Heliyon 7 (2021) e07999

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Performance of apical rooted cuttings of potato grown in Mollic Andosols under different nitrogen fertilization and irrigation regimes

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A R T I C L E I N F O

Keywords:
Water demand
Marketable tuber yield
Total tuber yield
Harvest index
Dry matter

A B S T R A C T

Potato productivity (*Solanum tuberosum* L) is generally influenced by several factors, including water and nitrogen (N), and potato requirement for these factors varies depending on the soil type and potato variety. This research aimed to determine the performance of apical rooted cuttings of potato grown in Mollic Andosols under different nitrogen fertilization and irrigation regimes. The treatments comprised 4 irrigation regimes of 100%, 85%, 75% and 50% of the crop evapotranspiration (ETC), where ETC100% was irrigated based on water depletion in the root zone two days after full irrigation, and 4 nitrogen rates of 0 (N0), 60 (N1), 90 (N2) and 130 kg.ha^{-1} (N3) applied in splits at 10 (40%), 30 (40%) and 50 (20%) days after planting. The results revealed that the water demand for apical rooted cuttings of potato (ETa) was on average 201.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively. It was observed that plant height and number of branches significantly ($P < 0.001$) varied under different N rates with the highest plant height (92.67 cm) and number of branches per potato plant (17) achieved when applying N3. Potato grown under full irrigation (ETC100%) with N3 produced the highest total potato tuber yield (58.28 t.ha^{-1}) and marketable tuber yield (54.21 t.ha^{-1}). The number of tubers per plant statistically reduced as the N deficit increased, with the maximum tuber number, 23, achieved under N3. It was observed that a significant Pearson correlation ($r = 0.7$***) existed between tuber number and total tuber yield. The maximum harvest index (HI), 57.12 %, was obtained under ETC50% with N3, while the highest tuber dry matter, 30 %, was observed under N3. To achieve a high tuber yield from apical rooted cuttings of potato in Mollic Andosols, this study recommends an irrigation regime of ETC100% and a nitrogen rate of 130 kg.ha^{-1}.

1. Introduction

Potato is the third most important worldwide food crop after rice (*Oryza spp*), wheat (*Triticum astivum*) (Campos, 2020). Its global cultivation area was estimated at 19.3 million ha with a production of 388 million tonnes. Asia and Europe account for about 81.17 % of the world production (FAOSTAT, 2017). In recent years, potato production has significantly increased in East Africa, showing that it plays a vital role in local food systems (FAOSTAT, 2017; Campos, 2020; Waaswa et al., 2021a). It has been added to the national priority list of crops in East Africa owing to its significant contribution to national food security (FAOSTAT, 2020). Water shortage due to a reduction in seasonal rainfall alongside soil N deficiency has lowered potato productivity in East Africa, especially in Kenya (Muthoni et al., 2021; Satognon et al., 2021b). A decline in seasonal mean precipitation from 737 to 126 mm in the growing areas was reported by Waaswa et al. (2021b). Apical rooted cuttings of potato were introduced in Kenya for disease-free seed production to increase potato yield in the face of climate variability. Compared to various crops, potato is more susceptible to drought, and water deficit and adequate irrigation without drought conditions all across its cycle generally results in high tuber yield (Taiy et al., 2017; Mattar et al., 2021). It needs about 25–50 mm of water per week, and this leads to potato response with an increase tuber yield up to 2 t.ha^{-1} for each 20 mm of irrigation amount applied (Asfary et al., 1983; Fabeiro et al., 2001). Its water demand was estimated at 350–800 mm depending on the soil type, irrigation management, cultivar, climates, field and environmental conditions (Bryan et al., 2013; Muthoni et al., 2017; Taiy et al., 2017; Tolessa, 2019; Kimathi et al., 2021).

High tuber yield of potato is generally obtained when soil moisture is kept consistently at an optimum level with N availability during the critical demand period (Badr et al., 2012). Potato is susceptible to fertilizer management practices, and inappropriate N supply negatively

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https://doi.org/10.1016/j.heliyon.2021.e07999
Received 12 July 2021; Received in revised form 14 August 2021; Accepted 13 September 2021

affects the qualitative and quantitative potato yield (Ayyub et al., 2019). Therefore, applying mineral N fertilizer is essential to improve potato productivity since the organic N is held up into soil particles and cannot be available to potato due to its short cycle (Ayyub et al., 2019). Due to a shortage of fallow land, Kenyan smallholder farmers face N deficit (Satognon et al., 2021a). Most of the soil types found in potato growing areas of Kenya are classified as Mollic Andosols. Andosols are the soils presenting an andic horizon to a depth of 30 cm or greater from the soil surface and a thick, dark-coloured and structured mollic horizon. They contain high base saturation and medium to high soil organic matter (Aran et al., 2001; Getahun and Selassie, 2017). They exhibit a high water infiltration rate and are stable and resistant to soil particle detachment and soil erosion (Hoyos and Comerford, 2005; Jiménez et al., 2006). Mollic Andosols properties are favorable for the cultivation of potato, sweet potato (*Ipomoea batata*), tea (*Camellia senensis*), sugar can (*Saccharum spp*), vegetables, wheat, tobacco (*Nicotiana tobacum*), and paddy rice (*Oryza spp*) crops. Therefore, water and N supplies in potato production in Mollic Andosols are important for controlling potato production levels, in areas of low rainfall. Shortage and high irrigation cost combined with high fertilizer prices have increased the total number of research on potato yield responses to N fertilization and irrigation (Ojala et al., 1990; Shock and Feibert, 2002; Steyn et al., 2007; Ati et al., 2010; Badr et al., 2012; Karam et al., 2014; El Mokh et al., 2015; Fandika et al., 2016; El-Abedin et al., 2017; Bani-Hani et al., 2018; Tang et al., 2018; Bohman et al., 2019; Kassaye et al., 2020; Djaman et al., 2021a; Satognon et al., 2021b).

High potato tuber yield and tuber quality are influenced mainly by the amount of irrigation and N applied. The requirement of these factors by potato depends on the cropping system. Innovative potato production systems involve N and irrigation optimization to reduce the underground water pollution by N leaching as well as the environmental impact (Waaswa and Satognon, 2020). The effects of both factors were often indicated in literature with dissimilar conclusions and recommendations as the optimum N rates differ across potato cultivars, soil types, climate and environmental contidtions (Bélanger et al., 2000; Getie et al., 2015; Setu and Mitiku, 2020). So far, no study has reported the management of these inputs in potato production in Mollic Andosols while using apical rooted cuttings, especially in Kenya. This becomes a great challenge for farmers producing potato in Mollic Andosols which is vulnerable to water infiltration and soluble elements. This research aimed to determine the performance of apical rooted cuttings of potato grown in Mollic Andosols under different nitrogen fertilization and irrigation regimes.

2. Materials and methods

2.1. Description of the experimental area

Between July 2020 and March 2021, a two-season experiment was carried under two different rain shelters at Agro-Science Park field, Egerton University (0.3031° S, 36.0800° E), Kenya. At an elevation of 2670 m a.s.l, the research area is situated in Agro-ecological zone III of Kenya. The soil types found in the experimental area are classified as Mollic Andosols (Jaetzold et al., 2007).

2.2. Variety

In this study, apical rooted cuttings of *shangi* potato were used as plant materials. This variety is mainly cultivated by farmers of the growing area (Janssens et al., 2013). The variety is mainly grown at an altitude above 1500 m. It is early maturing (≤3.5 months), high yielding and moderately susceptible to late blight (NPCK, 2019). Its tubers have oval-shaped silky cream skin with moderate to deep white eyes while fresh. *Shangi* is a medium-tall (just under 1 m) and semi-erect cultivar with moderately robust stems and broad light green leaves. It produces a lot of flowers, which are pink (NPCK, 2019). The crop requires a mean daily temperature range of 18–20 °C and less than 15 °C night-time temperature, but it performs well under 20–25 °C and below 20 °C for day and night temperatures, respectively (Kumar et al., 2015).

2.3. Experimental procedure

2.3.1. Initial soil physicochemical analyses

Before the experiment was set up, soil subsamples were randomly collected in a zig-zag pattern from six places in the research area at 2 distinct soil depths (0–0.15 and 0.15–0.45 m) to determine the baseline soil characteristics. These depths were considered because the potato root system lies between 0 to 0.40 m. To form one homogeneous composite soil sample per depth, the subsamples were mixed. The composite samples obtained per depth were thereafter air-dried at an ambient temperature (22–25 °C) for a week, crushed and sieved (through 2 mm sieve). The samples were analysed at the soil testing laboratory of KARLO (Kenya Agricultural and Livestock Research Organization), Nairobi.

For the physical properties, the proportions of the primary particles, including sand, silt, and clay, were determined following the hydrometer method. The textural class for the experimental soil was then obtained using the textural triangle (Bouyoucos, 1962). The bulk density (ρ_b) of the various soil depths was determined using the oven-drying method after soil samples were collected using core rings (Blake and Black, 1965). The soil moistures at field capacity (FC) and permanent wilting point (PWP) were determined by subjecting the samples to pF 2.5 and pF 4.2, respectively (Aschonitis et al., 2013). FC and PWP were used to compute the available soil water in the potato root zone (AW) following equation 82 of FAO (equation 1) (Allen et al., 1998).

$$AW = 1000 \times (\theta_{FC} - \theta_{PWP}) \times Z_r \tag{1}$$

where AW stands for available soil water (mm), Θ_{FC} and Θ_{PWP} for volumetric soil moistures at field capacity ($m^3\ m^{-3}$) and permanent wilting point, respectively ($m^3\ m^{-3}$) and Z_r for depth of crop root zone (m).

The readily available water in the potato root zone was determined using equation 83 of FAO (equation 2) (Allen et al., 1998).

$$RAW = pAW \tag{2}$$

where RAW is the readily available water (mm) and p is the percentage of AW that crops can deplete from their root zone before experiencing water deficit. The value of p varies between 0 and 1, depending on the crop. Potato has a p average fraction of 0.35. This value was obtained from Table 83 of FAO 56 (Allen et al., 1998). For accuracy purposes, samples were duplicated.

For the initial soil chemical analyses, the acidity level of the experimental soil (pH) was measured in a 1:2.5 (w/v) H_2O ratio. The total N of the experimental soil was estimated following the *Kjeldahl* digestion method (Okalebo et al., 2002). This method used metal-catalyzed acid digestion to convert nitrogen into ammonia (NH_3) (Motsara and Roy, 2008). The soil nutrients such as potassium (K), phosphorus (P), magnesium (Mg), manganese (Mn), calcium (Ca) and sodium (Na) were extracted following the Mehlich double acid method (Mylavarapu et al., 2002) (Mylavarapu et al., 2002). In this method, K and N concentrations were measured using a flame photometer at 766 and 589 nm wavelengths, respectively, while the concentrations of Mn, Mg and Ca were read from atomic absorption spectrometer (AAS) at wavelengths of 279.2, 285.2 and 422.7 nm, respectively. P was measured using UV - vis spectroscopy. The colorimetric method followed by UV - vis spectroscopy reading was used to determine the total carbon content of the samples (Anderson and Ingram, 1993). The exchangeable acidity of the samples was measured at a pH buffer of 5.5 (Okalebo et al., 2002). The concentrations of the soil micronutrients such as zinc (Zn), iron (Fe)and copper (Cu) were extracted using 0.1 MHCL in 1:10 (w/v) ratio, followed by AAS readings at wavelengths of 248.3, 324.7 and 213.9 nm, respectively (Mehlich et al., 1962; Githaiga et al., 2020). Samples were analysed with reference samples (with known values) to ensure that the analyses were of high quality.

2.3.2. Water analysis

An aliquot of irrigation water was taken to KALRO in Nairobi for analysis to determine its suitability for irrigation. The electrical conductivity (EC) and the pH was measured using the pH meter. Na and K concentrations were read from flame photometers at wavelengths of 589 and 766 nm, respectively, while the concentrations of Mg and Ca were read from AAS at wavelengths of 285.2 and 422.7 nm, respectively (Culkin and Cox, 1966). Chloride concentration was determined by titrating an aliquot of the irrigation water with potassium dichromate and silver nitrate solutions. The carbonate content of the water was analyzed as bicarbonate using the titration method (Culkin and Cox, 1966). The sulphate content of the water was analyzed following the turbid metric method. Mg, Na, and Ca concentrations were used to estimate the Na absorption ratio.

2.3.3. Rain shelter experiment

Rain shelter with dimensions of 14 m × 20 m was put into place in each growing season. The four sides of the structure were opened during the daytime to allow air inflow and closed at night. The minimum and maximum temperatures in the rain shelters were 12 and 22.1 and 15.5 and 27.3 °C for both seasons, respectively. Land preparation was conducted by ploughing the soil at depth of 0.30 m. The plots were thereafter prepared by levelling the soil to 0.4 m. The apical rooted cuttings of 7 cm of height were sourced from Stokman Rozen Company of Naivasha, Nakuru, Kenya. Each experimental plot of 2.5 m × 1 m size received nine apical rooted cuttings in a set of three rows at a spacing of 0.7 m × 0.3 m between lines and rows, respectively. This gave 47,617 apical rooted cuttings.ha^{-1}. Lateral driplines that supply 1.6 L.h^{-1} at 100 kPa inline drippers spaced at 30 cm were placed for each line to deliver the required amount of irrigation.

The treatments comprised 4 irrigation regimes of 100%, 85%, 75% and 50% of the crop evapotranspiration (ETC), where ETC100% was irrigated based on water depletion in the root zone two days after full irrigation, and 4 nitrogen rates of 0 (N0), 60 (N1), 90 (N2) and 130 kg.ha^{-1} (N3) applied in splits at 10 (40%), 30 (40%) and 50 (20%) days after planting. The treatments were laid out in randomized complete block design using a split-plot arrangement. The irrigation regimes and N rates were randomly assigned to the main plots and the subplots, respectively. The treatments were replicated in 3 different blocks. A 1.5 buffer separated the blocks and the experimental units. All the experimental units received the same amount of irrigation during the first 2 weeks to encourage plant root establishment. Variation in irrigation was initiated from the fourteenth day after planting. The driplines were atomized in terms of minutes for each main plot according to the water regime assigned. A Time-domain reflectometry (TDR) moisture meter was used to monitor the soil moisture during the growing seasons. Urea was utilized as a source of nitrogen fertilizer. At planting, 90 kg.ha^{-1} of potassium sulphate and 50 kg.ha^{-1} of triple superphosphate fertilizers were added to each experimental unit. The prevalent pests during the growing seasons were controlled using VOLTAGE 5EC (350 ml.ha^{-1}), while the early and late blight were controlled using Ridomil Gold MZ 68 WG (1 kg.ha^{-1}) and Mancozeb (1 kg.ha^{-1}) fungicides. Weeding was done manually every three weeks, and earthing up was carried a month after planting.

3. Data collection

Data were collected on crop water demand, plant height, number of branches per plant, total biomass, tuber number per plant, potato tuber yield, harvest index (HI) and tuber dry matter (DM).

3.1. Estimation of crop water demand

For potato water demand, the soil water content was taken every 2 days before and after each irrigation from planting until harvest with a TDR soil moisture. The difference in soil moisture values within two days from each plot was then obtained as volumetric water content (θ). The equivalent water depth (De) of plant-available water (m^{-3}) associated with this change was determined by following Marshall et al. (1996) 's equation (equation 3). Water demand of potato was determined using the water balance equation (equation 4) (Sharma et al., 2017). Since the experiment was conducted in rain shelters and the water was supplied using drip irrigation, P, D and R were assumed to be negligible. Therefore, equation four was summarized as equation 5.

$$De = \theta \times Z_r \tag{3}$$

where Z_r = layer depth

$$ET_a = P + I \pm \Delta s - R - D \tag{4}$$

where P is the amount of precipitation (mm), I is the amount of irrigation supplied (mm), ΔS is the difference in soil moisture contents in the potato root zone (mm), R is the loss due to runoff (mm) and D is the loss caused by deep drainage during the growing seasons (mm).

$$ET_a = I \pm \Delta S \tag{5}$$

3.2. Growth and yields data

The height and the number of branches per plant were collected as growth parameters. These parameters were collected every 2 weeks on 5 tagged plants per subplot from the fourteenth day after planting (DAP) until harvest. The height and the number of branches used in the data description were collected at 66 DAP since N was applied in splits. At harvest, five plants were randomly chosen and removed with the tuber from each subplot. The aboveground biomass and the tuber sample from each subplot were weighed separately using an electronic balance. The sum of their weight was recorded as total biomass. The tuber number per plant was counted and grouped in 4 different sizes (chats: tuber size <25 mm, C1: 26 mm < tuber size <45 mm, C2: 46 mm < tuber size <60 mm and ware: tuber size >61 mm in diameter). The fresh tuber yield was separated into 3 categories (total fresh, unmarketable and marketable tuber yield). The total fresh tuber yield was taken as the weight of the total tuber collected per plant. The unmarketable yield was taken as the weight of the chats since they are not marketable. The marketable yield was then estimated by subtracting the unmarketable tuber yield from the total tuber yield. The total biomass at harvest (Tbh) and the total tuber yield (Y) were used to estimate the harvest index (HI) of potato (Equation 6).

$$HI(\%) = \frac{Y\ (t.ha^{-1})}{Tbh(t.ha^{-1})} \times 100 \tag{6}$$

For the tuber dry matter (DM), four tubers of medium size randomly chosen from each subplot were washed, chopped and mixed. A sample weighing 200 g was taken and oven-dried to constant weight at 60 °C (Bekele and Haile, 2019). The samples were weighed, and the dry weight was recorded. The DM was thereafter computed using the formula below (equation 7).

$$DM(\%) = \frac{\text{Dry weight }(g)}{\text{Fresh weight }(g)} \times 100 \tag{7}$$

4. Data analysis

Before analysis, the normality of the data was checked at a probability level of 0.05 (Shapiro Wilk test) using R (version 4.1) (R-Core-Team, 2020). The same program was used to perform the analysis of variance (ANOVA). At the significant level of 0.05, the least-squares means (LSMEANS) was performed for treatment means separation. The Pearson correlation was also performed to test the relationship between tuber number and total tuber yield. Production functions were developed to determine the responsiveness of total fresh tuber yield, marketable yield and DM to N rate under different irrigation regimes in Mollic Andosols.

5. Results and discussion

5.1. Physico-chemical properties of the experimental soil

The soil at the experimental site had a sandy loam texture comprising on average 60.65% of sand, 28.2% of silt and 11.15% of clay (Table 1). The average soil moisture content of the experimental soil at FC from the upper layers to 0.45 m depth was 20.1 %, with a PWP of 12.05 % (Table 1). The experimental soil had a medium acidic pH and organic carbon content. The available total N of the experimental soil before planting was on average 0.15%, classified as low (Table 2). This showed that the soil at the experimental site was deficient in nitrogen. The irrigation water used had a high sulphate concentration and a moderate salinity level (Table 3). This indicated that the water was suitable for irrigation based on the USDA classification of irrigation water (Wilcox, 1955; Scherer et al., 1996; Bauder et al., 2011).

5.2. Difference in soil moisture and cumulative actual crop evapotranspiration (water demand)

Soil moisture was measured every two days before and after every irrigation event until harvest. The results showed that the difference in soil moisture under ETC100% was low during the first four weeks. This can be attributed to the fact that the root system of the apical rooted cuttings planted was not well established to facilitate the photosynthetic activities of the crop. A high difference in soil moisture was obtained between 35 and 87 DAP (Figure 1). This indicated that the period between 35 and 87 DAP formed the critical stage at which a slight water deficit might negatively affect the yield of apical rooted cuttings of potato. Before or after this period, water deficit can also affect potato growth and productivity since the crop requires high soil moisture throughout its growing season. Research conducted by Yactayo et al. (2013) on timely irrigation restriction showed that water restriction initiated in potato production between six and eight weeks after planting leads to low potato yield compared to water restriction initiated eight weeks after planting. Djaman *et al.* (2021a, b) found the highest average daily crop evapotranspiration of 6.5 mm.days^{-1} at bulking growth stage of potato. Shock and Feibert (2002) reported that severe water stress at an early stage (vegetative) could reduce potato tuber yield by approximately 40%. Camargo et al. (2015) indicated that soil moisture content should be maintained above 50% of the total available water throughout the growing season for sustainable potato production. A reduction in potato tuber yield by 12% and 42% was obtained when water stress condition was initiated at bulking and maturation growth stages, respectively (Karam et al., 2014).

Crop evapotranspiration is the evapotranspiration from the well-fertilized, disease-free plant cultivated in large farms under optimum soil moisture conditions and achieving full productivity in a given environmental or climatic conditions (Allen et al., 1998). The cumulative actual crop evapotranspiration (ET_a) is the cumulative crop evapotranspiration for a growing season. The ET_a of apical rooted cuttings of potato grown in Mollic Andosols was estimated on average at 201.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively (Table 4). These findings supported the previous research that found that potato water demand varied from 350 to 800 mm depending on the soil type, the environmental condition and the climatic condition (Steyn et al., 2007; Badr et al., 2012; Ati et al., 2012; Yactayo et al., 2013; Cantore et al., 2014; El Mokh et al., 2015; Farrag et al., 2016; Bohman et al., 2019; Elhani et al., 2019; Djaman et al., 2021a). In Peru, it was reported that potato ET_a varied from 400 to 800 mm (Haverkort, 1982). Another study estimated the potato water demand for optimum yield in California at 316–630 mm (Djaman et al., 2021b). Karam et al. (2014) reported seasonal irrigation water demand of potato grown in a semi-arid climate of Labanon at 500–560 mm. The average water demand for a high potato yield in Saudi Arabia was estimated at 1505 mm (El-Abedin et al., 2017). Potato water demand also depends on soil type

Table 2. Chemical properties of the experimental soil.

Depth (m)	0–0.15		0.15–0.45	
Soil parameters	Values	Classes	Values	Classes
Soil pH	5.43	Medium acid	5.46	Medium acid
Exchangeable acidity mmol L^{-1}	0.20	Adequate	0.21	Adequate
N %	0.16	Low	0.14	Low
Total organic carbon %	1.69	Moderate	1.61	Moderate
P mg.kg^{-1}	21	Low	19.1	Low
K mmol.L^{-1}	1.14	Adequate	1.11	Adequate
Ca mmol.L^{-1}	5.6	Adequate	5.4	Adequate
Mg mmol.L^{-1}	1.61	Adequate	1.43	Adequate
Mn mmol.L^{-1}	1.37	Adequate	1.25	Adequate
Cu mg.kg^{-1}	1.80	Adequate	1.71	Adequate
Fe mg.kg^{-1}	12.2	Adequate	12.2	Adequate
Zn mg.kg^{-1}	2.45	Low	2.42	Low
Na mg.kg^{-1}	0.18	Adequate	0.17	Adequate

Table 3. Chemical composition of irrigation water at the experimental site.

Chemical parameters	Values
pH	8.09
EC Ms.cm^{-1}	0.27
Na mmol.L^{-1}	0.37
K mmol.L^{-1}	0.12
Ca mmol.L^{-1}	0.04
Mg mmol.L^{-1}	0.05
Carbonates mmol L-1	ND*
Bicarbonates mmol.L^{-1}	0.75
Chlorides mmol.L^{-1}	1.92
Sulphates mmol.L^{-1}	49.9
Sodium adsorption ratio	1.74

ND* = not detected.

Table 1. Physical soil properties of the experimental site.

Depth (m)	Soil textural class				Moisture characteristic %				Bulk density (g.cm-3)
	Sand %	Silt %	Clay %	Class	FC	PWP	AW	RAW	
0–0.15	63.70	26.20	10.10	SL	19.90	12.30	7.60	2.66	1.26
0.15–0.45	57.60	30.20	12.20	SL	20.30	11.80	8.50	2.98	1.34

FC = field capacity, PWP = permanent wilting point, AW = available water, RAW = raidily available water of potato, SL = sandy loam.

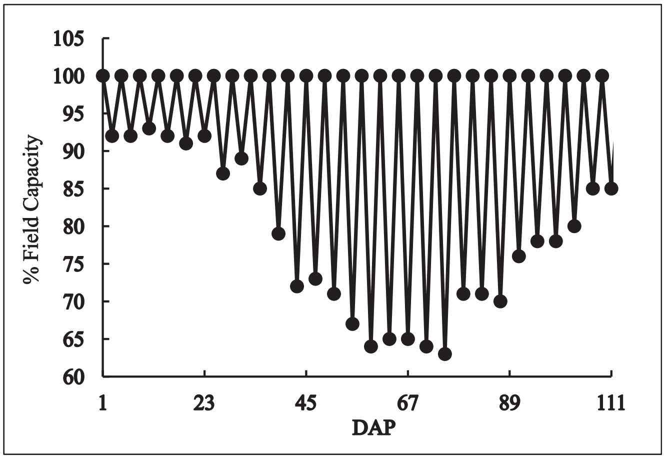

Figure 1. Variation in soil moisture under ETC100%.

Table 4. Cumulative actual crop evapotranspiration (mm) of the growing seasons.

	ETC100%	ETC85%	ETC75%	ETC50%
Season one	398.3	338.5	298.7	199.1
Season two	407.3	346.2	305.5	203.7

and irrigation management practice (Chen et al., 2019). Cumulative potato crop evapotranspiration was estimated respectively at 413.2 and 362.1 mm in loam and clay soil (Katerji et al., 2011).

5.3. Growth of apical rooted cuttings of potato grown in mollic Andosols under different N and irrigation regimes

Among the two factors and their interaction, only N fertilization exhibited a significant ($P < 0.001$) effect on the mean of plant height and the number of branches per plant (Table 5). A similar observation was made by Darabad (2014), who found that an increment in irrigation amount did not interfere with plant height. However, many studies have found that the height of potato plants increased with the irrigation amount supplied (Farrag et al., 2016; Zhang et al., 2017; Metwaly and El-Shatoury, 2017). This variation in findings could be described by the type of plant material used, the soil type or the environment. The height as well as the number of branches per plant widely varied under different

Table 6. Means of plant height and number of branches per plant under different N and irrigation regimes.

N-treatments	Potato plant height	Number of branches per plant
N3	92.67a	17a
N2	88.38ab	15b
N1	85.83bc	14c
N0	80.79c	11d
Lsd	4.7714	0.7827

The different letters indicate a significant difference within the same column, whereas the same letters indicate no significant difference at a significant level of 0.05.

N rates. The highest potato plant height (92.67 cm) was found under N3, whereas the least (80.79 cm) was observed under N0, but it did not differ statistically from the plant height found under N1 (Table 6). The same trend was also observed for the number of branches per plant with the largest (17) and the lowest (11) number of branches obtained under N3 and N0, respectively. Similar observations were made in previous studies (Tolessa et al., 2017; Setu and Mitiku, 2020).

5.4. Yields components of apical rooted cuttings of potato grown in mollic Andosols under different N and irrigation regimes

Irrigation×nitrogen effect on the total tuber yield and marketable yield was significant ($P < 0.001$), whereas the tuber number per plant was only influenced by N ($P < 0.001$) (Table 5). An application of 130 kgN.ha^{-1} produced the maximum total fresh tuber yield under different irrigation regimes (Table 7). A significant reduction in total tuber yield was also found when applying less amount of irrigation. This showed the sensitivity of apical rooted cuttings of potato to water deficit during its cycle. Reduction in fresh tuber yield caused by the progressive water stress averaged 8.62% with 15% (ETC85%) in reduction of irrigation amount. Besides, a reduction in the amount of irrigation applied by 25% (ETC75%) and 50% (ETC50%) reduced on average the total tuber yield by 15.90% and 35.57%, respectively, under different N-fertilization. For the interaction, the highest total fresh tuber yield was observed under ETC100% with 130 kgN.ha^{-1}. In comparison, the smallest was reported under ETC50% with 0 kgN.ha^{-1} (Table 7).

Full irrigation (ETC100%) generally produces the highest potato tuber yield (Wilcox, 1955; El Mokh et al., 2015; Bani-Hani et al., 2018; Elhani et al., 2019; Kassaye et al., 2020; Gogoi et al., 2020; Djaman et al., 2021a). According to the previous studies, increasing the amount of

Table 5. Means squares of plant height, number of branches per plant, tuber number per plant, total yield, marketable yield, HI and DM under different N and irrigation regimes.

Source	DF	Plant height	Number of branches per plant	Tuber number per plant	Total yield	Marketable Yield	HI	DM
Seasons	1	640.67	5.51	0.51	73.45	75.26	8.37	28.83*
Replication (season)	4	418.82	1.29	5.79	1.13	1.80	94.53	10.66
Regimes	3	118.69	27.12	67.68	964.98***	964.93***	423.99***	30.74
Seasons×regimes	3	196.64	2.54	10.34	27.88	18.74*	41.81	5.99
Replicate×regimes (seasons) (Ea)	12	99.57	1.78	8.63	16.32	13.25	27.03	3.68
Nitrogen	3	591.03***	127.59***	164.98***	2565.75***	2709.25***	57.81**	89.32***
Seasons×nitrogen	3	8.14	0.18	3.04	1.52	2.13	8.43	11.91
Regimes×nitrogen	9	120.50	1.07	10.93	58.91***	68.17**	94.32***	18.42
Seasons×regimes×nitrogen	9	89.04	0.87	9.58	15.55	8.03	14.60	19.53
Error (Eb)	48	61.02	2.16	5.10	6.65	6.72	12.03	11.20
CV		8.99	9.92	11.33	7.22	8.35	7.19	12.25
R2		0.74	0.83	0.81	0.97	0.97	0.85	0.62

Ea = error of the main plots, Ea = error of the subplots, CVa = coefficient of variation for the main plots, CVb = coefficient of variation for the subplots. '***', '**' and '*' are significance codes at 0.001, 0.01 and 0.05, respectively.

Table 7. Means of total tuber yield, marketable yield and HI under different N and irrigation regimes.

Irrigation regime	N rate (kgN.ha^{-1})	Total tuber yield (t.ha^{-1})	Marketable tuber yield (t.ha^{-1})	HI (%)
ETC100%	0	28.41hi	23.49g	40.85h
	60	33.66fg	28.66ef	47.60defg
	90	47.78c	41.97c	47.47def
	130	58.29a	54.21a	43.15gh
ETC50%	0	16.38k	11.21i	45.52eg
	60	26.30i	20.54gh	56.49a
	90	30.90gh	27.35f	54.68ab
	130	34.99ef	29.62ef	57.12a
ETC75%	0	22.15j	17.51j	47.91def
	60	34.06f	30.43f	50.99bcd
	90	38.36de	34.08de	48.96cde
	130	46.78c	43.45c	51.86bc
ETC85%	0	26.80i	21.32i	49.66cde
	60	35.68ef	31.21ef	40.94h
	90	39.67d	34.16d	43.64fgh
	130	51.33b	46.87b	45.49efg

The different letters indicate a significant difference within the same column, whereas the same letters indicate no significant difference at a significant level of 0.05.

water applied significantly increased potato tuber yield (Yuan et al., 2003; Camargo et al., 2015). A significant potato tuber yield reduction was observed when growing potato under ETC70% in silty-clay soil compared to ETC100% (Fleisher et al., 2008). Bohman et al. (2019) obtained a potato yield of 72.5 t.ha^{-1} under ETC100% with 270 kgN.ha^{-1} in frigid Entic Hapludolls soil in Becker, while Maltas et al. (2018) obtained a total fresh tuber yield of 73.7 t.ha^{-1} with 200 kgN.ha^{-1} in calcaric Cambrisol in Agroscope-Changins. This showed that the N requirement for a high potato tuber yield depends on the soil type.

The marketable yield is the most important part for farmers. This study showed that the marketable tuber yield under different irrigation regimes and N rates varied between 11.19 and 54.25 t.ha^{-1}. The marketable tuber yield under different N rates decreased with the increment of the water stress. The reduction in irrigation amount in Mollic Andosols by 15% (ETC85%), 25% (ETC 75%) and 50% (ETC50) resulted in a decrease of marketable tuber yield by about 10.01, 15.53 and 40.31%, respectively, under different N-fertilization (Table 7). This showed that an increment of N in water stress conditions in Mollic Andosols could not lead to a high change in marketable tuber yield obtained from apical rooted cuttings of potato, probably due to an adverse effect of excessive mineral N application on potato yield. According to Begum et al. (2018), suppressing water shortage in potato production can result in high potato productivity of 40–50 t.ha^{-1} or higher. The unexpected total potato yield and marketable yield responses to N level obtained in all irrigation treatments were also reported (Kirnak et al., 2005; Mellgren, 2008; El Mokh et al., 2015; Fandika et al., 2016; Bani-Hani et al., 2018).

The significance of the interaction effect of both factors on total fresh tuber yield and marketable yield showed that both factors were essential for high potato productivity in Mollic Andosols. Badr et al. (2012) and Elmetwalli and Elnemr (2020) also indicated that irrigation×nitrogen significantly affected potato yield. However, Bohman et al. (2019) observed that irrigation×nitrogen did not significantly affect fresh tuber yield and the marketable yield. Tolessa (2019) found that applying 207 kgN.ha^{-1} in rain-fed potato production can boost potato tuber yield and marketable yield by approximately 176% and 119%, respectively, compared to the unfertilized plots. Sebnie et al. (2021) reported that marketable potato yield generally increases with the N rate, and a high marketable yield of 45.5 t.ha^{-1} can be achieved when applying 138 kgN.ha^{-1}. In contrast, a fieldwork study in Ethiopia recorded a marketable potato yield of 25.5 t.ha^{-1} with 150 kg.ha^{-1}. The maximum marketable tuber yield of 54.25 t ha^{-1} achieved in Mollic Andosols of this study can be attributed to the significant interaction effect observed between the two factors. This finding confirmed the results of Zewide et al. (2012), Getie et al. (2015), El Mokh et al. (2015), Regassa et al. (2016), Ayyub et al. (2019), Setu and Mitiku (2020) and (Tang et al., 2021), who reported that marketable potato yield significantly increases with N dosage. This study suggests further research using higher N rates above the rates used to find the N level from which an increase in the amount of N in Mollic Andosols might decrease potato yield.

The maximum tuber number per plant (23) was achieved under N3. The Pearson correlation performed indicated that a significant relationship (r = 0.7***) existed between tuber number per plant and total tuber yield (Figure 2). Further correlation analyses revealed that an increase in total tuber yield of apical rooted cuttings of potato depended on the number of ware potato (r = 0.59***) and size two (C2) (r = 0.53***) tubers per plant (Table 8). This result implied that for obtaining an optimum potato yield in Mollic Andosols, the N fertilization and irrigation management that lead to a high number of C2 and ware should be practised by potato farmers. These results are not in agreement with the findings of Fandika et al. (2016) and El Mokh et al. (2015), who reported that potato tuber number per plant increased with irrigation amount. These findings aligned with those of Ayyub et al. (2019) and Setu and Mitiku (2020), who also found that an increment in the amount of N statistically increased tuber number plant. Moreover, El Mokh et al. (2015) indicated that a low tuber number per plant decreased the total potato tuber yield. On the contrary, Badr et al. (2012) found no relationship between total tuber yield and tuber number per plant.

5.5. HI and DM of apical rooted cuttings of potato grown in mollic Andosols under different N and irrigation regimes

The HI under various irrigation regimes was statistically (P < 0.01) affected by N fertilisation, irrigation and irrigation×nitrogen (Table 6). The HI increased with the water deficit regardless of the N rates. The highest HI, 53.54%, was observed in ETC50%, while the lowest was obtained in ETC100%. This did not confirm Fandika et al. (2016) results, who found that irrigation regimes did not interfere with HI. Regardless of the irrigation regimes, there was a significant increase in HI with an increment in the amount of N, with the greatest value of HI observed with N3. The maximum HI of potato for the interaction effect was found under ETC50% with N3 (Table 8). This showed that HI reversibly increased with the total tuber and marketable yield under all irrigation and N

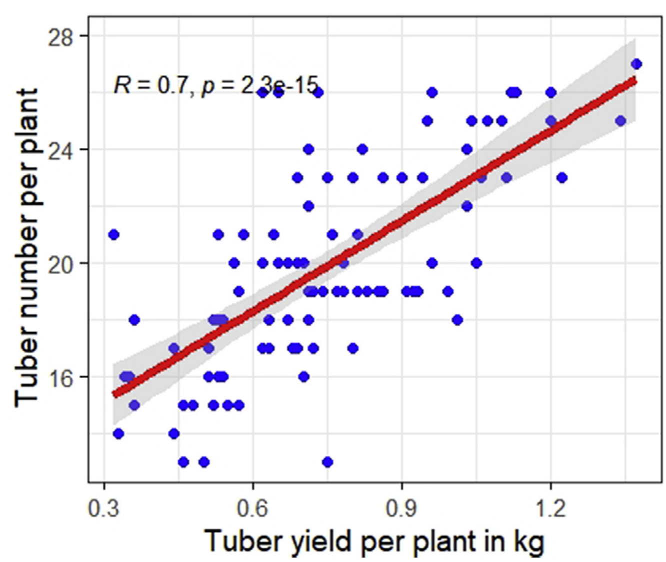

Figure 2. Relationship between tuber number per plant and tuber yield.

Table 8. Correlation between different potato tuber sizes and tuber yield per plant.

Tuber yield per plant	-0.19	0.21*	0.53***	0.59***
	Chat	0.012	-0.08	-0.22*
		Size one (C1)	0.30*	0.17
			Size two (C2)	0.38*
				Ware tuber

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

treatments. This is due to the high weight of aboveground biomass reported under ETC75%, ETC85% and ETC100%.

Only N-fertilization exhibited a significant (P < 0.01) effect on DM (Table 5). Comparison of DM across N rates indicated the highest DM under N3 while the smallest DM under N0 (Figure 3b). The tuber dry matter in different irrigation regimes did not differ significantly, but the highest (28.53%) and lowest (25.81%) DM regardless of N rates were found under ETC75% and ETC100%, respectively. Kashyap and Panda (2003) and Karam et al. (2014) found a high DM under water stress treatment compared to DM collected under ETC100%. However, Darwish et al. (2006) found an increase in DM with an increment in the amount of irrigation applied from ETC60% to ETC100% and then tended to decline as irrigation amount increased. Fleisher et al. (2008) and Camargo et al. (2015) indicated that severe water stress generally affected DM. Their different conclusions can be attributed to the potato genotypes used and the soil types. Milroy et al. (2019), Ayyub et al. (2019) and Maltas et al. (2018) indicated that DM increased with N rates. The findings of this study differed from the results of Sharifi et al. (2005) and (Janat (2007)),

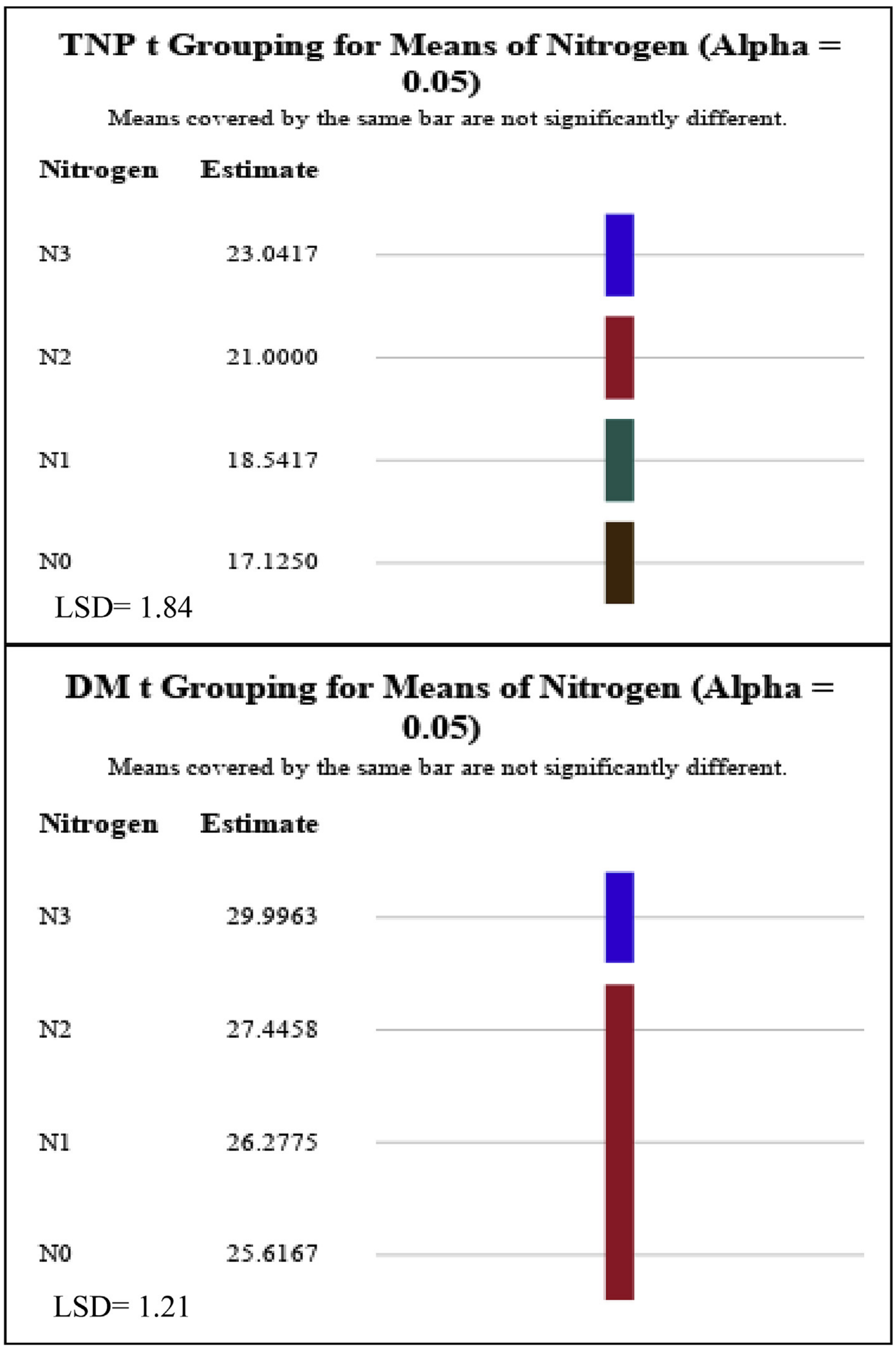

Figure 3. Means of tuber number per plant (TNP), and tuber dry matter content across N rates.

who found no significant increment in DM with N dosage. Further, this research did not tally with the results of Ahmed et al. (2009), who found a significant reduction in DM with N dosage.

5.6. Production functions

The production functions of total tuber yield, marketable and DM were developed for different irrigation regimes in Mollic Andosols to show their responsiveness to N levels in varied water stress conditions (Figures 4, 5, and 6). All the F-values obtained for the different fitted models were significant at 0.05 significant level. It was found that the relationships between both total tuber yield and marketable tuber yield and N-rate were linear. Linear regression was also observed between DM and N-rate. For the production functions of the total tuber yield, the following regression equations were found under different irrigation regimes:

ETC100%: $Y = 0.24X + 25.43$, $R^2 = 0.91$; *ETC85%*: $Y = 0.18X + 25.61$, $R^2 = 0.96$;
ETC75%: $Y = 0.19X + 22.18$, $R^2 = 0.99$ and *ETC50%*: $Y = 0.14X + 16.39$, $R^2 = 0.99$.

These regression equations showed that each kg of N applied in Mollic Andosols under ETC100%, ETC85%, ETC75% and ETC50% increased total potato tuber yield by approximately 240, 180, 190 and 140 kg.ha^{-1}. This indicated that an increment in a unit of N statistically increased total tuber yield under ETC100% compared to the deficit treatments. However, the slope obtained under ETC85% did not differ from the one observed in ETC75%. This showed that the increase in total tuber yield for each kg of N applied under ETC85% did not differ significantly from the increase in total tuber yield after each kg of N applied under ETC75%.

For the production functions of the marketable tuber yield, the following regression equations were found under different irrigation regimes:

ETC100%: $Y = 0.24X + 20.27$ $R^2 = 0.90$; *ETC85%*: $Y = 0.17X + 19.288$, $R^2 = 0.95$;
ETC75%: $Y = 0.15X + 17.66$, $R^2 = 0.99$ and *ETC50%*: $Y = 0.13X + 11.80$, $R^2 = 0.96$.

The slopes obtained indicated that for every kg of N applied, the marketable potato tuber yield increased by approximately 240, 170, 150 and 130 kg.ha^{-1} under ETC100%, ETC85%, ETC75% and ETC50%, respectively. All the production functions had a high coefficient of determination above 0.90. These functions also showed that marketable tuber yield obtained in ETC100% responded very well to N dosage compared to other irrigation treatments. Since irrigation regimes did not interfere with DM, the combined data from different plots were used to perform the relationship between DM and N rates. The following regression equation and was obtained; $Y = 0.03X + 24.95$, $R^2 = 0.84$. It was observed that every kg of N applied in Mollic Andosols increased DM of tuber by about 0.03 under different N and irrigation regimes.

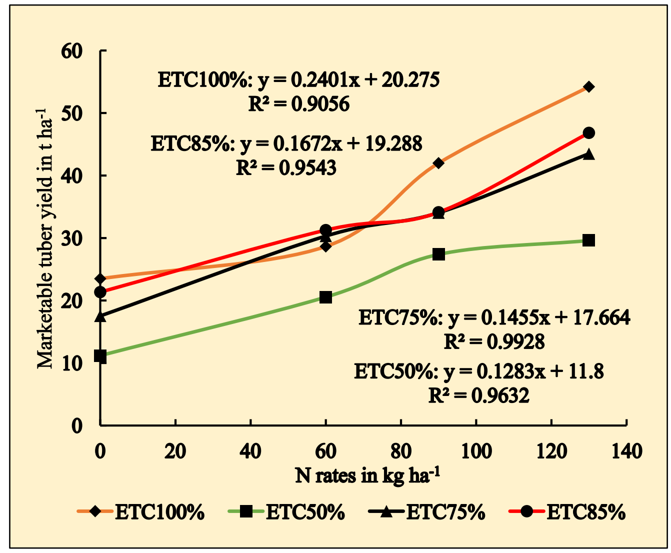

Figure 5. Relationship between N-rate and marketable tuber yield under different irrigation regimes.

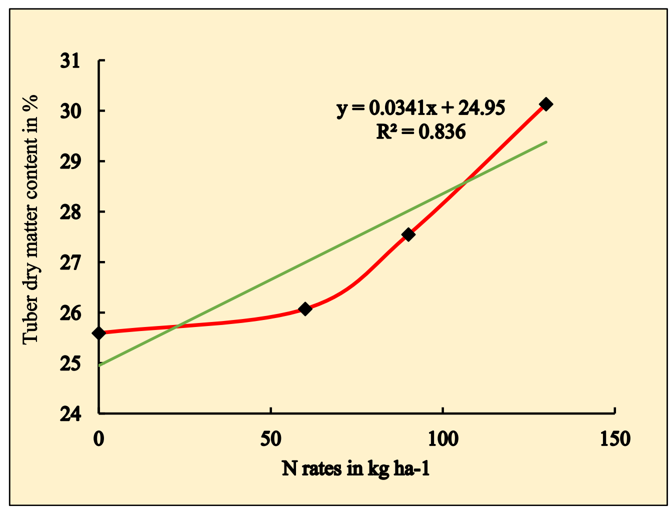

Figure 6. Relationship between DM of tubers and N-rate.

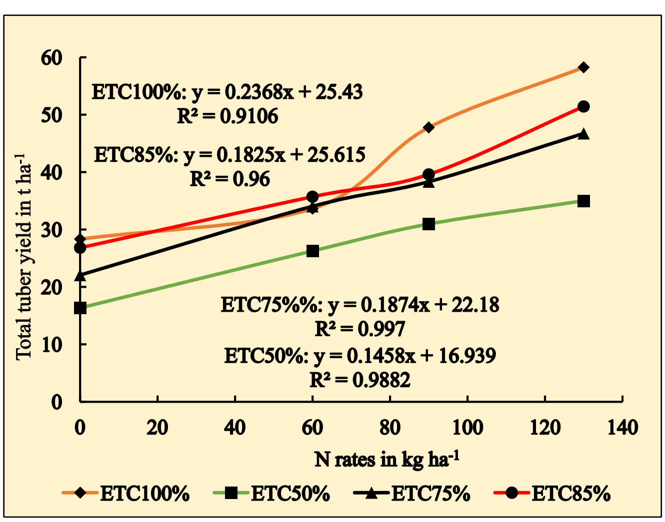

Figure 4. Relationship between N-rate and total tuber yield under different irrigation regimes.

6. Conclusion

Irrigation and N fertilization are the key factors in potato production. This study indicated that the difference in soil moisture content under potato production in Mollic Andosols was low during the first four weeks. The cumulative actual crop evapotranspiration (ETa) estimated in this study was on average 201.4, 302.1, 342.4 and 402.8 mm under ETC50%, ETC75%, ETC85% and ETC100%, respectively. Potato plant height, number of branches per plant, tuber number per plant and DM were generally responsive for N rate, while total tuber yield, marketable tuber and HI were more responsive to the interaction of both factors than a single factor. This study recommends an irrigation regime of ETC100% and N fertilizer rate of 130 kg.ha^{-1} in three split applications at 10

(40%), 30 (40%) and 50 (20%) days after planting for a maximum potato yield in Mollic Andosols in Kenya when planting apical rooted cuttings.

Declarations

Author contribution statement

Felix Satognon: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Joyce J. Lelei; Seth F.O. Owido: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

The authors acknowledged the support of MasterCard Foundation at Regional Universities Forum for Capacity Building in Agriculture (MCF@RUFORUM) through its program of Transforming African Agricultural Universities to Meaningfully Contribute to Africa' Growth and Development (TAGDev). Prof. Anthony Kibe and Prof. Paul K. Kimurto were also appreciated for their help, guidance, and recommendations throughout the fieldwork. The assistance of Emily Draru during fieldwork is also gratefully acknowledged by the authors. Authors recognize the good work of the eunidrip irrigation systems company (https://eunidripirrigationsystems.com/). The authors also praised the support of the various anonymous reviewers and editors whose comments and suggestions have greatly improved this work.

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