

Article

Interactive Effects of Nitrogen Application and Irrigation on Water Use, Growth and Tuber Yield of Potato under Subsurface Drip Irrigation

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Abstract: Potatoes are a high-value crop with a shallow root system and high fertilizer requirements. The primary emphasis in potato production is minimizing nitrogen-leaching losses from the shallow root zone through fertigation. Therefore, a field experiment was conducted for two consecutive years, 2018–2019 and 2019–2020 to assess the effect of nitrogen and irrigation amount and frequency on tuber yield, water balance components and water productivity of potatoes under surface and subsurface drip irrigation. The experiment was laid out in a split-plot design with three nitrogen levels (187.5 kg N ha⁻¹ (N₁), 150 kg N ha⁻¹ (N₂) and 112.5 kg N ha⁻¹ (N₃)) in main plots and six irrigation levels in the subsurface (drip lines were laid at 20 cm depth) and one surface drip in subplots. Irrigation scheduling was based on 100% of cumulative pan evaporation at an alternate (I₁) and two-day interval (I₂), 80% of cumulative pan evaporation at an alternate (I₃) and two-day interval (I₄), 60% of cumulative pan evaporation at an alternate (I₅) and two-day interval (I₆) and 80% of cumulative pan evaporation at alternate days with surface drip (I₇). Our results showed that potato transpiration was higher in N₁ and N₂ compared to N₃, while soil evaporation was higher in N₃ over N₁ and N₂. Irrigation regimes I₅ and I₆ had lower transpiration than I₁, I₂, I₃ and I₇, while I₇ had more soil evaporation than I₁, I₂ and I₃. Leaf area index (LAI), dry matter accumulation (DMA), root mass density (RMD) and tuber yield in N₁ and N₂ were at par but significantly higher than N₃. The LAI and DMA were statistically at par in I₁, I₂ and I₃ but significantly higher than recommended irrigation (I₇). Tuber yield was statistically at par in I₁, I₂, I₃ and I₇ but I₃ and I₇ saved 20% irrigation water compared to I₁ and I₂. On the other hand, real water productivity (WP_{ET}) under N₁ and N₂ were comparable in I₃ and I₄ but significantly higher than recommended practice (I₇) as pooled evapotranspiration (ET) and soil evaporation (E) in I₇ were 19.5 and 20.6 mm higher, respectively, than in I₃. Among interactive treatment combinations, N₁I₁, N₁I₂, N₁I₃, N₁I₇, N₂I₁, N₂I₂ and N₂I₃ recorded the highest tuber yields without any significant differences among them. Treatment N₂I₃ saved 20% nitrogen and irrigation water compared to all other combinations. Water productivity in N₁ and N₂ was comparable in I₃ and I₄ but significantly higher than recommended practice (I₇).

Keywords: potato fertigation; leaf area index; root mass density; real water productivity; field water balance



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1. Introduction

Potato (*Solanum tuberosum* L.) is the fourth-most-crucial vegetable crop, with a global production of 370 million tons [1]. India is the second-largest potato producer, with an

area of 2.17 million and a production of around 53.58 million metric tons [1]. Among the potato-growing zones of India, Punjab falls in the north-western plain, which accounts for about 5% of the total area under potato cultivation in India [2]. The main-season potato crop is popular among stakeholders in spring maize–rice–potato rotation. Spring maize and rice are high-water-requiring crops, and potato is sensitive to water stress which responds to frequent irrigation [3].

Moreover, potato is grown on raised beds and irrigated through furrows, accounting for significant water losses. Hence, the region's cultivation of water-guzzler rice and spring maize crops is becoming challenging as Punjab is already facing a water crisis [4]. The mean ground table has experienced a fall of 0.4 m year^{−1} in 80% of irrigated areas in central Punjab [5] since 1990. Thus this scenario of water scarcity in the region has necessitated the adoption of improved water management technologies such as drip irrigation to improve the water productivity of cropping systems. Surface drip irrigation in potato is recommended by researchers worldwide [6–8], but studies on the feasibility of subsurface drip irrigation systems in potato are limited. Thus, this experiment was planned to study the growth and yield of subsurface-drip-irrigated potato sown after spring maize and rice on the same drip lines. Potato is a shallow-rooted crop and is highly affected by excessive water and stressed water conditions [9]. Although furrow irrigation is the most common irrigation method in the Indo-Gangetic plains, drip irrigation has proved to be a good option in managing the volumetric inefficiencies in irrigation regimes resulting from too frequent or too much irrigation [10]. Agronomic inadequacies occur when plants are stressed due to insufficient water being frequently applied or excessive water application resulting in water logging or increasing the incidence of diseases [11].

Potato production is highly dependent on nitrogen (N), phosphorous (P) and potassium (K) applications [12]. Nitrogen is a dominant nutrient determining potato's growth, development, productivity and quality, and its optimal application improves yields [13], while excessive N may contaminate groundwater [14]. Therefore, in potato, water and nutrient management through a drip irrigation system can be the best option for maximization of potato productivity. Studies [15,16] have shown that the maximum productivity of potato can be obtained while keeping the soil moist and ensuring the N available during periods of high demand, which can be managed well with drip irrigation and fertigation. This system is most economical in giving the highest water productivity and saving about 40–50% of irrigation water compared to the furrow method [17]. It gives uniform water distribution with a significant reduction in water losses by percolation and runoff. This system is also beneficial on frosty nights as it reduces frost damage in plants in main-season crops. We hypothesize that subsurface drip irrigation is also used globally for potato production [18–20], in which drip lines are buried below the soil surface, providing water and nutrients directly to the root zone. Therefore, it has the potential to save water by reducing evaporation losses compared to other methods of irrigation, particularly in sandy loam soil [21]. Therefore, this experiment was planned to study the interactive effects of nitrogen, irrigation amount and irrigation frequency on potato growth, evapotranspiration and yield under subsurface drip irrigation.

2. Materials and Methods

2.1. Climate Conditions

A field experiment was conducted at Research Farm, Soil and Water Engineering, Punjab Agricultural University, Ludhiana, India, during 2018–2019 and 2019–2020. The layout of the experiment is given in Figure S1. Ludhiana is situated at 30°56' N and 75°52' E at 247 m above sea level. The area has a sub-tropical to semiarid climate with a hot and dry summer (April to June), hot and humid monsoon (July to September), mild winter (October to November) and cold winter (December to February). The mean minimum and maximum temperatures show considerable fluctuation during summer and winter. Maximum air temperature above 38 °C is expected during summer and frequent frosty spells in December–January. The average annual rainfall at Ludhiana is 755 mm, 75%

of which is received in the summer monsoon (July to September), complemented by a few low- to medium-intensity showers in winter. During the 2018–2019 potato season, the highest mean maximum air temperature was observed during October and lowest during January, while the mean minimum air temperature was lowest during December and highest during October. The maximum relative humidity was 71% observed in January. 2018–2019 (Table 1). The potato crop during 2018–2019 received 68.6 mm of rainfall. During 2019–2020, the weekly mean maximum air temperature in October was 30.6 °C while the minimum temperature was observed during January. The mean maximum relative humidity was 78.4% observed in January. The total rainfall was 123 mm.

Table 1. Weather parameters during potato growing season.

	2018–2019 Growing Season						2019–2020 Growing Season					
	T _{max}	T _{min}	RF (mm)	Epan (mm)	RH (%)	ET ₀ (mm)	T _{max}	T _{min}	RF (mm)	Epan (mm)	RH (%)	ET ₀ (mm)
October	31.0	16.2	0	96.6	64	97.0	30.6	18.4	0	76.7	68.2	87.8
November	26.8	11.8	2.6	64.0	63	59.3	28.0	22.0	35.2	56.8	68.2	57.1
December	20.6	5.5	0	40.6	68	40.9	15.9	7.5	46.8	30.5	79.0	33.5
January	18.5	6.2	66.0	43.1	71	41.31	16.6	6.7	39.8	27.7	78.4	42.1

T_{max} is maximum air temperature, T_{min} is minimum air temperature, Epan is open pan evaporation, RF and RH are rainfall and relative humidity, respectively, and ET₀ is potential evapotranspiration.

2.2. Experimental Site Description

Soil samples were collected randomly from four depths (0–15, 15–30, 30–60 and 60–90 cm) and three different field sites before the experiment started with the help of a screw auger. A composite sample was made and brought to the soil and water testing laboratory in the Department of Soil and Water Engineering to analyze the initial status of physical and chemical properties. The analysis was performed according to standard laboratory procedures. The experimental field soil was sandy loam in texture with pH 8.1, electrical conductivity 0.23 dS m^{−1}, organic carbon 0.48%, nitrogen 170.2 kg ha^{−1}, phosphorous 37.4 kg ha^{−1} and potassium 345 kg ha^{−1} in 0–15 cm soil depth. The bulk density of the soil was 1.52 g cm^{−3}. The physical properties of the soil are given in Table 2.

Table 2. Physical properties of experimental soil.

Soil Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Soil Texture	Bulk Density (g cm ^{−3})	Saturated Hydraulic Conductivity (cm h ^{−1})	Soil Moisture Retention (% v/v)	
							10 kPa	1500 kPa
0–15	70.8	20.4	10.8	Sandy loam	1.52	1.08	27.0	9.0
15–30	70.2	21.3	11.2	Sandy loam	1.61	0.64	27.2	9.2
30–60	69.7	22.2	11.7	Sandy loam	1.67	1.61	27.3	7.3
60–90	68.4	22.3	11.9	Sandy loam	1.64	1.27	23.0	6.0

In order to prepare good tilth before planting, the disc harrow was run twice, followed by two ploughings with a tractor-drawn cultivator. Drip lines were installed at a 20 cm depth below the soil surface with a tractor-drawn machine (as shown in the layout). The distance between the two drip lines was kept at 60 cm per row-to-row crop spacing. Ridges were made manually 60 cm apart in the east–west direction (Figure S1). The experiment was laid out in a split-plot design with three nitrogen levels of 187.5 kg N ha^{−1} (N₁), 150 kg N ha^{−1} (N₂) and 112.5 kg N ha^{−1} (N₃) in the main plots. Seven irrigation levels (six subsurface drip lines and one surface drip) were kept in the subplots. The irrigations were 100% of Epan at alternate day (I₁) and two-day intervals (I₂), 80% of Epan at alternate (I₃) and two-day intervals (I₄), 60% of Epan at alternate day (I₅) and two-day intervals (I₆) in the subsurface and 80% of Epan at an alternate day in surface drip (I₇). The potato

variety *Kufri Pukhraj* was planted on 18 October, during 2018–2019 and on 15 October in 2019–2020 at 20 cm plant-to-plant distance and 7–8 cm soil depth from the top of the ridge in rows as per the layout. All the plants emerged between 14 and 18 days. All the crop management practices were followed as per the practice package for cultivating vegetable crops. Fertilizer N was applied as per treatments. The recommended doses of phosphorus ($62.5 \text{ kg P}_2\text{O}_5 \text{ kg ha}^{-1}$) and potassium ($\text{K}_2\text{O } 62.5 \text{ kg ha}^{-1}$) were applied along with N in 16 splits at weekly intervals. A water meter was installed on 63 mm PVC pipe to measure the irrigation water delivered to each plot. Tensiometers were installed at 10, 20, 30, 60 and 90 cm depths in I_1 , I_3 , I_5 and I_7 to monitor soil matric potential (SMP) daily at 8 am during 2018–2019. However, during 2019–2020 SMP was monitored only during three major rain events. Soil water content was determined 24 h, 48 h and 72 h after each irrigation from 0–10, 10–20, 20–30, 30–40, 40–60 and 60–100 cm profile depths with FDR (Frequency domain reflectometry). Actual crop evapotranspiration (ET_a) was estimated from the soil water balance equation.

$$I + P = \text{ET}_a + D + R \pm \Delta\text{SW} \quad (1)$$

where I is irrigation water applied (mm), P is precipitation (mm), R is surface runoff (mm), D is deep drainage (mm) and ΔSW is the change in soil profile moisture storage (mm). Runoff was absent as sufficient dikes were maintained. Deep drainage was considered zero when soil profile moisture storage was less than the field capacity. When soil moisture storage exceeded the field capacity storage after irrigation or rainfall, deep drainage was calculated as the difference between the field capacity storage and soil moisture storage plus irrigation/rainfall [22]. Evapotranspiration (ET_a) was partitioned into soil evaporation (E) and transpiration (T_p) [23]:

$$E = \text{ET}_a \times e^{-\alpha \text{LAI}} \quad (2)$$

$$T_p = \text{ET}_a - E_s \quad (3)$$

where α is the extinction coefficient of radiation set as 0.56 [24], and LAI is the leaf area index (measured with the Sunscan Plant Canopy Analyzer of Delta T Devices) at different crop growth stages. The following equation already calibrated for Potato LAI [23] was used to partition LAI during crop growth and senescence:

$$\text{LAI}_{(t)} = \text{LAI}_{\max} \frac{1}{1 + e^{a_1(t - t_{\text{inf}})}} - e^{a_2(t - t_{\text{end}})} \quad (4)$$

where $\text{LAI}_{\max}$ is the maximum LAI value observed, a_1 and a_2 are shape factors controlling the growth and senescence rates, t_{inf} is the time at which the maximum growth rate is reached (inflexion point) and t_{end} is the time of complete senescence. The terms $\text{LAI}_{\max}$, t_{inf} , and t_{end} were measured and a_1 and a_2 were fitted [23]. Whole plants and roots were uprooted, sun-dried and then dried in an oven at 60°C until they reached a constant weight for measuring dry matter accumulation at 60, 75 DAP and at harvest, which was expressed in Mg ha^{-1} . The leaf area index was recorded periodically (30, 60, 90 and 120 DAS) using Sunscan Plant Canopy Analyzer based on the principle of Beer–Lambert's law. After calibration, the leaf area index was recorded from 12:00 to 2:00 p.m. on a sunny day from two locations in each plot and then averaged for the final reading of the leaf area index. Root-mass density was determined by collecting root samples with the help of tubes having an internal diameter of 5 cm from 0–15, 15–30, 30–45 and 45–60 cm depths from three places, under the plant, 7 cm from the base of the plant towards row and 7 cm from the base of the plant towards furrow. These samples were mixed, passed through a 32 mm mesh and washed in a running water channel by providing gentle pulsing with the hand to make the roots free from soil. Then roots were transferred to Petri dishes to remove inert material. Then roots were dried in an oven and root mass density was calculated by dividing the mass of dry roots by the volume of the tube. N uptake in plant samples was determined at 90 days. The digestion process was performed for nitrogen determination in plant samples.

During digestion, complex structures were broken into simple structures, releasing nitrogen as ammonium radicals. For digestion, 0.5 g of plant sample was taken in a digestion tube and mixed with 6 mL of concentrated sulphuric acid. Then, one teaspoon of mix from a mixture of CuSO_4 (100 g), K_2SO_4 (10 g) and selenium oxide (1 g) was added to the digestion tube. The solution was retained at room temperature for 24 h. Then, the digestion tube was heated up to 410°C for 2 h. After completion of digestion, the sample turned to light green or colourless. After digestion, distillation with 4% boric acid and titration with 0.1 N H_2SO_4 was performed to determine the plant nitrogen as per the KEL PLUS manual. Nitrogen uptake was determined by multiplying the N content with biomass and tuber yield. Real water productivity (kg m^{-3}) was calculated as the ratio of grain yield and evapotranspiration as described by [5,25]:

$$\text{WP}_{\text{ET}} = \text{GY} / \text{ET}_a \times 10 \quad (5)$$

where WP_{ET} is real water productivity (kg m^{-3}), ET_a is crop evapotranspiration (mm) and GY is grain yield (Mg ha^{-1}).

2.3. Statistical Analysis

Analysis of variance was performed using the Proc GLM procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC, USA). Significant mean differences were tested using 54 Fisher's protected least significant difference (LSD) tests at $\alpha = 0.05$. For pooled analysis, the year was the main factor to increase the precision. In addition, the regression procedure was used to test the nature of the relationship between different parameters.

3. Results and Discussion

3.1. Soil Matric Potential and Soil Moisture Distribution at Different Depths

Soil matric potential (SMP) values for different treatments throughout cropping season 2018–2019 are shown in Figure 1. At 10 cm depth, SMP in I_1 and I_3 varied between -38 and -48 kPa, except for two significant rain events (Figure 1 at the same depth, SMP for I_5 was even less and varied between -48 and -55 kPa. However, under surface drip (I_7), SMP at the surface layer was high and varied between 18 and 24 kPa. At 20 and 30 cm depths, the SMP was higher at 60 and 90 cm depths in I_1 , I_3 and I_5 due to placement of the dripper at these depths. Between these treatments, the highest SMP was observed in I_1 , followed by I_3 and I_5 . However, in I_7 , higher SMP was observed at 10 cm and 20 cm depths compared to 30, 60 and 90 cm depths. In all these treatments, more changes in soil matric potential occurred in 10, 20 and 30 cm depths. However, fewer fluctuations were observed at 60 and 90 cm, even during the major rain events, indicating no drainage in our experiments. Mean seasonal volumetric soil moisture (MSVSM) during the growing season (except major events) is presented in Table 3. During 2018–2019, in 0–10 cm depth after 24 h of irrigation, MSVSM in I_1 , I_2 , I_3 , I_4 , I_5 , I_6 and I_7 was 11.1, 12.1, 10.9, 10.7, 9.6, 9.3 and 18.7%, respectively. It dropped to 9.2, 10.1, 8.8, 5.6, 9.1, 8.8, 8.5, and 15.8%, respectively, after 48 h of irrigation which indicated that, throughout the season, the surface soil layer remained relatively wet in surface drip and dry in subsurface drip irrigation. After 24 h in the 10–20 cm soil layer, the seasonal volumetric soil moisture was higher in I_1 and I_2 by 2.1 and 2.0%, respectively, over I_7 , while in I_5 and I_6 , it was lower than I_7 by 1.8 and 2.8%, respectively. Compared to I_7 , I_3 had 0.5% more, but I_4 contained less moisture content in this layer. After 24 h in the 20–30 cm soil layer, MSVSM was higher in I_1 , I_2 , I_3 , I_4 , I_5 and I_6 by 8.0, 6.2, 4.4, 3.7, 0.7, and 0.6%, respectively, over I_7 . A similar trend was observed after 48 h of irrigation. In 30–40 cm depth after 24 h of irrigation, MSVSM was higher in I_1 , I_2 , I_3 , I_4 , I_5 and I_6 than I_7 by 6.0, 5.8, 4.3, 3.8, 1.7 and 0.9%, respectively. A similar trend was observed after 48 h of irrigation. In 40–60 cm soil depth after 24 h of irrigation MSVSM was higher in I_1 , I_2 , I_3 , I_4 , I_5 and I_6 than in I_7 by 4.7, 4.0, 3.6, 3.2, 2.3 and 2.4%, respectively. Similarly, during 2019–2020 (Table 4), MSVSM in I_1 , I_2 , I_3 , I_4 , I_5 , I_6 and I_7 was 12.0, 11.8, 11.1, 10.8, 10, 9.9 and 20.2%, which dropped to 9.2, 10.1, 8.8, 9.1, 8.8, 8.5 and 15.8%, respectively, after 48 h and further dropped to 8.9, 8.1, and 8.3% after 72 h in treatments I_2 , I_4 and I_6 ,

respectively. In 10–20 cm depth, after 24 h, MSVSM was higher in I₁, I₂ and I₃ by 2.1, 1.7 and 0.6%, respectively, but I₄, I₅ and I₆ contained 0.5, 2.8 and 3.3% less moisture content, respectively, than I₇. After 48 h, the moisture content was highest in I₁, I₂, I₃ and I₄ over I₇ by 2.4, 1.6, 0.3 and 0.2%, respectively, but I₅ and I₆ contained 2.0 and 2.3% less moisture content, respectively. In 20–30 cm soil depth, all the subsurface drip treatments contained more MSVSM over surface irrigation (I₇). The percent difference of I₁ over I₂, I₃, I₄, I₅, I₆ and I₇ was 9.6, 8.7, 6.1, 5.3, 3.7 and 3.5%, respectively, after 24 h and 8.6, 8.7, 5.4, 5.2, 4.3 and 4.2%, respectively, after 48 h. Similarly, in 30–40 cm soil depth, the percent increase in MSVSM in I₁, I₂, I₃, I₄, I₅ and I₆ over I₇ was 6.9, 6.0, 4.0, 2.9, 1.7 and 0.8, respectively, after 24 h. This difference was 6.7, 5.2, 3.5, 2.4, 0.7 and 0.9%, respectively, after 48 h. A similar trend was observed in the 40–60 cm soil layer.

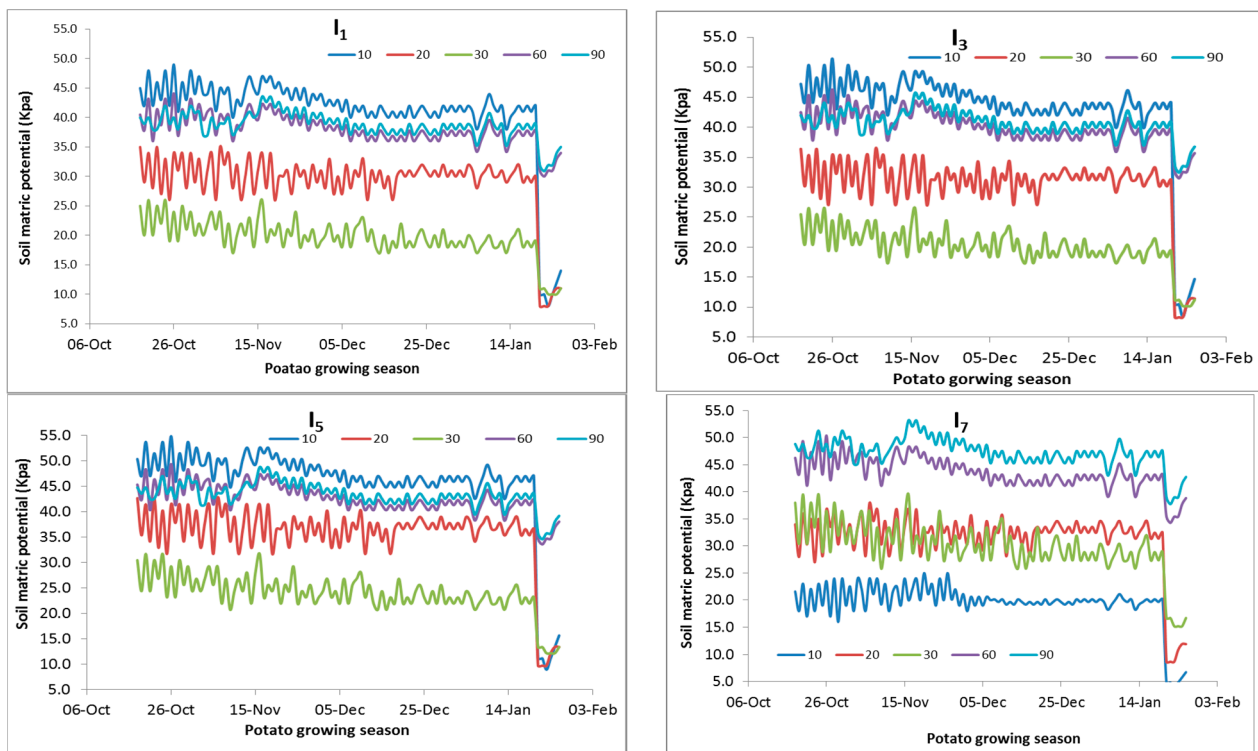


Figure 1. Soil moisture potential at different depths throughout the growing season of potato during the 2018–2019.

Table 3. Mean seasonal volumetric soil moisture content (%) in potato during 2018–2019.

Depth (cm)	Hours after Irrigation	I ₁	I ₂	I ₃	I ₄	I ₅	I ₆	I ₇
0–10	24	11.1 ^a	12.1 ^a	10.9 ^a	10.7 ^a	9.6 ^a	9.3 ^a	18.7 ^b
	48	9.2 ^a	10.1 ^a	8.8 ^a	9.1 ^a	8.8 ^a	8.5 ^a	15.8 ^b
	72		8.9 ^a		8.1 ^a		8.3 ^a	
10–20	24	17.2 ^a	18.1 ^a	15.7 ^{ab}	14.7 ^{ab}	13.3 ^b	12.3 ^b	15.1 ^{ab}
	48	12.5 ^a	12.5 ^a	12.1 ^a	11.3 ^a	10.1 ^a	10.2 ^a	11.5 ^a
	72		11.2 ^a		10.4 ^a	9.1 ^{ab}	8.5 ^b	
20–30	24	21.5 ^a	19.3 ^a	17.9 ^a	17.2 ^{ab}	14.2 ^b	14.1 ^b	13.5 ^b
	48	17.5 ^a	16.5 ^a	15.5 ^a	15.1 ^a	13.1 ^b	12.3 ^b	10.2 ^b
	72		14.4 ^a		13.1 ^a		10.1 ^b	
30–40 cm	24	17.1 ^a	16.9 ^a	15.4 ^a	14.9 ^{ab}	12.8 ^b	12.0 ^b	11.1 ^b
	48	16.4 ^a	15.1 ^a	14.2 ^{ab}	13.1 ^b	11.8 ^b	11.1 ^b	10.1 ^b
	72		14.8 ^a		12.5 ^b		10.8 ^c	

Table 3. Cont.

Depth (cm)	Hours after Irrigation	I ₁	I ₂	I ₃	I ₄	I ₅	I ₆	I ₇
40–60 cm	24	14.8 ^a	15.1 ^a	13.7 ^a	13.3 ^a	12.4 ^{ab}	12.2 ^{ab}	10.1 ^b
	48	14.1 ^a	13.8 ^a	13.2 ^a	12.5 ^a	12.1 ^a	12.1 ^a	9.9 ^b

Treatments with different lower case letters are significantly different at $p < 0.05$.

Table 4. Mean seasonal volumetric soil moisture content (%) in potato during 2019–2020.

Depth (cm)	Hours after Irrigation	I ₁	I ₂	I ₃	I ₄	I ₅	I ₆	I ₇
0–10	24	12 ^b	11.8 ^b	11.1 ^b	10.8 ^b	10 ^b	9.9 ^b	20.2 ^a
	48	11.3 ^b	10.8 ^b	10.5 ^b	9.9 ^b	8.5 ^b	8.1 ^b	16.9 ^a
	72		8.7 ^a	8.3 ^a	8.5 ^a		7.8 ^a	
10–20	24	18.2 ^a	17.8 ^a	16.7 ^{ab}	15.6 ^{ab}	13.3 ^b	12.8 ^b	16.1 ^{ab}
	48	15.5 ^a	14.7 ^{ab}	13.4 ^{ab}	13.3 ^{ab}	11.1 ^b	10.8 ^b	13.1 ^{ab}
	72		12.2 ^a		11.4 ^a		10.1 ^a	
20–30	24	22.4 ^a	21.5 ^a	18.9 ^{ab}	18.1 ^{ab}	16.5 ^b	16.3 ^b	12.8 ^c
	48	19.5 ^a	19.3 ^a	16.3 ^b	16.1 ^b	15.2 ^b	15.1 ^b	10.9 ^c
	72		15.1 ^a		14.1 ^a		12.9 ^b	
30–40	24	17.7 ^a	16.8 ^a	14.8 ^{ab}	13.7 ^{ab}	12.5 ^b	11.6 ^b	10.8 ^b
	48	16.8 ^a	15.3 ^a	13.6 ^{ab}	12.5 ^b	10.8 ^b	10.9 ^b	10.1 ^b
	72		14.1 ^a		11.4 ^b		10.1 ^b	
40–60	24	15.3 ^a	14.8 ^a	13.5 ^a	12.5 ^a	11.8 ^{ab}	11.2 ^{ab}	10.2 ^b
	48	15.1 ^a	14.1 ^a	13.2 ^{ab}	12.3 ^{ab}	11.5 ^{ab}	11.1 ^b	10.0 ^b
	72		13.2 ^a		11.1 ^a		9.8 ^a	

Treatments with different lower case letters are significantly different at $p < 0.05$.

3.2. Water Balance Components

3.2.1. Total Water Input

Irrigation was given to the crop based on E_{pan} according to the treatments (Tables 5 and 6). The potato crop during the growing season received 68.6 mm and 123.6 mm of rainfall during 2018–2019 and 2019–2020, respectively. During 2018–2019, total water input was 18.2% higher in I₁ or I₂ over I₃ and I₄ and 50.6% higher over I₅ and I₆, and the difference between I₃ and I₄ was 27% over I₅ and I₆. I₇ and I₃ treatments received a similar amount of total water. During 2019–2020, the percent difference between I₁ and I₂ over I₃ or I₄ was 9.8%, I₁ or I₂ over I₅ or I₆ was 24.8% and I₃ or I₄ over I₅ or I₆ was 13.3%.

Table 5. Water balance components of potato during 2018–2019.

Treatments	Irrigation (mm)	Rain (mm)	ET (mm)	Drainage (mm)	ΔS
N ₁ I ₁	160.8 ^a	68.6	223.2 ^a	0	6.4 ^a
N ₁ I ₂	158.6 ^a	68.6	215.2 ^a	0	10.0 ^a
N ₁ I ₃	126.0 ^b	68.6	208.4 ^a	0	−11.3 ^b
N ₁ I ₄	125.8 ^b	68.6	201.3 ^a	0	−11.6 ^b
N ₁ I ₅	83.7 ^c	68.6	186.3 ^b	0	−34.7 ^c
N ₁ I ₆	83.7 ^c	68.6	185.5 ^b	0	−36.2 ^c
N ₁ I ₇	126.0 ^b	68.6	230.2 ^a	0	−40.0 ^c
N ₂ I ₁	160.8 ^a	68.6	220.3 ^a	0	6.2 ^a
N ₂ I ₂	158.6 ^a	68.6	214.4 ^a	0	10.7 ^a
N ₂ I ₃	126.0 ^b	68.6	205.5 ^a	0	−10.3 ^b

Table 5. Cont.

Treatments	Irrigation (mm)	Rain (mm)	ET (mm)	Drainage (mm)	ΔS
N ₂ I ₄	121.0 ^b	68.6	199.9 ^a	0	−9.6 ^b
N ₂ I ₅	83.7 ^c	68.6	185.5 ^b	0	−33.2 ^c
N ₂ I ₆	80.7 ^c	68.6	183.3 ^b	0	−34.0 ^c
N ₂ I ₇	126.0 ^b	68.6	229.4 ^a	0	−39.1 ^c
N ₃ I ₁	160.8 ^a	68.6	219.9 ^a	0	9.5 ^a
N ₃ I ₂	158.6 ^a	68.6	211.5 ^a	0	23.1 ^b
N ₃ I ₃	126.0 ^b	68.6	201.2 ^a	0	−8.4 ^c
N ₃ I ₄	121.0 ^b	68.6	190.4 ^a	0	−0.8 ^c
N ₃ I ₅	83.7 ^c	68.6	174.4 ^b	0	−22.1 ^d
N ₃ I ₆	83.7 ^c	68.6	173.3 ^b	0	−23.9 ^d
N ₃ I ₇	126.0 ^b	68.6	225.4 ^a	0	−42.0 ^d

Treatments with different lower case letters are significantly different at $p < 0.05$.

Table 6. Water balance components of potato during 2019–20.

Treatments	Irrigation (mm)	Rain (mm)	ET (mm)	Drainage (mm)	ΔS
N ₁ I ₁	105.8 ^a	123	232.4 ^a	0	−3.6 ^a
N ₁ I ₂	104.3 ^a	123	230.1 ^a	0	−2.8 ^a
N ₁ I ₃	85.9 ^b	123	222.2 ^a	0	−13.3 ^b
N ₁ I ₄	84.8 ^b	123	220.4 ^a	0	−12.6 ^b
N ₁ I ₅	61.5 ^c	123	203.4 ^b	0	−18.9 ^b
N ₁ I ₆	60.7 ^c	123	201.3 ^b	0	−17.6 ^b
N ₁ I ₇	85.9 ^b	123	238.8 ^a	0	−29.9 ^c
N ₂ I ₁	105.8 ^a	123	232.4 ^a	0	−3.6 ^a
N ₂ I ₂	104.3 ^a	123	230.1 ^a	0	−2.8 ^a
N ₂ I ₃	85.9 ^b	123	221.1 ^a	0	−12.2 ^b
N ₂ I ₄	84.8 ^b	123	220.4 ^a	0	−12.6 ^b
N ₂ I ₅	61.5 ^c	123	203.4 ^b	0	−18.9 ^b
N ₂ I ₆	60.7 ^c	123	201.3 ^b	0	−17.6 ^a
N ₂ I ₇	85.9 ^b	123	236.2 ^a	0	−27.3 ^c
N ₃ I ₁	105.8 ^a	123	227.4 ^a	0	1.4 ^a
N ₃ I ₂	104.3 ^a	123	224.4 ^a	0	2.9 ^a
N ₃ I ₃	85.9 ^b	123	218.8 ^a	0	−9.9 ^a
N ₃ I ₄	84.8 ^b	123	220.4 ^a	0	−12.6 ^b
N ₃ I ₅	61.5 ^c	123	200.4 ^b	0	−15.9 ^b
N ₃ I ₆	60.7 ^c	123	198.8 ^b	0	−15.1 ^b
N ₃ I ₇	85.9 ^b	123	234.4 ^a	0	−25.5 ^c

Treatments with different lower case letters are significantly different at $p < 0.05$.

3.2.2. Evapotranspiration (ET) and Its Partitioning

During 2018–2019, the highest ET was observed in N₁ (207.2 mm), which was 0.8% and 3.9% higher than N₂ and N₃, respectively (Table 7). Transpiration in N₁ was 1.4 and 7.1% higher than N₂ and N₃, respectively. However, evaporation in N₃ was highest and was 10.8% and 9.4% higher than N₁ and N₂, respectively. During 2019–2020, the ET between nitrogen levels did not differ significantly, but in N₁ was higher by 0.4% and 7.8% than N₂ and N₃, respectively. However, evaporation in N₃ was higher by 15.6% and 14.3% than N₁ and N₂, respectively. ET and T in our experiment were comparable to another study conducted on drip irrigation [23]. The higher ET in N₁ and N₂ compared to N₃ may be due to more LAI in N₁ and N₂ than in N₃ (Table 8). The highest ET with a higher amount of nitrogen was also observed [26]. Among irrigation levels, during both years, ET was highest in I₇, with a difference of 23.3 and 15.6 mm over I₃ during 2018–2019 and 2019–2020, respectively. Despite receiving higher amounts of irrigation, lower ET was observed in I₁ and I₂ than recommended practice (I₇). However, the transpiration component was the

highest in I₁, and was higher by 6.9, 11.0, 18.4, 36.6, 41.3 and 9.8% over I₂, I₃, I₄, I₅, I₆ and I₇, respectively. Therefore, the highest ET in surface irrigated treatment (I₇) was due to an increase in evaporation (63.6 mm) which was 58.6, 43.8 and 51.7% higher than I₁, I₂ and I₃, respectively. The lowest evaporation in subsurface drip irrigation could be due to lower volumetric moisture content (%) in surface layers (Table 3) and higher leaf area index (Table 8) which resulted in higher transpiration. Similarly, during 2019–2020, transpiration was higher in I₁ by 3.5, 3.2, 9.2, 27.6, 32.5 and 8.5% than I₂, I₃, I₄, I₅, I₆ and I₇, respectively. The highest evaporation was recorded in I₇, followed by I₅ and I₆ and was the lowest in I₁. Amongst subsurface irrigation treatments, treatments with more frequent irrigation recorded more ET than deficit in less frequently irrigated treatments. It could be due to higher soil moisture availability, as also endorsed by [27].

Table 7. Evapotranspiration (ET_a) and its partitioning into soil evaporation (E) and transpiration (T_p).

Treatments	2018–19			2019–20		
	ET (mm)	T _p (mm)	E (mm)	ET (mm)	T _p (mm)	E (mm)
N ₁	207.2 ^a	160.2 ^a	46.9 ^a	221.8 ^a	169.5 ^a	52.3 ^a
N ₂	205.5 ^a	157.9 ^a	47.5 ^b	220.7 ^a	168.8 ^a	52.9 ^a
N ₃	199.4 ^b	149.5 ^b	52.0 ^b	217.2 ^a	157.2 ^b	60.5 ^b
Mean	204.0	155.9	48.8	219.9	165.2	55.3
I ₁	221.1 ^a	180.9 ^a	40.1 ^a	230.7 ^a	183.2 ^a	47.5 ^a
I ₂	213.7 ^a	169.3 ^{ab}	44.2 ^a	228.2 ^a	177.0 ^a	51.2 ^a
I ₃	205.0 ^a	169.9 ^{ab}	42.0 ^a	220.7 ^a	177.5 ^a	48.5 ^a
I ₄	197.2 ^{ab}	152.8 ^b	44.4 ^a	220.4 ^a	167.8 ^a	52.6 ^a
I ₅	182.1 ^b	132.4 ^c	49.7 ^b	202.4 ^b	143.6 ^b	58.8 ^{ab}
I ₆	180.7 ^b	128.0 ^c	57.7 ^{bc}	200.5 ^b	138.1 ^b	62.3 ^{ab}
I ₇	228.3 ^a	164.7 ^{ab}	63.6 ^c	236.5 ^a	168.9 ^a	67.6 ^b
Mean	204.0	155.9	48.8	219.9	165.2	55.3

Treatments with different lower case letters are significantly different at $p < 0.05$.

Table 8. Effect of nitrogen and irrigation on periodic leaf area index of potato.

Treatments	2018–2019				2019–2020			
	45 DAS	60 DAS	75 DAS	90 DAS	45 DAS	60 DAS	75 DAS	90 DAS
N ₁	3.45 (0.11)	4.97 (0.10)	4.98 (0.12)	4.31 (0.12)	2.96 (0.03)	4.87 (0.11)	4.89 (0.10)	4.33 (0.20)
N ₂	3.06 (0.13)	4.76 (0.11)	4.78 (0.11)	3.99 (0.11)	2.90 (0.02)	4.55 (0.11)	4.61 (0.11)	3.38 (0.18)
N ₃	2.65 (0.13)	4.40 (0.12)	4.38 (0.11)	3.45 (0.10)	2.78 (0.03)	4.16 (0.12)	4.19 (0.11)	2.62 (0.22)
Mean	3.05	4.71	4.71	3.86	2.88	4.54	4.56	3.34
LSD ($p = 0.05$)	0.39	0.29	0.31	0.32	0.06	0.31	0.29	0.66
I ₁	3.43 (0.13)	5.17 (0.05)	5.18 (0.04)	4.36 (0.05)	3.15 (0.02)	5.19 (0.03)	5.2 (0.02)	3.87 (0.01)
I ₂	3.22 (0.11)	5.11 (0.04)	5.13 (0.03)	4.24 (0.05)	2.90 (0.03)	5.08 (0.02)	5.11 (0.02)	3.81 (0.02)
I ₃	3.29 (0.14)	5.12 (0.05)	5.14 (0.05)	4.28 (0.06)	3.08 (0.02)	5.12 (0.04)	5.13 (0.03)	3.85 (0.01)
I ₄	2.99 (0.13)	4.72 (0.06)	4.78 (0.04)	3.92 (0.06)	2.80 (0.03)	4.35 (0.05)	4.38 (0.02)	3.22 (0.01)
I ₅	2.69 (0.11)	4.13 (0.05)	4.10 (0.03)	3.15 (0.05)	2.60 (0.02)	3.78 (0.02)	3.79 (0.03)	2.60 (0.02)
I ₆	2.58 (0.12)	3.71 (0.06)	3.60 (0.04)	2.92 (0.05)	2.54 (0.03)	3.45 (0.04)	3.44 (0.04)	2.47 (0.02)
I ₇	3.18 (0.13)	5.02 (0.06)	5.04 (0.05)	4.14 (0.04)	3.06 (0.04)	4.82 (0.03)	4.84 (0.03)	3.53 (0.01)
Mean	3.10	4.71	4.72	3.86	2.88	4.54	4.56	3.34
LSD ($p = 0.05$)	0.52	0.15	0.14	0.18	0.08	0.11	0.11	0.0
Interactions	NS	NS	NS	NS	NS	NS	NS	NS

Numbers given in parentheses indicate standard error.

3.2.3. Change in Seasonal Soil Moisture Storage

The seasonal change in soil moisture storage varied with nitrogen and irrigation during cropping seasons (Tables 5 and 6). During 2018–2019, in N₁, maximum extraction of profile water was found under I₇ (−40 mm) and I₆ (−36.2 mm) treatments followed by I₅

(−34.2 mm), I₃ (−11.3 mm) and I₄ (−11.6). However, the change in soil moisture storage was positive in I₁ (6.4 mm) and I₂ (10.0 mm). Under the N₂ level of irrigation, maximum extraction was observed under I₇ (−39.1 mm) followed by I₆ (−34.0 mm) and I₅ (33.2 mm), I₃ (−10.3 mm), I₄ (−9.6 mm), I₁ and I₂ (6.2 and 10.7 mm.). However, the profile storage was more under all the irrigation levels than N₁. Similarly, under N₃ treatment, maximum profile water extraction was observed in I₇ (−42.0 mm) followed by I₆ (−23.9 mm) and I₅ (−22.1 mm), I₃, I₄ (−8.4, 0.8 mm), I₃, I₁ (9.5 mm) and I₂ (23.1 mm). The profile moisture storage was more under the N₃ irrigation level, although a similar amount of irrigation was applied. It could be because of the significantly less biomass production and root development, which caused less water uptake by the crops and thereby less ET. Similarly, during 2019–20 (Table 6), profile moisture storage was negative. However, the profile was wetter than the first year, as rain events occurred after irrigation application. Higher extraction of moisture from profile under N₁ was observed in I₇ (−29.9 mm) followed by I₅ (−18.9 mm), I₆ (−17.6 mm), I₃ (−13.3 mm), I₄ (−12.6 mm), I₁ (−3.6 mm) and I₂ (−2.8 mm). A similar trend was observed in N₂ and N₃.

3.3. Plant Growth Parameters

Periodic Leaf Area Index (LAI), Total Dry Matter Accumulation and Root Growth

The leaf area index has been considered one of the prominent indicators of plant growth and yield, as it directly affects different eco-physiological processes in plants [28,29]. The leaf area index was significantly affected by different nitrogen and irrigation treatments throughout the crop growth period during both years (Table 8). LAI was at par in N₁ and N₂ at 45, 60, 75 and 90 DAS during 2018–2019. However, it decreased by 30.2, 12.9, 13.4 and 25.8% in N₃ at 45, 60, 75 and 90 DAP, respectively, during 2018–2019. The highest reduction in LAI was recorded with the reduction in nitrogen rate at 45 and 90 DAP. During 2019–2020, at 45 DAP, LAI did not differ in N₁ and N₂ treatments, but at 60, 75 and 90 DAP the highest LAI was observed in the N₁ treatment which was significantly higher than N₂ and N₃. It could be explained by the fact that this year, one fertigation at 60 DAP was delayed by three days due to continuous rains, and another was immediately followed by a major rain event. Rain might have leached the applied nitrogen. Among irrigation levels, the highest LAI was observed in I₁, which was at par with I₂, I₃ and I₇ at 45 DAP during both years. However, at 60, 75 and 90 DAP, LAI was at par in I₁, I₂ and I₃, which was significantly higher over I₇ and other treatments during both years. The highest LAI with the highest level of irrigation indicated higher photosynthesis due to higher radiation interception, as explained by [26,30]. The increase in LAI in I₁, I₂ and I₃ were also due to more root zone moisture (Tables 3 and 4).

The periodic dry matter accumulation (DMA) was significantly affected by nitrogen and irrigation regimes (Table 9). During 2018–2019, DMA did not differ significantly between N₁ and N₂ but decreased significantly with a further decrease in nitrogen level (N₃) at all the growth stages. A similar trend was observed during 2019–2020 except at 60 DAP, where biomass was significantly higher in N₁ compared to N₂ and N₃. Regardless of fertilizer application, the highest periodic DMA during both years was observed in I₁, which was followed by I₂, I₃ and I₇. The DMA was at par in I₁, I₂ and I₃ but significantly higher than recommended treatment (I₇) and all other treatments. Higher and frequent irrigation treatments under subsurface drip (I₁, I₂, I₃) favoured the improvement in plant vigour because of higher availability of moisture content in the root zone (Tables 3 and 4) and higher soil matric potential (−25 to −30 kPa) (Figure 1) compared to recommended (I₇) and other deficit irrigation treatments, which was further supported [31–34].

Table 9. Effect of nitrogen and irrigation on periodic dry matter accumulation (Mg ha^{-1}) of potato.

Treatments	2018–2019			2019–2020		
	60 DAS	75 DAS	90 DAS	60 DAS	75 DAS	90 DAS
N ₁	4.43 (0.11)	5.64 (0.13)	8.28 (0.15)	3.96 (0.01)	6.72 (0.03)	10.5 (0.13)
N ₂	4.17 (0.13)	5.27 (0.11)	8.04 (0.09)	3.72 (0.02)	6.66 (0.04)	10.1 (0.15)
N ₃	3.66 (0.15)	4.54 (0.16)	7.11 (0.11)	3.34 (0.04)	5.62 (0.06)	95.2 (0.19)
Mean	4.09	5.15	7.81	3.67	6.33	10.0
LSD ($p = 0.05$)	0.45	0.44	0.35	0.14	0.21	0.64
I ₁	4.55 (0.05)	5.77 (0.07)	8.53 (0.11)	4.19 (0.04)	7.04 (0.09)	10.7 (0.15)
I ₂	4.49 (0.03)	5.66 (0.06)	8.37 (0.10)	4 (0.05)	6.75 (0.10)	10.4 (0.16)
I ₃	4.32 (0.04)	5.6 (0.07)	8.27 (0.09)	4.06 (0.04)	6.8 (0.11)	10.1 (0.17)
I ₄	3.87 (0.04)	4.92 (0.08)	7.85 (0.11)	3.65 (0.03)	5.98 (0.08)	9.54 (0.14)
I ₅	3.7 (0.07)	4.52 (0.09)	7.04 (0.08)	3.15 (0.05)	5.7 (0.11)	8.92 (0.18)
I ₆	3.5 (0.07)	4.13 (0.08)	6.53 (0.11)	2.94 (0.06)	5.51 (0.10)	8.58 (0.17)
I ₇	4.2 (0.05)	5.46 (0.06)	8.09 (0.08)	3.94 (0.05)	6.56 (0.09)	10.0 (0.19)
Mean	4.06	5.15	7.81	3.7	6.33	9.75
LSD ($p = 0.05$)	0.23	0.26	0.29	0.18	0.31	0.54
Interactions	NS	NS	NS	NS	NS	NS

Numbers given in parentheses indicate standard error.

The distribution of root mass density of potato during both years is presented in Figure 2a,b. It was observed that a major portion of the roots was observed in 0–45 cm for all the treatments. Among different nitrogen levels, RMD was highest in N₁ in all the depths. During the first year (Figure 2a), RMD in N₁ was 17% and 26% higher over N₂ and N₃, respectively, in 0–15 cm depth. The difference was 16% and 31%, respectively, in 15–30 cm depth. In 30–45 cm depth, RMD in N₁ was 13% and 27.8% higher over N₂ and N₃, respectively. The difference between 45 and 60 cm depths was 12% and 26%, respectively. During 2019–2020 (Figure 2b), the mean RMD was 12.2% higher in N₁ over N₂ in all the depths. The difference between N₁ and N₃ was 38, 21.5, 24.0 and 26.6% in 0–15, 15–30, 30–45 and 45–60 cm depths, respectively. Among irrigation levels, all the subsurface drip irrigation treatments produced the highest RMD in 15–30 cm followed by 0–15 cm, 30–45 and 45–60 cm depths except I₇. In I₇, the highest RMD was observed in the 0–15 cm soil layer, followed by 15–30 and 30–45 cm depths. Mean RMD of I₇ was 1025.7, 398.0, 151.9 and 3.1 g m^{-3} in 0–15, 15–30, 30–45 and 45–60 cm soil depths, respectively. Respective values for I₁ and I₂ were 652.7, 721.6, 273.4 and 18.2 and 651.9, 720.9, 303.8 and 24.3 g m^{-3} . RMD of I₃ and I₄ was 641.9, 673.4, 287.1 and 21.3 and 629.5, 648.0, 278.0 and 6.1 g m^{-3} in 0–15, 15–30, 30–45 and 45–60 cm soil depths, respectively. The I₅ and I₆ treatments showed the lowest RMD in 0–15 and 15–30 cm soil depths but slightly more than I₁ and I₂ in 30–45 cm soil depth. Out of total the RMD of each subsurface irrigation treatment, 37–38% RMD was found in the 0–15 cm layer, 40–43% in 15–30 cm and 16–19% in the 30–45 cm layer. However, in the 45–60 cm soil layer, only 1–2% root mass density was found. On the other hand, in the surface drip irrigation treatment, 64.9% RMD was found in 0–15 cm depth, 25.2% in 15–30 cm, 9% in 30–45 cm and only 0.1% in 45–60 cm. These results are similar to those of [27,35]. Lu et al. [36] also reported that the 0–20 cm soil layer accounted for 62–68% of total root weight of potato under surface drip. Similar observations were observed in the second year of study (Figure 2b). However the difference between RMD of all the treatments in 0–15 cm and 15–30 cm soil layers was less than in the first year. RMD was more in 30–45 cm soil depth than in the first year. This may be because of more rain in the second year. Also, the overall total RMD was more in the second year of study than in the first year for all the treatments. A previous study [37] also reported decreased RMD in 0–30 cm depth in water-stressed conditions.

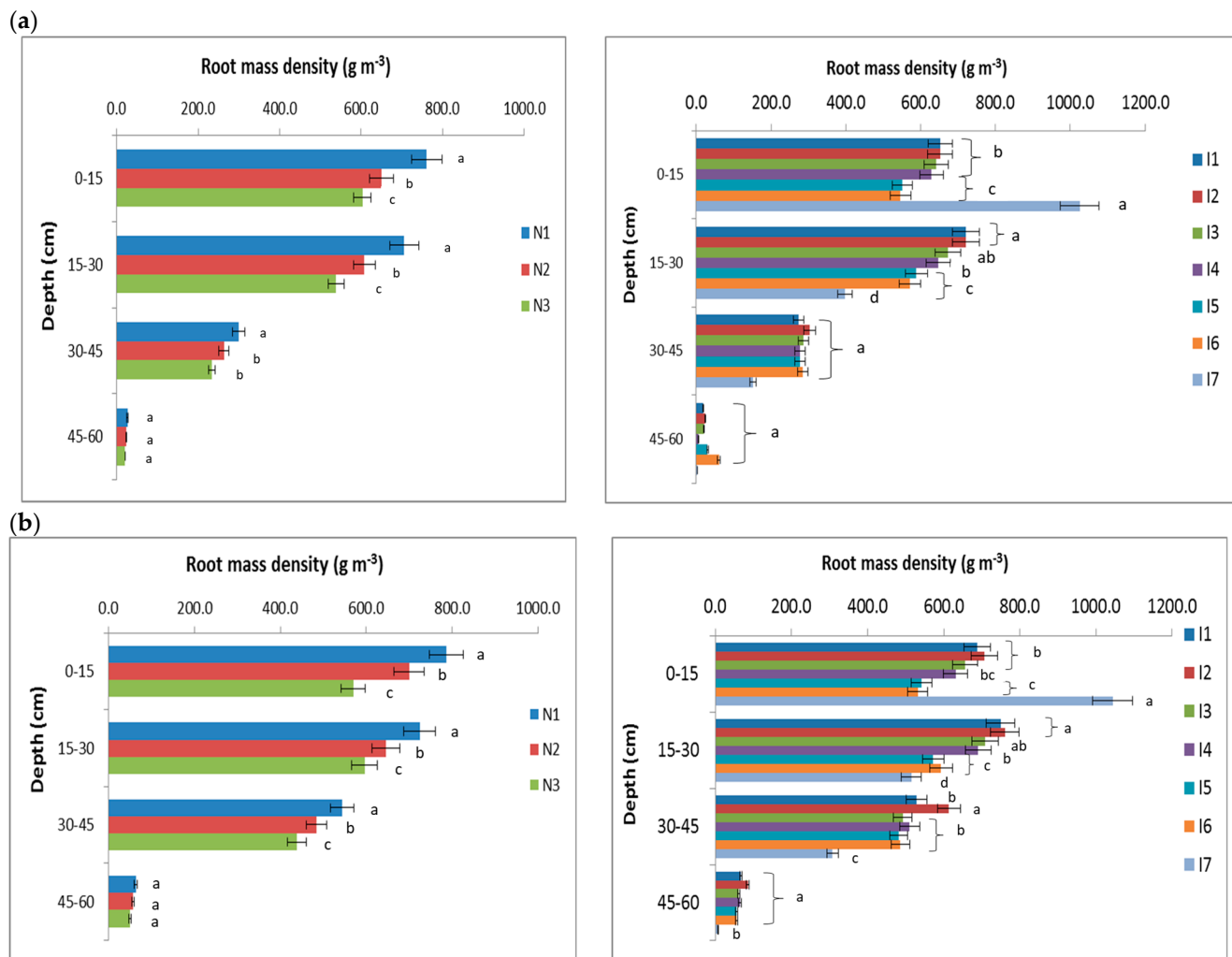


Figure 2. Root mass density of potato as affected by nitrogen and irrigation levels during 2018–2019 (a) and 2019–2020 (b). Treatments with different lower case letters are significantly different at $p < 0.05$.

3.4. Tuber Yield

Data on the tuber yield for both years are presented in Table 10. Tuber yield was affected significantly by nitrogen and irrigation during both years. During 2018–2019, tuber yield was at par in N₁ and N₂ but decreased (by 8.9% compared to N₁) significantly as the nitrogen level decreased to N₃. However, during 2019–2020, the highest mean tuber yield was obtained in N₁, which was significantly higher by 2.4 and 10.7% over N₂ and N₃, respectively. It could be either due to the difference in rain amount during both years or due to a delay in one fertigation because of rain. In addition to this, another significant rain event occurred immediately after fertigation, which may have leached the soil nitrogen [14,16]. Due to its shallow root system, potato responds to high nutrition as nitrogen may leach with higher irrigation below the root zone [14]. The highest tuber yield with a higher dose (240 kg N ha⁻¹) of nitrogen has been reported earlier [38]. The pooled analysis also showed that the highest tuber yield was recorded with an N₁ level of nitrogen which was significantly higher than N₂ and N₃. The tuber yield decreased with decrease in nitrogen (N₃), as a result of reduction in tuber weight by 21.31% and number of tubers per plant by 17.5% compared to N₁ (Tables 11–13) during 2018–2019. During 2019–2020, tuber weight was also reduced by 25.9% with a reduction in nitrogen level from N₁ to N₃. However, it was at par in N₁ and N₂. However, the number of tubers per plant decreased significantly (6.2%) with the decrease in nitrogen from N₁ to N₂, and it further decreased

by 19.8% as the nitrogen level further decreased to N_3 . The results are consistent with earlier findings [6,39], where drip irrigation significantly affected the weight of the tubers and the number of tubers per plant. Among various irrigation levels, the highest tuber yield was obtained in the I_1 treatment and was statistically similar to I_2 and I_3 during both years but was significantly higher than I_4 , I_5 , I_6 and I_7 . It could be because of higher root mass density in 15–30 cm soil depth in I_1 , I_2 and I_3 (Figure 2a) compared to I_7 , which led to more N uptake by plants under I_1 and I_2 . Higher water supply at frequent intervals caused increased transpiration (Table 7), which might have resulted in an enhanced tuber yield via gaseous exchange and photosynthesis [40]. However, tuber yield in I_7 and I_3 were also mutually at par. Decreased tuber yield with the reduction in irrigation amount below 50% of water depletion and SMP near -45 kPa [33,34,36,41,42] and the highest tuber yield with 100% ET_c was also reported [43]. Similar observations have also been reported in cereal [44]. The increase in potato yield with the highest level of irrigation was due to an increase in tuber weight, number of tubers per plant and evapotranspiration, as is clear from the potato production function (Figures 3–5). A linear relationship was found between tuber yield and tuber weight. The value of R^2 between tuber yield and tuber weight was 0.94 and 0.87 during 2018–2019 and 2019–2020, respectively. The R^2 value between tuber yield and number of tubers was 0.8782 and 0.9034 in 2018–2019 and 2019–2020, respectively. R^2 between tuber yield and ET (Figure 5) was 0.75 and 0.77 during 2018–2019 and 2019–2020, respectively. However, the R^2 between tuber yield and transpiration was 0.92 (Figure 6) during both years. Higher yield and yield attributes in I_1 could be because of more moisture at 30 cm depth and below compared to other treatments (Tables 4 and 5). Interaction results during both years revealed that at the highest nitrogen level (N_1), I_1 , I_2 and I_3 produced statistically similar yields as recommended (I_7), but at the N_2 level, I_1 , I_2 and I_3 produced statistically higher yields over I_7 . The results are in line with a study conducted in our region [45], that found a higher response of potato to a frequently irrigated treatment (ratio of irrigation water to pan evaporation 1.0) compared to a less-frequently irrigated treatment (ratio of irrigation water to pan evaporation 0.8). During both years and in the pooled analysis, the highest tuber yield (average 34.44 Mg ha^{-1}) was recorded in seven treatment combinations (N_1I_1 , N_1I_2 , N_1I_3 , N_1I_7 , N_2I_1 , N_2I_2 and N_2I_3) without any significant difference among them. Other treatment combinations recorded significantly lower tuber yield. The results align with other studies [20,46] in sandy loam soil.

Table 10. Effect of different nitrogen and irrigation levels on tuber yield (Mg ha^{-1}).

Treatments	2018–2019				2019–2020				Pooled Analysis			
	N_1	N_2	N_3	Mean	N_1	N_2	N_3	Mean	N_1	N_2	N_3	Mean
I_1	35.2	34.7	32.4	34.1 (0.27)	35.4	35.0	33.1	34.5 (0.22)	35.3	34.6	32.6	34.2
I_2	34.9	34.2	32.1	33.7 (0.26)	35.3	34.7	32.7	34.2 (0.21)	35.1	33.9	32.4	33.8
I_3	34.5	33.9	31.7	33.4 (0.25)	35.1	34.3	32.4	33.9 (0.19)	34.8	33.6	32.1	33.5
I_4	33.1	32.2	29.4	31.6 (0.23)	34.2	33.8	30.6	32.9 (0.23)	33.7	33.0	30.0	32.2
I_5	28.8	27.8	25.5	27.4 (0.22)	31.4	29.2	25.4	28.6 (0.20)	30.1	28.5	25.1	27.9
I_6	28.0	26.7	25.0	26.6 (0.25)	27.7	27.4	24.9	26.7 (0.23)	27.9	27.1	24.4	26.5
I_7	33.9	33.0	31.5	32.8 (0.26)	34.6	33.8	32.1	33.5 (0.22)	34.7	33.7	31.3	33.3
Mean	32.4	31.8	29.7	31.3	33.4	32.6	30.2	32.0	33.1	32.1	29.6	31.6
SE $\pm$	0.29	0.30	0.31		0.22	0.19	0.21					
LSD ($p = 0.05$)	$N = 0.95$ $I = 0.83$, $I \times N = 1.43$				$N = 0.57$, $I = 0.66$, $I \times N = 1.15$				$Y = 0.21$ $N = 0.26$, $Y \times N = \text{ns}$, $I = 0.44$, $I \times N = 0.74$, $Y \times N \times I = \text{ns}$			

Numbers given in parentheses indicate standard error.

Table 11. Effect of nitrogen and irrigation on tuber weight and No. of tubers per plant.

Treatments	2018–2019		2019–2020	
	Tuber Weight (g)	No. of Tubers/10 Plants	Tuber Weight (g)	No. of Tubers/10 Plants
N ₁	44.16 (1.58)	88.9 (1.22)	47.37 (2.12)	96.2 (1.93)
N ₂	41.54 (1.60)	86.0 (1.24)	44.01 (2.10)	90.5 (1.90)
N ₃	36.40 (1.63)	75.6 (1.26)	37.61 (2.28)	80.3 (1.96)
Mean	40.7	83.5	42.99	89.6
LSD ($p = 0.05$)	4.7	3.5	6.0	5.5
I ₁	44.9 (1.74)	96.8 (2.78)	48.61 (1.64)	104.7 (2.74)
I ₂	44.2 (1.73)	93.1 (2.81)	47.33 (1.61)	99.9 (2.75)
I ₃	43.5 (1.68)	90.7 (2.81)	45.31 (1.65)	97.0 (2.76)
I ₄	41.0 (1.71)	83.3 (2.88)	43.62 (1.64)	90.0 (2.73)
I ₅	35.6 (1.76)	70.5 (2.91)	37.29 (1.66)	74.8 (2.75)
I ₆	32.1 (1.77)	62.1 (2.93)	34.28 (1.65)	63.0 (2.76)
I ₇	43.5 (1.71)	88.1 (2.94)	44.50 (1.63)	93.7 (2.75)
Mean	40.7	83.5	42.99	89.6
LSD ($p = 0.05$)	5.0	8.4	4.9	8.3
Interactions	NS	NS	NS	NS

Numbers given in parentheses indicate standard error.

Table 12. N uptake by aboveground biomass and tubers (kg ha^{−1}) during 2018–2019.

Treatments	N Uptake by Biomass				Tuber N Uptake			
	N ₁	N ₂	N ₃	Mean	N ₁	N ₂	N ₃	Mean
I ₁	119.8	116.6	87.4	107.9 (2.31)	358.8	353.5	314.7	342.3 (2.80)
I ₂	113.6	109.5	84.4	102.5 (2.24)	355.6	349.0	308.3	337.6 (2.91)
I ₃	112.6	109.1	83.5	101.7 (2.45)	348.5	344.1	303.1	331.9 (2.51)
I ₄	103.6	95.4	73.6	90.9 (2.13)	331.4	318.3	276.4	308.7 (2.61)
I ₅	92.8	84.4	64.1	80.4 (2.34)	285.4	272.5	235.0	264.3 (2.55)
I ₆	86.6	77.8	55.3	73.2 (2.40)	274.8	256.7	230.1	253.9 (2.64)
I ₇	109.3	101.3	81.1	97.2 (2.23)	346.2	336.3	290.2	324.2 (2.60)
Mean	105.5	99.2	75.6		328.7	318.6	279.7	309.0
SE±	2.51	2.55	2.68		1.81	0.83	0.85	
LSD ($p = 0.05$)	N = 8.1 I = 6.5, I × N = 13.1				N = 5.5, I = 10.6, I × N = NS			

Numbers given in parentheses indicate standard error.

Table 13. N uptake by aboveground biomass and tubers (kg ha^{−1}) during 2019–2020.

Treatments	N Uptake by Biomass				Tuber N Uptake			
	N ₁	N ₂	N ₃	Mean	N ₁	N ₂	N ₃	Mean
I ₁	129.4	128.1	110.2	122.6 (1.29)	368.2	364.4	338.0	356.9 (1.51)
I ₂	127.4	125.6	109.1	120.7 (1.31)	367.4	360.6	329.8	352.6 (1.50)
I ₃	124.3	121.8	108.4	118.8 (1.34)	364.6	356.3	326.7	349.2 (1.52)
I ₄	107.7	102.3	85.1	98.4 (1.30)	349.1	344.4	302.5	332.0 (1.53)
I ₅	94.3	90.5	71.1	85.3 (1.28)	316.8	288.8	243.4	283.0 (1.50)
I ₆	86.1	76.5	65.2	75.9 (1.31)	274.2	263.1	236.7	258.0 (1.53)
I ₇	115.5	110.6	98.7	108.3 (1.32)	359.3	344.9	324.3	342.8 (1.52)
Mean	112.1	107.9	92.5		342.8	331.8	300.2	324.9
SE±	1.34	1.32	1.34		1.55	1.52	1.58	
LSD ($p = 0.05$)	N = 4.0, I = 4.1, I × N = 7.0				N = 4.7, I = 4.5, I × N = 7.2			

Numbers given in parentheses indicate standard error.

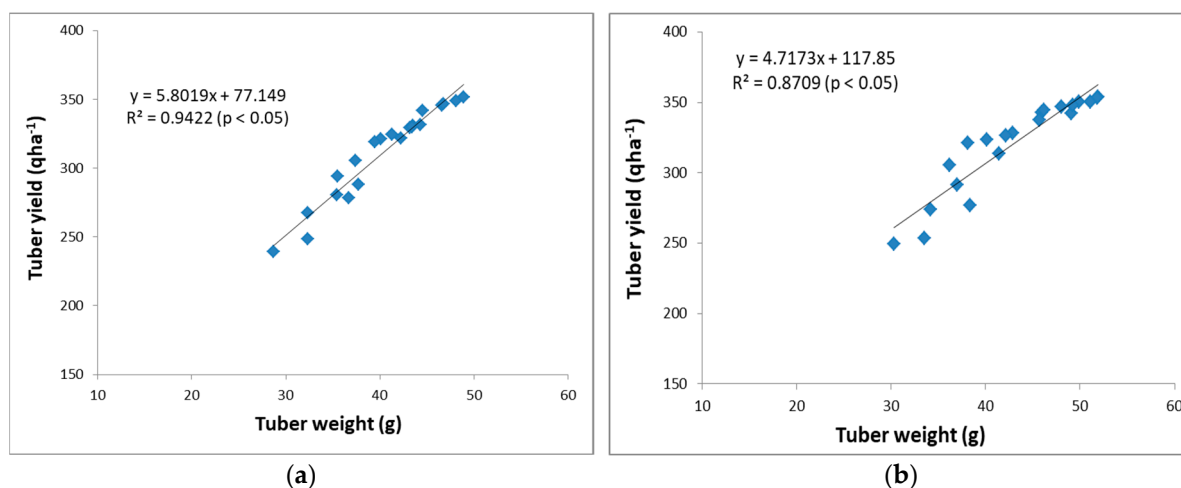


Figure 3. Relationship between tuber yield and tuber weight during (a) 2018–2019 and (b) 2019–2020.

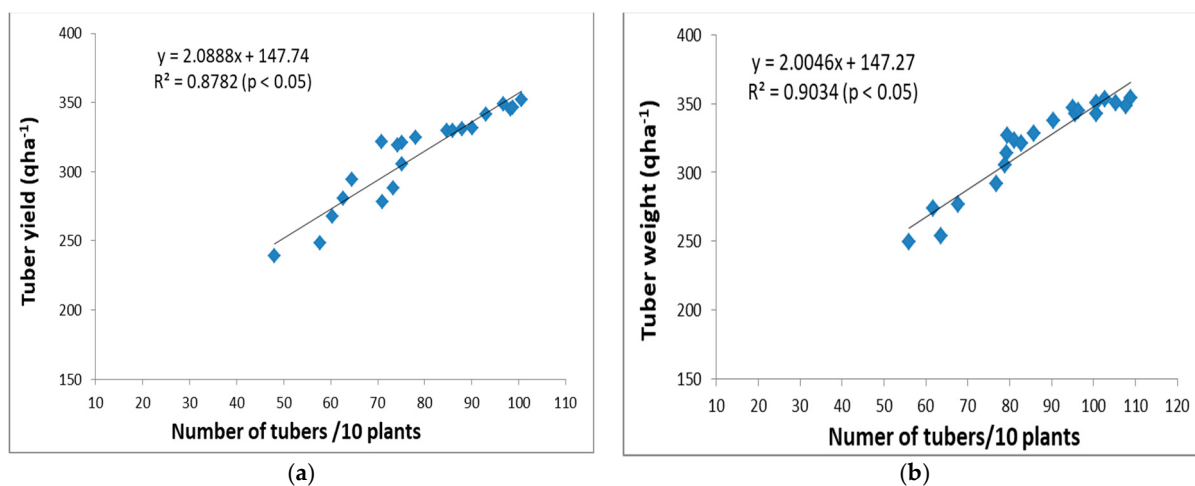


Figure 4. Relationship between tuber yield and number of tubers per 10 plants (a) 2018–2019 (b) 2019–2020.

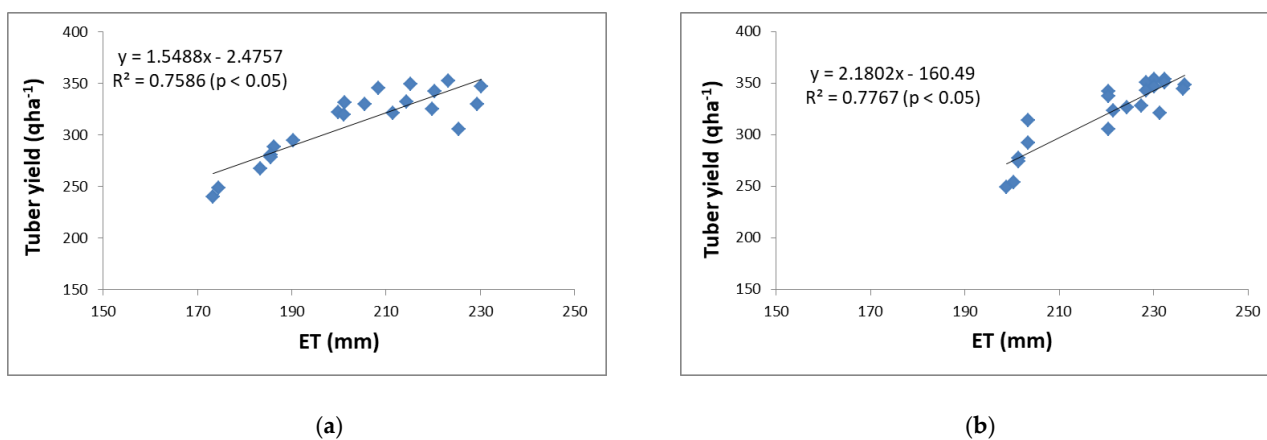


Figure 5. Relationship between tuber yield and ET (a) 2018–2019 (b) 2019–2020.

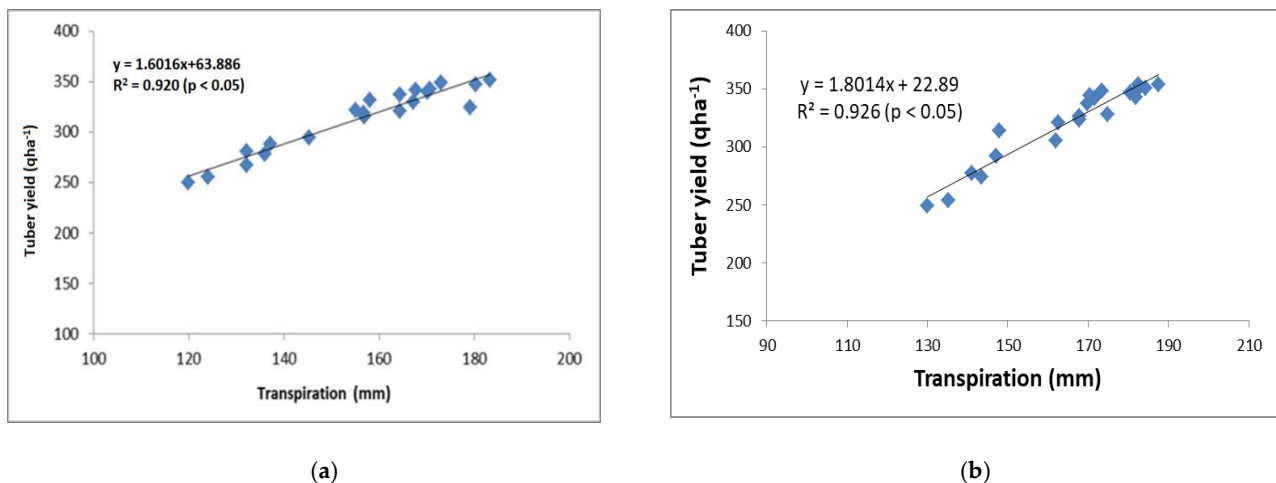


Figure 6. Relationship between tuber yield and transpiration (a) 2018–2019 (b) 2019–2020.

3.5. N Uptake by Aboveground Parts and Tubers

Nitrogen uptake at 90 DAP (days after planting) and tuber N uptake during both years are presented in Tables 12 and 13. During 2018–2019, N uptake aboveground was at par in N_1 and N_2 but significantly higher over N_3 . The difference between N_1 and N_3 was 39.5%. However, during 2019–2020, N uptake was significantly higher in N_1 than in N_2 and N_3 . This could be due to the difference in rain events in both years. Among irrigation levels, during both years, N uptake was at par among I_1 , I_2 and I_3 . The interaction between irrigation and nitrogen was also significant. The highest N uptake was observed in N_1I_1 , which was at par with N_1I_2 , N_1I_3 , N_1I_7 , N_2I_1 , N_2I_2 , N_2I_3 and N_2I_7 . N uptake by the tuber was also affected by nitrogen and irrigation during both years. During 2018–2019, the highest N uptake was observed in N_1 , significantly higher over N_2 and N_3 . It was higher by 4.2% and 30.4% over N_2 and N_3 , respectively. Similarly, during 2019–2020, N_1 recorded 3.8 and 14.2% higher N uptake over N_2 and N_3 , respectively. Among the irrigation levels, tuber N uptake was at par in I_1 , I_2 and I_3 but significantly higher than recommended practice and all other treatments. The highest tuber N uptake was observed during both years in N_1I_1 (358.8 and 368.2 kg ha⁻¹). It was at par with N_1I_2 , N_1I_3 , N_2I_1 and N_2I_2 . N uptake with an increase in N level from 160 to 340 kg N ha⁻¹ by aboveground biomass and tubers was also observed [20]. Singh et al. [45] on the same type of soil observed an increase in N uptake with increase in N rate from 135 kg ha⁻¹ to 225 kg ha⁻¹ and also reported an increase in mean N uptake by 13 and 24.9% in $I_{1.5}$ (1.5 ratios of irrigation to pan E) and $I_{2.0}$ (2.0 ratio of irrigation to pan E), respectively, over $I_{1.0}$ regime (1.0 ratio of irrigation to pan E). Similar effects of irrigation and N were observed on total N uptake in the sandy loam soil [47]. Higher N uptake by tubers in the highest level of nitrogen may have contributed towards the higher yield [48].

3.6. Real Water Productivity

Real water productivity (WP_{ET}) is the ratio of tuber yield and evapotranspiration. During both years (Table 14), the highest WP_{ET} (15.7 and 15.0 kg m⁻³) was obtained with N_1 and at par with N_2 (15.4 and 14.7 kg m⁻³) and significantly higher over N_3 (14.7 and 13.8 kg m⁻³). Higher water productivity by opting for drip irrigation and optimum nitrogen has also been found in potato and eggplant [20,48–50]. Among irrigation levels, the highest WP_{ET} was obtained with I_3 and I_4 (16.2 and 16.0 kg m⁻³, respectively), which was statistically higher than all the other treatments. During 2019–2020, WP_{ET} (15.3 kg m⁻³) was statistically higher in I_3 compared to all other treatments. The highest water productivity during the first year was obtained with N_1I_3 (16.6 kg m⁻³), followed by N_1I_4 and N_2I_3 (16.4 kg m⁻³). Similarly, in the second year, water productivity was highest

in N_1I_3 (15.8 kg m^{-3}), which was at par with N_2I_3 and N_1I_4 . Our findings agree with [20], who reported 16.7% higher water use by reducing 20% of applied water.

Table 14. Effect of irrigation and nitrogen on real water productivity (WP_{ET}) of potato (kg m^{-3}).

Treatments	2018–2019				2019–2020			
	N_1	N_2	N_3	Mean	N_1	N_2	N_3	Mean
I_1	15.8	15.7	14.8	15.4	15.2	15.1	14.4	14.9
I_2	16.2	16.0	15.2	15.8	15.4	15.1	14.5	15.0
I_3	16.6	16.4	15.9	16.2	15.8	15.5	14.8	15.3
I_4	16.4	16.1	15.4	16.0	15.5	15.3	13.9	14.9
I_5	15.5	15.0	14.6	15.0	15.4	14.3	12.6	14.1
I_6	15.1	14.6	14.4	14.7	13.8	13.6	12.5	13.3
I_7	14.7	14.4	14.0	14.4	14.6	14.6	13.7	14.3
Mean	15.7	15.4	14.9	115.4	15.1	14.8	13.8	14.5
LSD ($p = 0.05$)	$N = 0.43, I = 0.26, I \times N = 0.48$				$N = 0.42, I = 0.21, I \times N = 0.40$			

4. Conclusions

Under subsurface fertigation, lower nitrogen application (N_3) resulted in less LAI and DMA, which further reduced the transpiration and potato tuber yield compared to higher (N_1) and optimum nitrogen (N_2). The unproductive water losses of soil evaporation were much higher in surface than in subsurface drip irrigation. Tuber yield was statistically at par in combinations of N_1I_1 , N_1I_2 , N_1I_3 , N_1I_7 , N_2I_1 , N_2I_2 and N_2I_3 , which indicated that both 20% nitrogen and irrigation water could be saved with N_2I_3 compared to all other combinations. Therefore, subsurface drip irrigation with 80% of recommended nitrogen and irrigation can be a viable option for obtaining higher biomass, tuber yield and water productivity compared to surface drip irrigation with 100% recommended nitrogen and 80% irrigation water. Thus, statistically similar yield and higher real water productivity were obtained with the application of 20% less nitrogen with subsurface than surface fertigation.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy13010011/s1>, Figure S1: Layout of the field experiment.

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