



# Effect of Nitrogen Application and Fertigation Scheduling On Potato Yield Performance Under Drip Irrigation System

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## Abstract

The drip irrigation method offers the potential of higher application efficiency of water and allows precise placement of fertilizer directly in the root zone. The use of drip irrigation also facilitates the frequent application of fertilizer via injection in the irrigation system, which allows the conjunction between nutrient application and time of crop needs. The effect of nitrogen (N) rate and drip fertigation scheduling were evaluated on yield, N uptake, and recovery of potato grown on sandy soil. The N was applied at two rates under regular irrigation (control) or through drip irrigation along with four fertigation schedules including: equal doses applied at the weekly or biweekly intervals and different doses based on growth curve characters (12.5, 25, 50, and 12.5% of the total N amount) at the same intervals, for initial, developmental, mid, and mature stages, respectively. The N rate and wise fertigation scheduling significantly affected yield and yield components except for the tuber number per plant. The higher tuber yield was associated with a higher N rate when the respective nutrient was stage wise scheduled and typically responded to growth curve character than equal scheduling at any time intervals. The increase in yield was higher with wise weekly by 13 and 22% than with equal weekly or biweekly intervals, respectively. For this scenario, the modeled crop uptake at the weekly interval was 16% higher than equal applied at the same interval or even greater by 31% than equal applied at the biweekly interval. Similarly, the higher N rate and wise weekly scheduling increased N recovery and N use efficiency (NUE). Soil N movement with wise scheduling resulted in lesser leaching of  $\text{NO}_3^-$ -N to deeper soil layers, particularly with wise weekly scheduling. The framework presented in this study regarding the rate and N scheduling to copy with plant growth curve can sustain high crop yield while reducing  $\text{NO}_3^-$ -N leaching, increasing N uptake and recover.

**Keywords** Drip irrigation · Fertigation scheduling · Nitrogen incidence · Potato.

## Introduction

Optimizing resource use efficiency by better management of water and nutrients through fertilization strategies in crop production is now a concern in the world to enhance profit and minimize the cost of production. The constant trade

fluctuations and the historical increase in prices directly affect the production costs and increasing the efficiency in the use of fertilizers application via irrigation water becomes an important strategy. Traditional agricultural practices (flood/furrow irrigation and N broadcasting) are the most common practices used for growing potato in Egypt and the N requirement of potato is totally applied either pre-plant or in two split applications (prior to planting and before flowering). This traditional practice has led to low N and water use efficiency and to a low marketable yield of the crop (Hebbar et al. 2004; Badr et al. 2010).

Drip irrigation is an effective way to supply water to the roots of plants and save water while maintaining a high yield and excellent product quality. It can easily be used for fertigation through which fertilizer is placed in the active root zone and crop requirements can be met accurately (Badr et al. 2010; Li et al. 2018). Fertigation also reduces the nutrient loss that would normally occur with the con-

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ventional methods of fertilizer application and thus, permits better availability and uptake of nutrients by the crops, leading to higher yield with high fertilizer use efficiency (Hebbar et al. 2004; Fan et al. 2020). Fertigation also gives the flexibility of fertilizer application precisely according to the plants' requirements which, in turn, ensures the application of the proper amount of fertilizers at the particular growth stage (Zotarelli et al. 2009; Jha et al. 2015).

Drip fertigation scheduling for potato is critical because the potato root system is relatively shallow with most roots concentrated in the wetted soil volume near drippers or along each lateral line (Wang et al. 2006). The management of feed nutrients and their delivery to the crop has to be relatively flexible to meet its changing needs. It is best to start with moderate amounts of nutrients early in the season and increased concentrations as the plant grows (Hochmuth and Cordasco 2009) and to change according to the growth stages of the crop with a fertigation program being adjusted during the growing season to suit the plant development (Jha et al. 2015).

Potato (*Solanum tuberosum* L.) is one of the most important crops grown in Egypt for local consumption, export, and processing. In Egypt, potato cultivated area was 0.1510 million hectares with 5.2 million tons of production, resulting in 29.04 tons hectare of yield, making Egypt Africa's No. 1 potato producer (FAO 2021). The crop is very sensitive to mineral fertilizer management and fluctuations in nitrogen (N) supply can negatively affect the vegetative growth and ultimately the quantitative and qualitative yield of the tuber (Haider et al. 2012). The need for N in the potato crop is comparatively low within the first 4 to 5 weeks of growth (Zebarth and Rosen 2007) while the highest amount of N is needed during tuber bulking as approximately 58–70% of the total N is taken up during this development stage (Ojala et al. 1990). Not only is tuber size affected by N but also starch content, estimated by specific gravity, and sugar content are greatly affected (Bucher and Kossmann 2007).

Nitrogen fertilizers are commonly applied uniformly and such spatial variability in soil N availability is not taken into account. However, balanced application management and timely fertilizer scheduling are paramount and an imbalance in fertilizer application at the incorrect time is fatal not only to farmers but also to the quality and productivity of potato crops. There is a dire need to identify the balance fertilizer dose and the best suitable time. Therefore, the objective of the present study was to evaluate the effects of N fertilizer rate and drip fertigation scheduling on potato yield, N uptake, and N use efficiency to develop the best guidelines for N application management for potato grown on sandy soil.

## Material and Methods

### Location and Soil Properties

The experiment was conducted on a vegetable farm located at Wadi El-Tor, South Sinai province during the winter season (September–December) 2021 using a drip irrigation system. This area is an arable land in Sinai, and the agriculture there is based on growing vegetables on an intensive scale. The summer is hot, humid, arid, windy, and clear and the winters are cool, dry, and mostly clear. Over the course of the year, the temperature typically varies from 11 to 33 °C and is rarely below 8 °C or above 37 °C. The precipitation of the area does not experience significant seasonal variation in the frequency of wet days. The frequency ranges from 1 or 2 mm, throughout the year with a peak probability of 1–2 mm in January (CLAC 2021). The soil of the area was deep, well-drained sandy in texture which was classified as *Entisol-Typic Torripsamments*. The soil characteristics of the field site are presented in (Table 1).

### Experimental Design and Treatments

The experiment was conducted in a factorial randomized block design with three replicates per treatment that included two N rates applied at 240 and 360 kg ha<sup>-1</sup> defined as (N<sub>1</sub>) and (N<sub>2</sub>) and four drip fertigation schedules applied at equal doses in weekly (equal<sub>1w</sub>) or biweekly (equal<sub>2w</sub>) and in variable doses based on growth curve characters (stage wise scheduling) at the same intervals during the first 12 weeks of the growing season. This was done along with regular irrigation (control) with N fertilizer applied directly to the soil (Table 2). All treatments received the same amount of phosphorus 150 kg P ha<sup>-1</sup> and potassium 250 kg K ha<sup>-1</sup> for the whole season. The normal fertilizers used in the control treatment were ammonium sulphate,

**Table 1** Physical and chemical properties of the soil layer (0–40 cm) of the experimental site

Soil characteristic	Value
Sand (%)	87.5
Silt (%)	8.2
Clay (%)	4.3
pH (in water solution)	8.2
Total N mg kg soil <sup>-1</sup>	18.4
P <sub>2</sub> O <sub>5</sub> (mg kg <sup>-1</sup> )	7.2
K <sub>2</sub> O (mg kg <sup>-1</sup> )	28.3
CaCO <sub>3</sub> (%)	3.8
Organic matter (%)	0.48
Bulk density (g cm <sup>-3</sup> )	1.56
Field capacity at -0.03 MPa (g g <sup>-1</sup> dry weight)	0.11
Wilting point at -1.5 MPa (g g <sup>-1</sup> dry weight)	0.56

**Table 2** Treatment details: Factor A: (Nitrogen N<sub>1</sub> & N<sub>2</sub>) and Factor B: (Fertigation schedules)

Total N supply (kg h <sup>-1</sup> )	Fertigation schedules	N per growth stage (%)	Fertigation frequency (kg N h <sup>-1</sup> )	
			7 days	14 days
(N <sub>1</sub> ) 240	Control	a	–	–
	Equal	Frequently	20.0	40.0
	Wise	Initial (12.5)	7.5	15.0
		Developmental (25)	15.0	30.0
		Mid (50)	30.0	60.0
		Mature (12.5)	7.5	15.0
(N <sub>2</sub> ) 360	Control	a	a	–
	Equal	Frequently	30.0	60.0
	Wise	Initial (12.5)	11.5	23.0
		Developmental (25)	23.0	46.0
		Mid (50)	46.0	92.0
		Mature (12.5)	11.5	23.0

<sup>a</sup> Control with regular irrigation (½ at planting—½ one month later)

single super phosphate, and potassium sulphate, whereas, ammonium nitrates, phosphoric acid (85%), and potassium sulphate formed the source of water-soluble fertilizers in the fertigation treatments. Soil applied treatment received the entire P and K at planting in one dose and N in two splits at planting and 28 days after planting. The normal fertilizers were incorporated into the soil at a depth of 10cm, while water-soluble fertilizers were injected directly into the main tube of the irrigation system through an electrical pump device.

Before cultivation, a high-precision drip irrigation system (GR, 40cm dripper spacing delivering 2.5-litre h<sup>-1</sup> at operating pressure 100kPa) was deployed in the field at 1.0 meter apart to implement the irrigation treatment. Seeds of potato cultivar “Cara” were previously germinated for three weeks before planting in the field in early September. The plants were arranged in rows 25cm apart along drip lines (40,000 plants ha<sup>-1</sup>) in Plots (3.0m wide by 10.0m long).

### Growth Stages and Crop Water Requirement

Potato is about 130 days crop duration and can be divided into four growth stages, namely the initial, 25 days; developmental, 30 days; middle, 45 days; and tuber maturity, 30 days. The crop coefficient during the crop season was 0.50, 0.65, 1.15 and 0.75 for the same previous crop growth stages, respectively (Allen et al. 1998). Crop water requirements were estimated by multiplying reference evapotranspiration (ET) with crop coefficient (ETc=ET0×Kc) for different months based on crop growth stages of potato using the model suggested by Penman-Monteith’s formula (Allen et al. 1998). The total actual amount of irrigation water (ET) crop applied during the growing season was 360mm for all treatments. Irrigation was given to all treatments from local well water having EC (0.45dS/m) every three days, while regular irrigation was given every 6 days

accumulating with the previous 6 days of ET. The irrigation process was cut off 15 days before harvest to prevent secondary growth.

### Measurements of Crop Parameters

Leaf area index (LAI) was calculated for each treatment at 90 DAP following the standard formula (Gardner et al. 1985) as follows: leaf area (cm<sup>2</sup>)/ground area (cm<sup>2</sup>). Potato plants were harvested 145 days after planting and were further used to evaluate several growth parameters, as well as N leaf content. Plant growth components were determined from 10 randomly selected plants in each plot including total tuber yield, tuber number and average tuber weight per plant. Total fresh tuber yield was recorded on at least 20 plants in a row in each treatment replication and data were presented as ton per hectare. Seasonal crop N uptake was derived from the whole-plant sample data obtained 120 days after planting. Uptake of N was calculated as the product of the crop biomass (dry weight) and the N concentration in plant tissue from which the uptake per plant was derived based on plant population. Nitrogen use efficiency (NUE) was calculated using the following equation:

$$\text{NUE} = \frac{(Y_t - Y_0)}{N} \times 100$$

where Y<sub>t</sub> equals total yield under treatment, Y<sub>0</sub> equals total yield under unfertilized plot and N equals applied nitrogen. All equation variables are in units of kilogram per hectare. Post harvest N recovery was calculated using the following equation:

$$\text{N recovery (\%)} = \frac{(N_t - N_0)}{N_a} \times 100$$

where  $N_t$  equals the total crop N uptake (shoots + tubers) under treatment,  $N_0$  equals total N uptake under unfertilized plot and  $N$  equals applied nitrogen. The average crop N uptake from the unfertilized plots ( $N_0$ ) and total yield from the same plot ( $Y_0$ ) were  $8 \text{ kg N ha}^{-1}$  and  $0.75 \text{ t ha}^{-1}$ , respectively for the growing season.

### Plant and Soil Analysis

Total N content in the shoots and tuber was determined at Analytical Research Lab (National Research Centre, Giza, Egypt) using standard methods of analysis. Tissue samples were collected and oven-dried ( $65 \text{ }^\circ\text{C}$ ), ground to pass through a  $0.5 \text{ mm}$  sieve, and stored for dry weight analysis, with a thoroughly mixed  $5 \text{ g}$  portion of each sample stored. Tissue material was digested using  $\text{H}_2\text{SO}_4$  in the presence of  $\text{H}_2\text{O}_2$  and analyzed for total Kjeldahl N (Jones and Case 1991). Soil nitrogen status under different treatments was performed by sampling segments at  $0\text{--}20$  and  $20\text{--}40 \text{ cm}$  depth intervals in potato root zone directly under the water source using a tube auger from the experimental area. The concentration of soil nitrate was determined after one hour of the last fertigation event and just before the end of the irrigation cycle at about 90 DAPS of each treatment. Samples were air-dried ground and sieved through a  $2 \text{ mm}$  screen and analyzed for available  $\text{NO}_3\text{-N}$  using standard procedures described by (Jackson 1973).

### Statistical Analysis

Analysis of variance (ANOVA) was performed using the Costas program (Version 6.311 CoHort, USA 1998–2005) on the data of all yield and yield components (total dry biomass—tuber number—tuber weight) measured in the experiments. Means were compared by the least significant difference test (LSD) at  $P=0.05$ . Linear regression analysis was conducted to identify relationships between total tuber yield and the number of tubers per plant and average tuber weight per plant. The analysis was made with Excel and Sigma Plot 9.0 (Systat Software Inc. Point Richmond, CA USA).

**Table 3** Analysis of variance summary for tuber yield, total dry biomass, tuber number and tuber weight as affected by N rate and fertigation schedules

Source	Df	Tuber yield	Total dry biomass	Tuber number	Tuber weight
Replication	2	NS	NS	NS	NS
Nitrogen (N)	1	*	*	NS	*
Fertigation (F)	4	*	*	*	*
$N \times F$	4	*	*	*	*
Error	16	–	–	–	–
CV%	–	2.61	2.60	5.53	4.10

*df* degrees of freedom, *NS* not significant, *CV%* coefficient of variation

\* Significant at  $P \leq 0.05$

## Results

### Potato Yield and Yield Components

The analysis of variance showed significant N rate  $\times$  fertigation scheduling for almost yield components, therefore both factors were analyzed together (Table 3). Potato plants under the high N rate ( $N_2$ ) averaged significantly higher total tuber yield (23.43%) over the low N rate ( $N_1$ ) (Table 4). Overall, drip fertigation schedules increased yield by 25.32% and 36.47 with  $N_1$  and  $N_2$ , respectively compared to regular irrigation. The wise fertigation scheduling gave a significantly higher tuber yield over equal scheduling at both N rates. Moreover, the higher N rate coupled with wise weekly scheduling increased yield by 13 and 22% over equal weekly and biweekly scheduling, respectively. Similarly, the total dry biomass at final harvest was remarkable at the high N rate and with all drip fertigation schedules compared to regular irrigation. Further, the significantly higher total dry biomass was also observed with wise weekly fertigation over equal fertigation at any interval. Tuber number was not significantly affected by the increase in N rate or any other scheduling. The correlation analysis between tuber yield and tuber number per plant was weak ( $R^2=0.23$ ) (Fig. 1a), while the correlation between tuber yield and average tuber weight per plant is very strong ( $R^2=0.97$ ) (Fig. 1b).

Leaf area index (LAI) is the measure of source size when plants reached maximum growth rate at 90 DAP. Nitrogen fertilization significantly affected the development of LAI where a significantly higher value was recorded with an increasing N rate. Moreover, drip fertigation scheduling enhanced LAI over regular irrigation and the maximum value was recorded with weekly wise fertigation with remarkable shoot length over any other scheduling.

### Nitrogen Uptake, Recovery, and NUE

The higher N rate considerably increased total N uptake by an average of 43.30% over low N rate, thus mirroring the yield trend and total plant dry biomass (Table 5). Regular irrigation showed the lowest N uptake while drip

**Table 4** Yield and yield components of potato plants as affected by different nitrogen rate and fertigation schedules

Nitrogen	Control	Fertigation schedules				
		Equal <sub>1W</sub>	Equal <sub>2W</sub>	Wise <sub>1W</sub>	Wise <sub>2W</sub>	Mean
<i>Tuber yield (t ha<sup>-1</sup>)</i>						
N <sub>1</sub>	23.14 <sup>i</sup>	27.88 <sup>g</sup>	25.29 <sup>h</sup>	32.47 <sup>e</sup>	30.34 <sup>f</sup>	27.82 <sup>B</sup>
N <sub>2</sub>	28.56 <sup>g</sup>	37.84 <sup>c</sup>	35.15 <sup>d</sup>	42.76 <sup>a</sup>	40.13 <sup>b</sup>	36.89 <sup>A</sup>
Mean	25.85 <sup>E</sup>	32.86 <sup>C</sup>	30.22 <sup>D</sup>	37.62 <sup>A</sup>	35.23 <sup>B</sup>	–
<i>Total dry biomass (t ha<sup>-1</sup>)</i>						
N <sub>1</sub>	6.85 <sup>i</sup>	8.25 <sup>g</sup>	7.49 <sup>h</sup>	9.61 <sup>e</sup>	8.98 <sup>f</sup>	8.24 <sup>B</sup>
N <sub>2</sub>	8.45 <sup>g</sup>	11.20 <sup>c</sup>	10.40 <sup>d</sup>	12.66 <sup>a</sup>	11.88 <sup>b</sup>	10.92 <sup>A</sup>
Mean	7.65 <sup>E</sup>	9.73 <sup>C</sup>	8.94 <sup>D</sup>	11.13 <sup>A</sup>	10.43 <sup>B</sup>	–
<i>LAI (90 days)</i>						
N <sub>1</sub>	1.75	2.18	1.85	2.35	2.17	2.06
N <sub>2</sub>	2.13	3.24	3.19	3.72	3.39	3.13
Mean	1.94	2.71	2.52	3.04	2.78	–
<i>Tuber number (plant<sup>-1</sup>)</i>						
N <sub>1</sub>	7.24 <sup>a</sup>	7.54 <sup>a</sup>	7.58 <sup>a</sup>	7.98 <sup>a</sup>	7.90 <sup>a</sup>	7.24 <sup>A</sup>
N <sub>2</sub>	7.38 <sup>a</sup>	7.51 <sup>a</sup>	7.56 <sup>a</sup>	7.66 <sup>a</sup>	7.79 <sup>a</sup>	7.38 <sup>A</sup>
Mean	7.31 <sup>A</sup>	7.52 <sup>A</sup>	7.57 <sup>A</sup>	7.82 <sup>A</sup>	7.84 <sup>A</sup>	–
<i>Tuber weight (g plant<sup>-1</sup>)</i>						
N <sub>1</sub>	82 <sup>i</sup>	90 <sup>g</sup>	86 <sup>h</sup>	98 <sup>e</sup>	93 <sup>f</sup>	90 <sup>B</sup>
N <sub>2</sub>	88 <sup>g</sup>	112 <sup>c</sup>	108 <sup>d</sup>	128 <sup>a</sup>	119 <sup>b</sup>	111 <sup>A</sup>
Mean	85 <sup>D</sup>	101 <sup>C</sup>	97 <sup>C</sup>	113 <sup>A</sup>	106 <sup>B</sup>	–

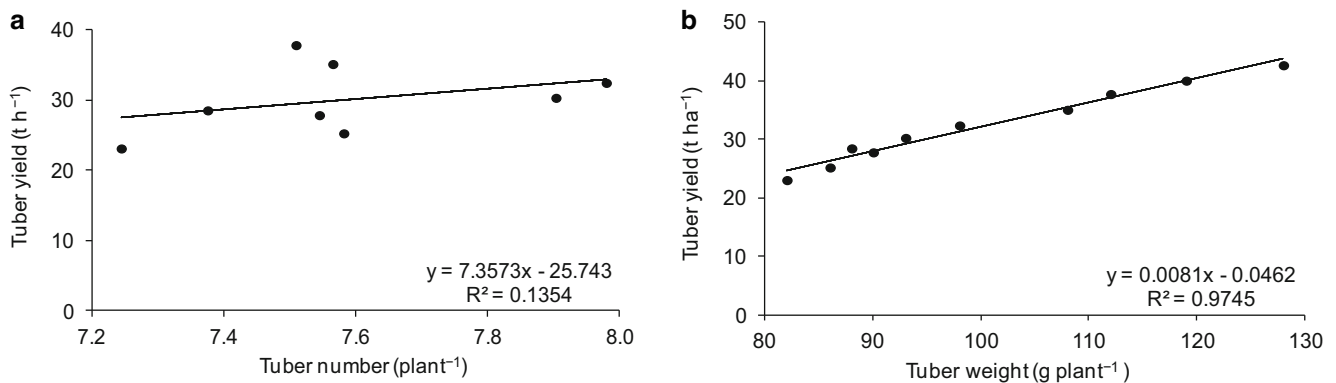
Values within the column followed by different letters are significantly different based on the least significant difference (LSD) at  $P \leq 0.05$ . Capital letters indicate significant differences among treatments and small letters indicate significant differences within treatments

fertigation schedules averaged higher increase of 33.92 and 36.30% over regular irrigation for N<sub>1</sub> and N<sub>2</sub>, respectively. As expected, N uptake was markedly higher under wise scheduling compared to equal schedule and registered 16 and 31% higher uptake with wise weekly over weekly and biweekly equal schedules, respectively. The yield of potato was highly correlated with total N uptake; the correlation coefficient was 0.98 and 0.96 for low and high N rates, respectively (Fig. 2). Similarly, N recovery was higher under all N fertigation schedules than with regular irrigation and increased with wise scheduling, particularly

at weekly interval; being 65 and 62% for N<sub>1</sub> and N<sub>2</sub>, respectively. Nitrogen use efficiency (NUE) was also higher in both N rates with all fertigation schedules; being the highest for the wise weekly scheduling and the reverse was true for the equal scheduling at any interval.

### Nitrogen Movement in Soil

Analysis of soil samples for both N rates with the different fertigation schedules indicated almost the same trend therefore we show only the results of the high N rate (Fig. 3).



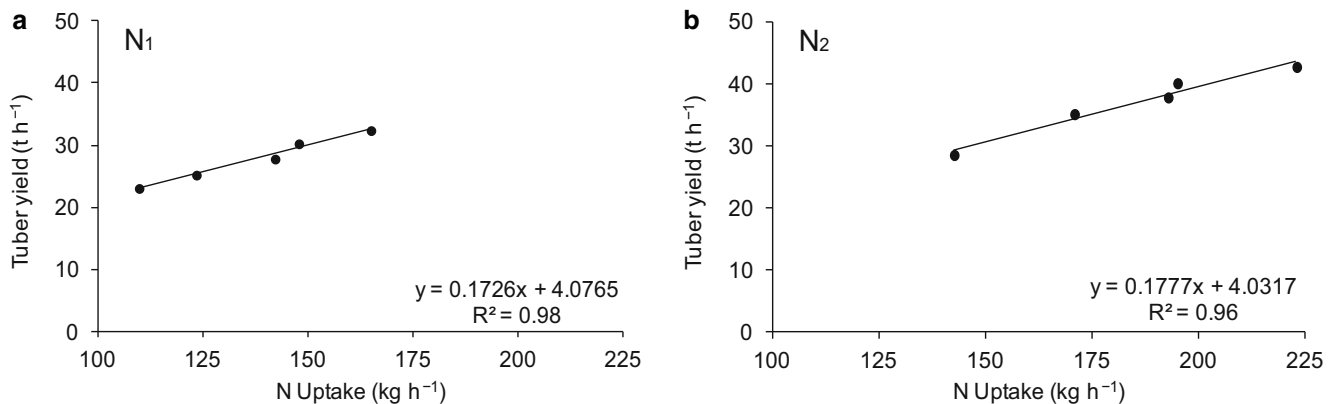
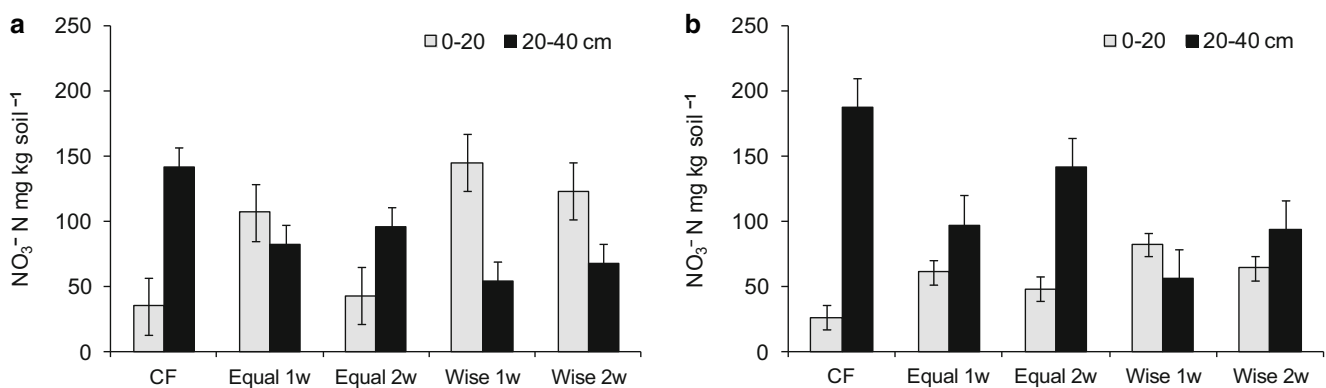
**Fig. 1** Relationship between total tuber yield and tuber number per plant (a), and total tuber yield and tuber weight per plant (b), of potato grown under different nitrogen rates and fertigation schedules

**Table 5** Nitrogen uptake, N recovery and NUE by potato plants as affected by different nitrogen rate and fertigation schedules

Nitrogen	Control	Fertigation schedules				Mean
		Equal <sub>1w</sub>	Equal <sub>2w</sub>	Wise <sub>1w</sub>	Wise <sub>2w</sub>	
<b>Total N uptake (kg h<sup>-1</sup>)</b>						
<i>N</i> <sub>1</sub>	101	133	114	155	139	128
<i>N</i> <sub>2</sub>	143	192	169	222	195	184
Mean	122	162	142	189	167	–
<b>N recovery (%)</b>						
<i>N</i> <sub>1</sub>	42	55	48	65	58	53
<i>N</i> <sub>2</sub>	40	53	47	62	54	51
Mean	41	54	47	63	56	–
<b>NUE (kg yield kg<sup>-1</sup>N)</b>						
<i>N</i> <sub>1</sub>	96	116	105	135	126	116
<i>N</i> <sub>2</sub>	79	105	98	119	111	102
Mean	88	111	102	127	119	–

Soil analysis also revealed that the concentrations of NH<sub>4</sub><sup>+</sup>-N were very low (less than 7 mg kg soil<sup>-1</sup>) and are not presented in details. The concentration of NO<sub>3</sub><sup>-</sup>-N at a depth of (0–20 cm) was appreciably lower with soil-applied treatment compared to other fertigation schedules at the end of the fertigation cycle where most of NO<sub>3</sub><sup>-</sup>-N moved to deeper soil layer. The movement of NO<sub>3</sub><sup>-</sup>-N under equal

doses schedules at the same soil depth showed a relatively leached zone either with one or two week intervals. Meanwhile, the concentration of NO<sub>3</sub><sup>-</sup>-N was considerably higher with both wise scheduling, particularly with wise weekly intervals. On the other hand, more NO<sub>3</sub><sup>-</sup>-N has been moved from the upper part of the soil profile to the deeper soil layer with regular irrigation at the end of the irrigation cy-

**Fig. 2** Relationship between potato tuber yield and total N uptake under low (a) and high N rate (b) for different fertigation schedules**Fig. 3** Concentration of nitrate in soil as affected by the higher nitrogen rate (*N*<sub>2</sub>) and different fertigation schedules at the end of fertigation cycle (a) and end of irrigation cycle (b)



cle as a result of successive irrigation indicating to a potential leaching risk. The same trend to regular irrigation was also observed in the upper part of the root zone with both equal schedules while the maximum value was observed with wise weekly scheduling which could maintain an appreciable amount of  $\text{NO}_3^-$ -N for plant uptake.

## Discussion

### Yield Response

Nitrogen application as a main factor of plant growth increased yield of potato and significant differences were found among the schedules of fertigation (Table 4). At the higher N rate, the yield was significantly higher under regular irrigation compared to the corresponding treatment with low N rate. This increase was appreciably expanded when N was applied through drip fertigation. Within N rates, the use of stage wise fertigation scheduling was pronounced particularly under 1 week interval compared to any other schedules. However, practices farming by applying water by flood or furrow systems and broadcast of N fertilizer on the soil surface resulted in large evaporation losses and large nutrient losses through seepage or percolation, therefore leading to lower yield productivity (Hebbar et al. 2004; Liu and Diamond 2005). As critical as fertilizers and irrigation management, both the timing and amounts applied to the crop must be managed to fulfill crop demands. However, drip fertigation in which water-solute fertilizers delivers directly in the root zone can facilitate water uptake and reduce the water loss in the conveyance and distribution system (Liao et al. 2019). These advantages of fertigation were more obvious with wise fertigation scheduling, particularly with weekly intervals, which markedly enhanced crop yield. This might be due to the frequent supply of N through drip irrigation at the proper time, which helps in meeting the nutritional requirement of the crop and leading to maximum uptake of the nutrients. The same positive effects of wise fertigation scheduling upon yield are widely reported in the literature (Arafa et al. 2009; Kuscu et al. 2014; Vasanthi et al. 2017).

Nitrogen management for the improvement of N efficiency is a high priority in potato cropping systems; typically, N is the most limiting nutrient in crop production and is higher in concentration than all other mineral nutrients in most plants (Nurmanov et al. 2019; Li et al. 2021). Optimal N nutrition contributes to the rapid formation of vegetative parts, and intensive photosynthesis, and allows utilizing soil moisture reserves more meaningfully during crop formation (Kumar et al. 2007; Tang et al. 2021). Several N fertilization rates have been advised as optimal for potato production. However, low N supply will not only

result in lower yield but will also reduce tuber size due to reduced leaf area and early defoliation (Goffart et al. 2008). Further, higher N rates are associated with more foliage and consequently promote photosynthetic action, and hence more translocation to tubers (Kumar et al. 2007). Applying the right source of N fertilizer at the right rate, time, and place can also maintain favorable moisture conditions in the root zone, facilitate the movement of nutrients to roots through mass flow or diffusion, and enhance nutrient uptake and availability to plants by synchronizing the water and fertilizer supply (Silber et al. 2003; Badr and Abou El-Yazied 2007). Total dry biomass at the final harvest was higher with all fertigation schedules than in regular irrigation and showed a similar trend to tuber yield. Given that vegetative growth is a part of the total biological yield of the crop and hence it has an important role in developing crop yields. Further, the difference in the dry matter production due to different treatments can be ascribed to the leaf area production.

Significantly higher leaf area index (LAI) was recorded with increasing N rate coupled with wise scheduling, indicated higher vegetative growth. Nitrogen has been shown to influence directly the LAI of potato, a functional trait that has already been used in crop management (Lemaire et al. 2007). This increase could have resulted in increased photosynthetic capacity and supply of assimilates necessary for high growth and development (Gathungu et al. 2016; Villa et al. 2017). The importance of canopy structure in light interception, crop growth, and yield has been pointed out in many studies. Kara and Mujdeci (2010) reported that LAI is a key structural characteristic of plants due to the role green leaves play in controlling many biological and physical processes in the plant canopy. Elsewhere, N has also been reported to increase the total chlorophyll content, meristematic cells, and growth, leading to the formation of branches in addition to leaf expansion (Tabassum et al. 2013).

Tuber number was not significantly affected by the increase in N rate or any fertigation scheduling. However, the correlation analysis between tuber yield and tuber number per plant was weak, indicating that tuber number was not or little responsible for increasing yield production (Fig. 1a). However, the increase in tuber yield was accompanied by an increase in average tuber weight per plant and the trend was similar to the tuber yield (higher tuber size is a desirable quality factor for many potato markets). The correlation between tuber yield and average tuber weight per plant is very strong (Fig. 1b), which indicates that tubers' weight is the main reason behind the increase in yield (Alva et al. 2012; Badr et al. 2012). Moreover, significantly higher elite tubers were found in  $\text{N}_2$  treatment with wise fertigation scheduling, indicating the beneficial use of accessible nitrogen if timed to the plant's needs.

## Nitrogen Uptake, Recovery, and NUE

Total aboveground N uptake was appreciably higher with the higher N rate than with a low N rate under all fertigation scheduling resulting from higher total dry biomass (Table 5). As expected, regular irrigation showed the lowest N uptake, while drip fertigation scheduling recorded the higher N uptake at any schedule. On the other hand, total N uptake appreciably varied under different fertigation schedules and was highly dependent on the rate and intervals of application. Nitrogen uptake was greatly enhanced by wise weekly scheduling compared to other schedules. This increase in N uptake was attributed to maintaining adequate soil solution N through stage wise scheduling which could have facilitated more N uptake. Similar results of optimizing N level with high fertigation frequency have been reported by (Badr et al. 2010; Farneselli et al. 2015). Support these results the differences in tuber yield between wise and equal scheduling for higher total N uptake which is in favor of the weekly interval. Such output points out that potato are highly in demand for N nutrition for growth and biomass development (Davenport et al. 2005). Similarly, N recovery was higher under all N fertigation schedules than with regular irrigation and increased with wise scheduling, particularly at weekly intervals (Li et al. 2021).

Nitrogen use efficiency (NUE) was obviously affected by the N rate, the most efficient treatments being those which received less amount of N indicating that NUE was inversely proportional to the amount of N applied. A similar trend was observed by Zotarelli et al. (2008) and Cabello et al. (2009), who found that plants grown under limiting N supply extracted more N from the soil in order to sustain crop N demand. The decrease of NUE with increased rates of N application has been also reported in other studies (Darwish et al. 2003; Anas et al. 2020). The decrease in NUE as the N rate increases could be attributed to the frequent addition of high concentrations of N that exceeded crop needs, thus saturation of reaction sites in the soil occurred, leading to further movement of N away from the root zone (Badr et al. 2012; Hirel et al. 2011).

However, the wise weekly and biweekly schedules registered the highest NUE indicating that drip irrigation can give full play to its advantages and effects under proper time and rate of N application as also reported by Li et al. (2021).

## The Status of Nitrogen in the Soil

Fertigation maintained a higher concentration of  $\text{NO}_3^-$ -N around the active part of the roots zone compared to entirely soil-applied treatment in regular irrigation (Fig. 3). Similarly,  $\text{NO}_3^-$ -N movement for the equal doses scheduling showed a leached zone in the upper part of soil profile

and more nitrate leaching occurred with a longer interval compared to the other lower interval durations. Given that water mass flow is the major factor responsible for N movement in the soil and it can diffuse fast enough with adjacent moving water to deeper soil layers (Singh et al. 2002; Zhang et al. 2013). Further, in sandy soil with low CEC nitrogen ions move along with water and thus it will be better to apply N fertilizers through drip irrigation in more doses to achieve maximum nutrient use efficiency (Hanson et al. 2006; Rivera et al. 2006). Therefore, the accumulation of available N tended to be higher with more frequent fertigation as reported by many authors (Li et al. 2004; Badr et al. 2011). In this context, our results showed that the concentration of soil  $\text{NO}_3^-$ -N in the root zone was considerably higher with stage wise fertigation schedules. This proves that timing and dose of N application is a critical option for higher yield where giving excess fertilizer, which is not in the need of plants or when plants are not ready to absorb will be washed away or evaporated from the soil surface (Qin et al. 2016; Li et al. 2021). Despite the high mobility of N, the observed increase in plant N uptake was expected under wise scheduling as related to more favorable growth conditions due to lower losses of N fertilizer from the soil which could preserve and maintain N fertilizer in the root zone (Zebarth and Rosen 2007; Cambouris et al. 2008). Moreover, wise fertigation scheduling helped in alleviating the problem of N leaching even at the end of the irrigation cycle which in turn influenced the yield and quality of potato.

## Conclusion

Considering the necessity of supplying the plant's N requirement to maintain its yield as well as reducing nitrate leaching due to inappropriate use of N fertilizers, fertigation design and management parameters need to be optimized for different soil types and crops. Therefore, the optimum fertigation scheduling presented in this study in sandy soil texture can be important and applicable. Stage wise fertigation scheduling based on growth curve characters, promoted potato yield and associated parameters compared to soil-applied treatment with regular irrigation or with equal N applications. Further, stage wise scheduling of N could maintained higher concentrations of N in the root zone and also increased N uptake, recovery and NUE. The positive effect of this scenario is the optimizing of the amount and frequency of water and fertilizer with required application rates during specific growth stages in coordination with crop demand for more precise water and nutrient management. However, as leaching is possible in sandy soil even with drip irrigation, it is extremely important that the nutrients



applied in any irrigation are not subject to leaching either during that irrigation or during subsequent irrigations.

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**Conflict of interest** M.A. Badr, E. Ali and S.R. Salman declare that they have no competing interests.

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