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Response of Onion to Deficit Irrigation Levels at Different Growth Stages on Yield and Water Productivity

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Abstract

The Ethiopian vegetable sub-sector, particularly onion, is crucial for the economy due to its high productivity and ease of cultivation. However, water scarcity in arid and semi-arid regions hinders its expansion. This study conducted at Wondo Genet Agricultural Research Center aimed to investigate the impact of deficit irrigation levels at various growth stages on onion yield and water productivity. The experiment employed a split plot design with four crop growing stages and three deficit irrigation levels. Results revealed that deficit irrigation significantly affected onion growth parameters and yield components. Bulb diameter, number of leaves per plant, and total bulb yield 5.84 cm, 6.85, 23.26 t/ha, respectively, were notably influenced by deficit irrigation levels, with the highest yields observed under full irrigation. Additionally, water use efficiency varied with deficit irrigation application timing, with the highest efficiency recorded during the maturation stage. Overall, deficit irrigation during initial and maturation stages at 55% ETc application level emerged as the most viable option, ensuring sustainable crop production in water-scarce areas. These findings underscore the importance of adopting deficit irrigation strategies to optimize water use efficiency and enhance onion yield in Ethiopia's vegetable sub-sector.

Keywords: Deficit, Onion, Growth Stage, Water Efficiency

1. Introduction

The vegetable sub-sector is one of the important sub-sectors of the Ethiopian economy. The high productivity and short growing period of vegetables, as compared to cereals and other annual crops, enable up to three production cycles per year, thus making vegetables the most preferred crop for irrigated agriculture (Etissa *et al*., 2016) [8]. Onion ranked the second in production of all vegetable crops next to tomato (Bossie *et al*., 2009) [3]. The area cultivated under onion is increasing from time to time, mainly due to its high profitability per unit area and ease of production, and increases in small scale irrigation areas. However, the expansion of irrigable land is highly constrained by a shortage of irrigation water in potential areas mainly arid and semi-arid areas (Nigussie *et al*., 2015; Etana *et al*., 2019) [9, 7].

The sustainable use of water in agriculture has become a major alarm. The adoption of strategies for saving irrigation water and maintaining acceptable yields may contribute to the preservation of this ever more restricted resource (Topçu *et al*., 2007) [10]. To alleviate these constraints, practicing deficit irrigation could increase the irrigation area with a limited yield reduction, which is likely to be more than compensated by a substantial increase in economic returns. To satisfy many users, water productivity should be increased. Deficit irrigation is known to increase water productivity with an insignificant or minimum yield reduction. A recent innovative approach to saving agricultural water is conventional deficit irrigation (Chai *et al*., 2016) [4].

The region surrounding to the study area holds immense potential for irrigation farming, owing to its surplus labor force and fertile land conducive to growing various vegetable crops. However, frequent competition among farmers for limited irrigation water resources often leads to conflicts among users. Therefore, the primary objectives of this study were to explore the impact of deficit irrigation levels at different growth stages on onion yield and water productivity, as well as to identify the growth stages of onions most sensitive to deficit irrigation levels.

2. Materials and Methods

2.1 Treatments and Experimental Design

A field experiment was conducted at Wondo Genet Agricultural Research Center. The experimental treatments were four crop growing stages (initial, development, bulb formation and maturation stages) and three deficit irrigation levels (85% ETc, 70% ETc and 55% ETc levels) and control irrigation of 100% ETc. The design of the experiment was a split plot design with three replications. The growing stages were arranged as a main plot and the deficit irrigation levels as sub-plots.

Table 1: Treatment combination

Main plot	Sub plot	Code
Initial stage	Irrigated at 100% ETc	T1
	Irrigated at 85% ETc	T2
	Irrigated at 70% ETc	T3
	Irrigated at 55% ETc	T4
Development stage	Irrigated at 100% ETc	T5
	Irrigated at 85% ETc	T6
	Irrigated at 70% ETc	T7
	Irrigated at 55% ETc	T8
Bulb formation stage	Irrigated at 100% ETc	T9
	Irrigated at 85% ETc	T10
	Irrigated at 70% ETc	T11
	Irrigated at 55% ETc	T12
Maturation stage	Irrigated at 100 % ETc	T13
	Irrigated at 85 % ETc	T14
	Irrigated at 70 % ETc	T15
	Irrigated at 55% ETc	T16

The main plot size was 3m by 16.5 m and the net plot size was 9 m^2. Each plot accommodated five planting ridges of 3 m long with spacing of 60 cm; spacing between two blocks was 3m. All plots were receiving 100% ETc except during the plant growth stages marked for the treatment.

2.2 Experimental Material

The *Bombay Red* onion variety was used as experimental material. It is well adapted to altitudes ranging from 700 to 2000 m.a.s.l. and widely cultivated in the study area. It also has light red skin color, reddish white bulb flesh color, a light pungent smell; a flat globe shaped a bulb with bulb size of 85 to100 gm. and can mature in 100 to120 days. The variety was released from the Melkasa Agricultural Research Center in 1980. Its yield potential is 30 t/ha. Bombay Red is susceptible to purple blotch disease; however, it is successfully produced by small farmers and commercial growers in most regions of the country (EARO, 2004).

2.3 Crop Establishment and Management Practices

The seeds were sown on a well-prepared seedbed of 1 m x 10 m at a seed rate of 100 grams/bed. The seedling management practice was followed as per the recommendation until seedlings reached the stage of transplanting. The seedlings were then transplanted on well-prepared experimental plots on both sides of a ridge at a row and plant spacing of 20 cm and 10 cm, respectively. Each plot has 10 rows of onion plants (two rows per ridge) and 30 plants in each row, for a total plant population of 300 in each plot. Onion seedlings transplanted to the experimental field received two common irrigations to ensure better plant establishment. One-time application of NPS at transplanting and split application of Urea at transplanting and 15 days after transplanting were done by hand placement at a rate of 200 kg/ha and 150 kg/ha, respectively. The chemicals Mankozium (3 liter/ha) and Redomil Gold (3 liter/ha) were used, to safeguard the crop against harmful insects and fungi, respectively.

2.4 Irrigation Scheduling and Management

Daily reference evapotranspiration (ETo) was calculated by applying the modified FAO Penman-Monteith equation based on daily record of climatic data (Allen, 1998) [1] using FAO CROPWAT software version 8.0.

2.5 Crop and irrigation water requirement

The amount of water needed (CWR) to balance the amount of water lost through evapotranspiration (ETc), is calculated from reference evapotranspiration (ETo) and onion crop coefficient (Kc) as per (Allen, 1998) [1]. The crop coefficient values were adopted from (Dirirsa *et al.*, 2015) [5] as 0.61 for the initial stage, 0.61<Kc<1.02 for the crop development stage, 1.02 for the mid-season stage and 0.8<Kc<1.02 for the late season stage. The crop water requirement (ETc) was then calculated using CROPWAT software over the growing season from ETo and the crop coefficients (Kc) indicated above.

$$\mathrm{ETc} = \mathrm{ETo} * \mathrm{Kc}$$

Where, ETc = crop evapotranspiration (mm/day), Kc = crop coefficient, and ETo = reference crop evapotranspiration (mm/day).

The net irrigation requirement was calculated using the CROPWAT software based on (Allen, 1998) [1] as follows:

$$\mathrm{IRn} = \mathrm{ETc} - \mathrm{Pe}$$

Where, IRn =Net irrigation requirement (mm), ETc in mm and Pe = effective rainfall (mm) which is part of the rainfall that enters into the soil and makes available for crop production. The effective rainfall (Pe) was estimated using the methods (Allen *et al.*, 1998) [1.

$$\mathrm{Pe} = 0.6 * \mathrm{P} - 10 \text{ for month } \mathrm{P} \leq 70 \text{ mm}$$
$$\mathrm{Pe} = 0.8 * \mathrm{P} - 24 \text{ for month } \mathrm{P} > 70\ mm$$

Where, Pe (mm) = effective rainfall and P (mm) = total rain falls.

The gross irrigation requirements account for losses of water incurred during conveyance and application to the field. The gross irrigation requirement was computed by adopting a field application efficiency of 60 % because the experiment was conducted at research center site. As stated by (Bakker *et al.*, 1997) [2], furrow irrigation application efficiencies normally vary between 45 and 60%. This is expressed in terms of efficiencies when calculating project gross irrigation requirements from net irrigation requirements, as shown below:

$$\mathrm{IRg} = \mathrm{IRn}/\mathrm{Ea}$$

Where, IRg = gross irrigation requirement (mm), IRn = net irrigation and Ea = irrigation efficiency.

2.6 Water use efficiency (WUE)

The water use efficiency was calculated by a ratio of total bulb yield (kg/ha) to the total ETc (m^3/ha) through the growing season and it was calculated using the following equation (Zwart & Bastiaanssen, 2004) [12].

$$\mathrm{WUE} = (\mathrm{Y}/\mathrm{ETc}) \qquad (3.11)$$

Where, WUE = water use efficiency (kg/m), Y= crop yield (kg/ha) and ETc = the seasonal crop water consumption by evapotranspiration (m^3/ha).

2.7 Agronomic Data Collection

Agronomic data recorded at the end of the final growth stage were plant height and the number of leaves per plant. These were taken from ten randomly tagged plants in the plot, excluding the border rows and border plants in the central rows, at the end of physiological maturity. Plant height was measured by measuring the main stem height from ground level up to the tip of the leaf with the help of ruler. The harvesting stage was determined when 50-75% of the leaves fell down. Bulbs were properly dried. The data were collected from the middle rows of a net plot area; the two outer most rows of each treatment were left as border effects. In addition, 20 cm of length on both ends of each harvestable row was also left as border effects.

The bulb yield obtained from each plot was then expressed as a tone per hectare (t/ha). Bulb diameter was recorded from sample of ten plants.

Plant height (PH):- Ten onion plants were selected from the interior rows to avoid the border effect. The height of these ten plants was measured from the soil surface to the tip of the plant using ruler or tape meter. The mean value of the ten plant height was recorded as plant heights of each plot.

Leaf number pre plant (LNPP):- Refers to the mean number of leaves produced by sampled plants at maturity. The total number of leaves on the sampled plants was counted and divided by the number of plants to get the mean leaf number per plant.

Bulb diameter (BD):- Refers to the diameter of ten randomly selected plant bulbs measured at the widest point in the middle portion of the mature bulb using a slide caliper.

Total bulb yield (TBY):- Was recorded from the net plot by weighing all bulbs taken from the central row and converting it to t/ha.

2.8 Statistical Analysis

The collected data were analyzed using SAS 9.0 statistical software appropriate for split plot design. When a treatment effect was found to be significant for a parameter the mean separation was carried out using the Least Significant Difference (LSD) at 5% probability level. The experiment was two factors (growth stages and DI level) with a split plot design during the analysis. Pearson correlation analysis was also used to determine the association between onion bulb yield and yield components.

3. Results and Discussion

3.1 Effects of Irrigation Levels on Growth Parameters

3.1.1 Plant height

Plant height has shown a non-significant difference due to the interaction of onion growth stage and irrigation levels. However, plant height was significantly affected at $P \leq 0.05$ due to deficit irrigation levels. The treatment receiving 100% ETc resulted in 47.97 cm of height and this was significantly different from the deficit irrigation levels with 70% ETc and 55% of ETc; nevertheless, there was non-significant difference with the DI level with 85% of ETc (46.27 cm tall). This is recognized as the ability of the onion plant to recover from the effects of water deficit irrigation levels with 70%, 55% of ETc if cell multiplication and growth are not affected during the treatment receiving 85% of ETc deficit irrigation level.

The statistical analysis result indicated that plant height was not significantly ($p > 0.05$) affected by the different growth stages. The plant height ranged from 45.43 and 47.97 cm. The lowest and highest plant heights were observed from treatments receiving deficit irrigation levels during initial stage and late stage, respectively.

3.1.2 Leaf number

The average number of leaves per onion plant remained statistically unchanged across different growth stages and their interaction ($P > 0.05$). However, a higher average number of leaves per plant, 6.86, was observed with deficit irrigation (DI) applied during the initial growth stages, while the lowest, 6.02, was noted with DI during bulb formation stages. Conversely, the average number of leaves per plant was significantly influenced by various deficit irrigation levels, ranging from 5.88 to 6.85. The highest leaf count was recorded in plots receiving 100% crop evapotranspiration (ETc), significantly differing from those subjected to 70% and 55% of ETc deficit irrigation levels ($p < 0.05$), although it showed no significant difference with the treatment at 85% of ETc deficit level. These findings suggest that a water deficit of up to 15% was tolerable to achieve a minimum of seven leaves per onion plant.

3.2 Effects of Deficit Irrigation on Yield and Yield Parameters

3.2.1 Bulb diameter

The bulb diameter exhibited a significant ($P \leq 0.05$) response to the timing of deficit irrigation across different growth stages. The highest bulb diameter, measuring 5.82 cm, was observed in plants subjected to deficit irrigation during the initial stage. Conversely, the least bulb diameter, measuring 5.51 cm, was recorded in plants receiving deficit irrigation at the development stage, although this difference was not statistically significant compared to bulb diameters at the bulb formation and maturation stages (5.64 cm and 5.56 cm, respectively). Generally, bulb diameter decreased with irrigation water deficit during the development and bulb formation growth stages of onion. The result was supported by (Zheng *et al.*, 2013) [11] who indicated that water stress at development and bulb formation stages of growth of onion significantly affected the size of onion bulbs.

Significant variations ($P \leq 0.05$) in bulb diameter were evident across different irrigation levels, with the highest diameter of 5.84 cm observed in the treatment receiving 100% irrigation, followed by 5.74 cm, 5.53 cm, and 5.42 cm in treatments subjected to 85%, 70%, and 55% of ETc deficit irrigation levels, respectively. A deficit in irrigation water up to 15% resulted in bulb diameters surpassing the mean value of 5.63 cm, aligning with previous findings (Enchalew *et al.*, 2016) [6] suggesting that increased soil moisture fosters larger bulb diameters. The interaction between growth stages and irrigation levels significantly (P

≤ 0.01) influenced both bulb diameter and length. Specifically, the treatment receiving 85% of ETc level recorded the highest bulb diameter (5.41 cm), significantly different from all other treatments except the control, while the lowest diameter (3.81 cm) was noted in the treatment subjected to 55% of ETc irrigation during the developmental stage, signifying a notable reduction compared to other treatments.

Table 2: Interaction effect of irrigation levels and growth stages on bulb diameter of onion (cm)

Growth stages	Levels of irrigation depth			
	100%	85%	70%	55%
Initial Stage	5.32^{ab}	5.00^{b}	4.59^{cd}	4.65^{c}
Development Stage	4.57^{cd}	4.65^{c}	4.49^{cd}	3.81^{f}
Mid-season Stage	5.15^{ab}	5.41^{a}	4.60^{cd}	4.46^{cde}
Late-season Stage	4.53^{cd}	4.37^{cde}	4.31^{de}	4.16^{e}
LSD 5 %		0.33		
CV	6.14			

Means with the same letter (s) in the columns and rows are not significantly different at P ≤ 0.05; CV = coefficient of variation

3.2.2 Total bulb yield

The total bulb yield exhibited significant differences among irrigation levels at P ≤ 0.01, with the highest yield of 23.26 t/ha recorded in the control treatment (full irrigation), significantly differing from treatments receiving 85%, 70%, and 55% of ETc. Conversely, the lowest yield of 19.71 t/ha was observed in treatments subjected to 55% ETc, showing a notable reduction compared to other treatments at the p ≤ 0.05 level. Notably, total bulb yield remained below the mean value of 21.46 t/ha under 70% and 55% water deficit. However, the yield increased to 21.86 t/ha in the treatment receiving 85% ETc, surpassing the mean value. The interaction between irrigation levels and growth stages significantly (P ≤ 0.05) influenced total bulb yields, with the lowest yield of 13.26 t/ha observed in treatments subjected to 55% of ETc at the developmental stage, followed by 15.93 t/ha in treatments at the bulb formation stage. These findings highlight the sensitivity of onion bulb production to deficit irrigation during the development and bulb formation growth stages, as supported by previous studies, indicating significant reductions in yield under water stress during these critical stages compared to non-stressed conditions. Conversely, deficit irrigation during the initial and maturation stages had minimal impact on bulb yield, suggesting a higher tolerance to water stress during these growth phases.

Table 3: Interaction effect of irrigation levels and growth stages on total bulb yield of onion (t/ha)

Growth stages	Levels of irrigation depth			
	100%	85%	70%	55%
Initial Stage	22.24^{abcd}	20.93^{abcde}	1955^{abcde}	19.40^{bcde}
Development Stage	21.13^{abcde}	19.17^{bcde}	17.11^{def}	13.26^{f}
Mid-season Stage	20.80^{abcde}	19.19^{bcde}	18.82^{cde}	15.93^{ef}
Late-season Stage	24.91^{a}	24.37^{ab}	23.26^{abc}	23.66^{abc}
LSD 5 %		5.46		
CV		23.49		

Means with the same letter (s) in the columns and rows are not significantly different at P ≤ 0.05; CV = coefficient of variation

3.3 Water Use Efficiency (WUE)

The analysis of variance revealed a significant (P ≤ 0.05) effect of deficit irrigation application at various growth stages on water use efficiency (WUE). However, irrigation levels and their interaction with different growth stages did not significantly affect WUE. Specifically, applying deficit irrigation during the maturation stage yielded the highest water productivity, with a WUE of 4.24 kg/m3, while the lowest WUE of 3.48 kg/m3 was observed from deficit irrigation at the bulb formation stage.

Table 4: Combined analysis of variance for Plant Height (cm), Number of Leaves per Plant, Total Bulb Yield (ton/ha), Bulb Diameter (cm) and WUE of stage and deficit irrigation for Onion Crop

Treatments	Plant Height (cm)	Number of Leaves per Plant	Bulb Diameter (cm)	Total Bulb Yield (ton/ha)	WUE (kg/m3)
Growth Stages					
Initial Stage	45.43	6.86	5.82^{a}	21.43^{b}	3.65^{b}
Development Stage	45.73	6.05	5.51^{b}	18.85^{c}	3.55^{b}
Mid-season Stage	46.20	6.02	5.64^{ab}	21.01^{b}	3.48^{b}
Late Stage	46.51	6.39	5.56^{b}	24.56^{a}	4.24^{a}
LSD (p=0.05)	Ns	Ns	0.22	1.08	0.18
CV	7.74	10.17	6.07	10.42	9.93
Irrigation Levels					
100%ETc	47.97^{a}	6.85^{a}	5.84^{a}	23.26^{a}	3.89
85%ETc	46.27^{ab}	6.67^{a}	5.74^{ab}	21.86^{b}	3.80
70%ETc	45.45^{bc}	5.93^{b}	5.53^{bc}	21.02^{b}	3.65
115%ETc	44.18^{c}	5.88^{b}	5.42^{c}	19.71^{c}	3.58
LSD (p=0.05)	2.05	0.37	0.22	1.08	Ns
CV	7.74	10.17	6.07	10.42	9.93

Remark: WUE: Water use efficiency, Ns: Non-significant

4. Conclusions and Recommendation

In conclusion, irrigation plays a pivotal role in global agriculture, yet increasing competition for water resources across various sectors necessitates efficient water management practices. Deficit irrigation emerges as a crucial strategy for sustainable crop production in water-scarce regions. Proper implementation of deficit irrigation can significantly enhance water productivity by consuming less water while maintaining comparable yields to unstressed crops. However, its success relies on identifying suitable crop types, varieties, and their sensitivity to deficit conditions. Our findings suggest that applying deficit irrigation during the initial and late growth stages incurs fewer negative impacts compared to deficit irrigation during bulb formation and development stages, which are more sensitive to water stress. Therefore, farmers are encouraged to adopt deficit irrigation practices, particularly during the initial and maturation stages, up to a 55% ETc application level, to optimize water use efficiency and crop yield in water-limited environments.

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