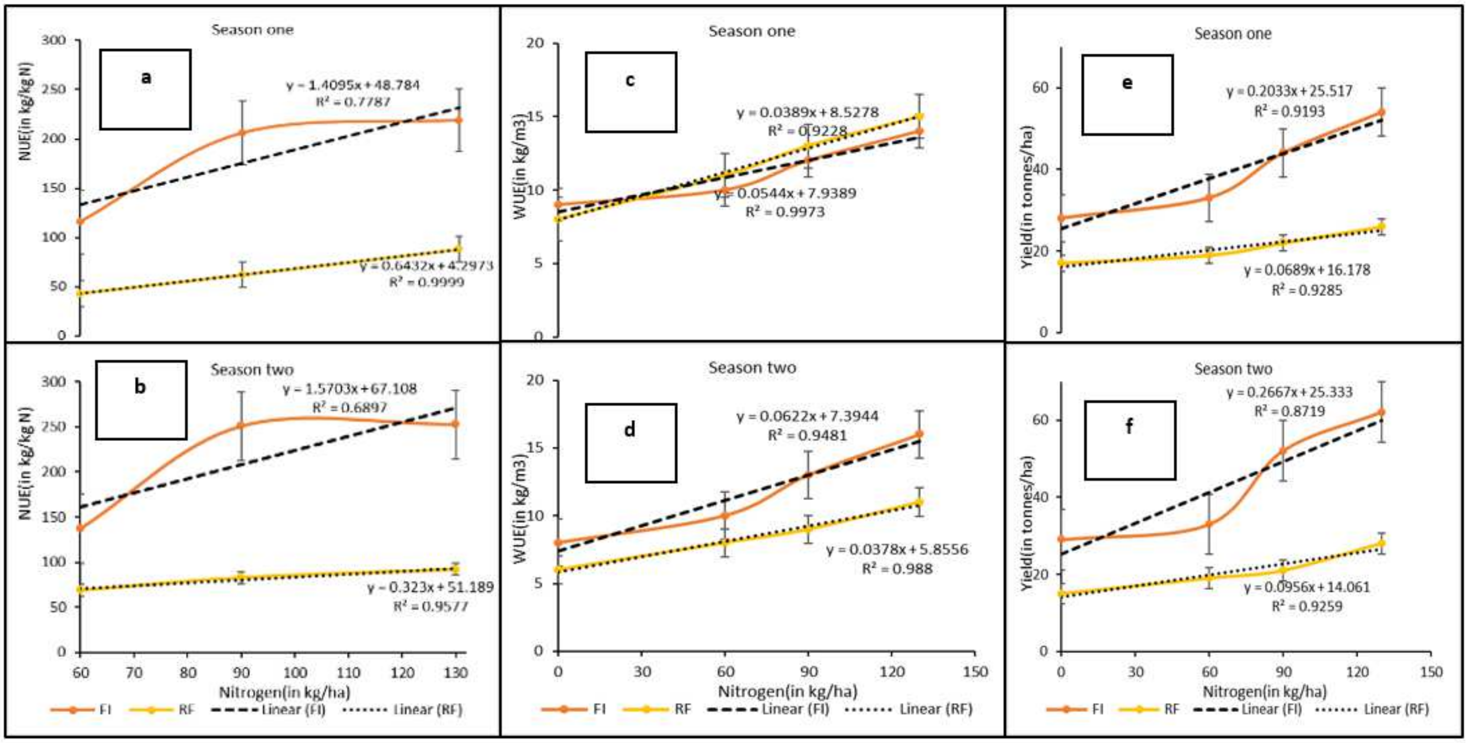

Figure 3

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

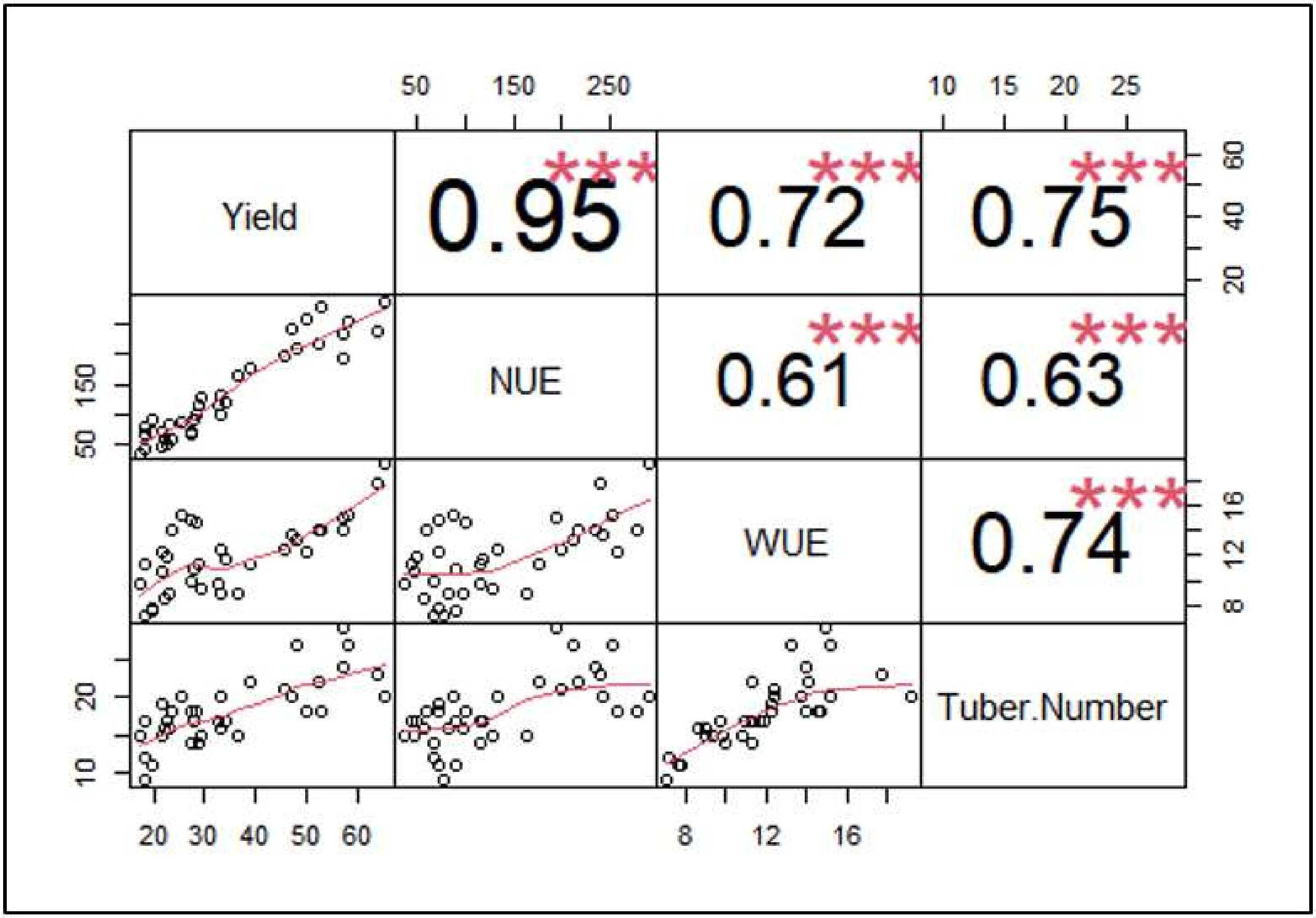

Figure 4

correlation between number of tuber/plant, tuber yield, WUE and NUE

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- dataset1.xlsx
- dataset2.xlsx