Effect of deficit irrigation and mulch on water use and yield of drip irrigated onions

A. A. Ramalan[1], H. Nega[2] & M. A. Oyebode[1]
[1]Department of Agricultural Engineering, Ahmadu Bello University, Nigeria
[2]Federal Ministry of Agriculture and Rural Development, Ethiopia

Abstract

A field experiment was conducted at Melkassa Agricultural Research Centre in the Central Rift Valley of Ethiopia (located at latitude 8° 24'N, longitude 39° 21'E and altitude 1,550 m above sea level) during the 2008/2009 dry season to study the 'Effect of deficit irrigation and different mulch covers on water use and yield of drip irrigated onion (Allium Cepa L., cultivar: Bombay Red)'. A drip irrigation system with 144 laterals was used for the experiment. Two factors, namely deficit irrigation at four levels (0, 25, 50 and 75% of Total Available Water, TAW) and mulch covers of four different types (no mulch or bare soil, straw mulch, clear plastic and black plastic) were combined in a randomized complete block design and laid out as treatments in plots 0.4 m x 5 m. Three replications were used. Results showed that onion bulb yield decreased with increase in levels of water deficit. In contrast, both crop water use and irrigation water use efficiencies increased with increase in water deficit level. Use of mulch significantly increased bulb yield. Plots with mulch covers yielded higher than 30 t.ha^{-1} compared to the bare soil yield of 28.3 t.ha^{-1} (straw>clear plastic>black plastic>bare soil). Water use was similarly reduced by the presence of mulch covers. A hydraulic performance evaluation of the drip system showed there was an average emitter flow rate variation of 13.7%, a coefficient of uniformity of 85% and an overall irrigation application efficiency of 94.4%.

Keywords: deficit irrigation, drip irrigation, water harvesting, mulch, irrigated onion, hydraulic performance of drip system, water use, water use efficiency.

1 Introduction

The dry land area of Ethiopia which includes the Central Rift Valley accounts for 67% of the total land mass of the country (EARO [5]). Approximately, 62% of the irrigable land of the country is located in this Valley. The major crop irrigated by farmers in the area, who are mainly smallholder and peasant, is onion. Rainfall, characteristically high intense and capable of causing erosion, rarely exceed 800 mm; most areas receive 500-800 mm annually (MOA) [12]. Annual potential evapotranspiration is high, thus placing high evaporative demand on water surfaces. As a strategy for reducing food insecurity, encouraging small-holder farmer investment in agriculture and increased exploitation of its water resources, the government introduced rain-water harvesting and small scale drip irrigation technologies. In this regard, over 100,000 units of water harvesting structures, hand-dug wells, low cost water lifting devices, and family drip irrigation systems deployed have achieved partial success in implementation. Knowledge gaps exit regarding the correct sizing of water harvesting tank, irrigation land size relative to household tank, effective use of harvested water and the economics of the whole system. These have to be addressed in a study. For a general objective, this pioneering study sought to evaluate the effect of deficit irrigation and use of mulch covers on water use and yield of drip irrigated onion targeting resource poor smallholder farmers in moisture deficient environment.

1.1 Deficit irrigation effects

Deficit (or regulated deficit) irrigation scheduling is one way of maximizing water use efficiency for higher yields per unit of irrigation water applied; the crop is exposed to a certain level of water stress either during a particular period or throughout the whole growing period (FAO [8]). The expectation is that any yield reduction resulting from the water stress will be insignificant compared with the benefits gained through diverting the saved water to irrigate other crops. For deficit irrigation and its schedules to be successful, some knowledge of crop response to water stress at specific growth stage or entire season is essential. FAO [8] suggested that crops, or crop varieties most suitable for deficit irrigation are those with short growing season and are tolerant to drought. In implementing deficit irrigation, consideration must be given to soil retention capacity, as well as, modification of agronomic practices like plant population, date of planting, fertilizer application, etc.

Crop water use efficiency is the ratio of crop yield (Y) to the amount of water depleted by the crop in the process of evapotranspiration (ET) and is expressed as $Kg.m^{-3}$ or $Kg.ha^{-1}mm^{-1}$. Irrigation water use efficiency, on the other hand, is a ratio of the crop yield (Y) to the total amount of water used in the field (WR). Since both the Crop and Irrigation water use efficiencies are ratios, their values can be increased by either increasing crop yield through better method of pest and disease control, plant breeding or decreasing evapotranspiration. Bekele and Tilahun [2] reported the positive effect of water stress at two growth stages of

onion. In contrast, Nigatu [16] reported no significant improvement in irrigation water use efficiency resulting from irrigation deficit. Under conditions of water shortage, the best growth stages at which to achieve maximum water savings in the irrigation of onion (cv: Bombay Red) without yield reductions exceeding 31% are development (bulb formation) and maturity stages at which 50% of water requirement is applied.

1.2 Mulch cover effects

Mulches can be composed of plant materials or they may be synthetic mulches consisting of plastic sheets (Allen et al. [1]). The sheets are generally transparent, white or black. Colour as observed by Allen et al. [1] influences albedo mainly during the early stage of crops. Plastic mulches substantially reduce evaporation of water from the soil surface especially under trickle/drip irrigation. Among its advantages in use is increase in soil temperature, reduced fertilizer leaching, reduced evaporation, cleaner product and reduced weed problems. Higher initial cost and management are some of its disadvantages. Studies reported in Allen et al. [1] indicated that the average approximate reductions in crop coefficient, Kc and surface evaporation for five horticultural crops (squash, cucumber, cantaloupe, watermelon and tomato) under complete plastic mulch compared with no mulch using drip irrigation system was 10-30% and 50-80% respectively. Douglas [4] reported yield increases over state average of four times for pepper, squash and watermelon; and three times for tomato when plastic mulch and drip irrigation were used.

1.3 Drip irrigation system hydraulics

Drip (or sometimes referred to as trickle) irrigation system derived its name from the manner in droplets reaches the soil surface. Michael [14] reported it as one of the latest of the systems and is become increasingly popular in areas with water scarcity and salt problems. Water from source passes through plastic pipes, constituting the main and laterals, into emitters positioned to supply each plant with the calculated water requirement at the same delivery rate. Pressure head losses are encountered in lines which result in uneven distribution of the discharges from the emitters. Mofoke et al. [15] reiterated that the most widely accepted hydraulic performance indices for assessing the drip irrigation system are emitter discharge, emitter flow rate variation, uniformity coefficient and emission uniformity.

2   Materials and methods

2.1 Climatic and soils description of the study area

The climate of the study area (Mekassa: located at latitude 8° 24'N, longitude 39° 21'E and altitude 1,550 m above sea level) is characterized as semi arid, having a long term (1977-2006) mean annual rainfall of 791.7 mm. The rainfall has a bimodal pattern with a short rain season from March to April, a dry spell, and a

long rain season from July to September. The long term mean maximum and minimum temperatures range from 30.9°C in May to 26.2°C in August and from 16.2°C in June to 10.8°C in December respectively. Recorded mean maximum and minimum temperatures which occurred in October and December were 28.18°C and 8.19°C respectively. The highest duration of sunshine was 10.4 hours in December with the lowest of 6.34 hours in October. The mean relative humidity was highest in October at 57.42% and lowest at 44.71% in December. Wind speed measured with the cup anemometer mounted at 2 m height recorded the highest mean wind speed of 10.04 m.s^{-1} in December while the lowest mean wind speed of 6.34 m.s^{-1} was in October. Pan evaporation was highest in December with a mean value of 7.27 mm.

2.2 Soil characteristics at site

The soil at the site is classified as Haptic Andosol with a characteristic feature of deep pumice or volcanic soil type having a high water retention capacity (Tesfaye and Walker, 2004) as cited by Nigatu [16]. A composite sample was collected at depth of 0-60 cm from the site and analyzed for physical and chemical characteristics at the Ethiopian National Soils Laboratory. The results show that the soil is loam in texture with a mean bulk density of 1.11 gm.cm^3 and slightly alkaline with a pH of 7.89 and an EC of 0.208 dS.m^{-1}. The soil was found suitable for irrigation. The soil was also assessed for infiltration using the Double Ring Infiltrometer.

2.3 The experiment

The two factors for investigation in the experiment were deficit irrigation at four levels (0, 25, 50 and 75% of Total Available Water, TAW) combined in a randomized complete block design with four types of mulch covers (no mulch, *tef* straw mulch, black and clear plastic mulches). These constituted sixteen treatments each laid in plots 1.8m x 5m. Each treatment was replicated three times, totalling forty eight plots covering a gross area of 0.086 ha.

2.3.1 Field operation

Onion seeds (Allium Cepa, L. Cv: Red Bombay) at the rate of 3 kg.ha^{-1} were sown on six seed beds 1m x 5m to raise the seedlings required at a nursery close to the site on August 28, 2008. Nursery bed management according to the recommendations of the Experiment Station were followed. At seven weeks after sowing when the seedlings were about 10-15 cm high and had three true leaves, they were transplanted to 40 cm wide planting beds at intra-row and inter-row spacings of 10 cm and 20 cm respectively. Prior to transplanting, soil moisture content at depths up to 30 cm were determined using the gravimetric method and one irrigation applied to raise the moisture content of the soil one day before transplanting to field capacity level. Transplanting was done on October 20, 2008. After transplanting, full irrigation to restore soil moisture content to field capacity, based on effective rooting depth of 15 cm, was given to all treatment plots. On 11 November, 2008, the irrigation and mulch treatments were imposed.

Fertilizers and pest control chemicals were applied based on recommendations of the Research Station. Urea at the rate of 100 kg.ha^{-1} was applied between rows in two equal doses at the time of transplanting and at 4 WAT. A uniform dose of Diammonium phosphate (DAP) at the rate of 200 kg.ha^{-1} was applied and incorporated in the soil before transplanting. Pesticides chemicals were applied at 3, 4, 5 and 8 WAT. Three hand-hoe weeding were carried out at 4, 6 and 10 WAT. The crop was harvested 18 WAT on January 31, 2009 when the tops of more than 50% of plants had fallen over.

2.3.2 Irrigation water source
Rainwater harvested from farm roads and stored in a 50 m^3 capacity underground tank, 6m deep, was the main source of the irrigation water. A 50 mm diameter petrol engine pump was used to lift water from the underground tank to a 1.5 m^3 capacity elevated tank, 2.5 m above ground. Pump capacity was calculated based on tank capacity and filling time.

2.3.3 Drip system components
Water from the elevated tank feeds into a supply line 20 mm diameter, 5 m long made from Low Density Polyethylene Pipe (LDPEP). A ball valve and a primary filter are fixed on the line and it terminated at a 20 mm, 19 m long mainline of the same material. Four sub mainlines each 34.6 m long, 20 mm diameter were connected to the mainline. Along each of the sub mainline, six tertiary lines each measuring 4.6 m, 20 mm were connected and it was on these tertiary lines that 12 mm diameter, 5m long, 70 cm spaced laterals with inline emitters took off. There were 144 laterals altogether installed. The hydraulic characteristics of the system installed that were evaluated included: emitter flow rate, emitter flow rate variation, uniformity coefficient, emission uniformity, and application efficiency.

2.3.4 Hydraulic characteristics of the system installed
2.3.4.1 Emitter flow rate The average flow rate of the emitters used in the experiment was measured from plots in which catch cans were randomly assigned plots and volumes of flow caught over a time period. The discharge, or flow rate out of single outlet emitter at a specified head was estimated thus:

$$q = \frac{V}{\Delta t} \qquad (1)$$

where q = single emitter discharge, litre/hour; V = volume of water collected from emitter, litres; and Δt = time duration of discharge collection, hour

2.3.4.2 Emitter flow rate variation Emitter flow rate variation was simply computed as:

$$q_{var}(\%) = 100\left(\frac{q_{max} - q_{min}}{q_{max}}\right) \qquad (2)$$

where q_{var} = emitter flow rate variation, %; q_{max}= the maximum emitter flow rate along a lateral, litre/hour; and q_{min} = the minimum emitter flow rate along a lateral, litre/hour.

2.3.4.3 Uniformity coefficient Uniformity coefficient was calculated using the Christiansen coefficient of uniformity formula given in Michael [14] as:

$$UC(\%) = 100\left(1.0 - \frac{\Sigma_x}{qn}\right) \qquad (3)$$

where UC(%) = Uniformity coefficient, %; q = average discharge of the emitters, litre/hour; n = number of emitters; and Σx = sum of the individual deviations of observed flow from the average discharge, litre/hour.

2.3.4.4 Emission uniformity The formula given by Howell and Hiller [9] cited in Michael [14] as used to estimate emission uniformity as:

$$Eu(\%) = 100\left(\frac{q_{low\ quarter}}{q}\right) \qquad (4)$$

where Eu = Emission uniformity in %; $q_{low\ quarter}$ = average discharge rate of the low quarter of the number of emitters observed, litre/hour; and q = average discharge rate of all observed emitters, litre/hour.

2.3.4.5 Application efficiency The overall application efficiency of the drip irrigation system was estimated from the relationship of Vermeiren and Jobling [18] given as:

$$Ea(\%) = Ks.Eu \qquad (5)$$

where Ea = Application efficiency, %; Ks = Average water stored in the root zone over average depth of water applied and is a coefficient which expresses the storage efficiency of the soil taking into account the pressure variation in the drip system (Ks=1 for loam soil) as in Vermeiren and Jobling [18] and Eu = as given in eq. (4).

2.3.5 Water use and water use efficiencies
Soil water use in the experiment was obtained principally from routine measurements of soil moisture content by the gravimetric method and use of Neutron probe meter. For the soil depth of 0-15 cm, soil samples were collected with soil auger just before irrigation and one day after irrigation to compute soil water contents as:

$$SW = \Theta v.Z = \Theta m.Bd.Z = \frac{(FW - DW)}{DW}.Bd.Dz \qquad (6)$$

where SW = Soil water content in the soil layer (0-15 cm), cm; Θv, Θm = volumetric and gravimetric moisture contents in the depth in cm^3/cm^3 and g/g respectively; Dz = depth of soil layer, cm; Bd = Bulk density of the soil, g/cm^3; and FW, DW= Wet and dried weights of soil sample, g.

For soil layer below 15 cm depth, the Neutron Probe meter (Model: 503 DR CPN Hydro Probe) with forty eight access tubes made of 5 cm diameter, 150 cm long aluminium pipes were used to obtain soil water content up to depths of 40 cm in increments of 7.5 cm. A calibration equation using the method in Eze et al. [6] was programmed into the probe so as to obtain direct readout moisture content in mm.

Total available water is the water held in the root zone depth at moisture contents defined as field capacity (upper limit) and permanent wilting point (lower limit). In the experiment, upper limits of soil moisture contents were fixed at 0, 25, 50 and 75% of TAW. Water use by the onion was therefore calculated based on change in soil moisture. The design of drip system predicated on zero runoff and deep percolation losses. The net depth of irrigation water applied was based on the moisture depleted from storage to satisfy actual crop evapotranspiration minus any rainfall in the interval plus leaching fraction (leaching was not considered in the study as the soil was non-saline). Effective rainfall was accounted for by the method suggested by FAO [7]. Gross depth of irrigation was calculated taking into account application efficiency of the system. Water use efficiency is a measure of crop water productivity which Michael [14] suggested can be measured in the form of:

$$CWUE = \frac{Y}{CWU} \qquad (7)$$

where CWUE = Crop water use efficiency, $kg.m^{-3}$; Y = Crop yield, $kg.ha^{-1}$; and CWU = Crop water use, mm

and

$$IWUE = \frac{Y}{IWU} \qquad (8)$$

where IWUE = Irrigation water use efficiency, $kg.m^{-3}$; Y = Crop yield, $kg.ha^{-1}$; and IWU = Irrigation water use, $m^3.ha^{-1}$.

3   Results and discussion

3.1 Emitter flow rate and flow rate variation

The results in Table 1 show emitter flow rate as affected by the number tested at a time using the catch can test method. At an operating pressure head of 2.5 m,

the average emitter flow rate was 0.6045 litre/hr while mean maximum and mean minimum values were 0.656 and 0.566 litre/hr respectively. The average obtained, though at a higher pressure head, was lower when compared with the manufacturer's specification of 1.3 litre/hr at a pressure head of 1.0 m. The mean coefficient of variation obtained for the results was 4.60, indicating relatively low variations of the mean.

Table 1:   Average, maximum and minimum emitter flow rates as affected by the number of treatments tested at a time using catch cans.

Parameters	Number of treatment plots tested at a time					
	48	24	18	9	3	Average
Average emitter flow rate, litre/hr	443.4	624.9	663.6	648.2	642.2	604.5
Maximum emitter Flow rate, litre/hr	480.0	670.0	760.0	680.0	680.0	656.0
Minimum emitter flow rate, litre/hr	410.0	580.0	620.0	610.0	610.0	566.0
Coefficient of variation, C.V. %	5.10	5.40	5.80	3.80	3.80	4.60

3.2 Emitter flow rate variation, uniformity coefficient, emission uniformity and application efficiency

The average emitter flow rate variation along laterals was 13.7%, as shown in Table 2. This value closely agreed with the findings in Michael [14] and Jensen [11] which stated that in drip systems, the average variation in discharge rate of individual emitters in a whole field should not exceed 20%.

Table 2:   Emitter flow rate variation, uniformity coefficient, emission uniformity and application efficiency as affected by the number of treatments tested at a time using catch cans.

Parameters	Number of treatment plots tested at a time[a]					
	48	24	18	9	3	Average[b]
Emitter flow rate variation, %	14.6	13.4	18.4	11.6	10.3	13.7
Uniformity coefficient, %	95.6	95.7	95.3	96.4	96.8	96.0
Emission Uniformity, %	93.1	93.6	94.0	95.0	96.0	94.4
Application Efficiency, %	93.1	93.6	94.0	95.0	96.0	94.4

[a]While testing specific treatments, gate valves for the others are closed.
[b]Each treatment had 3 plots due to replication.

Over the five separate tests, the average emission uniformity was found to 94.4% while the mean of the uniformity coefficient was 96%, signifying even distribution of water throughout the system. These results are supported by Merriam and Keller [13] who stated that a drip system with both emission uniformity and uniformity coefficient of 85% or greater, and with a discharge variation of less than 20% should be considered satisfactory.

The application efficiency obtained averaged 94.4%; this compared favourably to the results of Sijali [17] and IDN [10] who stated that drip irrigation systems are typically about 90% efficient as compared to sprinklers that are about 75% efficient.

3.3 Deficit irrigation and mulch effects on bulb yield and seasonal water use

The highest marketable bulb yield of 37.2 t.ha^{-1} was obtained at the 0% deficit irrigation level and the lowest mean yield of 24.32 t.ha^{-1} recorded at 75% level of irrigation deficit as presented in Table 3. The yield differences were significant at 1% level of probability. The yield reductions with increased deficit irrigation levels from 0 to 25, 50 and 75% were 16, 26, and 34.6% respectively which resulted from corresponding reductions of applied irrigation water of 14, 29 and 47%.

Effect of deficit levels on Crop water use and irrigation water use revealed significant differences in seasonal values of the water use. In a nutshell, allowing for no deficit, an onion crop in the Central Rift Valley requires 527.18 mm of irrigation water per season to yield 37.2 t.ha^{-1}. But, imposing a deficit level of 75% TAW the yield obtainable drops to 24.32 t.ha^{-1}. These results, up to deficit levels of 50%, tally with Doorenbos and Kassam [3] report which stated that for an optimum yield, onion requires 350-550 mm of water.

Use of mulch had resulted in significant yield differences (p=5%). Onion yield under straw mulch, though at par with the plastic mulches, out-yielded bare soil (no mulch). No yield advantage was observed using clear as against black mulch. Seasonal water uses were significantly reduced under mulches (straw>clear plastic>black plastic) than with bare soil which resulted in over 400 mm per season.

Though the data showed no significant differences resulting from the interaction of irrigation deficit and mulch covers, the combination I_oM_1 (0% deficit level, straw mulch) yielded highest, close to 40 t.ha^{-1}.

3.4 Deficit irrigation and mulch effects on water use efficiencies

Crop and Irrigation water use efficiencies were highest at the 75% irrigation water deficit at which 14.52 and 13.50 kg/m^3 were obtained respectively as Means followed by the same letter(s) in a column of any treatment group are not statistically different at the 5% (*), or 1% (**) probability level using the Duncan Multiple Range Test. ns=not significant.

I_o=0% deficit, I_1=25% deficit, I_2=50% deficit, I_3=75% deficit, M_o=no mulch, M_1=Straw mulch, M_2=clear plastic mulch, M_3=black plastic mulch.

CWUE=Crop water use efficiency, IWUE=Irrigation water use efficiency.

Table 3:   Onion bulb yield, crop water use, irrigation water use, CWUE and IWUE as affected by deficit irrigation and mulch covers at Melkassa in the 2008/2009 dry season.

Treatments	Marketable bulb yield (t.ha^{-1})	Crop water use (mm /season)	Irrigation water use (mm/season)	CWUE (kg/m^3)	IWUE (kg/m^3)
Deficit irrigation levels (%)					
I_o	37.20a	490.28a	527.18a	11.51b	10.70b
I_1	31.23b	420.38b	452.02b	11.20b	10.41b
I_2	27.39c	349.25c	375.53c	11.86b	11.03b
I_3	24.32d	259.73d	279.28d	14.52a	13.50a
Significance level	**	**	**	**	**
Mulch covers					
M_o	28.27b	417.77a	449.21a	10.29c	9.57c
M_1	31.71a	353.25b	379.84b	13.89a	12.92a
M_2	30.12ab	364.84b	392.30b	12.78ab	11.88ab
M_3	30.04ab	383.77b	412.66b	12.13b	11.28b
Significance Level	*	*	*	**	**
Interaction (deficit x mulch)					
I_oM_o	34.94	535.84	576.16	9.85d	9.16d
I_oM_1	39.46	449.60	483.44	13.17bc	12.25bc
I_oM_2	37.02	462.69	497.52	12.08cd	11.13cd
I_oM_3	37.38	512.97	551.58	10.93cd	10.17cd
I_1M_o	30.24	454.39	488.59	10.00d	9.30d
I_1M_1	32.86	402.40	432.69	12.28cd	11.42cd
I_1M_2	31.19	406.79	437.41	11.48cd	10.67cd
I_1M_3	30.65	417.92	449.38	11.03cd	10.26d
I_2M_o	26.84	365.40	392.90	11.10cd	10.33cd
I_2M_1	28.63	334.01	359.15	12.97bc	12.06bc
I_2M_2	27.11	343.70	369.57	11.87cd	11.04cd
I_2M_3	26.96	353.87	380.50	11.49cd	10.69cd
I_3M_o	21.07	315.47	339.21	10.20d	9.49d
I_3M_1	25.89	226.97	244.06	17.14a	15.94a
I_3M_2	25.14	246.17	264.70	15.68a	14.58a
I_3M_3	25.18	250.32	269.16	15.06ab	14.00ab
Significance Level	ns	Ns	ns	*	*
CV (%)	7.20	9.68	9.68	11.1	11.1

CWUE and IWUE. The other levels were statistically equal. Singular effect of use of mulch showed the straw mulch as the best material, though at par with

clear plastic (1% level). Bare soil (no mulch) was not efficient in conserving water. The interaction of deficit irrigation and mulch showed there were significant differences in efficiency values when tested at the 5% level. At I_3M_1, the highest CWUE of 17.14 kg/m^3 and IWUE of 15.94 kg/m^3 were obtained. The least was at I_oM_o. These results show the positive effect of mulch covers even with deficit levels up to 75%.

4 Conclusions

Results from the present level of work show that combining irrigation deficit with use of mulch covers, particularly straw mulch that is in abundance with farmers, presents a sustainable strategy for onion production in the semi-arid areas of Ethiopia. Use of plastic mulches did not show any superiority over straw mulches; laying difficulties with these materials in windy conditions present challenges to farmers. Imposing irrigation deficit levels beyond 50% is not advisable as marketable bulb yield and bulb sizes decline. The drip system technology used in the study is at entry level for farmers and it is aptly demonstrated from this work that the amount of water savings that can be achieved is substantial when compared to other irrigation systems.

Acknowledgements

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