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Effects of regulated deficit irrigation and mulch on yield, water use and crop water productivity of onion in Samaru, Nigeria

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ABSTRACT

This paper presents the findings of the effects of regulated deficit irrigation and mulch materials on yield, water use and water productivity of onion crop. The field experiments were conducted in 2008/09 and 2009/10 irrigation seasons at the Institute for Agricultural Research Samaru Zaria, Nigeria. Sixteen treatments comprising of four levels of water application depths (irrigating at 25, 50, 75, and 100% weekly reference evapotranspiration (WRET)) and four levels of mulching (no-mulch, using rice straws, black and white transparent polyethylene materials) were studied each season. Surface irrigation was used and the crop was planted in basins. Water applied per irrigation, soil moisture contents before and after irrigation was monitored throughout the seasons while the harvested bulb yields were weighted and graded. The bulb yields in the two seasons ranged from 6.3 to 20.6 t/ha. The seasonal water applied varied from 225 to 480 mm while the seasonal evapotranspiration (SET) computed from the soil moisture contents ranged from 201 to 376.3 mm. Further analyses of results showed that irrigating onion at 25% of WRET reduced bulb yield by about 50%. Applying water at 50% of WRET caused a yield reduction of about 15.5–23.0%. However, irrigating onion at 75% of WRET reduced bulb yield by less than 10%. Results also revealed that seasonal evapotranspiration (SET) of the onion crop were largely influenced by the depths of water applied rather than mulching. Irrigating the onion crop at 50 and 75% of WRET gives higher water productivity in terms of water supplied for the onion crop. Mulching with rice straw or black polyethylene did significantly improve the crop water productivity of the onion crop. In order to maximize irrigation water utilization under limited water supply to improve crop water productivity in the study area, onion crop should be mulched with rice or black polyethylene and water application depth per irrigation should be kept at 50–75% weekly reference evapotranspiration.

1. Introduction

The challenge of irrigated agriculture in our time is how to produce more crops from limited water supply. One way of tackling this challenge is adoption of practices that help to improve water management especially at field scale. The combine practice of regulated deficit irrigation and mulching appears to be very promising in achieving this goal. Regulated deficit irrigation is the practice of irrigating below crop water requirement. This can be carried out by either withholding or skipping irrigation event or reducing the amount of water applied per irrigation at some growth stages of the crop known to be less critical to moisture stress. This practice, although leads to reduction in crop yields in many instances, it saves water, labor cost, and in some cases, energy. Research evidences has shown that higher crop water productivities are sometimes recorded with deficit irrigation practice, especially if the moisture stress resulting from the deficit is not so severe (e.g. Sammis et al., 2000; Kirda, 2002; Igbadun et al., 2006). Kadayifci et al. (2005) reported that under conditions of scarce water supply, deficit irrigation can provide greater economic returns than maximizing yields per unit of area. There is no doubt that there is a growing interest in deficit irrigation as a means of improving water productivity.

Mulching, on the other hand, involves the use of organic or inorganic materials to cover the cropped soil surface. Mulching has the potential of reducing evaporation, conserve soil moisture, modify soil temperature, and improve aeration. Crop residues and grasses are typical organic materials commonly used for mulching, while synthetic materials (e.g. polyethylene sheet of different thickness and colors) are typical inorganic materials use for mulching. Research evidence had shown that soil surface evaporation contributes largely to the total evapotranspiration in the cropped field (Ahmad et al., 2007). Not until the crop attains full vegetative cover, evaporation dominates the moisture depleted from the plant root zone. Water loss through evaporation, though may have assisted

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Table 1
Weather data for the 2008/09 irrigation cropping season.

Month	Max. temp (°C)	Min. temp (°C)	Rel. humidity%	Wind speed (km/d)	Sunshine hours	ETo (mm/day)
December	29.7	12.0	21.0	229.0	9.7	4.4
January	28.7	11.0	33.0	235.5	8.9	5.0
February	31.6	14.7	27.0	229.3	9.6	5.7
March	33.2	17.3	33.0	183.0	9.0	6.9
April	35.7	24.6	55.5	197.4	8.5	7.2

in influencing the micro-climate in which the crop developed, is not beneficially used by the crop in yield production. Reducing the rate of evaporation by mulching the soil surface makes more water readily available in the soil. The crop is therefore able to balance its transpiration rate with atmospheric water demand, thus maintaining plant leaves turgidity, which in turn enhances radiation use efficiency and biomass yield production. Mulching with plant residues and/or synthetic materials is a well-established technique for increasing the profitability of many horticultural crops (Duranti and Cuocolo, 1989; Gimenez et al., 2002). Polythene mulch also increases soil temperature and moisture especially in early spring (Anisuzzaman et al., 2009). These synthetic mulches reduce weed problems and certain insect pests and also stimulate higher crop yields by more efficient utilization of soil nutrients (Rhu et al., 1990; Kashi et al., 2004).

Onion (*Allium cepa* L.) is one of the horticultural crops of high economic values, next to tomato, in Nigeria. The average annual production in the last five years in the Nigeria is put at 640,000 tons (FAOSTAT, 2011). In Northern Nigeria, the crop is largely cultivated under surface (wild flooding and check basin) irrigation method. The average yield at farmers' fields is about at 6–15 t/ha depending on the level of input available to the farmers. Seasonal water applied to the crop range from 400 to 700 mm depending on water availability and frequency of irrigation (NAERLS, 2009). The farmers' irrigation intervals range from 3 to 7 days, depending on soil type and access to water. The crop water productivity based on yield-water applied at farmer's level is between 0.5 and 2 kg/m^3, which are quite low. Although, the actual crop water requirement for onion in the study area has not been established, the reference evapotranspiration for the crop growing season which span from mid December to early March is between 450 and 500 mm.

The effects of regulated deficit irrigation on onion crop have not been explored in the study area. However, there are reports elsewhere that show that the onion crop is very responsive to water. According to Anisuzzaman et al. (2009), onion requires frequent irrigations because most of the crop water requirement is extracted from the top 300 mm depth of soil, and very little water from depths beyond 600 mm; thus the upper soil areas must be kept moist to stimulate root growth and provide adequate water for the plant. Shock et al. (1998, 2000) reported that onion yield and grade were very responsive to careful irrigation scheduling and maintenance of optimum soil moisture and that any soil moisture stressed even below field capacity caused yield reduction. Bekele and Tilahum (2007) in Ethiopia, found that water deficit at first and fourth growth stages, gave no significantly different yield from the optimum irrigation application. Furthermore, when water stress was imposed 30 days after transplanting for a period of 15 days, leaf area and bulb growth were considerably decreased with a reduction of 17–26% in onion yield (Bhatt et al., 2006). Soil water stress caused by withholding irrigation at both the third-leaf and seven-leaf stages reduced onion yield by 26% (Pelter et al., 2004). Ramalan et al. (2010) studied the effect of deficit irrigation and mulch on crop water use and yield of drip irrigated onion in the Central Rift Valley of Ethiopia and reported that onion bulb yield decreased with increase in levels of water deficit, while both crop water use and irrigation water use efficiencies increased with increase in water deficit level. Moreover, plots with mulch covers yielded higher than those that were not mulched.

The objective of this study was to evaluate the effects of regulated deficit irrigation scheduling and the use of selected mulch materials on crop yield, water use (crop water use and water applied) and crop water productivity of the onion crop. The goal was to explore options for maximizing onion yield with limited water application, and to promote onion cultivation using organic and synthetic mulch materials.

2. Materials and methods

2.1. Study location

The field trials were conducted during the dry seasons of 2008/09 and 2009/10 at the Institute for Agricultural Research (I.A.R.) irrigation fields in Samaru Zaria, Northern Nigeria. Samaru-Zaria lies on Longitude 7°35′N, Latitude 11°11′E, and altitude 686 m above mean sea level, and is located in the Northern Guinea Savannah ecological zone of Nigeria with a semi-arid climate. It has three distinct seasons which consist of a hot dry season which spans from March to May; warm rainy season which spans from June to early October, and the cool dry (harmattan) season which span from November to February. The average relative humidity is 36.0% during the dry season and 78.5% during the wet season and the average minimum and maximum temperatures are 15.6 °C and 38.5 °C, respectively. The on-set of rains in the area is in May, but effective rainfall begins in late June and lasts till early October, with the peak in August. The mean annual rainfall depth is 1150 mm, with an average peak of 650 mm in August, as obtained from the Meteorological Office of the Institute for Agricultural Research (I.A.R.). The cool-dry (harmattan) and hot dry seasons are the months for irrigation. The weather favors the growth of crops like wheat, tomato, onion, carrot, lettuce and cucumber, green maize, and sunflower, under total irrigation. Tables 1 and 2 show the weather conditions for the two seasons the experiments reported herein were carried out.

Table 2
Weather data for the 2009/10 irrigation cropping season.

Month	Max. temp (°C)	Min. temp (°C)	Rel. humidity%	Wind speed (km/d)	Sunshine hours	ETo (mm/day)
December	30.7	12.7	16.0	199.0	9.8	5.4
January	34.3	13.0	11.0	156.5	8.9	6.0
February	37.6	17.8	19.0	167.3	9.4	6.7
March	37.2	21.3	38.0	133.0	9.0	6.6
April	39.7	22.6	63.5	177.4	8.0	6.2

Table 3
Physical properties of the soil of the experimental site.

Depth (cm)	FC% dwb[a] @ 33 kPa	PWP% dwb @ 1500 kPa	Bulk density (g/cm^3)	Clay (%)	Silt (%)	Sand (%)	Textural class
0–15	13.5	6.1	1.58	29	40	31	Loam
15–30	15.7	6.5	1.60	39	36	25	Loam
30–45	18.8	8.7	1.45	41	30	29	Clay loam

[a] dwb: dry weight basis.

2.2. Soil of the experimental site

The soils of Samaru Zaria are mantle of residues overlain by aeolian deposits, classified as alfisols, based on the USDA (1975) classification (Aremu, 1980). The soil of the site where the experiments were carried out for the two seasons had the top soil (0–150 mm depth) as loam in texture, with a bulk density of 1.56 kg/m^3, while the 150–450 mm depth was clay loam with average bulk density of 1.61 kg/m^3. The total available water (TAW) was about 70 mm/450 mm depth. Table 3 shows some physical properties of the soil of the experimental site.

2.3. Description of experimental treatments

The field experiments consisted of 16 treatments in each season. The treatments were composed of four levels of irrigation (water application depths) and four levels of mulch practice, thus constituting a 2^4 factorial experiment. The four levels of irrigation include water application depths of 100, 75, 50, and 25% of weekly reference evapotranspiration (WRET), while the four levels of mulch practice consisted of no mulch (NM); use of rice straw (RSM), black polyethylene (BPM), and white transparent polyethylene mulch (WPM) as mulch materials. The 16 treatments were replicated three times, making a total of 48 plots. Table 4 gives further description of the experimental treatments.

The experiments were laid on the field with treatments assigned to plots in a randomized complete block design (RCBD), with the blocks lying across the general slope of the field. The blocks were separated by a distance of 1.5 m, while the basins in each block were separated by a distance of 0.5 m which serves as buffer to minimize lateral movement of water from one basin to another. The same field layout was used for the two seasons.

2.4. Agronomic operations

A land area of 50 m by 25 m was prepared into leveled basins of 2.5 m by 2.5 m and transplanted with onion seedling on 4th January 2009 (2008/09 season) and 18th December, 2009 (2009/10 season). The variety of onion planted in 2008/09 season was Composite IV, while in 2009/10 season the Red Creole variety was planted. The change in variety was due to due to inability to obtain Composite IV seeds to raise the nursery in 2009/10 season. Since the focus of the study was not centered on crop variety but on the crop response to deficit irrigation and mulching, the change in onion variety was not expected to affect the trend of result.

The onion seedlings were raised in the nursery and transplanted eight weeks after planting in 2008/09 season and six weeks after planting 2009/10 season. Onion seedlings are usually transplanted 6 weeks after planting in the study area. The delay in transplanting in 2008/09 session was due to logistics and late preparation of experimental plots. The transplanting was done in row at plant spacing of 20 cm between plant and 25 cm between rows giving a plant population of 153,600 stands per hectare. Fertilizer was applied at the rate of 150 kg/ha N, given in two applications. Diammonium phosphate fertilizer (NPK 15:15:15) was first applied at the rate of 75 kg/ha N at two weeks after transplanting and Urea fertilizer (NPK 46:0:0) was applied at the rate of 75 kg/ha N at six weeks after transplanting. The fertilizers and the rates of application were as recommended by the Institute for Agricultural Research, Samaru Zaria.

The mulch materials were placed six days after transplanting in both seasons. The polyethylene materials (both black and white) were cut to size and placed over the entire basin. Holes were created in accordance with the plant spacing and the onion seedlings were passed through the holes. The thickness of the polyethylene measured with a micrometer screw gauge was about 2 mm. The average weight of rice straw mulch spread in each of the plot with such treatment was 3.5 kg. Weeding was done twice, at three and six week after transplanting, before the addition of fertilizer. However, in the mulched plots, only the first round of weeding was carried out. The mulch materials were carefully removed and placed back after weeding. In the rice straw and black polyethylene mulched plots, weeds were effectively suppressed after the first round of weeding, so that there was no need for a second weeding. However, in the white polyethylene mulched plots weeds continued to grow, and unfortunately, weeding could not be carried out because it was no longer possible to remove the mulch material as such attempt may destroy the plant or the mulch materials. The rate of growth of

Table 4
Experimental treatments description.

Treatment no.	Treatment label	Description
1.	$I_{100}M_{NM}$	Water application depth of 100% WRET, no mulch.
2.	$I_{75}M_{NM}$	Water application depth of 75% WRET, no mulch.
3.	$I_{50}M_{NM}$	Water application depth of 50% WRET, no mulch.
4.	$I_{25}M_{NM}$	Water application depth of 25% WRET, no mulch.
5.	$I_{100}M_{RSM}$	Water application depth of 100% WRET, mulched with rice straw.
6.	$I_{75}M_{RSM}$	Water application depth of 75% WRET, mulched with rice straw.
7.	$I_{50}M_{RSM}$	Water application depth of 50% WRET, mulched with rice straw.
8.	$I_{25}M_{RSM}$	Water application depth of 25% WRET, mulched with rice straw.
9.	$I_{100}M_{WPM}$	Water application depth of 100% WRET, mulched with white polyethylene.
10.	$I_{75}M_{WPM}$	Water application depth of 75% WRET, mulched with white polyethylene
11.	$I_{50}M_{WPM}$	Water application depth of 50% WRET, mulched with white polyethylene
12.	$I_{25}M_{WPM}$	Water application depth of 25% WRET, mulched with white polyethylene
13.	$I_{100}M_{BPM}$	Water application depth of 100% WRET, mulched with black polyethylene
14.	$I_{75}M_{BPM}$	Water application depth of 75% WRET, mulched with black polyethylene
15.	$I_{50}M_{BPM}$	Water application depth of 50% WRET, mulched with black polyethylene
16.	$I_{25}M_{BPM}$	Water application depth of 25% WRET, mulched with black polyethylene

weeds in the white polyethylene mulch plots in the 2009/10 season was very high and affected the growth and development of the crop. Disease and pest attack were not noticed in the two seasons.

2.5. Irrigation water application

Surface irrigation method was used in the two seasons. Water was released from the main canal into a lateral ditch which conveys the water by gravity to the field ditches which service the basins. A pair of 5 cm diameter PVC tube of length 50 cm installed in each basin to admit water into the basins. The PVC tubes were installed through the embankment of each basin with one end in the field ditch and the other end in the basin. The tubes were installed to give a free orifice flow into the basins. Stage gauges were placed at the water inlet of each basin to measure the depth of water over each tube as water enters the basin. PVC corks were placed at the entrance such that when the corks were removed, water flows into the basins. When the desired depth of water was applied the PVC corks were used to stop the flow of water into the plot. Using the orifice flow equation and the depth of flow recorded from the stage gauge, the flow rates into each basin were quickly determined and related to time of application to give to each plot the desired depth of water application. The time required to apply the depth of water was monitored using a stop watch.

The amount of water applied at every irrigation event (a weekly irrigation interval) was observed throughout the crop growing season) was based on the reference evapotranspiration amount for that week of irrigation and the experimental treatment. The average weekly reference evapotranspiration for December, January, February, and March (rounded up to whole number) were 30 mm, 30 mm, 40 mm and 45 mm, respectively. Thus, for treatment irrigated at 100% WRET, water applied ranged from 30 mm to 45 mm depth depending on the month. The seasonal water applied for the treatments irrigated at 100%, 75%, 50%, 25% WRET were 485, 395, 305, and 225 mm, respectively in 2008/09 season, and 495, 405, 315, 230 mm. The difference in seasonal water applied was due to the number of irrigation carried out in the seasons, from transplanting to crop maturity, being 12 in 2008/09 season and 14 in 2009/10 season.

2.6. Soil moisture measurement

The soil moisture status of each plot was monitored throughout the crop growing season in both seasons using soil moisture resistance blocks. Three soil moisture resistance block (gypsum blocks) were installed in each plot at 10 cm, 22 cm and 37 cm depths to monitor the electrical resistance of the soil moisture at 0–15 cm, 15–30 cm and 30–45 cm depths, respectively. The gypsum blocks were locally fabricated and calibrated on the field to relate electrical resistance measured to gravimetric moisture content for the soil of the experimental site using the method of Ejieji and Fasasi (2003). The calibration curve was defined by the power function obtained as:

$$\mathrm{GMC} = 536.17 * \mathrm{RS}^{-0.394} \quad (r^2 = 0.937) \tag{1}$$

where GMC is gravimetric soil moisture content (%) and RS is soil moisture resistance in ohms (Ω).

Electrical resistance measurements were carried out twice a week, at two days after irrigation and on the seventh day (just before the next irrigation), and the reading converted to gravimetric moisture content (% dry weight basis) using Eq. (1). It was assumed that the soil, being largely loam in texture, will attain field capacity two days after irrigation. This was confirmed as moisture contents measured two days after irrigation were relatively close (±4%) to field capacity values obtained in the laboratory for the soil profile layers.

2.7. Crop maturity and harvest

The crop began to show signs of maturity (over 70% dropping of leave-head) at 12 and 14 weeks after transplanting in the 2008/09 and 2009/10 seasons, respectively. Irrigation was withdrawn that same week and soil moisture measurement was stopped two weeks after, particularly on 3rd April 2009 for the 2008/09 season and 7th April, 2010 for the 2009/10 season. Harvesting was carried out about one week after, particularly on 10th April 2009 for the 2008/09 season and 13th April, 2010 for the 2009/10. Harvesting was done by lifting the onion bulbs with the dry matter using a hand hoe. The eight rows in each plot were lifted (without discards), properly labeled and taken to be laboratory to cure for about two weeks. Thereafter, the onion bulbs were separated from the dry matter and weighed. The bulb were graded into marketable sizes of <5 cm, 5–7.5 cm and >7.5 cm using a grading box constructed for that purpose to observe the effect of the experimental treatments on bulb sizes. The weight of each grade size was weighed.

2.8. Determination of crop water use

The crop water use (actual crop evapotranspiration) between successive moisture measurements was estimated using the soil water depletion method, with the expression given as:

$$\mathrm{ET} = \frac{\sum_{i=1}^{n}(\mathrm{MC}_{1i} - \mathrm{MC}_{2i}) * A_{si} * D_i}{t} \tag{2}$$

where ET is average daily evapotranspiration between successive soil moisture content sampling periods (mm/day); MC_{1i} is soil moisture content (g/g) at the time of first sampling (2 days after irrigation) in the ith soil layer; MC_{2i} is soil moisture content (g/g) at the time of second sampling (7 days after irrigation) in the ith layer; A_{si} is bulk density (g/cm^3) of the ith layer; D_i is thickness of ith layer (mm); n is number of soil layers sampled in the root zone depth D, and 't' is number of days between successive soil moisture content sampling.

The weekly evapotranspiration was obtained as the product of the daily crop evapotranspiration between successive soil moisture content sampling and the number of days in the week (7), while the seasonal evapotranspiration was the summation of the weekly ET.

2.9. Computation of water productivity

The crop water productivity simply referred to the output (e.g. crop yield, economic returns) with respect to the water input in crop production. The output may be quantified in terms of physical yield or economic returns, and the water input may be the seasonal applied to the field, seasonal evapotranspiration or seasonal transpiration. In this study, crop water productivity is defined with respect to yield and seasonal water supply, and the expression is given as:

$$\mathrm{CWP}_{(\mathrm{irrigation})}\ (\mathrm{kg/m^3}) = \frac{\text{Crop yield (kg/ha)}}{\text{Seasonal irrigation water applied (m)}} \tag{3}$$

3. Results and discussion

3.1. Water use

Table 5 shows the season water applied (SWA) and seasonal evapotranspiration (SET) for the 2008/09 and 2009/10 seasons.

Table 5
Seasonal water applied (SWA) and Seasonal evapotranspiration (SET) for the two seasons.

Treatment	2008/09 season		2009/10 season	
	SWA (mm)	SET (mm)	SWA (mm)	SET (mm)
$I_{25}M_{BPM}$	225	210.5 d	230	213.4 d*
$I_{50}M_{BPM}$	310	298.4 c	315	283.7 c
$I_{75}M_{BPM}$	395	351.9 b	405	357.9 b
$I_{100}M_{BPM}$	480	362.7 a	495	376.3 a
$I_{25}M_{WPM}$	225	207.1 d	230	215.8 d
$I_{50}M_{WPM}$	310	295.3 c	315	282.2 c
$I_{75}M_{WPM}$	395	348.9 b	405	331.0 b
$I_{100}M_{WPM}$	480	355.9 b	495	358.1 b
$I_{25}M_{RSM}$	225	216.3 d	230	219.3 d
$I_{50}M_{RSM}$	310	285.8 c	315	273.2 c
$I_{75}M_{RSM}$	395	341.5 b	405	334.6 b
$I_{100}M_{RSM}$	480	374.1 a	495	351.5 b
$I_{25}M_{NM}$	225	201.9 d	230	209.9 d
$I_{50}M_{NM}$	310	297.3 c	315	274.1 c
$I_{75}M_{NM}$	395	358.8 b	405	348.1 b
$I_{100}M_{NM}$	480	371.2 a	495	369.3 a

* Means followed by the same letter(s) in a column are not significantly different at 5% level of significance.

The SWA ranged from 225 to 480 mm in 2008/09 season, and 230–495 mm in 2009/10 season while the SET was found to be between 201 and 374 mm in 2008/09 season and 209 and 376 mm in 2009/10 season. The least value in the range was also obtained in the I_{25} treatments with NM in both seasons, while the highest value in the range was recorded in the I_{100} treatment with RSM in 2008/09 season, and the I_{100} treatment with BPM in 2009/10 season. Doorenbos and Kassam (1986) reported that water requirement for optimum onion bulb yield is between 350 and 550 mm depth. The SET values of the I_{100} treatments for both seasons were found to be within Doorenbos and Kassam (1986) water requirement range. However, the SET of the I_{75} treatments were however relatively close to the lower end of the water requirement range.

Analysis of variance test indicated there was also no significant difference between the means of SET of the two seasons. While there was highly significant differences ($p < 0.01$) in the means of SET of the irrigation (water application depths) treatments, there was none among the mulch treatments. The interaction between irrigation and mulching was also non-significance. The results imply that seasonal evapotranspiration (SET) was largely influenced by the water application depth and not mulching. The influence of water application depths on seasonal evapotranspiration was expected since evapotranspiration is very much dependent on water supply and availability within the plant root zone. Although it was also expected that the mulching will affect SET since the evaporation component of the SET in the mulched treatment should be drastically reduced due to mulching, it could be that the moisture conserved from evaporation may have been used in the transpiration process; hence there was no significant difference in the mean SET of the mulched and the no-mulch treatments. Evidence of higher crop water use associated with transpiration in the mulched treatments may be seen from the high bulb yields obtained from the mulched treatments (especially from the rice straw and black polyethylene mulched materials) compared to the no-mulch treatments since onion yield is very responsive to water.

3.2. Crop yield

Tables 6 and 7 show the weights of the different sizes of bulb yields and total bulb yield for 2008/09 and 2009/10 irrigation seasons, respectively. The total bulb yields ranged from 9.5 to 20.6 t/ha with an average of 15.4 t/ha in 2008/09 season, while the bulb yield in 2009/10 season ranged from 6.3 to 17.1 t/ha with an average of 12.5 t/ha. The least yields were obtained from the $I_{25}M_{NM}$ treatment in both seasons, while the highest yields were obtained from the $I_{100}M_{RSM}$ treatment in 2008/09 season, and the $I_{100}M_{BPM}$ treatment in 2009/10 season. It was expected that the least irrigated treatments (I_{25}) will produce the lowest bulb yield while the fully irrigated treatments (I_{100}) will produce the highest bulb yield since onion is known to be very responsive to water. Similar trend of results were obtained by Bekele and Tilahum (2007) in Ethiopia where onion crop was irrigated using drip system. The least irrigated treatment (irrigated with 25% ETc) had the least bulb yield of 5.5 t/ha while the fully irrigated treatment (irrigated with 100% ETc) had the highest yield of 25 t/ha.

The bulb yields in 2008/09 season were found to be highly significantly different ($p \leq 0.01$) from those of 2009/10 season. The agronomic practices for both seasons were the same (except for age of seedling before transplanting). Moreover, no statistical significant difference was noticed between seasonal evapotranspiration values of same treatments for the two seasons. Therefore,

Table 6
Total bulb yield and yields of different sizes in 2008/09 irrigation season.

Treatment	Yield (t/ha) of different sizes			Total (t/ha)
	>7.5 cm	5.0–7.5 cm	<5.0 cm	
$I_{25}M_{BPM}$	1.4	3.6	6.7	11.6 c*
$I_{50}M_{BPM}$	2.1	5.8	6.7	14.5 b
$I_{75}M_{BPM}$	0.6	7.4	9.9	17.9 a
$I_{100}M_{BPM}$	0.6	8.9	10.5	20.0 a
$I_{25}M_{WPM}$	1.9	3.9	5.1	10.8 c
$I_{50}M_{WPM}$	1.7	4.3	6.8	12.9 c
$I_{75}M_{WPM}$	1.1	7.1	9.5	17.7 a
$I_{100}M_{WPM}$	0.8	7.9	10.5	19.2 a
$I_{25}M_{RSM}$	1.4	4.1	5.8	11.4 c
$I_{50}M_{RSM}$	1.0	6.0	8.2	15.1 b
$I_{75}M_{RSM}$	1.5	7.2	9.6	18.2 a
$I_{100}M_{RSM}$	2.2	6.4	12.0	20.6 a
$I_{25}M_{NM}$	2.1	2.7	4.7	9.5 d
$I_{50}M_{NM}$	1.4	4.4	6.8	12.7 c
$I_{75}M_{NM}$	2.0	6.2	8.1	16.3 b
$I_{100}M_{NM}$	2.0	6.2	9.9	18.0 a

* Means followed by the same letter(s) in the column are not significantly different at 5% level of significance.

Table 7
Onion yield of difference sizes for the 2009/10 season.

Treatment	Yield (t/ha) of different sizes			Total yield (t/ha)
	>7.5 cm	5.0–7.5 cm	< 5.0 cm	
$I_{25}M_{BPM}$	0.2	5.9	2.4	8.5 d*
$I_{50}M_{BPM}$	0.3	11.5	2.6	14.4 b
$I_{75}M_{BPM}$	1.0	11.8	3.9	16.7 a
$I_{100}M_{BPM}$	1.2	14.2	1.6	17.1 a
$I_{25}M_{WPM}$	0.0	3.9	3.8	7.7 d
$I_{50}M_{WPM}$	0.0	6.5	5.6	12.1 c
$I_{75}M_{WPM}$	0.3	10.8	2.5	13.5 b
$I_{100}M_{WPM}$	1.0	10.5	1.7	13.1 b
$I_{25}M_{RSM}$	0.1	5.1	2.8	8.0 d
$I_{50}M_{RSM}$	0.0	8.5	4.3	12.8 c
$I_{75}M_{RSM}$	0.0	8.7	5.5	14.3 b
$I_{100}M_{RSM}$	0.2	9.9	5.6	15.7 a
$I_{25}M_{NM}$	0.0	3.5	2.8	6.3 d
$I_{50}M_{NM}$	0.1	8.5	3.2	11.8 c
$I_{75}M_{NM}$	0.1	9.6	3.3	12.9 c
$I_{100}M_{NM}$	0.4	11.2	3.0	14.6 b

* Means followed by the same letter(s) in the column are not significantly different at 5% level of significance.

the probable reason for the difference between the bulb yields of the two seasons may be the difference in varieties planted. There was significant difference ($p \leq 0.05$) among the irrigation treatments in each season, but none among the mulch treatments. The interaction between irrigation and mulching was not significant. The mean ranking based on the Duncan Multiple Range test shows that in both seasons, the bulb yields of the treatments irrigated at 75% WRET (I_{75}) were not statistically significantly different from those that were fully irrigated (I_{100}). The reason for this may not be far from the fact that seasonal evapotranspiration of the I_{75} treatments were relatively near the water requirement for optimum yield production. It was however found that the bulb yields of the I_{100} and I_{75} treatments were highly significantly different from those of the I_{25} and I_{50} treatments in both seasons, and those of I_{50} were also different from the I_{25} treatments. This pattern of result was noticed both in the mulched and no-mulch treatments, which implies that irrespective of mulching, water application depth significantly influences bulb yield of onion, and this agrees with Ramalan et al. (2010) who reported that onion bulb yield decreased with increase in levels of water deficit.

Analyses of the percentage reduction in yields showed that irrigating onion at 25% of weekly reference evapotranspiration (WRET) reduced bulb yield by 44.4% and 49.6% in 2008/09 and 2009/10 seasons, respectively. Irrigating onion at water application depth of 50% of WRET caused a yield reduction of about 28.8% in 2008/09 and 15.5% in 2009/10. However, irrigating at water application depths of 75% of WRET only reduced bulb yield by about 5–9% in both seasons. This suggests that water application depth per irrigation may be reduced to 75% of atmospheric water demand without causing a significant lost in bulb yield of onion. The percent yield reductions obtained in this study, though lower than those reported by Bekele and Tilahum (2007), were found to be of similar trend, thus confirming the order of effect of deficit irrigation on onion bulb yield. Bekele and Tilahum (2007) reported yield reductions of about 78, 45 and 15% when onion crop was irrigated at 25, 50 and 75% of ETc, respectively. The differences between the yield reductions of this study and those reported by Bekele and Tilahum (2007) may among other reasons (differences in onion variety, study environment and method of irrigation), be attributed to the bases of the treatment schedules. While Bekele and Tilahum (2007) based their treatment schedule on ETc (crop evapotranspiration), the treatment schedule of this study was based on reference evapotranspiration ETo, which gives higher water application depth per irrigation compared to ETc.

It was also observed that the bulb yields of the treatments mulched with black polyethylene were not significantly different from those mulched with rice straw at the 0.05 level of significance. However, the bulb yield of the rice straw mulch and black polyethylene mulch treatments were significantly different from the yields of the white polyethylene and No-mulch treatments. The differences in yield between the rice straw mulch and black polyethylene mulch treatments and the No-mulch treatment were about 12% in the 2008/09 season and 15% in the 2009/10 season. These results imply that mulching significantly influence bulb yield of irrigated onion. This finding agrees with Ramalan et al. (2010) who recorded a 6% difference in bulb yields between treatments mulched with black polyethylene and No-mulch under a drip irrigation system at the Central Rift Valley of Ethiopia, and concluded that use of mulch covers significantly increased onion bulb yield.

However, the difference in yields between the white polyethylene mulch treatment and the other mulched treatments, and the insignificant difference between the white polyethylene mulch and no-mulch treatments may be as a result of weed proliferation in the white polyethylene mulch treatments. While the rice straw and the black polyethylene mulch effectively suppressed weed proliferation in field, weed continued to grow profusely in the white polyethylene mulch plots.

Table 8
Crop water productivities for 2008/09 and 2009/10 seasons.

Treatment	2008/09 season CWP (kg/m^3)	2009/10 season CWP (kg/m^3)
$I_{25}M_{BPM}$	5.16 a	3.96 b*
$I_{50}M_{BPM}$	4.68 a	4.57 a
$I_{75}M_{BPM}$	4.53 b	4.12 a
$I_{100}M_{BPM}$	4.17 c	3.45 d
$I_{25}M_{WPM}$	4.80 a	3.38 d
$I_{50}M_{WPM}$	4.16 c	3.84 b
$I_{75}M_{WPM}$	4.48 b	3.33 d
$I_{100}M_{WPM}$	4.00 c	2.65 e
$I_{25}M_{RSM}$	5.07 a	3.56 c
$I_{50}M_{RSM}$	4.87 a	4.06 a
$I_{75}M_{RSM}$	4.61 b	3.53 c
$I_{100}M_{RSM}$	4.23 c	3.17 d
$I_{25}M_{NM}$	4.22 c	2.80 e
$I_{50}M_{NM}$	4.10 c	3.71 b
$I_{75}M_{NM}$	4.13 c	3.19 d
$I_{100}M_{NM}$	3.75 d	2.95 d

* Means followed by the same letter(s) in a column are not significantly different at 5% level of significance.

A percentage analysis of the bulb sizes showed revealed that in 2008/09 season (Table 6) about 45–59% of the total bulb yields of the I_{50}, I_{75} and I_{100} treatments were less than 5.0 cm diameter size. About 28–40% of the total bulb yields of the same treatments were between 5 and 7.5 cm diameter size while between 3 and 22% of the total yield were above 7.5 cm diameter size. However, in 2009/10 (Table 7), over 50% of the total bulb yields of all the treatments, irrespective of water application depths, were within 5.0 and 7.5 cm diameter size while between 10% and 40% of the total bulb yields were under 5.0 cm diameter size. The bulbs of the I_{25} treatments mulched with white polyethylene and rice straw were all under 7.5 cm diameter sizes. There was no consistency therefore in the pattern of influence of irrigation depth and mulching on the sizes of the onion bulbs across seasons. It is not clear whether this result was affected by the difference in variety of onion planted in the two seasons.

3.3. Crop water productivity

Table 8 shows the values of the crop water productivity in terms of irrigation water applied ($CWP_{(irrigation)}$) for the two seasons. The $CWP_{(irrigation)}$ ranged from 3.8 to 5.2 kg/m^3 and 3.7 to 4.6 kg/m^3 in 2008/09 and 2009/10 seasons, respectively. The range of $CWP_{(irrigation)}$ obtained in this study compared closely with those obtained by Ouda et al. (2010) in Egypt. They reported a water productivity range of 3.04–6.40 kg/m^3 in a 3-year field study of impact of deficit irrigation on onion using fresh and drainage water. The water productivities of this study were however very low compared to 9.16–15.94 kg/m^3 obtained by Ramalan et al. (2010) under a drip irrigation system in Ethiopia. The reasons for this may be attributed differences in location of study, method of irrigation and crop variety.

Higher water productivities values were recorded in 2008/09 compared to 2009/10 seasons. This is because the yields of 2008/09 season were significantly higher than those of 2009/10 season while the water supplied in the two seasons were relatively the same. However, a similar trend was noticed in the water productivities in the two seasons. The analysis of variance on the $CWP_{(irrigation)}$ values indicated significant differences ($p < 0.05$) among the means of the irrigation treatments and also among the means of the mulch practice. The mean $CWP_{(irrigation)}$ for the

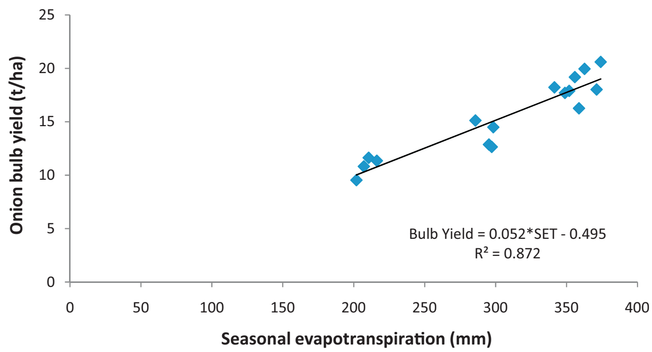

Fig. 1. Bulb yield-seasonal evapotranspiration relationship (2008/09 season).

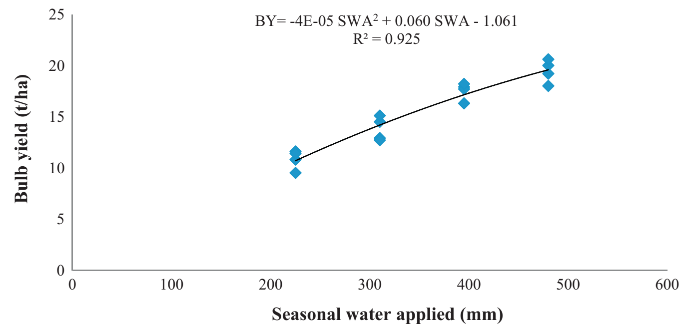

Fig. 3. Bulb yield-seasonal water applied relationship (2008/09 season).

I_{25}, I_{50}, I_{75} and I_{100} treatments were 4.8, 4.5, 4.4, and 4.0 kg/m^3, respectively, in 2008/09 season, and 3.3, 4.1, 3.8 and 3.1 kg/m^3, respectively, in 2009/10 season. It may be noticed that in both seasons, the I_{100} had the lowest mean $CWP_{(irrigation)}$.

Although the mean value of $CWP_{(irrigation)}$ of I_{25} treatments was the highest in 2008/09, it fell below those of I_{50} and I_{75} treatments in 2009/10 season. The CWP values of the I_{50} and I_{75} treatments were consistently higher in both seasons, which indicate that the I_{50} and I_{75} treatments were better results. The implications of these results are that irrigating at 100% weekly evaporative demand gives lower productivity in terms of water supply. The better prospect of increasing water productivity of the onion crop is to irrigate at 50–75% of weekly evaporative demand rather than at 25% or 100% weekly evaporative demand. The mean $CWP_{(irrigation)}$ of the BPM, WPM, RSM, and NM treatments were 4.6, 4.4, 4.9 and 4.1 kg/m^3, respectively in 2008/09 season, and 4.0, 3.3, 3.6 and 3.2 kg/m^3, respectively in 2009/10 season. It may be noticed that in both seasons, the water productivities of the mulch treatments were significantly higher (at the 0.05 level of significance) than the no-mulch treatment, which implies that mulching significantly affected the crop water productivity of the onion crop. The water productivities of the black polyethylene and rice straw mulch were also significantly different from the white polyethylene mulch treatment. The influence of weeds in the white polyethylene mulched treatments may be responsible for this difference. In order to increase water productivity in the irrigated onion field therefore, it is better to use rice straw or black polyethylene materials for mulching.

3.4. Yield-water use relationships

Figs. 1 and 2 show graphical relationships between onion bulb yield and seasonal evapotranspiration for 2008/09 and 2009/10 seasons, respectively, while Figs. 3 and 4 show relationships between bulb yield and seasonal water applied for 2008/09 and 2009/10 seasons, respectively. The relationship between the yield and seasonal evapotranspiration was linear in both seasons, implying that onion bulb yield was increasing with increase in evapotranspiration. A curvilinear (polynomial of 2nd order) was however found to best fit the relationship between bulb yield and seasonal water applied, implying that bulb yield plateau at some water supply level and decreases with additional water supply. Al-Jamal et al. (2000) and Ramalan et al. (2010) reported a linear relationship between onion bulb yield and season evapotranspiration and a curvilinear relationship between yield and seasonal water applied. According to Al-Jamal et al. (2000), the relationship between yield and water applied was curvilinear because part of the water applied went into deep drainage rather than to evapotranspiration. Although, Bekele and Tilahum (2007) did not present a graphical relationship between bulb yield and seasonal water applied, plotting their data revealed that the line of best fit was also curvilinear (2nd order polynomial).

The linear equation for the bulb yield (BY in t/ha) and seasonal evapotranspiration (SET in mm) relationship was obtained as Eqs. (4) and (5) for the 2008/09 and 2009/10 seasons, respectively:

$$BY = 0.052 * SET - 0.495, \quad r^2 = 0.822 \tag{4}$$

$$BY = 0.048 * SET - 2.087, \quad r^2 = 0.818 \tag{5}$$

Eq. (4) implies that bulb yield will be initiated after evapotranspiration threshold of 10 mm, and thereafter, about 0.52 t/ha of onion yield will be obtained for every increment of 10 mm evapotranspiration rate. Eq. (5) also implies that bulb yield of 0.48 t/ha will be obtained for every increment of 10 mm evapotranspiration rate after evapotranspiration threshold 43.5 mm. The difference in yield production per increment in evapotranspiration in both seasons is only about 7% which is not significant. This means that increment in evapotranspiration rate had about the same effect on the onion bulb yield in both seasons. This also implies that the irrigation regimes had the same effect on the onion crop irrespective

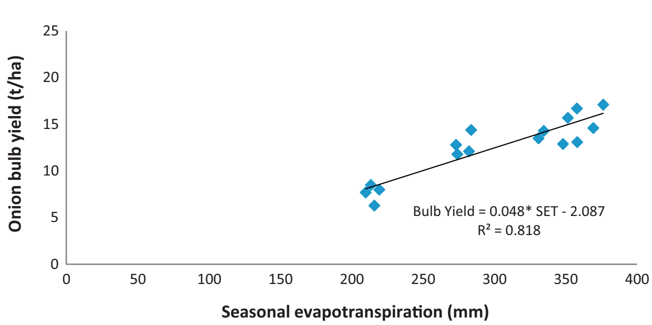

Fig. 2. Bulb yield-seasonal evapotranspiration relationship (2009/10 season).

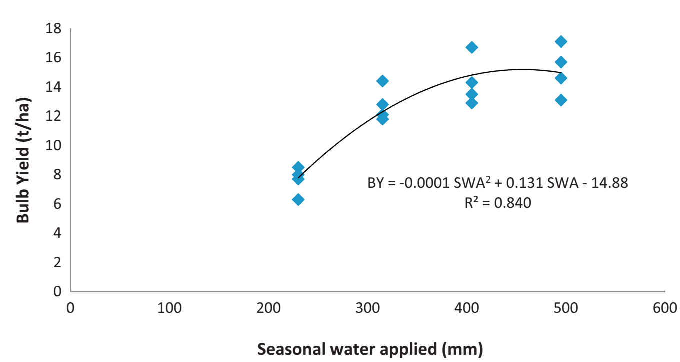

Fig. 4. Bulb yield-seasonal water applied relationship (2009/10 season).

of variety planted. However, the difference in the evapotranspiration thresholds may be attributed to differences in time of transplanting. The onion seedlings were transplanted at eight and six weeks in 2008/09 and 2009/10 seasons, respectively.

The relationship between bulb yield and seasonal water applied to the field was obtained as Eqs. (6) and (7) for 2008/09 and 2009/10 seasons, respectively:

$$BY = -0.00004 * SWA^2 + 0.06 * SWA - 1.061, \quad r^2 = 0.925 \qquad (6)$$

$$BY = -0.00001 * SWA^2 + 0.131 * SWA - 14.88, \quad r^2 = 0.840 \qquad (7)$$

The solutions of Eqs. (6) and (7) suggest that bulb yield was initiated after a threshold of 17.5 and 125 mm depth of water application in 2008/09 and 2009/10 season, respectively. Peak production will be reached at about 550–600 mm water application depth in both seasons and thereafter, bulb yield will decline with additional water application. Bulb yield will reduce to zero if seasonal water application depth is above 1184.3 mm. These findings will be useful in planning how to maximize bulb yield per water supply in the study area. The water requirement at which peak production was attained in this study slightly above the range of 350–550 mm depth given by Doorenbos and Kassam (1986) as water requirement for optimum bulb yield. It must however be noted that variability in the water requirement of any crop is a function of location and irrigation method. The difference in water threshold at which bulb yield is initiated between actual crop evapotranspiration and irrigation water applied may be associated with the water retained in the soil root zone depth and that loss to deep percolation.

4. Conclusion

The effects of regulated deficit irrigation and mulching with rice straw, black and white transparent polyethylene materials on yield, water use and crop water productivities of onion crop was studied using field experiments conducted in 2008/09 and 2009/10 irrigation seasons in Zaria Nigeria. The findings were that with or without mulching, irrigating onion at water application depth of 25% of weekly reference evapotranspiration (WRET) throughout the crop growing season reduces bulb yield by about half of what will be obtained if irrigation was at 100% of WRET. Irrigating onion at water application depths of 50% WRET reduces bulb yield by a quarter, while at water application depth of 75% the reduction in bulb yield will not be significant compared to irrigating at 100% WRET. Mulching with rice straw or black polyethylene material gave a yield increase of about 12–15% compared to a no-mulch condition. White polyethylene material was not as effective in suppressing weed compared to rice straw and black polyethylene. Thus bulb yield under white polyethylene mulch were not significantly different from a no-mulch condition. The seasonal evapotranspiration of the onion crop was largely influenced by the depths of water applied rather than the mulching. Although mulching was expected to have reduced evaporation, the water conserved may have by use for transpiration, hence no significant differences in SET of the mulched and no-mulch treatment. Irrigating at 50% and 75% of WRET gives better water productivity in terms of water supply for onion in this study. Mulching with rice straw or black polyethylene also significantly improves the crop water productivity of the onion crop, and is therefore recommended.

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