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Effects of nitrogen fertilization and micro-sprinkler irrigation on soil water and nitrogen contents, their productivities, bulb yield and economics of winter onion production

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Crops and Soils Research Paper

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Abstract

Onion is sensitive to soil water stress and nitrogen limitations, causing a marked reduction in yield and bulb quality. A field trial was set in the winter seasons of 2016–17 and 2017–18 to evaluate the effects of three micro-sprinkler irrigation levels at 0.6, 0.9 and 1.2 ratios of crop evapotranspiration (ETc) and four nitrogen levels at 0, 75, 100 and 120% of the recommended nitrogen dose (RDN), including surface irrigation at 40 mm cumulative pan evaporation (CPE) with 100% RDN (SN) using an augmented strip plot design on water and N distribution in soil, their productivities, onion yield and economics. Results indicated that the root zone water content increased by 5.2% for 1.2 ETc, and 1.4% for 0.9 ETc over the cropping period, but declined by 1.5% for 0.6 ETc with micro-sprinkler irrigation compared to surface irrigation with nitrogen fertilization (SN). The largest total root zone water depletion was in 1.2 ETc (16.7%), followed by SN (15.3%) and 0.9 ETc (15.0%). The high irrigation regime produced the maximum yield and nitrogen productivity, whereas deficit irrigation displayed the greatest water productivity. However, the coupling of micro-sprinkler irrigation at 1.2 ETc and 120% RDN led to an increase of onion bulb yield (22.6%), water productivity (42.7%), plant N uptake (29.0%) and net income (30.6%) with maximum benefit-cost ratio (3.19) compared to SN. However, as this study was only based on two seasons, more field trials will be needed to confirm the optimum amount of water and nitrogen for winter onion.

Introduction

The onion (*Allium cepa* L.) is a versatile bulbous vegetable and spice crop, grown widely in the temperate and tropical climates of the world (Job *et al*., 2016; Geries *et al*., 2021). In the global vegetable production scenario, it ranks second after potatoes. The plant is a member of the genus *Allium* in the Alliaceae family (Worku *et al*., 2020). It contains phenolic and flavonoid compounds that have potential anti-inflammatory, anti-cancer, anti-cholesterol and antioxidant values. Onion bulbs are rich sources of vitamins like A, B1, B2 and C, carbohydrates, proteins, minerals (K, Ca and Se), essential oils and pungent-smelling sulphur compounds (Salari *et al*., 2020). It is consumed mainly as fresh salads; however, the powdered, and dehydrated forms are also used in cooking and various cuisines to add flavour and texture (Pooja Rani *et al*., 2018). Onion is grown worldwide in an area of 3.97 Mha with an annual production of about 97.7 Mt (Geries *et al*., 2021). India is the second largest onion producer after China among the global onion growing countries. In India, onion is cultivated in about 1.17 Mha, with a production of 18.94 Mt and a productivity of 16.13 t/ha (Tripathi *et al*., 2017). The main reasons for low onion productivity in India compared to the Republic of Korea, China, the USA and Turkey are inadequate nutrition, non-availability or mismanagement of irrigation water, a lack of improved varieties and poor crop management (Kumar *et al*., 2007a, 2007b; Saxena *et al*., 2008; Bijay, 2010; Bagali *et al*., 2012).

Onion is a shallow-rooted plant with most fibrous roots concentrated in the top 30 cm of soil depth, whereby it extracts fairly large amounts of water and nutrients (Patel and Rajput, 2009). It is susceptible to water stress and nitrogen inadequacy throughout the growth period. The traditional surface method of irrigation causes excessive losses of water through deep percolation, runoff, evaporation and conveyance, including considerable nutrient leaching. The problems of conventional irrigation methods can be eliminated using the micro-sprinkler irrigation technology that can apply water according to the crop demand to ensure the efficient use of irrigation water, increase water and crop productivity with substantial water-savings (Shock *et al*., 2007; Kumar *et al*., 2007b; Pereira da Silva *et al*., 2013; Mane *et al*., 2014; Pawar *et al*., 2020; Piri and Naserin, 2020). In limited-water conditions, a precise deficit irrigation management strategy with proper irrigation scheduling can maintain a favourable soil moisture regime in the root zone, alleviate plant water stress and enhance water use efficiency with minimal yield decline (Pejic *et al.*, 2011; Pal *et al.*, 2021; Tolossa, 2021). Likewise, nitrogen is considered the key essential nutrient, which is actively involved in the production process through several physiological and biochemical reactions of plant metabolism (Nawaz *et al.*, 2017). As onion is a nutrient-exhaustive plant, adequate nitrogen supplementation can improve growth, yield and bulb quality (Moursy *et al.*, 2007; Nemat *et al.*, 2011; Dhital *et al.*, 2015; Geries *et al.*, 2021). It responds positively to incremental water and nitrogen application until the optimum yield level has been reached, which supports the necessity of planned irrigation and nitrogen management for achieving higher production (Abdissa *et al.*, 2011; Okumura *et al.*, 2011; Fatideh and Asil, 2012; Tsegaye *et al.*, 2016; Pawar *et al.*, 2020).

The onion is an emergent dietary cash crop grown extensively during the winter season in the Gangetic alluvial regions of India. Conventional irrigation and inadequate nitrogen fertilization, usually followed by farmers, results in declined yield, poor bulb quality and low input use efficiencies due to non-uniform water and nitrogen distribution around the root zone and the plant's exposure to varying water stress all along the growing period. No sufficient database information is available for water and nitrogen distribution patterns under micro-sprinkler irrigation and nitrogen fertilization in onion plants. A comprehensive understanding of the mechanism of spatiotemporal distribution of soil water and nitrogen and their movement in the onion root zone is essential for micro-sprinkler-based irrigation and nitrogen management strategies in the Indian subcontinent. The present investigation aimed to evaluate the water and nitrogen distribution at different growth stages of onion plants under different irrigation regimes through micro-sprinkler and nitrogen fertilization rates along with the bulb yield, water and N productivity. We hypothesized that micro-sprinkler irrigation with adequate watering and nitrogen fertilization could enhance soil water storage and N availability with greater water and N use efficiency for higher onion production and financial gains.

Materials and methods

Experimental site characteristics

Field trials were carried out on onion during the 2016–17 and 2017–18 winter seasons at the Central Research Farm of Bidhan Chandra Krishi Viswavidyalaya, Gayeshpur, West Bengal, India, located between the latitude of 22°58′31″ N and longitude of 88°26′20″ E at an average elevation of 9.75 m above mean sea level. The climate of this region is humid sub-tropical, with hot dry summers and cold winters. The mean annual rainfall is 1490 mm, of which 75% occurs during the monsoon season (June–September). Sporadic rainfall also happens during April–May and November–February. The amount of rainfall during the cropping periods of 2016–17 and 2017–18 was recorded at 25.5 and 16.9 mm, respectively. The atmospheric mean monthly temperature ranged from 25.4–37.6°C during the summer to 10.5–23.7°C during the winter. The average relative humidity for the season varied from 70 to 95%. The velocity of the wind was 0.20–3.69 km/h. Pan evaporation rate ranged from 0.9–1.4 mm/d for December–January to 4.2–4.6 mm/d for April–May. The depth of the water table remained 6.2–7.6 m below the ground surface. The soil at the experimental site had a sandy loam texture. Depth wise important physical and chemical soil properties are presented in Table 1.

Experimental design and treatments

The field trial was set in an augmented strip plot design with three replications per treatment. There were 13 treatments comprising three levels of crop evapotranspiration-based irrigation with micro-sprinkler at 0.6 ETc (M_1), 0.9 ETc (M_2) and 1.2 ETc (M_3) as main factors and four levels of recommended dose of nitrogen at 0% (N_0), 75% RDN (N_1), 100% RDN (N_2) and 120% RDN (N_3) as sub-factors, including a control treatment (SN) having conventional surface irrigation at 40 mm CPE with 100% RDN.

Crop management practices

The experimental field was subdivided into 39 subplots, each measuring a size of 3 m × 3 m. A 1.5 m wide buffer strip was provided in between and across the subplots to eliminate seepage movement and micro-sprinkling effects from the neighbouring plots. In between two replications, a 1.0 m wide irrigation cum drainage channel was made, and irrigation water was carried through this channel. Forty-five-days old healthy seedlings of onion (*A. cepa* L.) cv. Suksagar were transplanted at 20 cm × 15 cm spacing on 10th of December 2016 and 18th of December 2017, accommodating 300 plants in each subplot. During bed preparation, farmyard manure at 15 t/ha was incorporated and properly mixed with the soil. The recommended dose of fertilizer, i.e., N: P_2O_5: K_2O at 80: 40: 60 kg/ha in the region was applied during both seasons. In this study, the flexible dose of N was imposed at 0, 75, 100 and 120% of RDN, while the P and K doses remained the same. Full P and K doses were applied as basal to all plots during transplanting. N was top-dressed in three splits, one-half at transplanting and one-fourth each at 30 and 60 days after transplanting (DAT). Standard cultural operations, plant protection measures and agronomic management practices were equally performed in all plots. The entire plant was harvested at maturity, on 8th of April 2017 and 2nd of April 2018.

Irrigation scheduling

Micro-sprinkler irrigation was scheduled at 0.6, 0.9 and 1.2 ratios of ETc at 3-day intervals on onion in each experimental year. The amounts of water using micro-sprinkler irrigation were measured by the following formula (Zheng *et al.*, 2013):

$$I = \text{ETc} - \text{Re} = \text{Ep} \times \text{Kp} \times \text{Kc} - \text{Re} \ (\text{when ETc} < \text{Re}, \ I = 0) \quad (1)$$

where I is the irrigation amount (mm), ETc represents crop evapotranspiration (mm), Ep indicates 3-day cumulative pan evaporation (mm) recorded from a USDA class A pan evaporimeter, Kp is the pan coefficient, Kc denotes the crop coefficient, and Re specifies effective rainfall (mm). Kp was assumed to be 0.75 after considering relative humidity and rainfall (Doorenbos and Kassam, 1979). Kc values chosen for onion during the irrigation period were 0.52, 0.85, 1.04 and 0.87 at the seedling, bulb initiation, bulb development, and maturity stages, respectively (Bandyopadhyay *et al.*, 2003). Each micro-sprinkler had a designed discharge rate of 39 l/h at a pressure of 1.5 kg/cm^2 and

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Table 1. Physical, hydro-physical and chemical properties of the experimental soil

Soil depth (cm)	(%) Sand	Silt	Clay	Textural class	BD (Mg/m^3)	SHC (mm/h)	FC (%, g/g)	PWP (%, g/g)	AW (%, g/g)	pH (1:2)	EC (dS/m)	SOC (g/kg)	Ava. N (kg/ha)	Ava. P (kg/ha)	Ava. K (kg/ha)
0–15	70.2	15.7	14.1	Sandy loam	1.49	23.0	36.0	10.8	25.2	6.90	0.10	4.6	196.6	31.8	135.6
15–30	72.4	16.2	11.4	Sandy loam	1.53	18.2	32.3	9.5	22.8	6.82	0.08	4.0	171.4	29.4	137.0
30–45	79.9	12.2	7.9	Sandy loam	1.56	15.4	30.1	8.3	21.8	6.91	0.09	3.6	168.2	25.6	130.2
45–60	74.5	14.1	11.4	Sandy loam	1.51	21.3	19.8	8.7	11.1	6.80	0.07	3.1	161.8	23.2	126.2

BD, bulk density; SHC, saturated hydraulic conductivity; FC, field capacity; PWP, permanent wilting point; AW, available water; EC, electrical conductivity; SOC, soil organic carbon; Ava. N, available nitrogen; Ava. P, available phosphorus; Ava. K, available potassium.

a wetted diameter of 3 m. The full irrigation amount applied through micro-sprinkler-based 100% ETc for onion was estimated by the following relationship:

$$V = \frac{A \times (ETc - Re)}{1000 \times Em} \qquad (2)$$

where V is irrigation volume (L), A is subplot area (m^2), ETc is crop evapotranspiration (mm), Re is effective rainfall (mm), and Em is irrigation efficiency of micro-sprinkler (85%). All plots were given a common irrigation of 40 mm depth one day before transplanting to overcome seedling injury, better seedling establishment, and to maintain uniform soil moisture. Groundwater was used as a source of irrigation, which was started at 7 DAT and suspended 10 days before harvesting in all treatments. The volumes of water applied for various irrigation treatments are shown in Table 2.

Determination of actual evapotranspiration

Seasonal water consumption or actual evapotranspiration (ETa) for onion plants during the entire growing period was determined by the field water balance equation (Simsek *et al*., 2005):

$$\text{ETa} = I + P + G - R - D \pm \Delta\text{SWS} \qquad (3)$$

where I is irrigation (mm), P is rainfall (mm), G is upward flux from groundwater (mm), R is surface runoff (mm), D is drainage below root zone (mm), and ±ΔSWS is soil water storage depletion from root zone profile (mm). The rainfall amount retained in the rooting depth and used for estimating plant evapotranspiration needs was taken as effective rainfall (Re). In this study, G, R and D were not considered for ETa calculation. Thus, the above Eqn. (3) became:

$$\text{ETa} = I + \text{Re} \pm \Delta\text{SWS} \qquad (4)$$

Water productivity

Water productivity for each treatment was calculated as the ratio of total bulb yield to seasonal ETa by the equation (Lipovac *et al*., 2022):

$$\text{WP} = \frac{Y}{\text{ETa}} \qquad (5)$$

where WP = water productivity (kg/m^3), Y = bulb yield (kg/ha) and ETa = seasonal actual evapotranspiration (m^3/ha).

Nitrogen productivity

Nitrogen productivity was determined by the equation (Haile *et al*., 2012):

$$\text{Nitrogen productivity} = \frac{\text{Bulb yield}}{\text{Fertilizer N applied}} \qquad (6)$$

Soil water studies

The periodic soil water contents at a depth of 0–0.15, 0.15–0.30, 0.30–0.45 and 0.45–0.60 m for each irrigation treatment, just before and 24 h after irrigation or rainfall, during planting and harvesting, and at 20-day intervals in each experimental year (December–March), were monitored using a soil profile probe

Table 2. Effect of different levels of micro-sprinkler irrigation and nitrogen fertilization on bulb yield, water productivity and nitrogen productivity in onion (2-year pooled data)

Treatment	Bulb yield (t/ha)	Water productivity (kg/m^3)	Nitrogen productivity (kg bulb/kg N)	Amount of water applied (m^3)
M_1N_0	5.7	3.4	–	10.0
M_1N_1	6.4	3.7	106	10.0
M_1N_2	7.0	4.1	88	10.0
M_1N_3	7.7	4.5	80	10.0
M_2N_0	6.7	3.1	–	15.1
M_2N_1	8.0	3.7	134	15.1
M_2N_2	9.5	4.3	118	15.1
M_2N_3	10.5	4.8	109	15.1
M_3N_0	7.4	2.8	–	20.1
M_3N_1	9.0	3.4	151	20.1
M_3N_2	10.4	3.9	130	20.1
M_3N_3	11.3	4.2	117	20.1
SEM	0.07	0.04	0.98	
CD (0.05)	0.19	0.13	3.21	
Overall mean MN	8.3	3.8	115	
SN (control)	9.2	3.0	115	24.0
S.E.M.	0.41	0.07	1.19	
CD (0.05)	NS	0.19	2.41	

M_1, micro-sprinkler irrigation at 0.6 ETc, M_2, micro-sprinkler irrigation at 0.9 ETc, M_3, micro-sprinkler irrigation at 1.2 ETc; SN, surface irrigation with 100% RDN; N_0, no-N; N_1, 75% RDN; N_2, 100% RDN; N_3, 120% RDN; RDN, recommended dose of nitrogen; NS, not significant; S.E.M., standard error of mean; CD, critical difference.

device. In the micro-sprinkler system, soil water contents were measured at 100 cm away from the micro-sprinkler head along the lateral. Onion was reported to spread about 85–90% of its fibrous roots at 0.30 m, 8–9% at 0.45 m, and 1–2% at 0.60 m depth of the soil profile (Patel and Rajput, 2009). As most of the plant water requirement is extracted from a depth of 0.30 m and very little water is extracted beyond 0.60 m depth, the effective root zone depth of onion in this study was considered to be 0.30 m. The water percentage for each soil depth was converted into depth (cm) by multiplying the soil bulk density and thickness of the soil horizon to measure the soil water content in root zone depth. It was also expressed on volume basis in m^3/m^3.

Measurement of soil available nitrogen

For determination of available N contents in the soil for different N-fertilized and unfertilized plots under micro-sprinkler and surface irrigation, representative composite soil samples from different depths (0–0.15, 0.15–0.30 and 0.30–0.45 m) of the middle rows of each subplot were collected at vegetative (10–30 DAT), bulb development (60–90 DAT) and maturity (90–110 DAT) stages of onion plants in both cropping seasons. A soil auger was used for gathering soil samples, which were processed and analysed for available N content by the standard method.

Determination of plant nitrogen uptake

Five plants (including aerial and underground parts) were randomly collected from the middle rows of each subplot at vegetative (10–30 DAT), bulb development (60–90 DAT) and maturity (90–110 DAT) stages of the onion plants. These samples were washed first with tap water, followed by dilute hydrochloric acid and double distilled water. The washed plant samples at each sampling date were separated into leaves (above-ground parts) and bulbs with roots (underground parts). The leaves and bulbs were separately chopped into several small pieces, oven-dried at 65°C for 24 h and the dry matter yield of the tops and bulbs recorded. The dried samples were grounded into a fine powder, sieved through a 1-mm mesh and homogenized. The weighed samples were digested in tri-acid mixtures of 10:4:1 (v/v) of HNO_3:$HClO_4$:H_2SO_4 and the N in the extract was analysed by the titration method (Jackson, 1973). N uptake by the tops and bulbs was calculated by multiplying the N concentration with the corresponding dry weight of the tops and bulbs of the plants.

Initial soil analysis

The representative initial soil samples were processed and analysed for textural composition (Bouyoucos, 1962), bulk density (Bodman, 1942), field capacity and permanent wilting point (Richards, 1954) and hydraulic conductivity (Bouma, 1981) (Table 1). Soil pH and EC were measured in 1:2 soil–water suspensions (Jackson, 1973). Soil organic carbon was estimated by wet oxidation procedure (Walkley and Black, 1934). The soil available N was determined by the alkaline permanganate method (Subbiah and Asija, 1956). The soil available P was extracted with 0.5 M $NaHCO_3$ and extracted P was determined by the ascorbic acid blue colour method (Olsen *et al.*, 1954). Soil available K

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was extracted with neutral normal NH_4OAc and K in the extract was estimated flame photometrically (Jackson, 1973) (Table 1). The soil available water was estimated by subtracting the permanent wilting point from field capacity.

Economic analysis

The economic assessment of onion cultivation under varied levels and methods of irrigation coupling with different nitrogen fertilization was worked out to select the better irrigation-nitrogen combination for a recommendation to the regional farmers. The economic assessment for onion in terms of gross income, net income and benefit cost ratio (BCR) was computed by averaging the 2016–17 and 2017–18 seasons' regional market prices for all inputs used, including labour costs and outputs (Special expert committee on cost estimates, GoI, New Delhi; Department of Consumer Affairs, Ministry of Consumer Affairs, Food and Public Distribution, Government of India, https://consumeraffairs.nic.in).

Statistical analysis

The growth stage-wise seasonal data recorded for water, soil and plant variables was processed by one-way analysis of variance using the statistical software SAS (Version 9.2, SAS, Inc., Cary, N.C.). The differences between the mean values of individual treatments and their interactions for each experimental season were compared using the Fisher's least significant difference (LSD) test at 5% level of probability (Gomez and Gomez, 1984). Since the variabilities of data for the two seasons evaluated by Bartlett's χ^2 test were found to be homogeneous, and the interactive relationships between irrigation and N-fertilization were almost identical, the two seasons' data were pooled to draw conclusions.

Results

Onion yield, water and nitrogen productivity under different irrigation and N fertilizations

The yield of onion bulbs increased significantly as a result of increasing micro-sprinkler irrigation and N fertilization level combinations (Table 2). The interactive effect between M and N revealed that the M_3N_3 attained the maximum yield (11.3 t/ha), whereas the traditional SN recorded a bulb yield of 9.2 t/ha, which is considered to be a moderate yield. The yield increase for the MN combinations in comparison to the SN was 22.6, 12.9, 14.2 and 2.9% for M_3N_3, M_3N_2, M_2N_3 and M_2N_2, respectively.

Water productivity (WP) increased significantly with a decrease in micro-sprinkler irrigation levels and increased with an increase in nitrogen levels (Table 2). However, the highest WP (4.80 kg/m^3) was recorded in M_2N_3. As compared with SN, WP increased by a range of 14.6–26.8% for N_1, 31.9–47.1% for N_2, and 42.7–62.7% for N_3, with increasing irrigation levels from M_1 to M_3.

Likewise, increasing micro-sprinkler irrigation and decreasing nitrogen fertilization levels resulted in a consistently significant increase in nitrogen productivity. The $M \times N$ interaction effect demonstrated that nitrogen productivity significantly increased with increasing micro-sprinkler irrigation levels at a given N rate, while it was dramatically decreased with enhancing N rates at a specific irrigation level (Table 2). However, M_3N_1 registered the highest nitrogen productivity, followed by M_2N_1, and M_3N_2, contributing about 30.9, 16.2 and 12.9%, respectively, over the 115 kg bulb/kg N productivity of SN.

Root zone water content and its depletion rate during the growing period under different irrigation and N fertilizations

The average soil water content in different depths of the root zone profile during the cropping period from 10 to 110 DAT was influenced by various scheduling of micro-sprinkler irrigation and traditional surface irrigation with N fertilization (Fig. 1). Results indicated that soil water content in each irrigation treatment at all growth stages was at its minimum in the surface layer (0–0.15 m depth), which increased differently with the incremental depth of the root zone profile and attained its maximum at the lower layer (0.45–0.60 m depth). Likewise, soil water content decreased to different extents with increasing plant age from 31 to 70 DAT in all rooting depths at all irrigation regimes, suddenly increasing from 71 to 90 DAT, and thereafter decreasing at 91–110 DAT. Irrespective of growth stages, the overall increase in soil water content at 0–0.15, 0.15–0.30, 0.30–0.45 and 0.45–0.60 m depths of the root zone profile was 5.9, 5.8, 3.6 and 5.5% for M_3, followed by 1.8, 1.5, 1.0 and 1.1% for M_2, respectively, over those of SN. Contrarily, mostly a decrease in soil water content in each soil depth at all growth stages was observed in M_1 compared to SN with the overall corresponding negative values being 1.1, 1.9, 1.2 and 1.8% for 0–0.15, 0.15–0.30, 0.30–0.45 and 0.45–0.60 m depths, respectively (Fig. 1). The root zone water stock at 10, 30, 50, 70, 90 and 110 DAT under various irrigation treatments followed almost similar pattern of distribution to those of the full rooting depths (Fig. 2). In most of the cases, the water stock among the irrigation treatments was lower in M_1 across the soil depths at all growth stages. Over the cropping period, the average root zone water stock increased by 5.2% for M_3 and 1.4% for M_2, but decreased by 1.5% for M_1 as compared to SN.

During the growing period, there was a variable pattern of depletion and gain of the root zone water content as a result of various irrigation treatments (Fig. 3). At 30 DAT, soil water depletion from the rooting depth was 3.2% for SN and 0.3% for M_3; whereas there was a gain in water content of 2.8% for M_1, followed by 1.5% for M_2. At 31–50 and 51–70 DAT, the soil water depletion from the rooting depth at all irrigation treatments was variable, ranging from 6.0–10.7% for M_1, 8.0–9.6% for M_2, 8.6–10.2% for M_3, and 5.1–7.9% for the SN regime and the declining trend was relatively higher in the latter than in the former growing period. In contrast, at 71–90 DAT, a gain in root zone water status was detected at all irrigation regimes, with a maximum of 6.5% for M_3, followed by 4.0% for M_1, 2.9% for M_2, and a minimum of 1.6% for SN. With further advancement of the cropping period (91–110 DAT), the maximum depletion was noticed in M_3 (4.3%), followed by M_1 (2.9%), M_2 (2.1%), and SN (1.6%). At the end of the growing season, the total depletion of root zone soil water content under different irrigation treatments was maximum in M_3 (16.7%), followed by SN (15.3%), and M_2 (15.0%) and the minimum in M_1 (12.8%).

The average rate of root zone soil water depletion due to various irrigations at different stages of plant growth followed the same trend as in total soil water depletion from the rooting depth (Fig. 4). It is evident that the gain (+) and depletion (−) rates of root zone water along the growing period varied from

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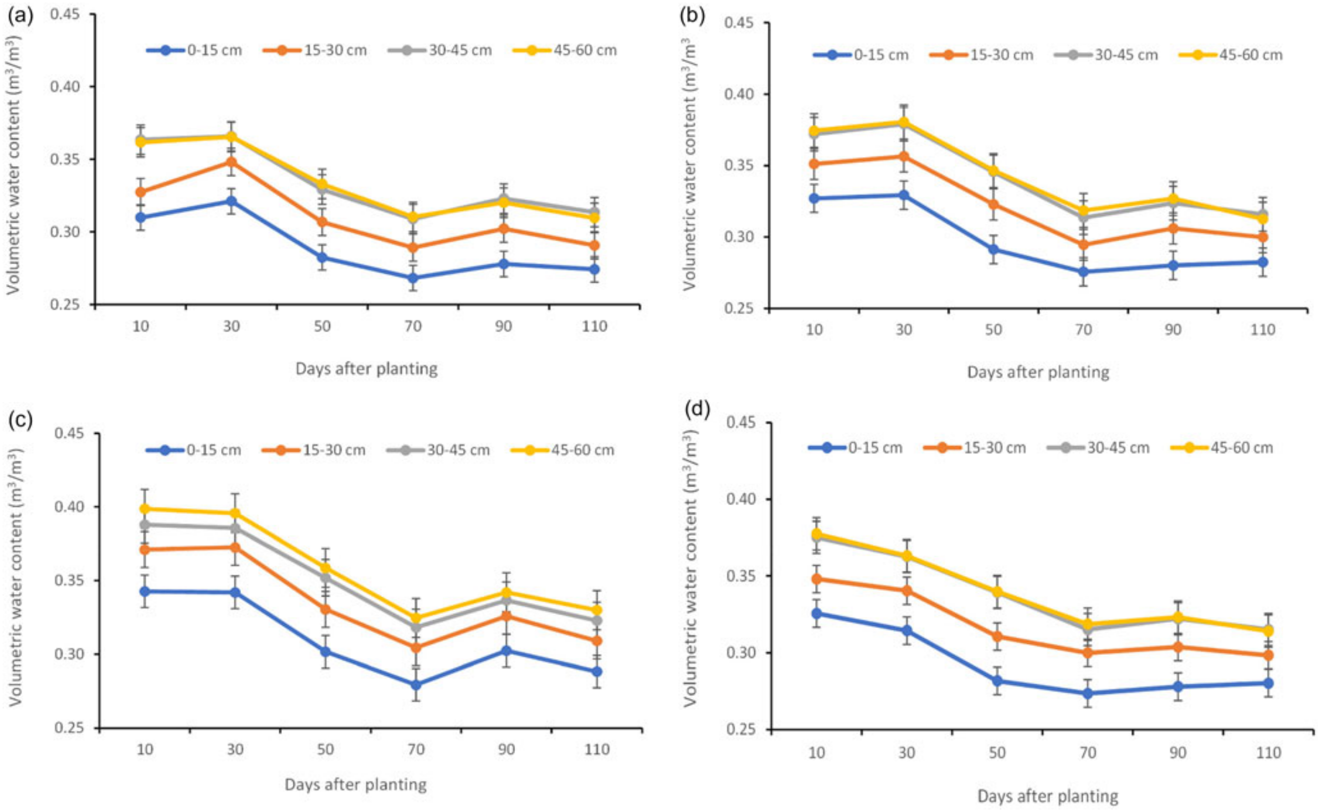

Figure 1. Depth-wise soil water content at different growth stages of onion plants under various micro-sprinkler irrigation scheduling at (a) 0.6 ETc, (b) 0.9 ETc, (c) 1.2 ETc, and (d) surface irrigation with nitrogen fertilization (SN) system.

+0.20 to −0.53% for M_1; +0.14 to −0.48% for M_2, +0.33 to −0.51% for M_3, and +0.08 to −0.40% for SN, with an average of −0.13, −0.15, −0.17 and −0.16% for M_1, M_2, M_3 and SN, respectively. The efficiency of the onion plant in removing soil water from the rooting depth in response to various irrigation treatments can be arranged in the order of $M_3 > SN > M_2 > M_1$. It is also noted that the depletion rate of root zone soil water along the growth stages followed an inconsistent or asymmetrical pattern under various irrigation treatments.

Soil available nitrogen under different irrigation and N fertilizations

The average available N content in soil significantly increased with increasing levels of irrigation with micro-sprinkler along the root zone profile at all growth stages (Fig. 5). Averaging over the soil depths, the available N content for M_2 and M_3 increased by 2.1, 2.0 and 2.1%, and 3.7, 3.7 and 3.8% at the vegetative, bulb development, and maturity stages, respectively, above

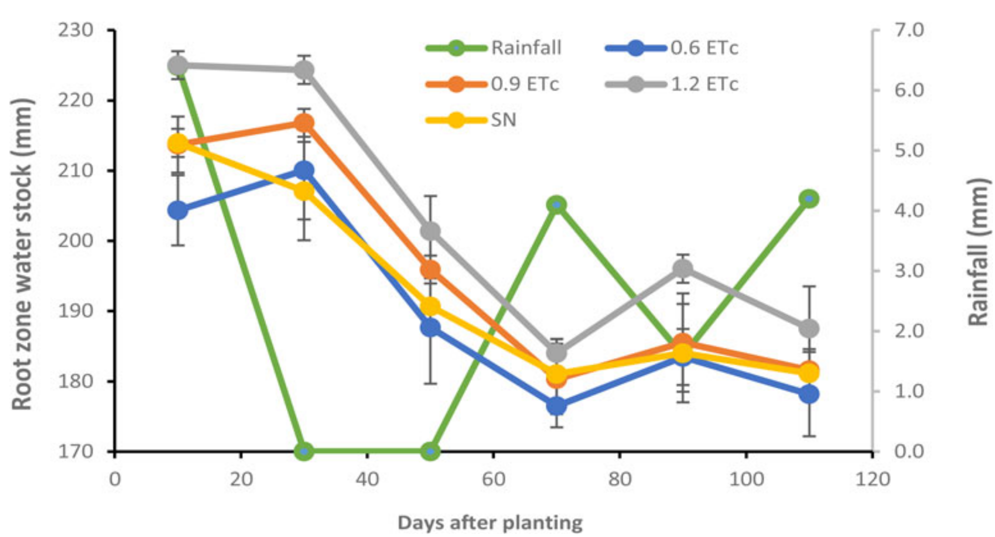

Figure 2. Root zone soil water content at different growth stages of onion plants under various micro-sprinkler scheduling and surface irrigation with nitrogen fertilization. (Error bars indicate ± Standard error of mean).

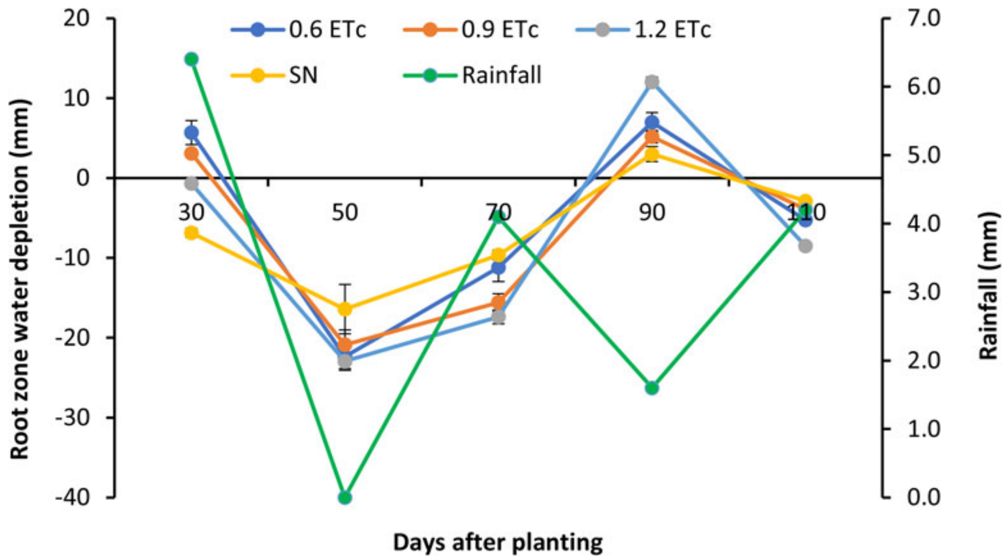

Figure 3. Root zone soil water depletion at different growth stages of onion plants under various micro-sprinkler scheduling and surface irrigation with nitrogen fertilization. (Error bars indicate ± Standard error of mean).

the N content of M_1. Similarly, notwithstanding growth stages, the accumulation of available N contents at each irrigation regime was maximum at 0–0.15 m depth (169.1–199.4 kg/ha) and decreased steadily by 10.3 and 7.0%, 10.9 and 7.7% and 10.8 and 7.8% at 0.15–0.30 m and 0.30–0.45 m depths for M_1, M_2 and M_3, respectively. Notably, at each irrigation treatment, the available soil N content was consistently reduced with incremental depth in the vegetative stage, whereas the same was first sharply decreased at 0.15–0.30 m depth, followed by an increase at 0.30–0.45 m depth in the bulb development and maturity stages.

The average soil N content markedly increased due to increments of N fertilization in each rooting depth at all growth stages (Fig. 5). The maximum increase in soil N availability, disregarding the micro-sprinkler irrigations, was 12.0, 13.2 and 12.8% for N_3, followed by 9.6, 11.4 and 10.7% for N_2, and 7.0, 8.5, and 8.7% for N_1 at the vegetative, bulb development, and maturity stages, respectively, over those of the unfertilized treatment, N_0. Likewise, regardless of the growth stages, the available N contents due to different N-fertilizations were highest at 0–0.15 m depth (169–199 kg/ha), which were decreased by 11.8, 11.8, 11.1 and 7.6% at 0.15–0.30 m depth, and 9.9, 9.3, 8.9 and 1.1% at 0.30–0.45 m depth for N_3, N_2, N_1 and N_0, respectively. The availability of soil N increased with the increment of N doses, reaching its maximum at 0–0.15 m depth at all growth stages. However, the value reduced gradually with depth in the vegetative stage, while it sharply dropped at 0.15–0.30 m depth followed by a variable increase at 0.30–0.45 m depth in the bulb development and maturity stages. The highest available soil N content was found in N_3, followed by that of N_2, N_1 and N_0, at all soil depths and all growth stages. The relative increase in the soil available N over the unfertilized treatment N_0 in the vegetative stage at

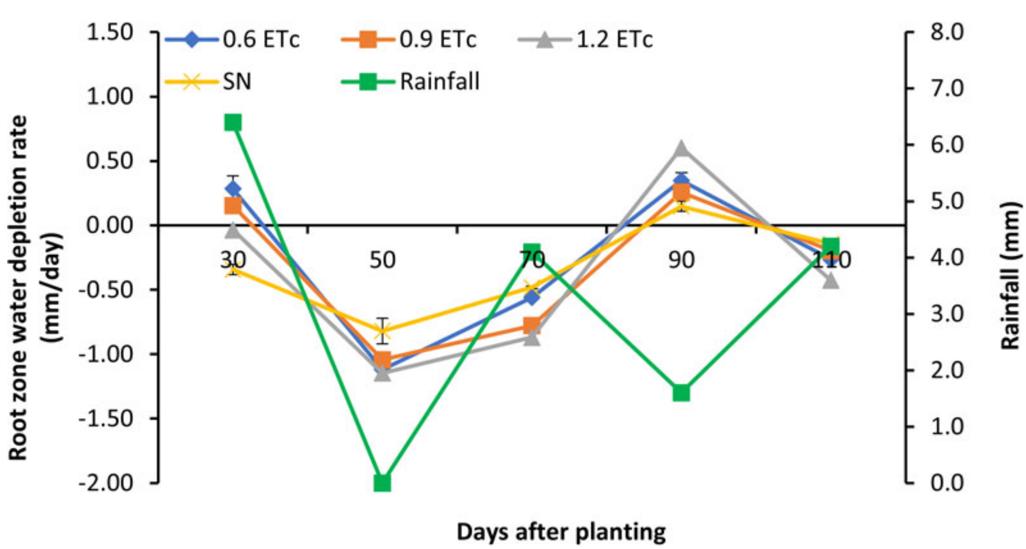

Figure 4. Root zone soil water depletion rate at different growth stages of onion plants under various micro-sprinkler scheduling and surface irrigation with nitrogen fertilization. (Error bars indicate ± Standard error of mean).

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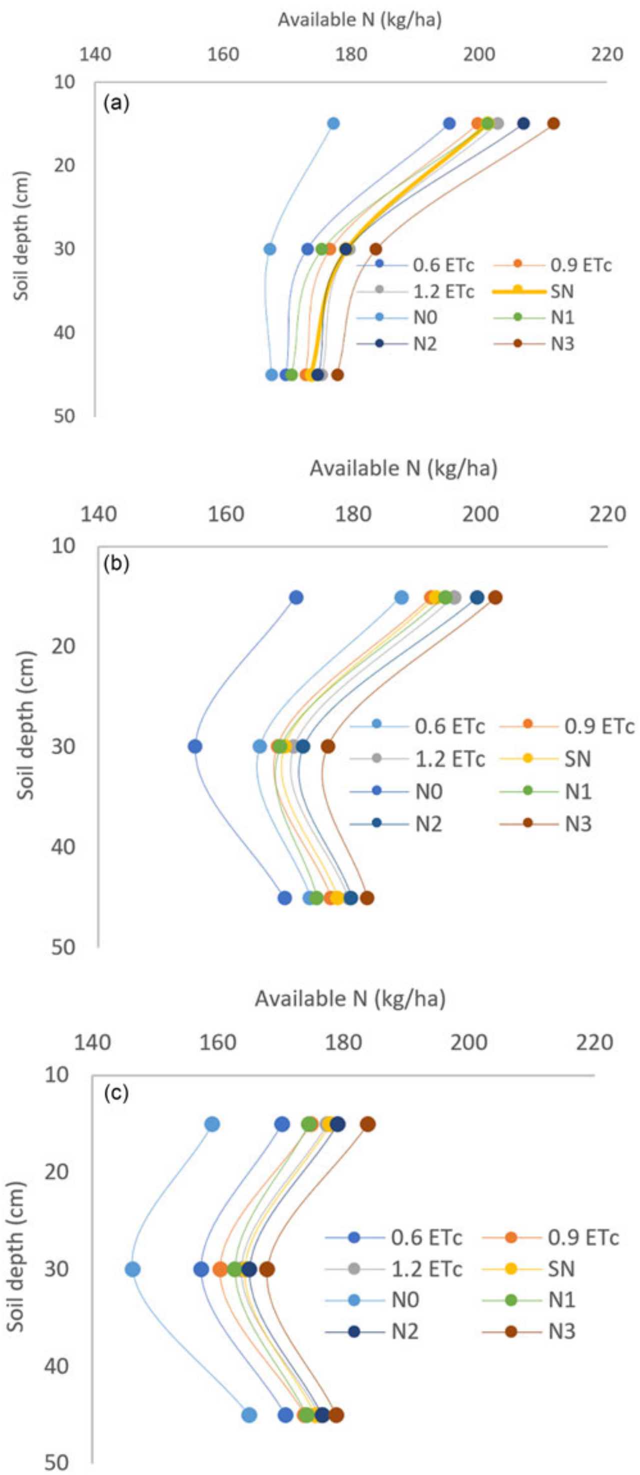

Figure 5. Available soil N at (a) vegetative, (b) bulb development and (c) maturity stages of onion plants under different levels of micro-sprinkler and surface irrigation systems and rates of nitrogen fertilization (N0, no N; N1, 75; N2, 100 and N3, 120% of recommended nitrogen dose).

0–0.15 m, 0.15–0.30 m and 0.30–0.45 m depths was 13.7, 5.0, and 1.9% for N_1; 16.7, 7.2, and 4.4% for N_2, and 19.5, 10.0, and 6.1% for N_3. The corresponding values for the bulb development stage were 13.7, 8.6 and 3.1% for N_1, 16.8, 10.9 and 6.3% for N_2, and 18.5, 13.4 and 7.7% for N_3, and for the maturity stage, the values were 9.6, 11.2 and 5.6% for N_1, 12.6, 12.7 and 7.1% for N_2, and 15.5, 14.7 and 8.4% for N_3.

The interactive relationship between M × N indicated that under a specific micro-sprinkler irrigation or N rate, the available N content consistently increased with increasing N rate or enhanced micro-sprinkling watering at all soil depths and growth stages (Table 3). The surface irrigation with 100% RDN (SN) also followed the same trend. Out of 12 MN combinations, eight treatments recorded a decrease, with some minor deviations, while four treatments displayed an increase in the mean availability of soil N at all soil depths and growth stages as compared with those of SN. The maximum increase in soil N content against SN along the root zone profile varied from 0.4–2.5, 1.5–3.6, and 0.2–1.1% for M_2N_2; 2.5–5.7, 2.7–4.8, and 2.0–3.8% for M_2N_3; 1.7–5.1, 3.1–6.0, and 2.1–2.6% for M_3N_2; and 3.8–7.4, 4.0–7.8, and 3.0–5.4% for M_3N_3 in the vegetative, bulb development, and maturity stages, respectively. Averaging over the soil depths and growth stages, a relative increase in soil N content over the SN treatment was 1.4, 3.4, 3.2 and 5.2% for M_2N_2, M_2N_3, M_3N_2 and M_3N_3, respectively.

Plant nitrogen uptake under different irrigation and N fertilization

The mean N uptake by onion plants consistently and significantly increased with increments of micro-sprinkler irrigation and nitrogen fertilization combinations at all growth stages (Table 4). It is evident that plant top-N decreased while bulb-N increased by varying magnitudes with the advancement of the growing periods at all levels of micro-sprinkler irrigation and nitrogen combinations, and the effects were more obvious at the higher levels of irrigation N fertilization combinations than the lower levels. The interactive relationship between M × N showed that the M_3N_3 treatment recorded the highest plant N uptake of 39.3, 140 and 162 kg/ha at the vegetative, bulb development and maturity stages, respectively, being significantly superior to the remaining MN combinations (Table 4). The conventional SN practices exhibited moderate plant N uptake, corresponding to 33, 104 and 125 kg/ha at the vegetative, bulb development and maturity stages, respectively; these values were found to increase by 7.9, 19.4 and 15.1% for M_2N_3; 9.6, 20.2 and 15.5% for M_3N_2; and 19.0, 34.4 and 29.0% for M_3N_3, respectively. The other MN treatments recorded considerably lower values at all growth stages as compared to SN, except M_2N_2 at the bulb development stage, where plant N uptake showed a larger value (110 kg/ha).

Economics of different irrigation and nitrogen management practices

Out of 12 micro-sprinkler irrigation-nitrogen management practices for onion production, three treatments were most suitable in terms of higher seasonal net income gains, and benefit-costs ratio (BCR) as compared to the surface irrigation-nitrogen combination (Table 5). The net income and BCR of \$2570/ha and 3.2, respectively were observed to be the maximum in M_3N_3, followed by that of \$2343/ha and 2.9 in M_2N_3, and \$2307/ha and 2.9 in M_3N_2, while the conventional SN recorded the corresponding values of net income and BCR as \$1967/ha and 2.5, respectively. The M_2N_2 and SN treatment combinations were almost competitive for monetary gains.

Table 3. Interaction effects of micro-sprinkler irrigation and N fertilization levels on soil available N contents at different growth stages of onion (pooled data of 2-year)

	Available N (kg/ha)								
	Vegetative (10–30 DAT)			Bulb development (61–90 DAT)			Maturity (91–110 DAT)		
	Soil depth (cm)			Soil depth (cm)			Soil depth (cm)		
Treatment	0–15	15–30	30–45	0–15	15–30	30–45	0–15	15–30	30–45
Interaction (M × N)									
M_1N_0	175	165	164	168	153	166	156	144	162
M_1N_1	197	172	169	190	167	171	171	159	170
M_1N_2	203	175	172	195	170	176	175	162	174
M_1N_3	206	179	175	197	172	180	179	164	177
M_2N_0	178	167	168	171	155	169	160	147	165
M_2N_1	202	175	171	196	168	174	175	163	175
M_2N_2	206	180	175	200	172	180	180	165	177
M_2N_3	213	185	178	202	176	182	185	168	179
M_3N_0	178	169	171	173	158	172	162	149	168
M_3N_1	205	179	173	197	171	177	178	166	178
M_3N_2	212	182	178	205	175	183	183	169	179
M_3N_3	216	188	180	208	180	185	188	172	181
S.E.M.	0.9	0.6	0.6	0.6	0.4	0.6	0.6	0.6	0.5
CD (0.05)	2.7	1.9	1.7	1.8	1.2	1.8	1.7	1.7	1.5
Control vs. MN									
Overall mean MN	199	177	173	192	168	176	174	161	174
SN (control)	201	179	174	193	169	178	178	164	176
S.E.M.	0.8	0.7	0.8	0.6	0.4	0.6	0.7	0.6	0.5
CD (0.05)	1.7	1.5	NS	NS	0.9	NS	1.4	1.2	1.0

M_1, micro-sprinkler irrigation at 0.6 ETc; M_2, micro-sprinkler irrigation at 0.9 ETc; M_3, micro-sprinkler irrigation at 1.2 ETc; SN, surface irrigation with 100% RDN; N_0, no-N; N_1, 75% RDN; N_2, 100% RDN; N_3, 120% RDN; RDN, recommended dose of nitrogen; DAT, days after transplanting; NS, not-significant; S.E.M., standard error of mean; CD, critical difference.

Discussion

Effects of irrigation, nitrogen fertilization, and their interaction on yield, water, and nitrogen productivity of onion

The increased bulb yield under non-stressed irrigation (1.2 ETc) with a micro-sprinkler was attributed to the faster food material production in leaves due to the constant and adequate availability of moisture in plants and its translocation to bulbs (Tsegaye *et al.*, 2016; Worku *et al.*, 2020). Application of 40% deficit irrigation with a micro-sprinkler (0.6 ETc) caused severe soil water stress as a result of the quick recession of plant-available water in the rhizosphere, which led to a decrease in photosynthetic area, insufficient assimilate production, restricted mobilization of the photosynthates to the bulbs, and thus, poor bulb expansion and the lowest yield (Kumar *et al.*, 2007b; Enchalew *et al.*, 2016). The increase in bulb yield at a higher rate of N (120% RDN) was likely caused by improved photosynthetic rate, greater assimilate production and partitioning into the bulbs, which might have increased the size and weight of onion bulbs (Tsegaye *et al.*, 2016; Nawaz *et al.*, 2017). Similarly, the maximum yield under higher irrigation level at 1.2 ETc through a micro-sprinkler combining with 120% RDN (M_3N_3) compared with the conventional method of surface irrigation and 100% RDN (SN) was attributed to the enhanced water and N availability in the root zone and plant utilization in an optimal soil water-nutrient environment. The results are consistent with the findings of Fatideh and Asil (2012) and Gebregwergis *et al.* (2016).

WP for onion was significantly impacted by the amount of irrigation applied and the yield levels obtained. The highest WP (3.71 kg/m^3) was achieved from micro-sprinkler irrigation both at 40% (0.6 ETc) and 10% (0.9 ETc) deficit irrigation levels, receiving low to nearly optimal water quantities. A significantly higher WP (6.40–12.12 kg/m^3) under 40% deficit irrigation using micro-sprinklers in arid climates was noted by Kumar *et al.* (2007b) and Mane *et al.* (2014). The lowest WP at full irrigation (100% ETc) and the highest at 75% deficit irrigation (25% ETc) throughout the onion growth stages in a semi-arid climate was recorded by Tolossa (2021). The results of this study suggest that, when water is limited, irrigation at 0.9 ETc with a micro-sprinkler can be the most appropriate irrigation strategy for higher bulb production, maximum WP, and considerable water savings. The probable reasons for higher WP with high to nominal deficit irrigation with micro-sprinkler are full utilization of water for yield enhancement because of intermittent controlled

Table 4. Effect of micro-sprinkler irrigation and nitrogen fertilization levels on nitrogen uptake at different growth stages of onion (pooled data of 2-year)

	Nitrogen uptake (kg/ha)						
	Vegetative (10–30 DAT)	Bulb development (61–90 DAT)			Maturity (91–110 DAT)		
Treatment	Tops (Total)	Tops	Bulb	Total	Tops	Bulb	Total
M_1N_0	21.6	24.8	28.5	53.2	22.4	40.7	63.0
M_1N_1	24.9	27.7	37.9	65.6	24.6	52.6	77.2
M_1N_2	28.9	31.7	46.8	78.5	27.1	64.5	91.6
M_1N_3	31.7	34.6	56.1	90.6	29.4	74.9	104
M_2N_0	23.0	27.1	38.0	64.7	24.2	51.4	75.6
M_2N_1	28.2	33.0	55.5	88.5	29.3	72.9	102
M_2N_2	32.4	36.8	73.0	110	32.4	92.8	125
M_2N_3	35.6	40.4	84.1	124	35.4	109	144
M_3N_0	26.1	29.4	45.1	74.5	26.2	60.3	86.5
M_3N_1	32.3	37.0	67.2	104	31.5	89.9	121
M_3N_2	36.1	40.9	84.4	125	34.9	110	145
M_3N_3	39.3	44.8	95.3	140	37.6	124	162
S.E.M.	0.4	0.5	0.8	0.9	0.3	1.5	1.6
CD (0.05)	1.3	1.6	2.3	2.6	0.9	4.3	4.7
Control vs. MN							
Overall mean MN	30.0	34.0	59.3	93.3	29.6	78.6	108
SN (control)	33.0	38.3	65.9	104	33.0	92.4	125
S.E.M.	0.4	0.6	0.8	0.9	0.3	1.5	1.6
CD (0.05)	0.8	1.1	1.5	1.8	0.7	3.0	3.2

M_1, micro-sprinkler irrigation at 0.6 ETc; M_2, micro-sprinkler irrigation at 0.9 ETc; M_3, micro-sprinkler irrigation at 1.2 ETc; SN, surface irrigation with 100% RDN; N_0, no-N; N_1, 75% RDN; N_2, 100% RDN; N_3, 120% RDN; RDN, recommended dose of nitrogen; DAT, days after transplanting; S.E.M., standard error of mean; CD, critical difference.

Table 5. Economics of winter onion cultivation in USD ($) under different combinations of irrigation levels and nitrogen rates (average data of 2-year)

Treatment	Production cost ($/ha)	Gross income ($/ha)[a]	Net income ($/ha)	Benefit-cost ratio
M_1N_0	779	1708	929	1.2
M_1N_1	791	1909	1118	1.4
M_1N_2	795	2102	1306	1.6
M_1N_3	799	2308	1510	1.9
M_2N_0	782	1990	1207	1.5
M_2N_1	795	2400	1605	2.0
M_2N_2	799	2835	2036	2.6
M_2N_3	802	3145	2343	2.9
M_3N_0	786	2204	1418	1.8
M_3N_1	799	2704	1905	2.4
M_3N_2	803	3109	2307	2.9
M_3N_3	806	3376	2570	3.2
SN	787	2755	1967	2.5

M_1, micro-sprinkler irrigation at 0.6 ETc; M_2, micro-sprinkler irrigation at 0.9 ETc; M_3, micro-sprinkler irrigation at 1.2 ETc; SN, surface irrigation with 100% RDN; N_0, no-N; N_1, 75% RDN; N_2, 100% RDN; N_3, 120% RDN; RDN, recommended dose of nitrogen.
[a]Average marketing price of dry onion during the 2016–17 and 2017–18 seasons: $299.4/t.

watering, minimum drainage and runoff losses, and a favourable water-nutrient environment in the rooting zone for encouraging better plant growth and yield. Increased WP with a higher N rate was specifically due to better N nutrition, as onion is a shallow-rooted, severe nutrient depleting plant requiring higher N for producing the highest bulb yield, which is in agreement with the findings of Nemat *et al.* (2011), Fatideh and Asil (2012), Dhital *et al.* (2015), and Piri and Naserin (2020). Similarly, the increased WP (2.7–14.6%) under severe deficit to optimally high irrigation regime with micro-sprinkler, along with the sub-optimal to higher N rate as compared with the farmers' traditional irrigation and N fertilization practices, was due to higher water and nitrogen usage by the plants for production purposes, as also reported by Tsegaye *et al.* (2016).

The highest nitrogen productivity at the highest irrigation amounts using micro-sprinkler was due to the improvement in bulb production per unit of applied N. The lowest nitrogen productivity at severe deficit irrigation with micro-sprinkler was due to acute plant water stress, poor photosynthesis rate, and other biochemical activities, leading to reduced bulb production. These findings are in agreement with those of Mane *et al.* (2014). Nitrogen productivity decreased with increasing levels of nitrogen fertilizer application. The interactions showed that, in contrast to SN, the greater N productivity resulting from a moderate deficit to optimal watering through a micro-sprinkler (0.9–1.2 ETc) combined with suboptimal to optimal N fertilization (75–100%

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RDN) was due to improved bulb output per unit of applied fertilizer N.

Spatiotemporal distribution of root zone water content, and its depletion rate during the growing period

Bandyopadhyay *et al.* (2003) found that the increase in soil water content with rooting depth along the growing period with various irrigation treatments was due to the combined effects of successive irrigation events, the existence of earlier soil moisture regimes, and rainfall occurrence. Whereas the decreases in water content in different soil depths with the cropping period were ascribed to the differential soil water extraction by enlarged root mass at varied plant ages, and deep percolation loss beyond the rooting depth, as induced by different irrigation levels. In this study, the root zone water content at each soil depth, growth stage, and over the whole growing period was greater under micro-sprinkler irrigation with 1.2 ETc (200 mm), followed by nominal deficit irrigation with 0.9 ETc (150 mm) as compared to conventional irrigation using a larger amount of water (240 mm), which was explicitly due to the intermittent micro-sprinkler watering in small fractions according to the plant water need across the cropping season. The lower corresponding root zone water content under surface irrigation were because of excessive watering each time with longer intervals, thereby causing a maximum water loss in deep drainage below the root zone under gravitational force. The lowest water content under the severe deficit irrigation scheduling at 0.6 ETc through a micro-sprinkler was attributed to the minimum water application (100 mm), which resulted in acute water stress at all rooting depths along the growing period.

The higher soil water depletion under an unstressed irrigation regime at 1.2 ETc and marginal deficit irrigation at 0.9 ETc with micro-sprinkler was due to greater water absorption from the active root zone by plants for the higher vegetative and reproductive growth, and bulb production. Increased water depletion under surface irrigation was specifically due to augmented soil water storage with depth for a shorter duration with bulk water loading, followed by a rapid recession due to deep percolation without production purposes. The high water-stressed regime with micro-sprinkler at 0.6 ETc could lead to a decrease in water availability as well as depletion of root zone water content. Bandyopadhyay *et al.* (2003) attributed marginal depletion or gain of root zone soil water in the vegetative stage to the mutual effects of slower plant evapotranspirative demand due to minimum foliage development, deep drainage from upper portions of the soil profile, as facilitated by coarse-textured soil with high hydraulic conductivity, and the incidence of low rainfall. Conversely, higher depletion of root zone soil water during bulbing, early bulb development and bulb maturation periods was ascribed to higher plant evapotranspiration demand with trace rainfall conditions. In this study, the gains in soil water status at all irrigation regimes during the peak bulb development period (80–90 DAT) were the result of sudden rainwater intrusion into soil already wetted from the preceding irrigation events. Further, as the onion has a shallow fibrous root system and its roots are spread within 0.45 m depth, the excess water that moved from the upper soil layers and accumulated at 0.45–0.60 m depth was not available to plants for production purposes.

The wet moisture regime with micro-sprinkler caused a greater depletion rate of root zone soil water, while the dry moisture regime with micro-sprinkler resulted in a lower depletion rate. The depletion rate in SN was intermediate between M_2 and M_3. The asymmetrical pattern of soil water depletion rate at different stages of growth cycles could be due to the differential soil water extraction by plant roots, the establishment of various soil water statuses as a result of different levels of irrigation imposition, unexpected rainwater entry onto the onion field, and variable losses of water via deep percolation.

Effects of irrigation, nitrogen fertilization, and their interaction on soil available nitrogen

The higher N content in the top-most soil layer compared to the layers below observed in this study agrees with the previous reports of micro-sprinkler fertigation (Rajput and Patel, 2006; Anita Fanish and Muthukrishnan, 2013; Archana and Maragatham, 2017). The highest N availability at 0–0.15 m and 0.15–0.30 m depths along the growth stages indicated better N nutrition for onion plants. However, as the cropping period advanced and especially during the bulb development and maturity stages, there was a redistribution of available N in the root zone, where soil N contents decreased at 0–0.30 m depth and then increased at the 0.30–0.45 m depth. This reduction of soil N concentrations from the effective rooting depth (0–0.30 m) was attributed to plant uptake under higher soil moisture regimes, followed by N leaching with the downward moving water. Onion is a shallow, fibrous rooted nitrogen-loving plant that is likely to exhaust the maximum plant available N from a depth of 0–0.30 m. Amounts of adequate water in the active rooting depth also favour the mineralization and transportation of soil N. Substantial amount of available N was accumulated in the bottom layer at all growth stages (Fig. 5), which is out of reach of the plant roots for consumptive use. The vertical movement of soil N and thus the chances of N leaching were more evident at a higher level of watering with a micro-sprinkler at 1.2 ETc than at the lower level with 0.6 ETc. This is indicative of a close relationship between available N and water content in the soil, as also reported by Anita Fanish and Muthukrishnan (2013). Archana and Maragatham (2017) explained that the soluble nitrate ion (NO_3-N) has a greater tendency to leach downward with water movement, and a substantial portion is gathered in the deeper soil layers.

Sivasakthi *et al.* (2014) reported that higher concentrations of available N in the topmost layer (0–0.15 m depth) than in the bottom layers of the root zone profile in response to increasing rates of N-fertilizer application throughout the growth period might be attributed to increased bacterial activity in the soil. Archana and Maragatham (2017) found that the downward movement of N from the surface to the deeper layers was the difference in concentration gradient developed due to mass flow, which causes the transfer of N from the maximum to the minimum concentration. There were increased concentrations of soil N of 1.9, 3.1 and 5.6% for N_1; 4.4, 6.3 and 7.1% for N_2; 6.1, 7.7 and 8.4% for N_3; and 3.7, 5.0 and 6.4% for SN at the vegetative, bulb development and maturity stages, respectively (Fig. 5). These indicate the possibility of more N leaching from the soil available N pool beyond the active rooting depth at all growth stages, and it is more evident under a higher rate of N fertilization than a lower rate in this sandy loam soil. Thus, a higher rate of fertilizer N application beyond plant requirements at different phenological stages may be avoided to limit the leaching loss of N from the soil, promote efficient utilization of applied N, and thus reduce the environmental hazards of crop management.

Bhatti *et al.* (2019) reported the effect of increasing levels of micro-sprinkler irrigation coupled with increasing N rates on the greater availability of soil N along the rooting depths and growing periods as the positive and synergistic impact of controlled intermittent watering and N fertilization. The present study showed that the application of lesser amounts of water, by employing marginal deficit irrigation at 0.9 ETc, or optimally high irrigation at 1.2 ETc, with the micro-sprinkler in tandem with 100% N fertilization (M_2N_2 and M_3N_2) increased the soil available N contents by 1.4 to 3.2% compared with the farmers' traditional practices of surface irrigation with more water usage in association with 100% N fertilization (SN). Such relative values were increased to 3.4 to 5.2% when the same micro-sprinkler irrigation levels were combined with a 120% N application (M_2N_3 and M_3N_3). These results have given ample opportunities to the farmers to manage the marginal deficit or optimally high irrigation scheduling with the micro-sprinkler in coupling with the full or 20% higher dose of nitrogen, according to resource availability, for maximum utilization of water and nitrogen for higher onion production and profit gains. The moderate availability of soil N under surface irrigation with optimum N fertilization could be attributed to more N leaching loss from this sandy loam soil as facilitated by bulk water loading at every irrigation event, which eventually causes a moderate utilization of soil water and N by the plants with a reflection of moderate bulb yield. More leaching loss of N in nitrate form with the downward movement of water by the furrow method of irrigation was observed by Santos *et al.* (1997) and Shedeed *et al.* (2009). Li *et al.* (2007) and Gholamhoseini *et al.* (2013) reported that the magnitudes of NO_3-N leaching are related to the abundance of root zone NO_3-N concentration, its quantity, and speed of water passing across the soil profile. In addition, coarse-textured soils are most influential for promoting seasonal N leaching (Gardenas *et al.*, 2005). Based on this evidence, the reduced availability of soil N in this study and the consequent lower uptake by the plants under SN treatment can be explained. Results further indicate that a sizable amount of available N was accumulated at 0.30–0.45 m soil layer along the growth stages, which is likely to be out of reach of the plant roots. The possibility of N leaching from the soil N pool of the effective rooting depth (0–0.30 m) was more marked under higher levels of N fertilization and micro-sprinkler irrigation. Thus, the application of fertilizer N in several splits in conjunction with intermittent watering with the micro-sprinkler matching plant requirements at different growth stages may be prudent to inhibit water loss and N leaching from this coarse-textured sandy loam soil.

Effects of irrigation, nitrogen fertilization, and their interaction on plant nitrogen uptake

The greater N uptake by the plant-tops and bulbs under unstressed (1.2 ETc) than mild and severe stressed (0.9 and 0.6 ETc, respectively) irrigations through the micro-sprinkler with increasing age of the plant was attributed to the favourable water regime in the root zone along the growing period as a result of frequently small quantity of watering, which is likely to have stimulated the better root mass growth, the higher availability and accessibility of native and applied N to the roots for efficient absorption, transfer to the leaves, higher food material production in the leaves, and subsequent allocation of food to other plant organs, which would be in agreement with Neeraja *et al.* (2001) and Bhatti *et al.* (2019). In contrast, the corresponding lower N uptake under the severe water stress condition attributed to the reduced root growth, lower N availability in the rhizosphere, less N absorption by the roots, low photosynthate production, and restricted movement of nutrients from the leaves (source) to the bulbs (sink), which ultimately results in decreased bulb yield, as explained by Thangasamy (2016). The reduction of plant-top N uptake at maturity as compared to the bulb development stage under all irrigation and nitrogen treatments was due to the shedding of older leaves followed by remobilization and translocation of assimilate from source (leaves) to sink (bulbs) due to their higher mobility in the phloem (Thangasamy, 2016). Likewise, the increased plant-tops and bulb N uptake in response to the incremental N fertilization into the soil could be ascribed to the development of massive as well as deep root growth to absorb more labile N from a large volume of soil (Negash *et al.*, 2009), causing an increase in photosynthetic area (leaf number and leaf area) and accelerating the synthesis of more chlorophyll and amino acids (Neeraja *et al.*, 2001; Abdissa *et al.*, 2011) and subsequent partitioning of assimilate to storage organs, i.e., bulbs (Abdissa *et al.*, 2011; Zewdu, 2014). The least N uptake by the plant-tops and bulbs under unfertilized N treatment was probably due to the reduction of fine root spread in the zones of low soil N availability and the decreased leaf and bulb dry matter production in onion plants (Kemal, 2013; Bhatti *et al.*, 2019). Likewise, in the present study, higher N uptake by plant-tops and bulbs under unstressed or nominally stressed irrigation regimes with the micro-sprinkler, accompanied by a 100% N or 120% N application (M_2N_3, M_3N_2 and M_3N_3) as compared with conventional surface irrigation with 100% N (SN) could result in the adequate plant available water and nitrogen in the rooting depths, more efficient absorption by the roots, the higher rate of photosynthesis and food material production, and its subsequent translocation to bulbs. In dry soil conditions due to a high deficit irrigation regime with suboptimal N fertilization, adequate amounts of plant-available N would not be available in the rooting area and thus hindered plant N nutrition (Brewster, 1994). In the present study, the moderate plant N uptake in the SN treatment was the result of more soil evaporation and deep percolation losses of water during and after the irrigation events, unregulated N leaching, frequent soil–water stress, and distortion in water and nutrients, especially nitrogen absorption by the stunted root mass, which collectively decreased the photosynthesis and other metabolic activities, reduced assimilate production and partitioning that led to the moderate yield.

Economic evaluation of different irrigation and nitrogen management practices

The economic viability of various irrigation-nitrogen fertilization management strategies showed that under the conditions of adequate water and nitrogen resource availability, micro-sprinkler-based irrigation at 1.2 ETc coupled with 120% RDN (M_3N_3) was the best treatment combination to increase the net income by 30.6% with maximum BCR over surface irrigation with 100% RDN (SN). When there is a shortage of water or nitrogen resources, deficit irrigation at 0.9 ETc with 120% RDN (M_2N_3) or high irrigation at 1.2 ETc through micro-sprinkler with 100% RDN (M_3N_2) was the alternative that increased net incomes (17.2–19.1%), and modest BCR over the traditional SN method. Under scarce water and nitrogen supply, micro-sprinkler deficit irrigation at 0.9 ETc with 100% RDN (M_2N_2) was preferred over SN due to marginally higher net income (3.5%) with 50% less water usage.

Conclusions

Micro-sprinkler irrigation at 120% of crop evapotranspiration (ETc) in combination with 120% of the recommended nitrogen (RDN) fertilization produced the maximum bulb yield, higher water productivity, highest income generation and greater retention of plant available soil water and nitrogen in the root zone during the growing periods. However, as this study was only based on two seasons, more field trials will be needed to confirm the optimum amount of water and nitrogen for winter onion. In the context of limited water and nitrogen supplies, micro-sprinkler-based mild deficit irrigation at 0.9 ETc with 100% RDN is a viable alternative to farmers' traditional surface irrigation with 100% RDN (SN) due to competitive yield performance, marginally higher financial gains and reduced water usage for onion production.

Data availability. The original data supporting this study are included in the article and if additional data required can be available on request from the corresponding author.

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References

Abdissa Y, Tekalign T and Pant LM (2011) Growth, bulb yield and quality of onion (*Allium cepa* L.) as influenced by nitrogen and phosphorus fertilization on vertisol I. growth attribute biomass production and bulb yield. *African Journal of Agricultural Research* **6**, 3252–3258.

Anita Fanish S and Muthukrishnan P (2013) Nutrient distribution under drip fertigation systems. *World Journal of Agricultural Sciences* **9**, 277–283.

Archana HA and Maragatham N (2017) Nitrogen, phosphorus and potassium dynamics in soil under drip and micro sprinkler fertigation and its effects on turmeric yield. *Chemical Science Review and Letters* **6**, 2058–2062.

Bagali AN, Patil HB, Guled MB and Patil RV (2012) Effect of scheduling of drip irrigation on growth, yield and water use efficiency of onion (*Allium cepa* L.). *Karnataka Journal of Agricultural Sciences* **25**, 116–119.

Bandyopadhyay PK, Mallick S and Rana SK (2003) Actual evapotranspiration and crop coefficients of onion (*Allium cepa* L.) under varying soil moisture levels in the humid tropics of India. *Tropical Agriculture* **80**, 83–90.

Bhatti S, Sharma JC and Kakar R (2019) Effect of irrigation and nitrogen levels on nutrient uptake, water use efficiency and productivity of onion (*Allium cepa* L.) in Himachal Pradesh. *International Journal of Current Microbiology and Applied Sciences* **8**, 398–408.

Bijay K (2010) Indian Horticulture Database (2009). National Horticulture Board, Ministry of Agriculture, Government of India, Guragaon, p. 267.

Bodman GB (1942) Monograph for rapid calculation of soil density, water content and total porosity relationship. *American Society of Agronomy Journal* **34**, 885–903.

Bouma J (1981) Soil survey interpretation: estimating use-potentials of a clay soil under various moisture regimes. *Geoderma* **26**, 165–177.

Bouyoucos GJ (1962) Hydrometer method improved for making particle size analysis of soils. *Agronomy Journal* **54**, 464–465.

Brewster JL (1994) *Onion and Other Vegetable Alliums*. Wallingford: CAB International, p. 236.

Dhital M, Shakya SM, Sharma MD and Dutta JP (2015) Effect of different levels of nitrogen on commercial onion varieties for off season green production in Western Chitwan, Nepal. *International Journal of Research* **2**, 268–273.

Doorenbos J and Kassam AH (1979) Yield response to water. FAO Irrigation and Drainage Paper No. 33, FAO, Rome, Italy, p. 193.

Enchalew B, Gebre SL, Rabo M, Hindaye B, Kedir M, Musa Y and Shafi A (2016) Effect of deficit irrigation on water productivity of onion (*Allium cepa* L.). *Irrigation and Drainage Systems Engineering* **5**, 172.

Fatideh MM and Asil MH (2012) Onion yield, quality and storability as affected with different soil moisture and nitrogen regimes. *South-Western Journal of Horticulture, Biology and Environment* **3**, 145–165.

Gardenas AI, Hopmans JW, Hanson BR and Simunek J (2005) Two-dimensional modeling of nitrate leaching for various fertigation scenarios under micro-irrigation. *Agricultural Water Management* **74**, 219–242.

Gebregwergis F, Weldetsadik K and Alemayhu Y (2016) Effect of irrigation depth and nitrogen levels on growth and bulb yield of onion (*Allium cepa* L.) at Alage, Central Rift valley of Ethiopia. *International Journal of Life Sciences* **3**, 152–162.

Geries LSM, El-Shahawy TA and Moursi EA (2021) Cut-off irrigation as an effective tool to increase water-use efficiency, enhance productivity, quality and storability of some onion cultivars. *Agricultural Water Management* **244**, 106589.

Gholamhoseini M, Agha Alikhani M, Modarres Sanavy SAM and Mirlatifi SM (2013) Interactions of irrigation, weed and nitrogen on corn yield, nitrogen use efficiency and nitrate leaching. *Agricultural Water Management* **126**, 9–18.

Gomez KA and Gomez AA (1984) *Statistical Procedures for Agricultural Research*, 2nd Edn. Los Banos, Philippines: International Rice Research Institute.

Haile D, Nigussie D and Ayana A (2012) Nitrogen use efficiency of bread wheat: effects of nitrogen rate and time of application. *Journal of Soil Science and Plant Nutrition* **12**, 389–410.

Jackson ML (1973) *Soil Chemical Analysis*. New Delhi: Prentice Hall of India Pvt. Ltd.

Job M, Bhakar SR, Singh PK, Tiwari GS, Sharma RK, Lakhawat SS and Sharma D (2016) Water requirement and soil moisture distribution studies of drip irrigated onion crop under plastic mulched and non-mulched condition. *International Journal of Environmental Science and Technology* **5**, 176–184.

Kemal YO (2013) Effects of irrigation and nitrogen levels on bulb yield, nitrogen uptake and water use efficiency of shallot (*Allium cepa var. ascalonicum* Baker). *African Journal of Agricultural Research* **8**, 4637–4643.

Kumar S, Imtiyaz M, Kumar A and Singh R (2007a) Response of onion (*Allium cepa* L.). to different levels of irrigation water. *Agricultural Water Management* **89**, 161–166.

Kumar S, Imtiyaz M and Kumar A (2007b) Effect of differential soil moisture and nutrient regimes on postharvest attributes of onion (*Allium cepa* L.). *Scientia Horticulturae* **112**, 121–129.

Li J, Hong-yan JI, Li B and Li Y-C (2007) Wetting patterns and nitrate distributions in layered-textural soils under drip irrigation. *Agricultural Sciences in China* **6**, 970–980.

Lipovac A, Stricevic R, Cosic M, Durovic N (2022) Productive and non-productive use of water of common bean under full and deficit irrigation. *Acta Horticulturae* **1335**, 635–641. Proc. IX Int. Symp. on Irrigation of Horticultural Crops, Eds. C. Xiloyannis *et al.*.

Mane MS, Kadam GG and Patil ST (2014) Effect of irrigation levels on vegetative growth and yield characteristics in white onion (*Allium cepa* L.) in Konkan region. *International Journal of Agricultural Engineering* **7**, 422–426.

Moursy ME, Khalifa HE, Attia MM, Sayed MA and Osman AM (2007) Effect of organic and nitrogen fertilizers and plant densities on onion production in sandy soil under drip irrigation system. *Alexandria Journal of Agricultural Research* **55**, 103–108.

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Nawaz MQ, Ahmed K, Hussain SS, Rizwan M, Sarfraz M, Wainse GM and Jamil M (2017) Response of onion to different nitrogen levels and method of transplanting in moderately salt affected soil. *Acta Agriculturae Slovenica* **109**, 303–313.

Neeraja G, Reddy KM, Reddy MS and Rao VP (2001) Influence of irrigation and nitrogen levels on bulb yield, nutrient uptake and nitrogen use efficiencies in *rabi* onion (*Allium cepa*). *Indian Journal of Agricultural Sciences* **71**, 109–112.

Negash A, Mitiku H and Yamoah C (2009) Growth and bulb yield response of onion (*Allium cepa* L.) to nitrogen and phosphorous rates under variable irrigation regimes in Mekelle, Northern Ethiopia. *Journal of the Dry Lands* **2**, 110–119.

Nemat MA, Abd El-Kader AA, Attia M and Alva AK (2011) Effects of nitrogen fertilization and soil inoculation of sulfur-oxidizing or nitrogen-fixing bacteria on onion plant growth and yield. *International Journal of Agronomy* **2011**, 316856.

Okumura RS, Mariano DC and Zaccheo PVC (2011) Uso de fertilizante nitrogenado na cultura do milho. *Pesquisa Aplicada and Agrotecnologia* **4**, 226–244.

Olsen SR, Cole CV, Watanabe FS and Dean LA (1954) Estimation of available phosphorus extractable. *Nature* **213**, 418–419.

Pal P, Bam N, Patra SK and Ray R (2021) Deficit irrigation-nutrient coupling on growth, yield, fruit quality and water use efficiency of Indian jujube. *International Journal of Bio-resource and Stress Management* **12**, 142–150.

Patel N and Rajput TBS (2009) Effect of subsurface drip irrigation on onion yield. *Irrigation Science* **27**, 97–108.

Pawar DD, Dingre SK and Kale KD (2020) Productivity, storability and economics of micro-sprinkler fertigation for winter onion (*Allium cepa* L.) in semi-arid conditions. *International Journal of Bio-resource and Stress Management* **9**, 1096–1109.

Pejic B, Gvozdanovi-Varga J, Mili S, Ignjatovi-Cupina A, Krstic D and Cupina B (2011) Effect of irrigation schedules on yield and water use of onion (*Allium cepa* L.). *African Journal of Biotechnology* **10**, 2644–2652.

Pereira da Silva AJ, Coelho EF and de Miranda JH (2013) Efficiency of water application of irrigation systems based on microsprinkling in banana plantations. *Scientia Agricola* **70**, 139–146.

Piri H and Naserin A (2020) Effect of different levels of water, applied nitrogen and irrigation methods on yield, yield components and IWUE of onion. *Scientia Horticultarae* **268**, 109361.

Pooja Rani, Batra VK, Bhatia and AK and Shiwani (2018) Influence of drip irrigation and nitrogen fertigation on growth parameters of onion (*Allium cepa* L.). *International Journal of Current Microbiology and Applied Sciences* **7**, 2946–2951.

Rajput TBS and Patel N (2006) Water and nitrate movement in drip irrigated onion under fertigation and irrigation treatments. *Agricultural Water Management* **79**, 293–311.

Richards LA (1954) *Diagnosis and Improvement of Saline and Alkali Soils.* United States Salinity Laboratory Staff, Agriculture Hand Book No. 60. Washington, DC: United States Department of Agriculture, pp. 107–108.

Salari H, Hansra BS and Saharawat YS (2020) Effect of cultural practices on quality and yield of onion (*Allium Cepa* L. Var. Safid e Paisaye). *Journal of Ecoscience and Plant Revolution* **1**, 9–14.

Santos DV, Sousa PL and Smith RE (1997) Model simulation of water and nitrate movement in a level-basin under fertigation treatments. *Agricultural Water Management* **32**, 293–306.

Saxena AK, Singh S, Srivastava A and Gautam P (2008) Yield target approach under integrated nutrient management for assessing fertilizer requirements of onion in Mollisols of Uttarakhand. *Indian Journal of Horticulture* **65**, 302–306.

Shedeed SI, Zaghloul SM and Yassen AA (2009) Effect of method and rate of fertilizer application under drip irrigation on yield and nutrient uptake by tomato. *Ozean Journal of Applied Sciences* **2**, 139–147.

Shock CC, Feibert EB and Saunders LD (2007) Short-duration water stress decreases onion single centers without causing translucent scale. *HortScience* **42**, 1450–1455.

Simsek M, Tonkaz T, Kacira M, Comiekcioglu N and Dogan Z (2005) The effects of different irrigation regimes on cucumber (*Cucumis sativus* L.) yield and yield characteristics under open field conditions. *Agricultural Water Management* **73**, 173–191.

Sivasakthi S, Khanna M, Singh M, Parihar SS, Singh DK, Kumar R and Sahoo PN (2014) Distribution of water and nitrogen in soil under drip and micro-sprinkler irrigation fertigation of garlic (*Allium sativum* L.) crop. *Asian Journal of Applied Sciences* **7**, 453–469.

Subbiah BV and Asija VN (1956) A rapid procedure for determination of available nitrogen in soils. *Current Science* **31**, 196–198.

Thangasamy A (2016) Quantification of dry matter accumulation and nutrient uptake pattern of short day onion (*Allium cepa* L.). *Communications in Soil Science and Plant Analysis* **47**, 246–254.

Tolossa TT (2021) Onion yield response to irrigation level during low and high sensitive growth stages and bulb quality under semi-arid climate conditions of Western Ethiopia. *Cogent Food and Agriculture* **7**, 1859665.

Tripathi PC, Sankar V and Lawande KE (2017) Microirrigation in onion (*Allium cepa*) and garlic (*A. sativum*) – a review. *Current Horticulture* **5**, 3–14.

Tsegaye B, Bizuayehu T, Woldemichael A and Mohammed A (2016) Yield and yield components of onion (*Allium cepa* L.) as affected by irrigation scheduling and nitrogen fertilization at Hawassa area districts in southern Ethiopia. *Journal of Medical and Biological Science Research* **2**, 15–20.

Walkley A and Black IA (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* **37**, 29–38.

Worku A, Jalata Z and Nandeshwar BC (2020) Effect of deficit irrigation on yield and yield components of onion (*Allium cepa* l.) cultivars in Horo district, Western Ethiopia. *Advances in Crop Science and Technology* **8**, 454.

Zewdu JN (2014) Impact of irrigation and nitrogen levels on bulb yield, nitrogen uptake and water use value of shallot (*Allium cepa var. ascalonicum* Baker). *International Journal of Irrigation and Water Management* **2014**, 7. Available at www.internationalscholarsjournalsorg

Zheng J, Huang G, Wang J, Huang Q, Pereira LS, Xu X and Liu H (2013) Effects of water deficits on growth, yield and water productivity of drip-irrigated onion (*Allium cepa* L.) in an arid region of Northwest China. *Irrigation Science* **31**, 995–1008.