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Optimizing yield and irrigation water productivity of wheat under Sahel conditions in North East Nigeria

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ABSTRACT

Unsustainable irrigation practices are a major threat to the available water resources and food security of the country. This research was conducted to determine the optimal wheat grain yield and water productivity (WP) under limited irrigation practices for the enhanced livelihood of small farmer holdings in the Sahel region of northeast, Nigeria. The research was carried out in randomized complete block design (RCBD) with split plot arrangement and replicated three times. The main plot treatment was 7 (I1), 10 (I2), and 14(I3) days irrigation intervals, while the subplot factor was 100 (V1), 85 (V2), and 70% (V3), of crop water requirement (ETc) replacement. The cropWat model was used to determine the crop water requirement (ETc) of the wheat (var. Norman) used in the research. The findings indicated that a 7-day irrigation interval increased grain yield by 20.18 over a 10-day irrigation interval and by 63.10% over 14-day irrigation intervals. Grain yield was found to decrease by 44.80 and 747.25kgHa-1 respectively for 85 and 70% ETc replacement irrigations from full ETc replacement irrigation. Crop water use efficiency was higher and better (0.74 mm-kg/ha) with I1V2 irrigation treatment for wheat and saved 11.55.50 m3 irrigation water over other irrigation schedules. It is recommended that 7 7-day irrigation interval be maintained, while irrigation depth can be reduced by up to 15% for optimum water productivity.

Contribution/Originality: The results from this study indicated that the irrigation intervals of 10 and 14 days are not suitable for wheat production in the Sahel regions of Northeast, Nigeria. The 7-day irrigation interval with 85% ET replacement is recommended to improve the water productivity of wheat grown in the Sahel agroecological zone of Nigeria.

1. INTRODUCTION

The main issues that the majority of people in the Chad basin are dealing with are the availability of sufficient water for crop production and food security. Crop productivity and food security are being negatively impacted by the agriculture sector's unsustainable usage of freshwater [1]. Both the global water demand and the level of water stress are rising as a result of the world's population expansion and economic development. Therefore, the question of how to attain sustainable development and improve the management of water resources becomes one that the governments of all nations need to think about and resolve. Irrigation accounted for 87% of the world's water extraction (extraction minus return) approximately ten years ago. Meanwhile, those irrigated areas produced 40–

45% of the world's food [2]. The recent increase in irrigation farming brought on by the drought and the need for food security has led to overexploitation of groundwater resources, which is expected to worsen in the years to come [3]. In arid and semi-arid environments, the primary problem impeding crop production is water constraint [4]. Presently, 40% of global crops are grown on irrigated land, demonstrating the continued importance of irrigation in assuring food production [5]. It is forecasted that by 2030, there will be a 50% increase in water consumption, and 4 billion people, or half of the world's population, will likely experience severe water shortage. This will mostly happen in South Asia, the Middle East, and Africa [6]. Crop water productivity has become a key strategy for dealing with water scarcity and improving the relationship between crops and water. Crop water productivity (CWP) is defined as the amount of product produced per unit of water applied. Farmers typically focus on increasing profitability or enhancing food security rather than prioritizing water productivity [7]. Water plays a crucial role in the growth and yield of crops, especially in dry and semiarid regions where water is limited [8]. Efficient water use is essential for optimizing irrigation schedules, and improving water availability, soil quality, and crop yield [9].

A significant agricultural issue is using less land and water while producing a sufficient, safe, and balanced diet to feed the world's expanding population [7]. Achieving global food security requires increasing agricultural water productivity since unsustainable water use can impede food production [10]. Measures to improve agricultural water productivity and reduce the gap between supply and demand for water are needed to remedy the imbalance the water-related yield gap must be considered [11]. Water-saving agriculture involves implementing various strategies to efficiently use water and improve crop water productivity [12]. One approach is deficit irrigation, which can reduce water usage while enhancing water efficiency and productivity at different scales [12, 13]. Additionally, enhancing agricultural production is crucial for increasing income, household food supply, food security, and poverty reduction and it can also improve land productivity and boost farming profits through better input management [14].

The Sahel region has a semi-arid to arid climate with high temperatures and erratic rainfall patterns which are often major constraints to agricultural production [15]. The usually short rainy season in North East Nigeria further restricts wheat production by reducing its cropping opportunity for irrigation during the cold dry season. These circumstances make it necessary to create plans that optimize water use and raise crop yield levels. Since irrigation is crucial to the Sahelian wheat cropping, it must be carefully managed to ensure the area's agriculture is sustainable. To further maximize water use efficiency in the area, enhancing irrigation infrastructure and management techniques is indispensable [16]. This study was, therefore, designed to estimate the water consumption and productivity of irrigated wheat during the dry season in the Yobe basin. The goal was to identify the most effective irrigation strategy to optimize wheat yield and water productivity in the region.

2. MATERIALS AND METHODS

2.1. Location Description

The research was conducted on the floodplains of the Yobe River in the Bursari Local Government Area (12.24 – 13.00° N, 11.00 – 11.48°E) of Yobe State, Nigeria (Figure 1). It is located about 12 kilometers northeast of Gashua, Bade Local Government Area (LGA). The research site experiences three distinct seasons in a year: a hot and dry one from March to June, a wet one from July to September/October, and a cold and dry one from November to March. The area receives 350 to 400 mm of rain on average per year. During the harmattan season, the average temperature is about 20°C, while the average temperature ranges from < 20°C during the harmattan season to about 44°C in the hot, dry months. The soils of the study area were mostly dominated by sandy loam texture alfisols. However, sandy clay and clay loam also exist in the riverine alluvial deposits in the area. The area is characterized by Sahel savanna sparse vegetation. During the dry seasons, the area's farmers primarily grow vegetables, rice, wheat, and maize. The main source of water for irrigation in the area is the Yobe River, with some over-flooded retention ponds and tube wells dug on the floodplain of the river.

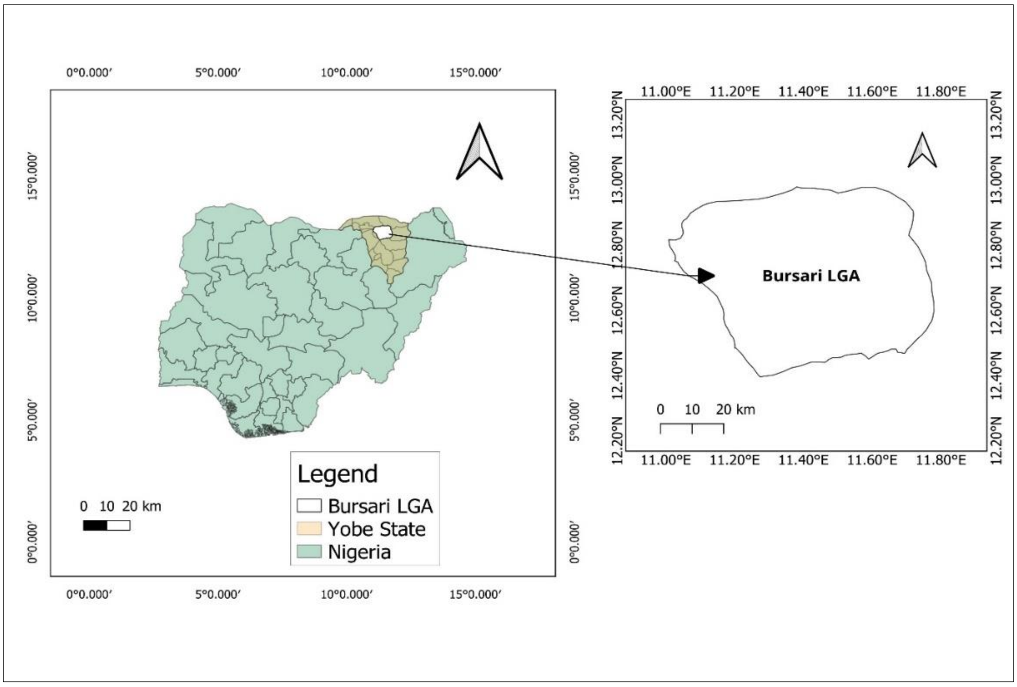

Figure 1. The research area location map (Bursari local government area (LGA)).

The main source of water for irrigation in the area is the Yobe River, with some over-flooded retention ponds and tube wells dug on the floodplain of the river. The irrigation method used was surface irrigation by using Polyvinyl chloride (PVC) pipe networks to supply water to the check basins formed on the farm.

2.2. Meteorological Data

Climatic data for the area were obtained from the meteorological station located inside the Federal University, Gashua. The data collected include precipitation, air temperature, relative humidity, wind speed, and sunshine hours (Table 1). The data was used in the determination of potential and actual evapotranspiration using Cropwat model 8.4.

Table 1. Meteorological data of Gashua, Yobe State (2013 – 2023).

Month	Rain mm	Min. temp °C	Max. temp °C	Humidity %	Wind km/Day	Sun hours	Rad MJ/m²/Day	ET_o mm/Day
January	0	12.6	31	22	69	7.7	18.1	3.6
February	0	14.3	33.8	21	70	7.9	19.8	4.04
March	0	18.8	40	20	72	6.8	19.5	4.65
April	1	21.6	42.5	25	86	6.8	20	5.43
May	6.4	24.1	41.6	43	130	8.1	21.8	6.4
June	46.2	24	38.5	51	156	8	21.3	6.25
July	131.5	22.5	34.7	64	190	7.1	20	5.52
August	184.8	21.7	31.8	74	138	5.9	18.4	4.35
September	74.3	21.8	32.3	71	70	7.9	21.2	4.47
October	4.2	19.8	35.8	49	69	8.7	21.2	4.67
November	0	16.5	35.1	27	78	8.9	20	4.4
December	0	13.2	31.3	24	86	8.9	19.2	4.03
Average	448.4	19.2	35.7	41	101	7.7	20	4.82

Note: MJ = Megajoule

2.3. Experimental Design and Treatments

The experiment was laid out as a split plot design and replicated three (3) times, giving a total of 27 plots and the area of each plot is 2.4 x 3m. The two factors involved were: irrigation frequency and volume. The level of the irrigation frequency included: irrigation every 7 days (I1), irrigation every 10 days (I2), and irrigation after every 14 days (I3) arranged in the main plot while, the irrigation volume was; 100% of the crop water requirement (ETc) as (V1), 85% of ETc (V2) and 70% of ETc (V3) plots placed in the subplots. The levels of the factors were combined to form 9 treatments.

2.4. Field Measurement Data

The field data collected by the research farm include the plant height (cm), 1000 grain weights (g), straw weights (kg/ha), grain yields (kg/ha), harvest index (%), and applied irrigation water (m^3) for each treatment.

Harvest Index (HI): The ratio of grain (weight) to total above-ground biomass weight on a dry matter basis.

HI = Grain weight/ grain weight + straw weight.

2.5. Crop Water Productivity Estimation

Productivity, as defined by the FAO, is the relationship between an input unit and output [7]:

• The quantity or value of the product is the output (numerator).

• The amount or value of water utilized or consumed (ET) is the input (denominator).

Transpiration controls the amount of water that crops produce. However, because it is challenging to distinguish between transpiration and evaporation, evapotranspiration (ET) is employed to determine how much water is used [17].

Equation 1 was used to get the CWP for each treatment based on the harvested wheat yield [18].

$$CWP = \frac{Y}{10 \times ETa,seasonal} \qquad (1)$$

Where: CWP is the crop water productivity (kg/m^3), *Y is* the wheat yield (kg/ha), and ETa (seasonal) is the total actual evapotranspiration throughout the growing season of the wheat.

The irrigation water productivity (IWP) was calculated using the following equation [19]:

$$IWP = Y/I \qquad (2)$$

Where: IWP is the irrigation water productivity (kg/m^3), *Y is* the wheat yield (kg/ha), and *I* is the total irrigation amount throughout the growing season of the wheat.

2.6. Cropwat Model

A comprehensive set of irrigation levels and timings based on crop growth stage is offered by the CropWat model. When accurate input data is included, the observer can use the model's simulated output to estimate crop evapotranspiration. Version 8.0 of the CROPWAT model incorporates the updated Penman-Monteith approach, as stated in Equation 3 [20, 21].

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2\ (e_s - e_a}{\Delta + \gamma(1+0.34u_2)} \qquad (3)$$

Where:

ET_o reference evapotranspiration [mm day^{-1}],

R_n net radiation at the crop surface [MJ m^{-2} day^{-1}],

G soil heat flux density [MJ m^{-2} day^{-1}],

T mean daily air temperature at 2 m height [°C],

U_2 wind speed at 2 m height [m s^{-1}],

e_s saturation vapor pressure [kPa],

e_a actual vapor pressure [kPa],

e_s - e_a saturation vapor pressure deficit [kPa],

Δ slope vapor pressure curve [kPa °C-1],

γ psychrometric constant [kPa °C-1].

The reference evapotranspiration, ET_o, provides a standard to which:

- Evapotranspiration at different periods of the year or in other regions can be compared.
- Evapotranspiration of other crops can be related.

The crop coefficient (K_c) for winter wheat was determined based on [20]. The ET_o obtained from the FAO Penman-Monteith method and the K_c were used to calculate the ETa depending on actual weather data as follows:

$$ET_a = ET \times K_c \qquad (4)$$

3. RESULTS AND DISCUSSIONS

Responses of straw and grain yield to irrigation regimes varied significantly ($P < 0.05$) as well as irrigation interval versus irrigation volume interaction (Table 2). Both straw and grain yields were higher (12741.69 and 4255.68kg ha^{-1} respectively) under a 7-day irrigation interval and decreased with a decrease in irrigation frequency. Irrigation volume treatment had an effect also on both straw and grain yields, with 100 and 85% of the irrigation requirement producing higher yields significantly at par. Harvest index was higher with 7 days irrigation interval (33.87%) and 100% of ET (29.99%), but both were at par with 10 days interval and 85% of ET respectively, while the minimum was recorded with 14 days interval and 70% of ET (Table 2).

Table 2. The main effect of irrigation regimes on straw and grain yield (kg/ha) and harvest index (%) of wheat.

Irrigation regime	Straw yield (kg/ha)	Grain yield (kg/ha)	Harvest index (%)
Irrigation interval (I)			
I_1	12741.69^a	4255.68^a	33.87^a
I_2	10740.40^b	3397.04^b	32.14^a
I_3	9823.45^c	1570.46^c	16.39^b
LSD	429.39	161.46	3.56
Irrigation volume (V)			
V_1	13083.74^a	3338.41^a	29.99a
V_2	11646.90^a	3293.61^a	27.51^{ab}
V_3	8574.88^b	2591.16^b	24.89^b
LSD	1748.57	217.80	3.97
I x V	*	*	*

Note: I_1 = 7 days irrigation interval, I_2 = 10 days irrigation interval, I_3 = 14 days irrigation interval, V_1 = 100% of ET, V_2 = 85% of ET, V_3 = 70% of ET. LSD = Least significant difference. ^{a,b,c} Within the column, mean values with the same letter are not significantly different, * = significant interaction.

The interaction effect of irrigation interval and irrigation volume (I x V) on straw yield (Table 3) showed that 7 days interval with full irrigation requirement (I_1V_1) significantly produced the highest yield (15439.32kg ha^{-1}) while the least was recorded under 14 days interval and 70% of ET (I_3V_3). Grain yield was significantly higher (4749.51kg ha^{-1}) with the interaction of 7 days intervals with 85% of irrigation water requirement (I_1V_2), while the minimum (1435.72kg ha^{-1}) was recorded under 14-day irrigation interval and 70% of ET (I_3V_3). It could be related to water stress which adversely impacts many physiology of plants leading to a reduction in growth, development, and productivity [22].

To match the crop's water requirements with its maximum production, the ideal irrigation scenario must be modified (i.e. wheat grain yield). It is crucial to stress that the best yield was not always obtained with the full irrigation requirement treatment (V1). This demonstrates the beneficial and negative effects of varying irrigation volumes and frequencies on wheat grain yield. In a similar vein, the harvest index was comparable to that of I1V3 but much greater with I1V2 and I2V1 (Table 3). This indicated that both irrigation frequency and volume are important in determining the best irrigation scenario for dry-season wheat in North Yobe State.

Table 3. Interaction effect of irrigation intervals and volume on wheat yield parameters.

Treatments	Straw yield (kg/ha)	Grain yield (kg/ha)	Harvest index (%)
I_1V_1	15439.32^{a}	4571.23^{a}	29.68^{b}
I_1V_2	13201.84^{b}	4749.51^{a}	35.98^{a}
I_1V_3	9583.92^{e}	3446.30^{c}	35.97^{a}
I_2V_1	12489.53^{b}	3800.94^{b}	30.40^{b}
I_2V_2	11358.15^{c}	3498.73^{c}	30.81^{b}
I_2V_3	8373.51^{f}	2891.46^{d}	35.20^{a}
I_3V_1	11322.37^{c}	1643.07^{e}	14.60^{d}
I_3V_2	10380.72^{d}	1632.58^{e}	15.75c^{d}
I_3V_3	7767.22^{f}	1435.72^{e}	18.83^{c}
LSD	743.72	279.66	3.56

Note: I_1 = 7 days irrigation interval, I_2 = 10 days irrigation interval, I_3 = 14 days irrigation interval, V_1 = 100% of ET, V_2 = 85% of ET, V_3 = 70% of ET. $^{a, b, c, d, e, f}$ Within the column, mean values with the same letter are not significantly different.

The crop water requirements (ET_c) according to treatments' main effect differed significantly as 7 days of irrigation would require more water than 10 and 14-day intervals (Table 4). Regarding crop water use efficiency (CWUE), results revealed that it was higher with I_1 and decreased with reduced frequency of irrigation, while irrigation volume showed no significant differences between the 100 and 85% ETc watering regimes. The amount of water used was higher in I_1 and V_1 as in ET_c because of the frequency and high volume respectively. Crop water productivity was higher in I_1 and V_1 also, this could be attributed to high frequency and maximum ET replacement as similarly reported by Ahmed, et al. [23].

Table 4. The main effect of irrigation regimes on crop water use efficiency and productivity of wheat.

Irrigation regime	ETc (mm)	CWUE (mm-kg/ha)	Water used (m^3)	CWP (m^3/kg/ha)
Irrigation interval (I)				
I_1	623.24^{a}	6.57^{a}	6505.17^{a}	0.66^{a}
I_2	529.76^{b}	5.25^{b}	4553.62^{b}	0.52^{b}
I_3	436.27^{c}	2.45^{c}	3252.58^{c}	0.25^{c}
SE	63.59	0.24	1623.45	0.02
Irrigation volume (V)				
V_1	735.40^{a}	5.06^{a}	7658.01^{a}	0.51^{a}
V_2	623.13^{b}	4.84^{a}	6502.50^{b}	0.34^{a}
V_3	511.20^{c}	4.36^{b}	5355.00^{c}	0.31^{b}
SE	97.44	0.31	2113.08	0.03
I x V	*	*	*	*

Note: I_1 = 7 days irrigation interval, I_2 = 10 days irrigation interval, I_3 = 14 days irrigation interval, V_1 = 100% of ET, V_2 = 85% of ET, V_3 = 70% of ET. $^{a, b, c}$ Within the column, mean values with the same letter are not significantly different, * = significant interaction.

Table 5 presents the results of the interaction effect of irrigation intervals and volume on wheat water use efficiency, water use, and productivity. The I_1V_1 treatment had the highest ETc (735.40 mm), which suggests that it uses the most water because it is irrigated frequently and replaces all of the ET. This is consistent with findings by Islam, et al. [24] who reported higher ETc with more frequent and full irrigation. The treatment I_3V_3 had the lowest ETc (357.84 mm), indicating the least amount of water used with fewer irrigation frequencies and the least amount of ET replacement.

The highest CWUE (7.31 mm-kg/ha) was found in I_1V_2, suggesting that the most effective way to utilize water for higher yields is to combine frequent irrigation with 85% ET replacement. This is consistent with the findings of Zhang, et al. [25] who reported the benefit of regulated deficit irrigation in enhancing crop water use efficiency of wheat. The treatment combinations (I_3V_1) had the lowest CWUE (2.15 mm-kg/ha), indicating inefficient water usage under infrequent irrigation and complete ET replacement treatments (Table 5).

The largest water use was found in I_1V_1 treatment (7658.00 m^3), which could be due to the highest ETc and frequent irrigation applied. According to Mallareddy, et al. [26] frequent irrigation with full ET replacement leads to higher total water usage. While, I_3V_3 (2677.50 m^3) had the least amount of water used, which corresponds to the lowest ETc and the least amount of irrigation (Table 5). Reduced irrigation water volume and multiple irrigations (I_1V_2) improved soil water storage (SWS) uptake and utilization reduced total water use and resulted in significantly higher irrigation water use efficiency (IWUE) [27]. I_1V_2 had the highest CWP (0.51 m^3/kg/ha), which suggests that it has the best water productivity when it is irrigated often with 85% ET replacement. Moderate water deficits maintained higher yields and significantly improved HI and Moderate water stress maximizes CWP which ensures healthy crop growth [28]. The lowest CWP (0.15 m^3/kg/ha) was found in I_3V_1, indicating low water productivity with less frequent irrigation and complete ET replacement (Table 5).

Table 5. Interaction effect of irrigation intervals and volume on wheat water use efficiency and productivity.

Treatments	ETc (mm)	CWUE (mm-kg/ha)	Water used (m^3)	CWP (m^3/kg/ha)
I_1V_1	735.40^a	5.97^c	7658.00^a	0.42^c
I_1V_2	623.13^c	7.31^a	6502.50^b	0.51^a
I_1V_3	511.20^f	6.44^b	5355.00^d	0.45^b
I_2V_1	625.09^b	4.96^e	5360.60^c	0.35^e
I_2V_2	529.66^d	5.38^d	4552.75^e	0.37^{de}
I_2V_3	434.52^h	5.40^d	3748.50^g	0.38^d
I_3V_1	514.78^e	2.15^g	3829.00^f	0.15^g
I_3V_2	436.19^g	2.51^{fg}	3251.25^h	0.18^{fg}
I_3V_3	357.84^i	2.68^f	2677.50^i	0.19^f
LSD	11.04	0.41	281.19	0.04

Note: I_1 = 7 days irrigation interval, I_2 = 10 days irrigation interval, I_3 = 14 days irrigation interval, V_1 = 100% of ET, V_2 = 85% of ET, V_3 = 70% of ET. $^{a, b, c, d, e, f, g, h, i}$ Within the column, mean values with the same letter are not significantly different.

4. CONCLUSION

The study showed that 7-day irrigation intervals had the highest yield compared to 10 and 14-day irrigation intervals, while the yield under irrigation depth (volume of water applied) was higher with 100% and 85% irrigation replenishment of the wheat crop's water requirements. As the amount of irrigation water applied grew, so did the overall amount of water utilized in the various irrigation scenarios. Rather than depending solely on strict watering intervals, the irrigation schedule should be adjusted to the crop's water requirements. It is advised to be aware of the irrigation needs throughout growth phases to guarantee an adequate supply of irrigation water at certain times, such as flowering, and prevent severe stress.

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