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Improving onion productivity and producer income through nitrogen management

T.M. Dinega [1], A. Haile [2], H.M. Beshir [2] (*)

[1] *Department of Plant Science, Alage ATVET College, P.O. Box 77, Algae, Ethiopia.*

[2] *School of Plant and Horticultural Sciences, Hawassa University, P.O. Box 05, Hawassa, Ethiopia.*

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(*) **Corresponding author:**
hussien@hu.edu.et

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Abstract: Intensifying nitrogen (N) management can improve yield and bulb quality in onions. A field experiment was conducted to determine the optimum N rate and application frequency for high onion productivity. Treatments comprised levels of nitrogen (N): 50, 100, 150, 200, or 250 kg ha^{-1}, and nitrogen application frequency: all at once, twice, three times, or four times. The N rate and application frequency affected growth performance, bulb characters, yield, and bulb quality of onions. The supplement of 150 kg ha^{-1} N at three times the application frequencies generated the highest marketable yield (46.5 t ha^{-1}) with the highest net benefit (626317 ETB ha^{-1}). Application of 150 kg ha^{-1} of inorganic nitrogen with three times the application frequency improves the marketable yield of onions with the highest and most acceptable net benefit. The intensive and economical use of inorganic nitrogen and its frequency of application increased the growth and economic yield of onions in field conditions.

1. Introduction

Intensive nutrient management for onions (*Allium cepa* L.) involves using fertilizer as efficiently as possible. The principle behind nutrient management is balancing soil nutrient inputs with crop requirements (Fekadu and Dandena, 2006). Nitrogen (N) is an essential nutrient whose deficiency limits crop productivity. Compared to other vegetables, onions require high amounts of nitrogen and are applied at different times during the growth (Geisseler *et al.*, 2022). The recovery of fertilizer can be low, 30 to 40% (Halvorson *et al.*, 2002; Sharma *et al.*, 2012), due to the shallow onion root system. Low N fertilizer recovery in onions is, in part, due to the variable amounts of mineral N present in the soil before sowing (Brewster, 2008). Appropriate N fertilizer management requires knowledge of crop demand and the time it is needed (IPNI, 2012).

A low rate of N causes a low yield of onions due to a shortage of N required for the chlorophyll pigment that is responsible for photosynthesis (Jilani *et al.*, 2004; Khan *et al.*, 2021). Excessive N is hazardous to the environment, weaken the foliage and predispose the plants to pathogenic diseases (Geary *et al.*, 2015). These factors decreased the potential of processing photosynthesis that resulted in yield reduction due to a decrease in assimilates in plant leaves (Reay *et al.*, 2012).

The frequency of N application affects the productivity of onions (Grant *et al.*, 2012). When applying N fertilizer all at once, more N is susceptible to denitrification, leaching, or volatilization. When N fertilizer is applied faster than plants can use it, soil bacteria convert it to nitrate and decrease N use efficiency (Zhang *et al.*, 2013).

The majority of small-scale farmers use less nitrogen and apply it all at once, which is sub-optimal (Shura *et al.*, 2022). There is often excessive application of N fertilizer by large-scale commercial farmers near harvest. It is assumed that synchronization of crop demand for N fertilizer and time of application with sufficient amounts improves yield of onions and reduces waste of N, reducing production costs and environmental pollution due to unused excess N leaching in different forms (Geisseler *et al.*, 2022). However, the optimum amount of N that matches the crop demand during the growth period is little explored. We hypothesized that the low N use efficiency of the onion due to its shallow and sparse root system can be improved by controlled application of N fertilizer during the growth period. Therefore, this work was conducted to determine the optimum N rate and proper application frequency during the growth period for economically feasible onion production.

2. Materials and Methods

Site description

The study was conducted at Alage Agricultural Technical Vocational Educational and Training College, near Bulbula Town, Ethiopia, under supplemental irrigation (when precipitation is lacking) from June to October 2021. The area is situated between 7°65" N latitude and 38°56" E longitude at 1600 m above sea level in the dry plateau of the southern part of the Ethiopian rift valley system. The area is characterized by a bimodal rainfall pattern where a short rainy season occurs during March and April and the main rain starts in June and extends to September, with high rainfall in July and August. The mean annual rainfall is 800 mm, and the annual mean minimum and maximum temperatures are 11 and 29°C, respectively. The soil of the area ranges from sandy loam to sandy clay loam, with some clay loam and a few clay soils, and is slightly alkaline, pH 7.8 (Alemayehu and Bewket, 2016).

Physico-chemical properties of the experimental field soil

Before planting, five soil samples were randomly taken from the field at a depth of 0 to 20 cm in a zigzag pattern using an auger. Samples were mixed to produce a representative composite sample of 1 kg. The soil sample was air-dried and ground to pass 2 and 0.5 mm (for total N) sieves and analyzed for total P, total N, pH, organic carbon (OC), exchangeable cations, and physical properties at the Batu Agricultural Research Centre Soil Laboratory.

The soil was a silty clay loam with 18.0% sand, 50.5% silt, and 31.5% clay. The soil was slightly alkaline in reaction, with a pH (H_2O 1:2.5) of 7.82, which is within the range of ideal soil pH for onion bulb production (Graham *et al.*, 2004). Total N, available P, organic carbon (OC), and CEC of the soil before planting were 0.12%, 11.48 mg kg^{-1}, 1.39%, and 31.74 cmol (+) kg^{-1}, respectively. The total N content of the soil was within the range of low, according to Havlin *et al.* (1999). The cation exchange capacity (CEC, 31.74 meq/100 g) of the soil was high according to the rating of Jackson (1975). The carbon-to-nitrogen ratio (C:N) was 11.5%.

Planting materials

The onion, cv. Bombay Red, was used. It is adapted to areas of 700 to 2000 m above sea level. The size of the bulb of this variety ranges from 85 to 90 g, with a yield potential of 25 to 30 t ha^{-1} under research conditions (Lemma and Shimeles, 2003). Sources of fertilizers were urea (46% N) and Triple Super Phosphate (TSP) (46% P_2O_5) for N and phosphorus, respectively. The nitrogen fertilizer was applied immediately after weeding. Onion seeds were sown 56 days before transplanting on a 1 m wide seed bed 10 m in length (area 10 m^2). Seedlings were grown under suitable conditions of fertilization, weeding, and pest control. Seven days before transplanting, seedlings were gradually exposed to field conditions and withheld from the water supply (hardened off) in the nursery, and then manually transplanted at 56 days old. The TSP was applied during transplantation. All cultural practices and crop protection measures (diseases and insect control) were carried out uniformly for all plots (EARO, 2004).

Treatments, design and experimental procedure

Treatments were arranged in factorial combinations in a randomized complete block design with three replications. While transplants were being developed, the soil was manually pulverized twice with an oxen-driven plough. After the soil was pulverized, levelling and ridge preparation were done with hoes and spades. Rates of N were: 50, 100, 150, 200, or 250 kg ha^{-1} in band application according to application frequencies, which were: NAF1 (all at once 1 week after transplanting), NAF2 (half of the N at 1 week after transplanting, another half of the N at 21 days after transplanting), NAF3 (one-third of the N at 1 week after transplanting, one-third of the N at 21 days after transplanting, and one-third of the N at 42 days after transplanting), or NAF4 (one-fourth at 1 week after transplanting, one-fourth of the N at 21 days, one-fourth of the N at 42 days after transplanting, and one-fourth of the N at 63 days after transplanting). Treatment combinations were assigned randomly to experimental units within each block. The national blanket recommendation of N fertilizer for onion production is 100 kg ha^{-1}, which could be considered a control treatment. Double row planting was done by hand on ridges about 20 cm high at a spacing of 40 cm for water furrows, 20 cm between rows on raised beds, and 5 cm between plants within rows. There were 60 plots corresponding to the 20 treatment combinations with three replications. The unit plot size of the experiment was 2 x 2.5 m (5 m^2). Blocks were separated by 1.5 m, and the space between each plot within a block was 1 m. In each plot, 10 rows were prepared, and in each row, 50 seedlings were manually planted. Generally, 500 onion seedlings were planted per plot. The outer 2 rows on both sides of the plot and the 2 plants at both ends of the rows were border plants. The plants in the six central rows were used for measurements.

Data collection

Ten plants were randomly selected from each plot's central six rows, and data on growth performance, quality indicators, and yield components were recorded for each of them. For the data on bulb yield, all of the plants in each plot were harvested. Thus, the following information was collected:

Maturity and growth parameters

Days to maturity were recorded as the number of days from seedling transplanting to a day at which more than 80% of the plants in each plot showed yellowing of leaves or attained physiological maturity. Plant height was measured from the ground to the tip of the leaves on 10 randomly selected plants from the central rows in each plot at maturity. Leaf length was recorded at physiological maturity from the sheath to the tip of the leaf from the third youngest leaves of ten representative plants, which was used to count the number of leaves per plant using a ruler. Leaf diameter was measured from the third-youngest leaves at the bottom, middle, and tip parts of the leaves from ten randomly selected plants using a veneer caliper. Leaf number per plant was counted as the total number of leaves from 10 randomly selected plants at maturity, and the average of the ten plants was taken. The aboveground biomass was harvested by cutting the plant at the crown part, drying it in an oven at 650°C until a constant weight was attained, and the shoot dry matter was determined and expressed in grammes at harvest. Additionally, the total dry biomass was determined by summing the shoot and bulb dry weights of the sample.

Yield and yield related parameters

The mean bulb diameters of ten sample bulbs were measured at the maximum wider portion of matured bulbs using calipers. The bulb length of ten sample bulbs was measured along the length of the bulb from the basal end to the top end, at which the bulb neck was removed from matured bulbs using calipers after harvest. The average fresh weight of ten randomly taken mature bulbs was measured using a sensitive balance and finally expressed in grammes. Fir bulb dry weight Ten bulbs were randomly taken from each plot and chopped, mixed thoroughly, placed in an aluminum paper bag, and put in the oven to dry at 650°C until a constant dry weight was attained. Then each sample was immediately recorded as a bulb's dry weight. The bulb dry matter concentration (%) was determined by randomly selecting ten bulbs from each plot and chopping them, mixing them thoroughly, then weighting them and recording the fresh weight. Then each subsample was placed in an aluminum paper bag and put in an oven at 650°C until constant dry matter was attained. Each sub-sample was then immediately weighed and recorded as a dry matter yield. The dry matter concentration was determined using the loss weight, and the fresh sample was weighed to the nearest gramme using the formula set by Ruck (1969) and Dantata (2014):

$$\text{Bulb dry matter concentration} = \frac{\text{Bulb dry weight}}{\text{Bulb fresh weight}} \text{ x } 100$$

Marketable bulb yield (t ha^{-1}) was determined from the weight of healthy and marketable bulbs that range from 20 g to 160 g in weight (Lemma and Shimeles, 2003). The marketable yield was determined from the net plot at the final harvest. Unmarketable bulb yield (t ha^{-1}) was measured as the total weight of unmarketable bulbs that are undersized (<20 g), diseased, decayed, and bulbs from plants with physiological disorders such as thick neck and split were measured from a net plot at final harvest.

Undersized bulb yield (t ha^{-1}) was determined by taking under sized bulbs (<20 g) as unmarketable bulbs per net plot and converted to t ha^{-1} as determined. Total bulb yield (t ha^{-1}): The total bulb yield was measured from the total harvest of net plot as a sum weight of marketable and unmarketable yields that was measured in kg per plot and finally converted into t ha^{-1}. Harvest index (%) was expressed as the ratio of total bulb dry weight to the total biomass dry weight and expressed in percentage.

$$\text{Harvest index (HI)} = \frac{\text{Bulb dry weight}}{\text{Total dry biomass}} \times 100$$

The TSS was determined at harvesting time from ten randomly selected bulbs per plot using the procedures described by Waskar *et al.* (1999). Aliquot juice was extracted using a juice extractor, and 50 ml of the slurry was centrifuged for 15 minutes. The TSS was determined by a hand refractometer (ATAGO TC-1E) with a range of 0 to 32 Brix and resolutions of 0.20 Brix by placing 1 to 2 drops of clear juice on the prism, washing it with distilled water, and drying it with tissue paper.

Data analysis

Data were subjected to analysis of variance using Stat-8 software (ver. 8.1.1, Analytical Software, Tallahassee, FL). Assumptions of ANOVA were tested, and no violation was observed. The data analysis was done with a generalized linear model. The N rate and application frequency were fixed effects, and the block was random. If the interaction was significant, it was used to explain the results. If the interaction was not significant, the main effects were separated using LSD (Walter and Duncan, 1969).

Economic analysis

A partial budget analysis was made to determine the exact rate of return that producers gain on their investment by changing existing cultural practices to alternative ones. The potential response of added fertilizer corresponding to labor costs and the price of fertilizers (variable costs for urea fertilizer at 16.2 birr) throughout the crop growing season was evaluated. The birr is the local currency. 1 birr is equal to 0.031 US during the growth period. The economic outcome was analyzed using agronomic indices for N and its frequencies. The economic analysis was computed using accepted procedures (CIMMYT, 1988), where: Avy (gross average bulb yield, average yield of each treatment); Ajy (adjusted yield, the average yield adjusted downward by 10% to reflect the difference between experimental yield and yield of the farmers); GFB (gross field benefit determined by multiplying field price that farmers receive for the crop by adjusted yield); NFB (net field benefit calculated by subtracting total costs from gross field benefit; GFB for each treatment); and MRR (marginal rate of return %) calculated by dividing change in net benefit by the marginal cost reflecting change in cost (CIMMYT, 1988).

3. Results and Discussion

The main effects of N rate and application frequency influenced plant height, leaf length, leaf width, and number of leaves. The interaction effect of two factors was not significant for these parameters. Plant height increased with increasing N rate from 50 to 250 kg ha^{-1} N. The tallest and shortest onion plants were at 250 kg ha^{-1} and 50 kg ha^{-1}, respectively. Onions treated with N at 250 kg ha^{-1} exceeded their mean height by 34.23% compared with the 50 kg ha^{-1} N-treated onions (Fig. 1A). In response to An N application frequency, the tallest plants were for 3 time's N application (Table 1). Application of N at all frequencies (once, twice, and four times) was not different for plant height. The increase in plant height with the addition of higher N fertilizer could be attributed to the increased availability of N for growth as a result of protein synthesis and the accumulation of carbohydrates (Rizk, 2012). The tallest plants recorded at three applications of N may be because of increased N use efficiency, decreasing N loss by leaching and volatilization (Rizk, 2012). Application of N three times better matched the availability of N with crop N demand compared to application all at once, or 2 or 4 applications of N (Brewster, 2008). This result is consistent with the findings of Morsy *et al.* (2012) and Nasreen *et al.* (2007), who reported onion plant height increased as

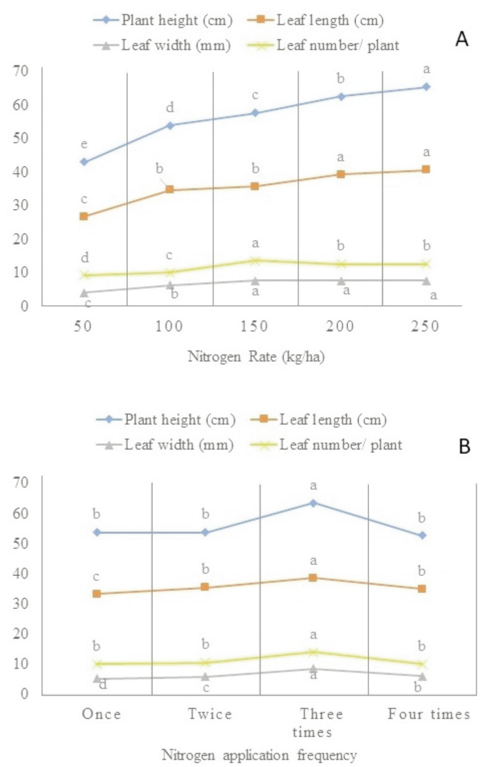

Fig. 1 - The effect of nitrogen rate (A) and application frequency (B) on plant height, leaf length, leaf diameter and leaf number of onion.

N fertilizer rate increased.

Shorter leaves were from the 50 kg ha^{-1} N that decreased by about 31.56% and 33.95% compared to values obtained from 200 and 250 kg ha^{-1} N, respectively (Fig. 1). The effects of 100 and 150 kg ha^{-1} N were similar. The influence of N rate at 200 and 250 kg ha^{-1} was not significant for leaf length. The longest and shortest leaves were when N fertilizer was applied three times and all at once, respectively (Fig. 1B). These values agree with Rao *et al.* (2013), who reported that higher N fertilization increased onion leaf length, and Khan *et al.* (2002), where the longest leaves were when N was applied three times. Increased leaf length at three times N applications could be due to increased recovery of N by onions and decreased N loss (Ali and Ceyhan, 2001).

The narrowest leaves were from plants treated with 50 kg ha^{-1} N. Leaf diameter increased with increased N, from 50 to 150 kg ha^{-1}. The N rates of 150, 200, and 250 kg ha^{-1} had similar leaf diameters (Fig. 1A). Leaf diameter was influenced by the frequency of N applications. Three times N application increased leaf diameter by 38.99% compared to applying N all at once (Fig. 1B). The increase in leaf diameter with an increase in N rate from 50-150 kg

Table 1 - Interaction effects of N rate and application frequency on bulb size, marketable bulb yield, total bulb yield, bulb dry weight, total dry biomass, and total soluble solids of onions

Treatments		Average bulb size (g plant^{-1})	Marketable bulb yield (t ha^{-1})	Total bulb yield (t ha^{-1})	Bulb dry weight (g plant^{-1})	Total dry biomass (g plant^{-1})	Total soluble solids (°Brix)
Nitrogen rate (kg ha^{-1})	Nitrogen application frequency						
50	Once	31.55 k	25.75 j	28.00 k	5.01 i	3.65 i	9.27 i
	Twice	40.23 j	31.17 hi	33.17 ij	6.12 h	3.83 h	10.17 h
	Three times	44.25 ij	33.58 gh	35.00 hij	7.08 g	4.58 gh	10.47 fg
	Four times	43.44 ij	30.43 i	32.38 j	7.45 g	4.94 g	10.03 gh
100	Once	53.00 hi	29.52 i	32.33 j	8.72 f	6.00 f	10.73 efg
	Twice	56.27 gh	34.42 fg	36.00 ghi	8.95 f	6.15 ef	11.05 def
	Three times	57.88 fgh	39.48 de	41.12 de	10.15 e	6.92 de	11.59 cd
	Four times	63.52 defg	36.27 fg	38.00 fg	9.19 f	6.13 ef	11.0 2def
150	Once	62.92 efgh	30.78 hi	33.32 ij	10.42 e	7.37 cd	10.62 fg
	Twice	82.33 b	45.17 bc	46.97 b	12.01 cd	8.83 b	11.06 def
	Three times	94.00 a	46.95 a	48.84 a	13.95 a	9.79 a	12.30 b
	Four times	66.39 cdefg	43.5 bc	45.16 bc	11.39 d	7.85 c	11.14 def
200	Once	69.67 cde	33.75 fgh	36.18 gh	11.67 d	7.87 c	10.42 fg
	Twice	75.35 bc	42.5 bcd	44.37 bc	12.15 cd	8.19 bc	11.36 de
	Three times	70.29 cde	42.50 bc	45.08 bc	12.95 b	8.81 b	12.36 b
	Four times	70.79 cde	43.83 bcd	45.57 bc	12.79 bc	8.25 bc	11.37 de
250	Once	66.00 defg	36.73 ef	39.33 ef	11.93 cd	7.87 c	10.73 efg
	Twice	67.92 cdef	42.92 bc	39.32 ef	12.74 bc	8.19 bc	11.15 def
	Three times	73.51 bcd	47.88 bcd	45.04 bc	12.77 bc	8.81 b	13.13 a
	Four times	69.59 cde	43.92 ef	43.60 cd	12.72 bc	8.25 bc	12.24 bc
LSD		10.28	3.124	2.84	0.9	0.9	0.74
α		**	**	**	*	**	**
CV (%)		9.88	5.02	4.33	5.17	7.64	4.02

Means followed by the same letters within a column are not significantly different at P<0.05.

ha^{-1} and 3 applications of N could be associated with a better supply of N and better N use efficiency. Application of N with three or more applications and a higher supply of N could increase leaf thickness, capture resources for photosynthesis, and promote better growth and development. The lowest leaf diameter was due to the low N rate applied to onions (Abdissa *et al.*, 2011; Woldeyohannes *et al.*, 2013; Seid *et al.*, 2014).

Increasing N from 50 to 150 kg ha^{-1} increased leaf number. Beyond 150 kg ha^{-1}, the number of leaves decreased. Onion leaf number increased as the N fertilizer rate increased from 50 to 150 kg N ha^{-1} (Fig. 1A). Increasing N frequency from one to three applications increased leaf number. At 4 N applications, leaf number decreased (Fig. 1B). This may be due to a lack of enough nitrogen at the early growth stage at which leaf formation was initiated. When N is applied four times during the growth period, a quarter of it will not be used by the onion plants for the initiation of leaf formation due to late application (Geisseler *et al.*, 2022). Increases in the number of leaves with a further increase in the rate of N could be attributed to enhanced photo-assimilate production, cell division, and vegetative growth (Suthar, 2009). The N plays a role in leaf production and vegetative growth (Nasreen *et al.*, 2007). Increases in the number of leaves per plant with up to 3 applications of N may be attributed to increasing N use efficiency (Geisseler *et al.*, 2022). This indicates that one-third of the N fertilizer in the first application was enough for leaf number production and vigorous vegetative growth, which agrees with Mengel *et al.* (2006).

Bulb diameter and bulb length were influenced by N rate and N application frequency, but the interaction of N rate and frequency was not significant. Increasing the N rate from 50 to 150 kg ha^{-1} increased bulb diameter by 43.66%. Increasing the N rate beyond 150 kg ha^{-1} did not increase bulb diameter (Fig. 2B). The widest bulbs were for the 3-times N application (Fig. 2B), which agrees with Nasreen *et al.* (2007). Development of wider bulbs with increasing frequency and rate of N fertilizer could be associated with the availability of more growth resources due to efficient N use as bulbs develop. Increasing N rate and split application are associated with promoting cell elongation, above-ground vegetative growth, and the synthesis of chlorophyll, resulting in dark green leaves (Geisseler *et al.*, 2022). These results agree with Soleymani and Shahrajabian (2012) and Ghaffoor *et al.* (2003).

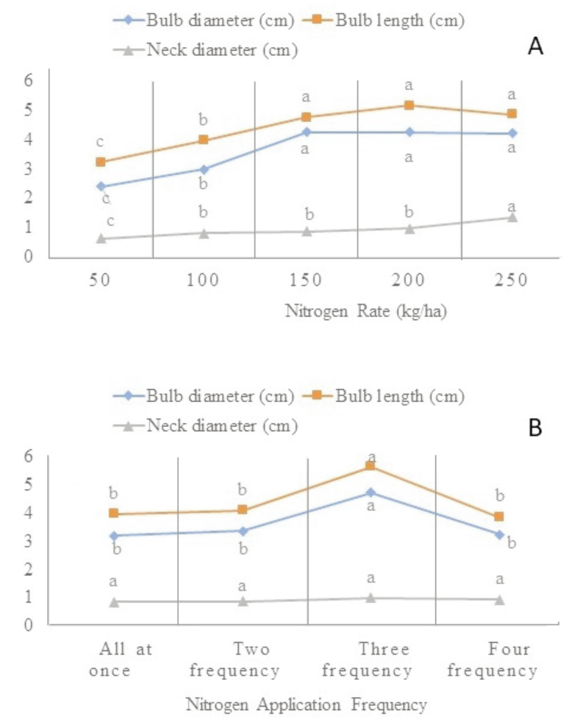

Fig. 2 - The effect of nitrogen rate (A) and application frequency (B) on bulb diameter, bulb length and bulb neck of onion.

Increasing the rate of N application from 50 to 150 kg ha^{-1} increased bulb length. At N rates of 150, 200, or 250 kg ha^{-1} bulb lengths were similar (Fig. 2A). Increasing application frequency up to three times increases bulb length. When all N fertilizer was applied at once, bulb length was reduced (Fig. 2B). The reason for the longest bulbs at 150 kg ha^{-1} N could be the supply of optimum N (Fageria and Baligar, 2005). The increase in bulb length at 3 N applications might be due to the recovery of N by onions and its subsequent use for growth (Singh and Chaure, 1999; Bahadur and Singh, 2005; Mengel *et al.*, 2006).

Bulb neck thickness was only affected by the N rate. The widest bulb necks were due to the application of 250 kg ha^{-1} N, and the narrowest bulb neck diameter was 50 kg ha^{-1} N (Fig. 2A). The reason for the widest neck diameter at 250 kg ha^{-1} N rate might be due to high N that resulted in excessive vegetative growth and delayed maturity, resulting in a large neck size (Grant *et al.*, 2012; Morsy *et al.*, 2012). The increase in neck diameter might show its involvement in the synthesis of amino acids, as they link together to form proteins and make up metabolic processes required for plant growth, including neck thickening (Jilani, 2004).

The main effects of N rate and N application frequency influenced the shoot dry matter weight and harvest index of onion plants. The interaction effect of an N application and its application frequency was not significant. The unmarketable yield was only affected by the N rate. Bulb dry matter, dry total biomass weight, bulb fresh weight, marketable bulb yield, total soluble solids, and total bulb yield were affected by the interaction effect of N rate and application frequency in addition to the main effects.

The highest shoot dry matter weight was 250 kg ha^{-1} N. As the N rate increased from 50 to 250 kg ha^{-1}, the shoot dry matter of onions increased by 50.51% (Fig. 3A). This might be due to excessive vegetative growth that resulted from the application of excess N (Kandil *et al.*, 2013). The lowest shoot dry weight yield on 50 kg ha^{-1} N might also be because of N deficiency, which limits cell division and expansion, chloroplast development, chlorophyll concentration, and enzyme activity (Soleymani and Shahrajabian, 2012). The highest shoot dry matter weight per plant was at 3 N applications. The lowest shoot dry matter weight was from treatment at N applied once (A). Shoot dry matter yield from 3 applications of N increased by 17.42% compared to shoot dry matter produced when N was applied at one time (Fig. 3B). Three applications of N fertilizer increased the N use efficiency of onions (Sharma, 1992). The present finding agrees with Nasreen *et al.* (2007), who indicated the shoot dry matter weight increased with an increment of N fertilizer rate applied three times.

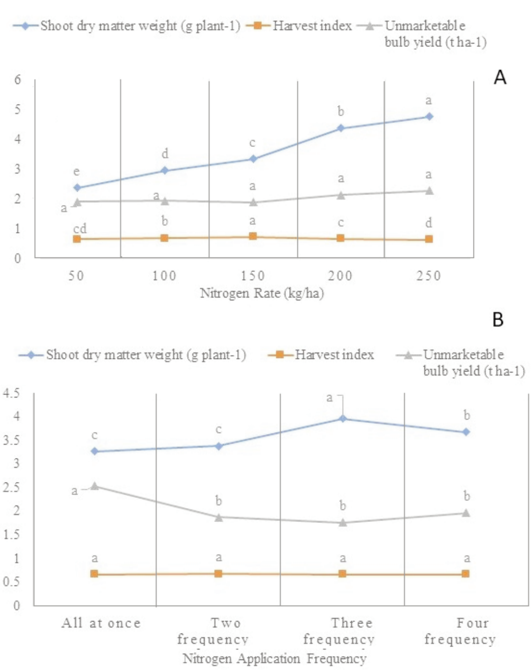

Fig. 3 - The effect of nitrogen rate (A) and application frequency (B) on shoot dry matter, harvest index and unmarketable yield of onion.

The harvest index was increased from 63.74 to 71.51% as N was increased from 50 to 150 kg ha^{-1}. Beyond 150 kg ha^{-1} N, the harvest index decreased (62.2% at 250 kg ha^{-1} N) due to increase aboveground dry biomass compared to the bulb weight of onions. The harvest index recorded at 50 kg ha^{-1} N was similar to that recorded at 200 and 250 kg ha^{-1} N (Fig. 3A). The average harvest index across all N rates was 66.2%. The highest harvest index at 150 kg ha^{-1} N might be due to increased bulb weight due to enough N sufficient for photosynthesis and assimilate production that increased bulb dry weight with optimum above ground biomass resulting in a higher harvest index (Geisseler *et al.*, 2022). The low harvest index from treatment with 50 kg ha^{-1} was due to low bulb dry matter weight due to N deficiency (Nasreen *et al.*, 2007). The low results obtained from 200 and 250 kg ha^{-1} might be because of etiolated growth of aboveground biomass and low bulb growth performance resulting from the application of excess N (Negash *et al.*, 2009; Abdissa *et al.*, 2011).

With increasing frequency of N up to 3 applications, the unmarketable bulb yield of onions decreased. The highest value of unmarketable bulb yield was all N applied once. This was followed by the 4N applications. The lowest unmarketable bulb yield was 3 N applications (Fig. 3B). The unmarketable yield from the application of all N at once was exceeded by the unmarketable yield from three applications of N. This may be due to the loss of N because of volatilization and leaching of N, which decrease N use efficiency if N supply is sufficient. Sustainable application of N during the active growth period can decrease unmarketable bulb yield (Balemi *et al.*, 2007; Biesiada and Kołota, 2009; Soleymani and Shahrajabian, 2012).

Increasing the rate of nitrogen application up to 150 kg ha^{-1} increased the average bulb weight by increasing the frequency of nitrogen application up to three times. The highest average fresh bulb weight was recorded at an N rate of 150 kg ha^{-1} applied three times (Table 1). This treatment approximated the expected bulb weight for the cultivar. The lowest bulb size was for the 50 kg ha^{-1} N all applied at once (Table 1). Application of 150 kg ha^{-1} N three times exceeded the lowest fresh bulb weight recorded at 50 kg ha^{-1} N all applied at once by 66.4%.

The increase in fresh bulb weight with an increase in nitrogen fertilizer rate might be due to a sufficient supply of nitrogen that enhances cell division and expansion, chloroplast development, chlorophyll concentration, and enzyme activity. The increase in fresh bulb weight with increasing nitrogen application frequency up to 3 times might be due to the increasing matching of the crop demand for N with the plant requirement for N (Khan *et al.*, 2002; Yadav *et al*., 2003). When all of the nitrogen is supplied ahead of crop growth, more of that nitrogen is susceptible to denitrification, leaching, or volatilization (Brady, 1985).

Increasing the N from 50 to 150 kg ha^{-1} increased the production of marketable bulbs across the board by increasing the N application frequency up to three times. Beyond that, marketable bulb yield was not increased. The highest marketable bulb yield was from onions, which provided 150 kg ha^{-1} N in 3 applications. The lowest marketable bulb yield was in response to 50 kg ha^{-1} N applied at once (Table 1). This might be attributed to an optimum rate of N fertilizer and sustained application of N in relation to the demand of the crop, with reduced loss of N. Split applications can be timed to match the N available with crop demand. This reduces the residence time of fertilizer N in the soil and the risk of N being lost. The marketable bulb yield of onions per unit area is a function of the N dose supplied and the application frequency of N fertilizer (Naik and Hosamani, 2003; Latif *et al.*, 2010). A higher marketable bulb yield was achieved at a 150 kg ha^{-1} rate of N fertilization applied three times (Balemi *et al.*, 2007; Soleymani and Shahrajabian, 2012).

Total bulb yield increased in response to increasing N rates up to 150 kg ha^{-1} across increasing frequency of N application up to 3 times. The highest total bulb yield was obtained from onion plants at 150 kg ha^{-1} N and 3 applications (Table 1). The lowest total bulb yield was in response to the application of N at 50 kg ha^{-1} all at once. The increased total bulb yield in response to 150 kg ha^{-1} N and 3 applications might be due to plants receiving enough N. High N use efficiency and crop recovery occurred when N was applied 3 times during active growth (Tsai *et al.*, 2012). The decrease in total bulb yield with application of N beyond 150 kg ha^{-1} might be due to luxury consumption of N that affects onion plant metabolism by decreasing the ability of the root surface to absorb phosphorus and decreasing the assimilate preparation (Mahdieh *et al.*, 2012). The highest bulb yield due to the application of 150 kg ha^{-1} N applied three times agrees with Gebremedhin *et al.* (2018). Enhanced leaf number and length may lead to increased assimilate production and increased bulb yield (Geisseler *et al.*, 2022). The dose of N up to 120 kg ha^{-1} increased total bulb yield, but below this rate, total bulb yield decreased (Jilani *et al.*, 2004). A low rate of N applied all at once produced lower total yields compared to higher N doses applied in 3 splits (Balemi *et al.*, 2007; Soleymani and Shahrajabian, 2012).

Plants treated with 150 kg ha^{-1} N applied three times produced the highest total dry biomass. Plants treated with 50 kg ha^{-1} N all at once produced the lowest dry total biomass weight (Table 1). The total dry biomass from plants treated with 150 kg ha^{-1} N applied three times was about 64.09% higher than the lowest total dry biomass weight produced by onion plants treated with 50 kg ha^{-1} N applied all at once (Table 1). An increase in total dry biomass in response to an increasing rate of N may be associated with sufficient supply and efficient use, which enhance vegetative growth and contribute to an improved rate of photosynthesis and assimilate production (Nasreen *et al.*, 2007; Sikder *et al.*, 2010; Daniel *et al.*, 2021).

Total soluble solids increased with increasing N across the frequency of application. The highest total soluble solids were for plants grown at 250 kg ha^{-1} N with 3 applications. The lowest total soluble solids were for plants grown at 50 kg ha^{-1} N applied all at once (Table 1).

Total soluble solids from treatment with 250 kg ha^{-1} N applied three times exceeded total soluble solids obtained at 50 kg ha^{-1} N applied all at once by about 29.4% (Table 1). The possible reason for increasing total soluble solids with a higher application rate of N along with increasing N application frequency might be increased chlorophyll content and dry weight per plant (Naik and Hosamani, 2003; Mengel *et al.*, 2006; Moursy *et al.*, 2007; Morsy *et al.*, 2012).

The minimum acceptable MRR is 100% (CIMMYT, 1988). The labor cost for applying N fertilizer was increased depending on the labor required for each N fertilizer application frequency. The cost of labor for N fertilizer application was 100, 200, 300, and 400 birr ha^{-1} for 1, 2, 3, or 4 applications of N fertilizer, respectively. The field price of onions during harvesting was 15 birr per kg. All total variable costs were subtracted from the gross benefit to obtain the net benefit (Table 2).

Table 2 - Cost benefit analysis[z] of nitrogen and its application frequencies

Nitrogen rate	Nitrogen application frequency	Average marketable yield	Adjusted marketable yield [y]	Gross field benenit	Nitrogen cost	Labour cost for nitrogen application	Total variable cost	Net benefit	Dominance	Marginal rate of return (%)
50	Once	25.75	23.18	347700	1761	100	1861	345839	-	-
50	Twice	31.17	28.05	420750	1761	200	1961	418789	N	729.50
50	Three times	33.58	30.22	453300	1761	300	2061	451239	N	324.50
50	Four times	30.43	27.39	410850	1761	400	2161	408689	D	
100	Once	29.52	26.57	398550	3522	100	3622	394928	D	
100	Twice	34.42	30.98	464700	3522	200	3722	460978	N	5.90
100	Three times	39.48	35.53	532950	3522	300	3822	529128	N	681.50
100	Four times	36.27	32.64	489600	3522	400	3922	485678	D	
150	Once	30.78	27.43	411450	5283	100	5383	406067	D	
150	Twice	45.17	40.65	609750	5283	200	5483	604267	N	45.24
150	Three times	46.95	42.26	633900	5283	300	5583	628317	N	240.50
150	Four times	43.5	39.15	587250	5283	400	5683	581567	D	
200	Once	33.75	30.38	455700	7044	100	7144	448556	D	
200	Twice	42.5	38.25	573750	7044	200	7244	566506	D	
200	Three times	42.97	38.673	580095	7044	300	7344	572751	D	
200	Four times	43.83	39.45	592750	7044	400	7444	585306	D	
250	Once	36.73	33.06	495900	8805	100	8905	486995	D	
250	Twice	42.92	38.63	579450	8805	200	9005	570445	D	
250	Three times	42.5	38.25	573750	8805	300	9105	564645	D	
250	Four times	41.25	37.125	556875	8805	400	9205	547670	D	

[z] The analysis was performed according to accepted procedures (CIMMYT, 1988).

[y] Adj. yield = adjusted marketable yield downward by 10%.

[w] D = dominated (any treatment that has net benefits that are less than or equal to those of a treatment with lower costs that vary is dominated; CIMMYT, 1988).

N = non-dominated, *= the exchange rate of the US dollar to birr was 38 birr in 2021.

Partial budget analysis indicated the highest MRR of 7.295% was from an application of 50 kg ha^{-1} N rate in 2 applications. For every 1 birr invested in 100 kg ha^{-1} N applied three times, growers can expect to recover the 1 birr and obtain an additional 7.295 birr. The higher net benefit with an acceptable MRR of 240.50% was from 150 kg ha^{-1} N applied three times (Table 2). The most attractive combinations for farmers were in response to an application of 150 kg ha^{-1} N, which provided three times the highest marketable yield and net benefit. Onion producers may maximize their net benefit by using 150 kg ha^{-1} of N applied three times.

4. Conclusions

The interaction of N rate and application frequency resulted in the highest total bulb yield (48.84 g plant^{-1}), marketable bulb yield (46.95 t ha^{-1}), total dry biomass weight (13.5 g plant^{-1}), and bulb dry biomass yield (9.7 g plant^{-1}), when the combination of N rate at 150 kg ha^{-1} and three times application frequencies of N was realized. The highest value of total soluble solids (13.13°Brix) was recorded at the treatment combination of 250 N kg ha^{-1} with three times the application frequency. The partial budget analysis revealed that the highest net benefit of Birr 628317 with an acceptable MRR of 240.5% was obtained from the application of N at 150 kg ha^{-1} and three frequencies of N application. Generally, the treatment combination of an N rate of 150 kg ha^{-1} with three times the N application frequency can be recommended to achieve a high bulb yield of onions with the highest net benefit.

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