



Soil Physical Properties and Water Utilization of Okra Under Irrigation and Mulching in Northern Guinea Savanna, Nigeria



Yusuf S. Alasinrin¹ , Abdulkadir A. Wahab² ,
Haliru A. Girei³ , Shamsiddeen M. Jibrin⁴ ,
Isiaka Karim¹ , Olasunkanmi A. Odewole¹ ,
Saheed S. Togun¹

1 - Department of Agronomy, University of Ilorin, Ilorin.

2 - Department of Crop Production, Kwara State University,
Malete

3 - Department of Soil Science, Federal University Dutse

4 - Crop Science Department, Saadu Zungur University,
Bauchi

Corresponding Author: Alasinrin Yusuf,

Received: 1 December 2024

e-mail: alasinrin.sy@unilorin.edu.ng

Accepted: 20 January 2025

Abstract

During the dry season, a field experiment was carried out at the IAR Irrigation Research Farm in Kadawa, Nigeria. The study investigated the impacts of controlled deficit irrigation and different mulch levels on soil hydro-physical traits and water efficacy in okra production (*Abelmoschus esculentum* L.). A total of Sixteen (16) treatment combinations were investigated: four irrigation levels (100, 85, 70, and 55% using weekly reference evapotranspiration (WRETo)) and four mulch levels (no mulch, 2, 4, and 6 kg/plot of rice straw). Soil samples at depths of 0-15 and 15-30 cm were analysed for bulk density (BD), total porosity (TP), saturated hydraulic conductivity (Ksat), and water retention across soil matrix potentials. Theta probes were used to measure soil moisture continually. The results showed that BD was statistically similar between 100% and 55% WRETo at 0-15 cm, but higher at 100% WRETo than at 85 and 70% WRETo. There were no significant variations in BD, TP, Ksat, or water potential across mulch layers or irrigation treatments at either depth. The RETC model effectively predicted soil hydraulic properties under the two treatments. Regarding yield, mulching at the M6 level boosted okra yield over other mulch treatments. The 55% ETo treatment achieved the highest irrigation water use efficiency (IWUE) at 20.99 kg/m³ compared to 100% ETo at 17.65 kg/m³. M6 and M4 mulch applications produced higher IWUE than M2 and M0 treatments, demonstrating that deficit irrigation and optimal mulching can improve water use efficiency in okra.

Keywords: deficit irrigation schedule, different mulch, soil physical properties, and RETC.

Introduction

Soil's water-holding capacity is influenced by its physical and chemical qualities, which determine the duration that a plant can be sustained before it requires irrigation or rainfall. These properties also dictate the frequency of irrigation, the amount and rate of water application, and plant evapotranspiration (Irmak et al., 2016). Frequent irrigation and intensive cultivation can lead to the erosion of up to 48 t/ha of fertile topsoil (Bhatti et al., 2021). Kang et al. (2021) found that integrating knowledge of soil physical properties with other agricultural techniques has been instrumental in enhancing water irrigation efficiency, developing high-yielding farmland, and increasing productivity while conserving soil and water. Soil texture and structure form the foundational matrix, collectively creating the void geometry within the soil. According to Montzka et al. (2017), soil classification has typically relied on one main technique, from which additional physical parameters such as hydraulic conductivity, total available water, water-holding capacity, and infiltration capacity are estimated or inferred.

Soil water is depleted through evapotranspiration, which depends on soil moisture availability (Irmak et al., 2016). Tolomio and Casa (2020) stated that when the soil is sufficiently wet, it supplies water quickly enough to meet the crop's atmospheric demand, allowing water uptake to equal actual evapotranspiration (ETa). However, as soil water content decreases, the water becomes more tightly bound to the soil matrix, making it harder to extract.

When soil moisture falls below a soil water availability threshold, water can no longer move quickly enough to the roots to meet transpiration demands, causing the roots to begin experiencing stress (Huang et al., 2020). This is in line with Singh et al. (2015) finding that the portion of total available moisture (SMta) that a crop can absorb from the root zone without experiencing water stress is known as readily available moisture (SMra). In arid and semi-arid regions such as Nigeria, precipitation is low, and water is scarce thereby becoming a critical resource, and competition for it is becoming increasingly intense (Ikhuoso et al., 2020). Environmental degradation linked to water use is a significant concern, especially in rural areas where most food is produced, and the population relies heavily on natural water sources for survival. This fact is affirmed in the study by Kaziboni (2024) that water scarcity is a pressing issue, leading to substantial social, cultural, and economic disadvantages. This problem is largely due to inadequate water resource development and management in Nigeria.

Farmers face growing competition with cities and industries for dwindling water supplies (Matemilola, 2017). Additionally, vast areas remain unirrigated due to a lack of irrigation water. Therefore, innovative tactics are essential to enhance the efficient use of available water. Mulching provides significant benefits by conserving soil moisture while controlling soil temperature. Both organic and synthetic mulches help retain soil moisture by reducing evaporation. Wang et al. (2019) found that using wheat straw mulch reduced evaporation by 50% under winter wheat, conserving approximately 80 mm of water during the growing season. Additionally, mulch enhances yield by improving soil physical conditions, such as increasing stability in the topsoil (Wang et al., 2019) and enhancing the quality of wheat grain (Luo et al., 2020). It also increases water infiltration and storage in the rhizosphere, while improving soil structure and macro-porosity (Ikhuoso et al., 2020).

Consequently, the combined use of regulated deficit irrigation and mulching shows great promise in achieving these outcomes.

The objectives of this study are to determine the effects of regulated deficit irrigation scheduling and organic mulch on selected soil physical properties, to assess the impact of the retention curve (RETC) computer code on soil under regulated deficit irrigation and organic mulch, and to assess the effects of regulated deficit irrigation and organic mulch on okra yield and water utilization.

Materials and Methods

The trial was carried out during the dry season at the irrigation research farm of the Institute for Agricultural Research (IAR), Kadawa (N11° 39', 08° 27'E'). The distribution of rainfall in Kadawa is primarily defined by six months of rainy and dry seasons with average monthly temperature that varies from 27.8°C in March to 34.4°C in May (Usman et al., 2018).

The experiment was laid out in a randomized complete block design arranged in a split-plot arrangement and three replications. The experiment involves four levels of controlled deficit irrigation (water application depths) and four levels of mulching applications. Irrigation treatments were fitted to the main plots (blocks), whereas mulch treatments were assigned to the subplots. The irrigation consists of water application depths of 100, 85, 70, and 55% of weekly reference evapotranspiration (WRETo), with mulch treatments of no mulch (NM), 2.0, 4.0, and 6.0 kg/plot of rice straw, respectively. Two seeds of Okra (Clemson Spineless variety) were sowed per hole, with an inter and intra-row spacing of 30 cm x 30 cm. As a side dressing, 250 kg/ha of compound fertilizer (NPK 15:15:15) was applied once two weeks after sowing (WAS).

The surface irrigation approach was adopted in this study due to its affordable price and simplicity of maintenance. Water from the main canal was fed weekly into a lateral ditch that served the basins. To allow water into the basins, a pair of 50cm long polyvinyl chloride (PVC) tubes with a diameter of 5cm were put on one side of the basin's bunds. The tubes were built to allow for free orifice flow into the basins. Stage gauges were installed at the water entry to monitor the depth of water over each tube as it entered the basin. A PVC cork was put at the opening so that when it was removed, water flowed into the basins. The time needed to apply water to the specified depth was monitored using a stopwatch; after the desired depth of water was achieved, the PVC cork was used to halt the flow of water into the plot (Michael, 2008).

Undisturbed and intact soil samples were collected from the experimental site before land preparation and from each plot after harvest at 0-15 and 15-30cm depth using auger and cores, respectively. Soil water retention was determined from undisturbed core samples using pressure plate extractors (Klute, 1986). The undisturbed soil samples were saturated for 24 hours and samples were equilibrated at suction points of 0 bars (Maximum retention capacity), 0.1 bars, 0.3 bars (field capacity) 0.5 bars, 1.0 bar 5 bars, 10 bars and 15 bars (permanent wilting point). The water content was measured gravimetrically after oven-drying.

The soil moisture content was then determined by the following formula:

$$\text{oil moisture retention} = \frac{\text{soil moist weight} - \text{oven dry weight}}{\text{oven dry weight}} \quad \text{Equation 1}$$

Soil physical traits such as bulk density, saturated hydraulic conductivity, total porosity, and soil texture classes were determined using standard protocols described by Haung et al. (2020). Van Genuchten et al. (1991) developed RETC computer code that was used to fit soil water retention, $\theta(h)$, and hydraulic conductivity vs. tension, $K(e)$ data to models of the $\theta(h)$ and $K(h)$ functions. The derived data was used to solve van Genuchten's (1980) water retention model, presented in equation (6). The Rosetta software was used to generate the closed-form expressions of van Genuchten parameters (θ_s , θ_r , α , and n) from the data of particle size distribution, soil bulk density, and volumetric soil water content at -33 and 1500 kPa (Schaap et al. 1998). In addition to the determined soil water retention values, the Rosetta program output data were used as input data in RETC. The RETC output file, which included measured and fitted connections between pF matric potential (hPa), soil water content ($\text{cm}^3 \text{ cm}^{-3}$), and unsaturated hydraulic conductivity, $k(h)$ (cm day^{-1}), was converted to an Excel file for analysis.

Yield and yield parameter (kg/ha) were measured during the research period while water use efficiency (WUE) or water utilization of okra was estimated using the formula in equation (2) as the ratio of total pod weight (kg/ha) to total irrigation water applied.

$$WUE = \frac{[Y]}{[\sum ET]} \quad \text{Equation 2}$$

where Y is the yield (kg/ha) and ET water use in (mm/day).

The actual evapotranspiration was computed from observed soil moisture content data using the Theta probe (Michael, 2008), as stated in equation (3).

$$ETa = \frac{[M1 - M2]}{100} Di \times Bdi \quad \text{Equation 3}$$

where ETa is the actual crop evapotranspiration in millimetres per day, M1 is the volumetric moisture content in grams per gram at the first sampling (2 days after irrigation), M2 is the volumetric moisture content at the second sampling (7 days after irrigation), Di is the root zone depth, and Bdi is the soil bulk density.

Data obtained from all the measured parameters were subjected to analysis of variance (ANOVA) using SAS statistical package version 9.2 (2004) and treatment means with significant differences at a 5% probability level ($P < 0.05$) were separated using Tukey's Honestly Significant Difference (HSD) test. Linear regression analysis was used to determine relationships between some parameters such as soil water content, hydraulic conductivity, bulk density and total porosity.

Results and Discussion

Table 1 shows the impacts of controlled deficit irrigation and mulch levels on soil bulk density (BD), total porosity (TP), and saturated hydraulic conductivity (Ksat) at depths of 0–15 and 15–30 cm. The soil BD varied from 1.49 to 1.59 g/cm³, indicating high BD. Plots treated with 100 and 55% weekly ETo showed statistically identical BD values of 1.59 and 1.53 g/cm³, respectively. Treatment plots with 100% ETo showed significantly higher bulk density ($P \leq 0.05$) compared to 85 and 70% ETo. There was no significant difference ($P \geq 0.05$) between irrigation treatments at 15-30 cm depth and mulch treatments on soil BD at both depths. The higher soil BD observed in treatments supplied with comparatively higher water deficit (55%) and fully irrigated (100%) may be due to low (high deficit) and high (no deficit) water content in the soil which inhibited the activities of microorganism acting upon soil organic carbon/ matter (SOC/SOM). Rizwan et al. (2014) found high soil BD in deficit irrigation treatments as compared with full irrigation treatment. However, Abu and Malgwi (2011) found that higher soil BD is continuously reduced with increases in deficit water level and irrigation frequency. They ascribed the increase in soil bulk density at high irrigation levels to the use of shorter irrigation frequencies combined with a decrease in SOC/SOM, which resulted in soil particle rearrangement and pore reorientation.

Table 1. Effect of regulated deficit irrigation and mulch levels on soil bulk density, total porosity and saturated hydraulic conductivity.

Treatments	0-15 cm			15-30 cm		
	BD (g/cm ³)	TP (%)	Ksat (cm/s)	BD (g/cm ³)	TP (%)	Ksat (cm/s)
Irrigation Level						
I₅₅	1.53ab	42.23a	13.57a	1.54a	41.95a	11.56a
I₇₀	1.51b	42.96a	12.54a	1.57a	40.91a	12.17a
I₈₅	1.49b	43.43a	13.22a	1.55a	41.45a	12.45a
I₁₀₀	1.59a	40.04a	11.53a	1.56a	41.32a	12.88a
Mulch Level						
M6	1.54a	42.04a	12.68a	1.57a	40.63a	13.15a
M4	1.56a	41.23a	12.29a	1.56a	41.29a	11.12a
M2	1.53a	42.23a	13.28a	1.54a	42.04a	11.99a
NM	1.51a	42.96a	12.61a	1.55a	41.67a	12.80a
MSD	0.096	3.607	5.0558	0.097	3.667	5.180
Interaction						
I x M	NS	NS	NS	NS	NS	NS

BD, soil bulk density; TP, total porosity; Ksat, saturated hydraulic conductivity; I₅₅, I₇₀, I₈₅ and I₁₀₀ are water application depths of 55%, 70%, 85% and 100%. NM, no mulch; M2, M4 and M6 are 2, 4 and 6 kg/plot mulch. MSD; Minimum significant difference.

The result showed that total porosity (TP) ranged between 39.8 - 43.4% and saturated hydraulic conductivity (Ksat) ranged between 11.5 - 13.6 cm/s. There was no significant difference ($P \geq 0.05$) in mean values between irrigation treatments at depths of 0-15 and 15-30 cm. Similarly, there was no significant ($P \geq 0.05$) difference between the mulch treatment on

BD, TP and at Ksat 0-15 and 15-30 cm depths. There was no also significant ($P \geq 0.05$) difference in water content at various matric potentials between the irrigation and mulch levels at the 0-15 cm and 15-30 cm depths (Table 2). The non-significant difference observed between mulch treatments on the soil BD, total porosity (TP), Ksat and water retention at various matric potential kPa at both 0-15 and 15-30 cm depths could be due to the short duration (1 year) of the study. However, Pervaiz et al. (2009) found that organic mulch enhanced soil organic matter (1.32 g kg^{-1}), soil water content (17%), bulk density (1.35 g cm^{-3}), and soil strength (464 kPa) when compared to the control. Sharma et al. (2009) compared leaf mulch levels: no mulch (M0), two (M1), four (M2), and six (M3) t ha^{-1} . Decreased bulk density was noted under mulch levels of 6 t ha^{-1} (1.40 g cm^{-3}) compared with no mulch (1.44 g cm^{-3}). Table 3 also shows soil water retention as affected by deficit irrigation and mulch levels. The data obtained showed no significant difference ($P \leq 0.05$) in water content at various matric potentials between the irrigation and mulch levels at the 0-15 cm and 15-30 cm depths.

Table 3 shows the fitted values of the van Genuchten parameters and the estimated sum of squares (SSQ) derived from the RETC software. The controlled deficit irrigation and mulch treatments showed no significant ($P \leq 0.05$) changes in residual moisture content (θ_r), saturated moisture content (θ_s), curve fitting parameter (n), and inverse of air entrance point (α). The estimated sum of squares (SSQ) of fitted values vs observed water contents from RETC projected saturation hydraulic conductivity. The estimated sum of squares (SSQ) values indicate the retention models' relative accuracy in representing the observed data. Generally, when the value of SSQ decreases, the precision of fitting using the retention curve model (RETC) is thought to increase van Genuchten et al. (1992). The non-significant in van Genuchten parameter could be due to the measured moisture content which showed no significant difference. Although Porebska et al. (2006) reported significant differences in van Genuchten parameters in different soil types, the differences were not due to management practices. They attributed the differences to variations in soil physical and chemical properties of the study area. Based on the SSQ, it was observed that van Genuchten's model with Mualem-based restriction successfully and with high precision described soil water retention under all the irrigation and mulch levels.

Figure 1 (A, B, C, and D) depicts the graphical relationship between measured and fitted water content for irrigation treatment at different mulch levels (0-15 cm and 15-30 cm soil depths). Figures (A, B, C, and D) show the relationship between pF soil matric potential and water content derived from both measured and fitted values at various soil depths, mulch levels, and irrigation schedules. As shown in Figure 1 (A, B, C, and D), the measured and fitted values are close to the 1:1 line, which represents the point at which the measured and fitted data are equivalent. The coefficients of determination (R^2) all exceeded 0.9. R^2 was used to determine the fitness of a water retention (RETC) model by comparing observed and fitted values (Maggi, 2017). These results showed that the van Genuchten parameters in Table 4 best reflected the hydraulic properties of the study location. The water retention curve indicates the status of soil moisture in a soil as the matric potential changes. The soil in this study had a sandy loam texture, and there was variance in water retention at varying pF across mulch layers under irrigation treatments (Figure 2).

Table 4 highlights the mean yield and yield component of okra as impacted by irrigation and mulch treatments. The means ranged from 5.2 – 8.1 cm, 2.2 – 2.9 cm, 13.6 – 16.7 num/plant, and 4014.5 – 6186.2 kg/ha for pod length, pod diameter, number of pods, and total yield, respectively. The result indicated that treatment with 100% weekly reference evapotranspiration (ET_o) significantly ($P \leq 0.05$) produced more number and lengthy pods of greater diameter and higher yield than the other treatments though statistically at par with treatment application of 85% ET_o in pod diameter and yield.

Similarly, treatment with 85% ET_o had more numbers and lengthy pods significantly higher than the other treatments and higher yield than 55% ET_o. The lowest pod length, number of pods, and total yield were recorded at 55% ET_o treatment. These findings may be linked to an adequate supply of crop water requirements, resulting in improved physiological processes and crop performance with 100% ET_o treatments as opposed to controlled deficit treatments, which expose the plant to certain stress.

This work lends support from the work of Al-Harbi et al. (2008) who reported that the reduction of applied water may affect the physiological processes of okra and tended to expose the plants to water stress which will be reflected to the water absorbed and transmission to the different parts of the plant. Panigrihi and Sahu (2013) also evaluated the effects of regulated deficit irrigation on the yield of okra as compared to the no-soil water deficit treatment. The yield and yield component were all greatly improved under adequate water application than regulated deficit irrigation.

Mulch level showed significant ($P \leq 0.05$) effects on yield and yield component (Table 5). It was noticed that the 6 kg mulch level produced more lengthy pods of great diameter and higher yield than others, except in pod diameter and yield where M6 and M4 t/ha were at par. Similarly, M4 and M2 t/ha mulch levels resulted in more pods and higher yield than M0 t/ha. Lengthy pods were obtained under M4 t/ha rather than 2 t/ha and NM which were similar and M4, M2 and M0 t/ha produced statistically similar pod diameters. The superiority in yield parameters under more organic mulch levels may be due to the effects of mulch on water loss through evaporation, influencing micro-climate in which crops develop and stimulate higher crop yields by more efficient utilization of soil nutrients.

Alyokhin et al. (2020) reported that mulching with plant residues and/or synthetic materials is a well-established technique for increasing the profitability of many horticultural crops. Mulched treatments could have increased the availability of water in the soil which in turn improved the nutrient uptake of okra. Similarly, Hingonia et al. (2016) reported that organic mulched treatments significantly improve total uptake of N, P and K than corresponding un-mulched ones.

Table 2. Effects of regulated deficit irrigation and mulch levels on soil water content at various matrix potential at Kadawa in dry season.

Water content at various matric potentials (cm ³ / cm ³)														
0-15 cm								15-30 cm						
Treatments	0	10	33	100	500	1000	1500	0	10	33	100	500	1000	1500
Irrigation Level														
I ₅₅	0.49a	0.38a	0.34a	0.30a	0.26a	0.23a	0.21a	0.48a	0.41a	0.39a	0.36a	0.30a	0.28a	0.26a
I ₇₀	0.48a	0.37a	0.34a	0.29a	0.25a	0.23a	0.21a	0.46a	0.39a	0.37a	0.33ab	0.29a	0.26ab	0.24a
I ₈₅	0.49a	0.35a	0.31a	0.28a	0.24a	0.21a	0.20 a	0.46a	0.39a	0.37a	0.34a	0.29a	0.26ab	0.25a
I ₁₀₀	0.48a	0.40a	0.36a	0.32a	0.27a	0.25a	0.23a	0.45a	0.36ab	0.32ab	0.29ab	0.26ab	0.23ab	0.22a
Mulch Level														
M2	0.47a	0.37a	0.33a	0.29a	0.26a	0.22a	0.20a	0.46a	0.37a	0.34a	0.32a	0.28a	0.25a	0.24a
M4	0.50a	0.38a	0.35a	0.31a	0.27a	0.23a	0.22 a	0.45a	0.38a	0.36a	0.32a	0.28a	0.26a	0.24a
M6	0.48a	0.37a	0.34a	0.30a	0.27a	0.25a	0.23a	0.47a	0.39a	0.36a	0.34a	0.28a	0.24a	0.23a
NM	0.50a	0.38a	0.33a	0.28a	0.23a	0.21a	0.20a	0.48a	0.40a	0.38a	0.35a	0.30a	0.28a	0.26a
MSD	0.084	0.067	0.065	0.061	0.058	0.056	0.0485	0.055	0.049	0.043	0.046	0.052	0.055	0.052
Interaction														
I x M	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

I₅₅, water application depth of 55%; I₇₀, water application depth of 70%; I₈₅, water application depth of 85%; I₁₀₀, water application depth of 100%; NM, no mulch; M₂, 2 kg/plot mulch; M₄, 4 kg/plot mulch; M₆, 6 kg/plot mulch and MSD; Minimum significant difference. Means with the same letter in a column are not significantly different at a p<0.05 using Tukey's Honestly Significant Difference (HSD) test.

Table 3. Effects of regulated deficit irrigation on van Genuchten parameters at Kadawa

Factor levels/interaction	van Genuchten parameters									
	0-15 cm					15-30 cm				
	θ_r	θ_s	α	N	SSQ	θ_r	θ_s	α	N	SSQ
Irrigation Levels(I)										
I ₅₅	0.08	0.41	0.06	1.28	0.05	0.07	0.41	0.04	1.29	0.03
I ₇₀	0.05	0.37	0.02	1.24	0.02	0.06	0.38	0.03	1.23	0.02
I ₈₅	0.06	0.41	0.03	1.26	0.02	0.06	0.40	0.04	1.25	0.03
I ₁₀₀	0.05	0.40	0.02	1.26	0.02	0.06	0.39	0.03	1.25	0.02
Mulch Levels(M)										
M0	0.06	0.41	0.03	1.29	0.02	0.06	0.41	0.02	1.20	0.02
M2	0.06	0.40	0.03	1.26	0.02	0.06	0.41	0.02	1.24	0.02
M4	0.06	0.38	0.04	1.25	0.03	0.06	0.40	0.02	1.21	0.01
M6	0.07	0.39	0.04	1.23	0.03	0.06	0.43	0.02	1.21	0.03
MSD	0.03	0.05	0.04	0.06	0.02	0.01	0.03	0.01	0.05	0.00

θ_r , residual moisture content; θ_s , saturated moisture content; n, curve fitting parameter; α , inverse of air entry point; SSQ, estimated sum of square; I₅₅, water application depth of 55%; I₇₀, water application depth of 70%; I₈₅, water application depth of 85%; I₁₀₀, water application depth of 100%; M0 (0 t/ha), M2 (3.2 t/ha); M4 (6.4 t/ha), M6 (9.6 t/ha) and MSD; Minimum significant difference, Means with the same letter within each factor are not significantly different at 5% level of probability using Tukey's Honest Significant Difference (HSD) test.

Table 5 shows seasonal actual evapotranspiration (SETa) and irrigation water use efficiency (IWUE) of okra. There was a substantial difference ($P \leq 0.05$) in seasonal actual evapotranspiration (SETa). The fully irrigated treatment with 100% ETo exhibited higher SETa than the other deficit irrigation treatments. Also, treatment with 85% ETo resulted in significantly higher ($P \leq 0.05$) ETo than 55% ETo but comparable to 70% ETo treatments. The lower SETa noticed with treatments treated to higher deficit irrigation might be attributed to the greater induction of soil moisture deficit over time, which builds interface hydraulic conductivity resistance at the soil-root interface, resulting in SETa loss. Igbadun *et al.* (2012) discovered substantial changes in SETa between mulch treatments, suggesting that stored moisture may have been employed for transpiration. The lack of a significant effect of mulch treatments on SETa found in the current study might be attributed to the study's short length, which requires additional investigation. A significant treatment effect ($P \leq 0.05$) was established in the analysis of variance for WUE values as presented in Table 5. The data show that the mean values for 55, 70, 85, and 100% ETo were 21.1, 19.3, 19.4, and 17.7 kg/m³.

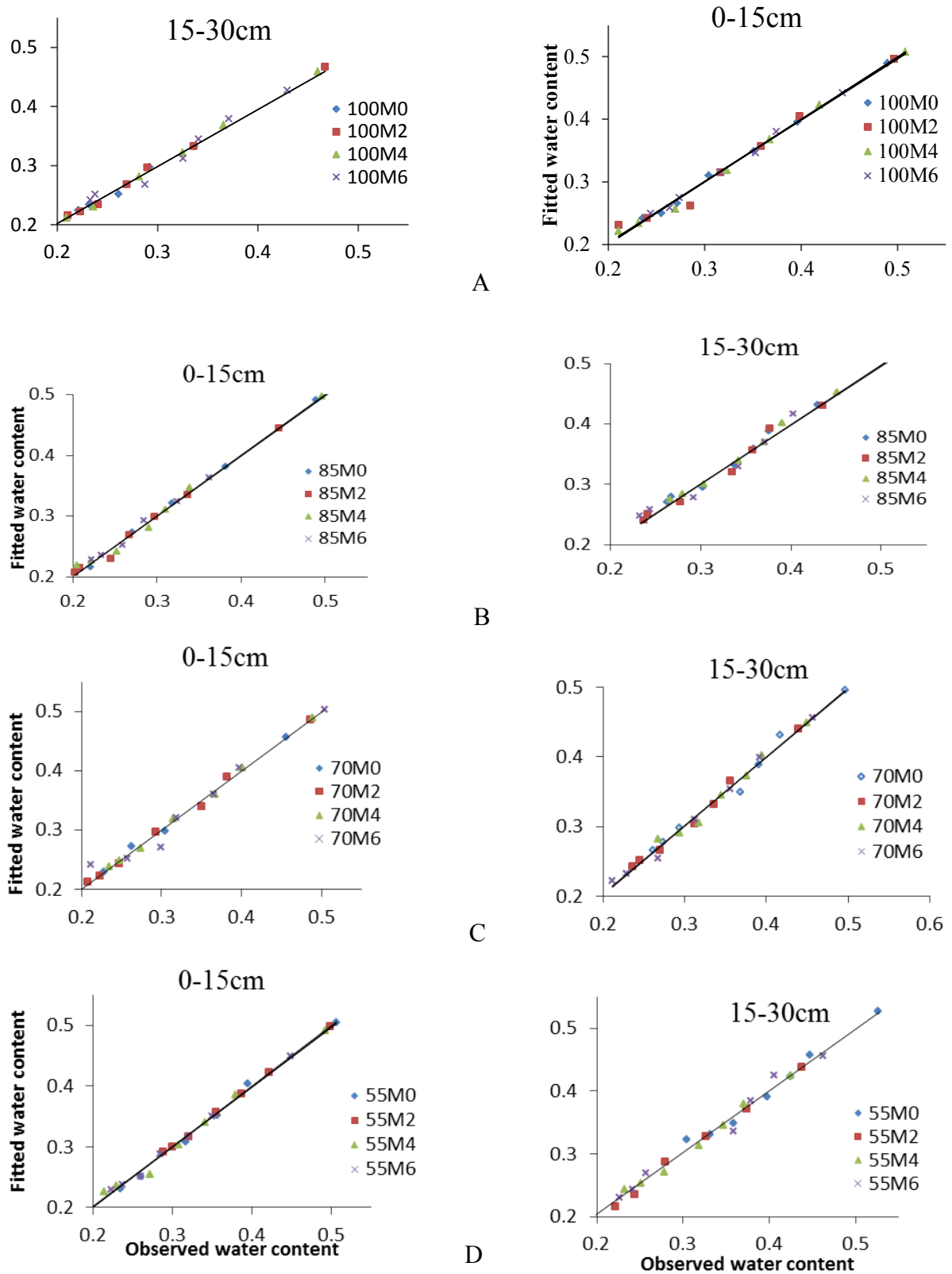


Figure 1 (A-D). Measured and fitted water content for irrigation treatment under various mulch levels at 0-15 and 15-30 cm depths.

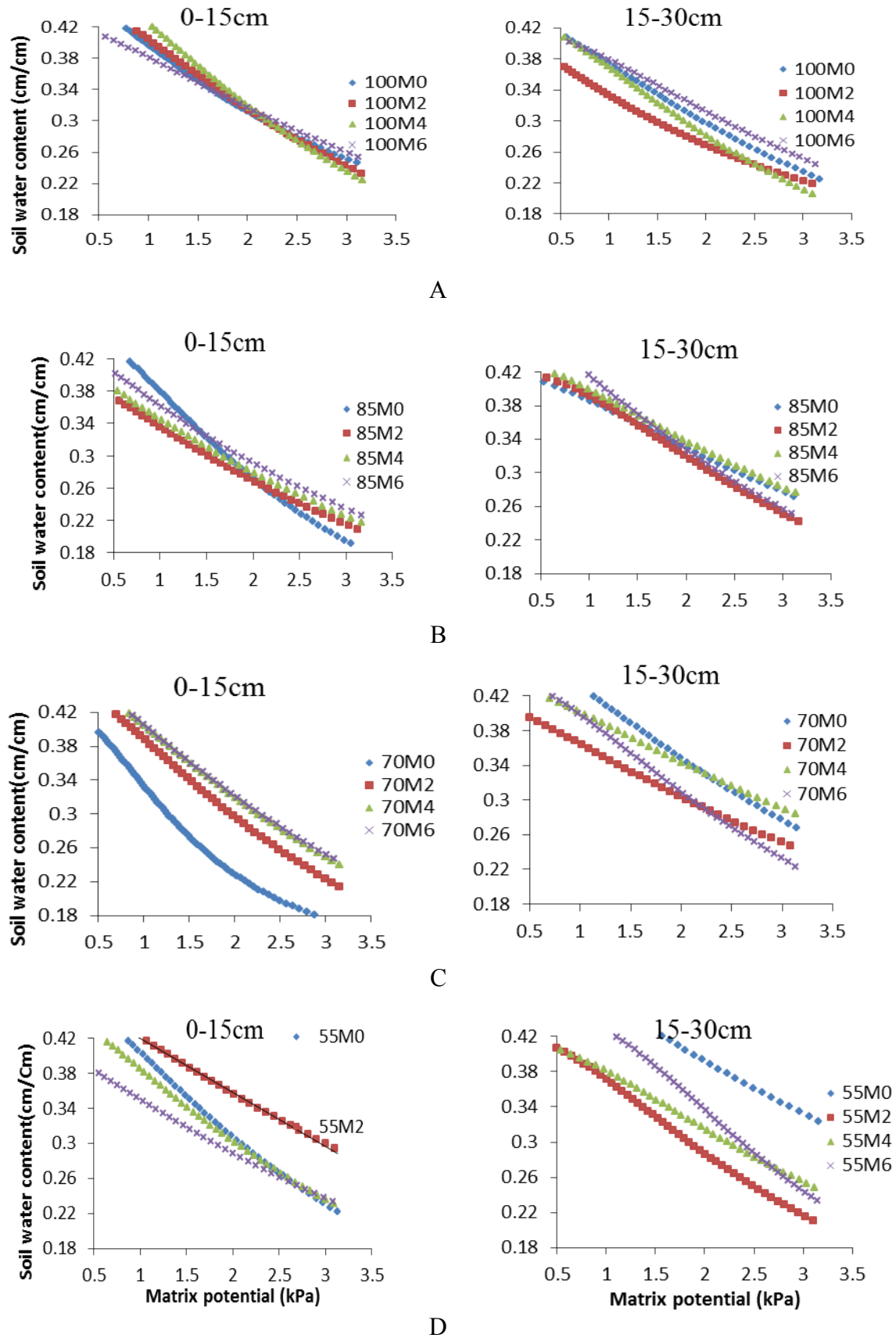


Figure 2 (A-D). Relationship among pF soil matrix potential 1 and water content derived from both measured and fitted values at 0-15 and 15-30 cm soil depths under different mulch levels.

Table 4. Means of okra yield and yield components as influenced by deficit irrigation and mulch levels at Kadawa.

Factor levels/interaction	Pod Number	Pod length (cm)	Pod Diameter (cm)	Yield (Kg/ha)
Irrigation level (I)				
I ₁₀₀	16.67 ^a	8.08 ^a	2.90 ^a	6186.2 ^a
I ₈₅	15.55 ^b	7.55 ^b	2.65 ^{ab}	5745.0 ^{ab}
I ₇₀	14.12 ^c	6.11 ^c	2.32 ^b	4523.6 ^b
I ₅₅	13.63 ^d	5.23 ^d	2.22 ^b	4014.5 ^c
Mulch level (M)				
M0	13.88 ^c	6.32 ^c	2.38 ^b	4708.5 ^b
M2	14.65 ^b	6.42 ^c	2.38 ^b	4883.5 ^b
M4	15.42 ^b	6.80 ^b	2.54 ^{ab}	5339.8 ^a
M6	16.02 ^a	7.43 ^a	2.78 ^a	5537.5 ^a
MSD	0.302	0.187	0.396	445.30
Interaction				
I x M	NS	NS	NS	NS

I₅₅, I₇₀, I₈₅ and I₁₀₀ are water application depth of 55%, 70%, 85% and 100%. NM, no mulch; M2, M4 and M6 are 2, 4 and 6 kg/plot mulch. MSD; Minimum significant difference.

The 55% of ETo treatments demonstrated significantly higher values ($P \leq 0.05$) compared to other treatments (Table 5). Water application depths of 70 and 85%, as well as 85 and 100% ETo, had statistically equivalent results. However, treatment with 70% ETo had a much greater value than 100% ETo therapy. There was a substantial ($P \leq 0.05$) difference in mean mulch levels. Treatments with M6 and M4 t/ha mulch exhibited a greater IWUE than those with M2 and M0 t/ha, which were comparable. Water use efficiency (WUE) is enhanced by increasing yield or lowering water consumption, and irrigation water may be utilized to reduce agricultural water usage while preserving yield and quality (Igbadun and Oiganji, 2012). In this study, water productivity enhanced with deficit irrigation treatments. When plant stomata are opened to allow for the absorption of CO₂, there may be a significant loss of water in fully irrigated treatment. When the moisture stress caused by the shortfall was less severe, Igbadun and Oiganji (2012) found that using deficit irrigation practices increased crop water production. According to Teklu (2017), deficit irrigation can give higher economic returns than maximizing yields per unit of land when there is a limited supply of water. High WUE suggests that okra water production increased with organic mulch containing M6 and M4 t/ha of rice straw compared with M2 t/ha and M0 t/ha treatments. Mulching also decreased evapotranspiration and soil water depletion as was observed by Huang et al. (2005), whose results revealed that higher crop productivity could be achieved by using a proper combination of straw mulch and irrigation. Similar results on WUE were also revealed by Zhang et al. (2007) who noted mulching effects on soil evaporation and transpiration and found decreased evaporation and increased transpiration rate, leading to increased wheat yields and WUE. However, there was no significant ($P \geq 0.05$) difference among the mulch treatments in SETa.

Table 5. Means of seasonal actual evapotranspiration and irrigation water use efficiency of okra at Kadawa.

Factor levels/ Interaction	SETa (mm)	IWUE (kg/m ³)
Irrigation Levels(I)		
I ₁₀₀	286.38 ^a	17.65 ^c
I ₈₅	270.59 ^b	18.36 ^{bc}
I ₇₀	268.62 ^{bc}	19.28 ^b
I ₅₀	261.90 ^c	20.99 ^a
Mulch Levels(M)		
M0	270.45	17.16 ^b
M2	270.48	17.98 ^b
M4	271.11	19.95 ^a
M6	275.42	21.20 ^a
MSD	0.29	1.81
Interaction		
I x M	NS	NS

SETa, seasonal actual evapotranspiration and IWE, irrigation water use efficiency; I₅₅, I₇₀, I₈₅ and I₁₀₀ are water application depths of 55%, 70%, 85% and 100%. NM, no mulch; M2, M4 and M6 are 2, 4 and 6 kg/plot mulch. MSD; Minimum significant difference.

Conclusion

It can be concluded that 100% actual evapotranspiration treatment resulted in high soil bulk density. The use of the RETC model predicted with high precision the hydraulic properties of the studied soil under various irrigation and mulch practices at different soil depths, indicating its validity in the determination of hydraulic properties of such soil type. The growth and yield of okra decreased as deficit irrigation increased. However, a reasonable amount of water was saved in deficit treatments compared to full irrigation treatment with irrigation water application depth of 55% ETo giving better water productivity in terms of water supply for okra in this study. Similarly, mulching the field with 4 and 6 kg/ha rice straw resulted in higher yield and higher water use efficiency compared to the other mulch levels.

Conflict of Interest: The researcher declared no conflict of interest.

Financial Disclosure: The research was self-sponsored.

Acknowledgements: The researchers used this medium to acknowledge the Institute of Agriculture Research, Ahmadu Bello University Zaria for approval of the use of the Kadawa field for this research.

Authors' contributions: **S.Y. Alasinrin:** Writing – original draft, Supervision, Resources, Investigation, Data curation, Conceptualization. **Wahab, A., A:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Girei A. H.:** Writing – review & editing, Resources, Methodology. **Jibrin, M. S.:** Formal analysis, Data curation. **Karim, I.:** Review & editing Methodology and Data curation. **Odewole, A. O.:** Writing – review & editing and Methodology, **Togun, S. S.:** Data curation.

References

- Abu, S.T. and Malgwi, W.B. (2011) Spatial Variability of Soil Physico-Chemical Properties in Kadawa Irrigation Project in Sudan Savanna Agroecology of Nigeria. *International Journal of Agricultural Research*, 6, 714-735. <http://dx.doi.org/10.3923/ijar.2011.714.735>
- Al-Harbi, A. R., Al-Omran, A. M. and El-Adgham, F. I. (2008). Effect of drip irrigation levels and emitters depth on okra (*Abelmoschus esculentus*) growth. *Journal of Applied Sciences*, 8: 2764-2769. <https://doi.org=jas.2008.2764.2769>
- Alyokhin, A., Nault, B., & Brown, B. (2020). Soil conservation practices for insect pest management in highly disturbed agroecosystems—a review. *Entomologia Experimentalis et Applicata*, 168(1), 7-27. <https://doi.org/10.1016/j.compgeo.2016.12.025>
- Bhatti, M. T., Ashraf, M., & Anwar, A. A. (2021). Soil erosion and sediment load management strategies for sustainable irrigation in arid regions. *Sustainability*, 13(6), 3547. <https://doi.org/10.3390/su13063547>
- Igbadun, H. E. and Oiganji, E. (2012). Crop coefficients and yield response factors for onion (*Allium Cepa*. L) under deficit irrigation and mulch practices in Samaru, Nigeria. *African Journal of Agricultural Research*, 7(36): 5137-5152. <https://doi.org/10.5897/AJAR12.689>
- Ikhuoso, O. A., Adegbeye, M. J., Elghandour, M. M. Y., Mellado, M., Al-Dobaib, S. N., & Salem, A. Z. M. (2020). Climate change and agriculture: The competition for limited resources amidst crop farmers-livestock herding conflict in Nigeria-A review. *Journal of Cleaner Production*, 272, 123104. <https://doi.org/10.1016/j.jclepro.2020.123104>
- Irmak, S., Djaman, K., & Rudnick, D. R. (2016). Effect of full and limited irrigation amount and frequency on subsurface drip-irrigated maize evapotranspiration, yield, water use efficiency and yield response factors. *Irrigation Science*, 34, 271-286. <https://doi.org/10.1007/s00271-016-0502-z>
- Hingonia, K., Singh, R. K., Meena, R. N., Verma, H. P., & Meena, R. P. (2016). Effect of mulch and irrigation levels on yield and quality of barley (*Hordeum vulgare* L.). *Journal of Pure and Applied Microbiology*, 10(4), 2925-2930. <https://doi.org/10.22207/JPAM.10.4.58>
- Huang, Y., Chen, L., Bojie, F., Huang, F. and Gong, J. (2005). The wheat yields and water-use efficiency in the Loess Plateau: Straw mulch and irrigation effects. *Agricultural Water Management*. 72(3): 209-222. <https://doi.org/10.1016/j.agwat.2004.09.012>
- Huang, Z., Liu, Y., Tian, F. P., & Wu, G. L. (2020). Soil water availability threshold indicator was determined by using plant physiological responses under drought conditions. *Ecological Indicators*, 118, 106740. <https://10.1016/j.ecolind.2020.106740>
- Kang, J., Hao, X., Zhou, H., & Ding, R. (2021). An integrated strategy for improving water use efficiency by understanding physiological mechanisms of crops responding to water deficit: Present and prospect. *Agricultural Water Management*, 255, 107008. <https://doi.org/10.1016/j.agwat.2021.107008>
- Kaziboni, A. (2024). Exclusion and invented water scarcity: a historical perspective from colonialism to apartheid in South Africa. *Water History*, 1-19. [10.1007/s12685-024-00339-4](https://doi.org/10.1007/s12685-024-00339-4)

- Klute, A., and Dirksen. C. (1986). Hydraulic conductivity and diffusivity: laboratory methods. In: Methods of Soil Analysis. Pt. 1. 2nd ed. A. Klute (ed.). *Agron. Monogr.* 9. ASA, Madison, WI, pp. 687–734. <https://doi.org/10.2136/sssabookser5.1.2ed.c28>
- Luo, C. L., Zhang, X. F., Duan, H. X., Mburu, D. M., Ren, H. X., Kavagi, L., ... & Xiong, Y. C. (2020). Dual plastic film and straw mulching boosts wheat productivity and soil quality under El Nino in semiarid Kenya. *Science of the Total Environment*, 738, 139808. [10.1016/j.scitotenv.2020.139808](https://doi.org/10.1016/j.scitotenv.2020.139808)
- Maggi, S. (2017). Estimating water retention characteristic parameters using differential evolution. *Computers and Geotechnics*, 86, 163-172. <https://doi.org/10.1016/j.compgeo.2016.12.025>
- Matemilola, S. (2017). The challenges of food security in Nigeria. *Open Access Library Journal*, 4(12), 1. [10.4236/oalib.1104185](https://doi.org/10.4236/oalib.1104185)
- Michael A. M. (2008). Irrigation Theory and Practice. 2nd Edition- Revised and Enlarged. VIKAS Publishing House PVT Limited. ISBN: 8125918671, 9788125918677
- Montzka, C., Herbst, M., Weihermüller, L., Verhoef, A., & Vereecken, H. (2017). A global data set of soil hydraulic properties and sub-grid variability of soil water retention and hydraulic conductivity curves. *Earth System Science Data*, 9(2), 529-543. <https://doi.org/10.5194/essd-9-529-2017>
- Panigrahi, P., and N. N. Sahu. "Evapotranspiration and yield of okra as affected by partial root-zone furrow irrigation." (2013): 33-54.
- Pervaiz, M. A., Iqbal, M. K. and Hassan, A. U. (2009). Effect of mulch on soil physical properties and N, P, K concentration in maize (*Zea mays* L.) shoots under two tillage systems. *International Journal of Agriculture Biology*, 11:119-124. 08–271/MSI/2009/11–2–119–124.
- Porebska, D., Slawinski, C., Lamorski, K. and Walczak, R. T. (2006). Relationship between van Genuchten parameters of the water retention curve equation and physical properties of soil solid phase. *International Agrophysics* 20, 153–159.
- Rizwan, Y., Jamil S., Waqas, A., Muhammad, S. R., Muhammad, S., and Saeed A. Q. (2014). Effect of Deficit Irrigation and Mulch on Soil Physical Properties, Growth and Yield of Maize. *Environment and Ecology Research*, 2(3): 122-137. <https://doi.org/10.13189/eer.2014.020302>
- Schaap, M. G., Leij, F. J. and van Genuchten, M. Th. 1998. Neural network analysis for hierarchical prediction of soil hydraulic properties. *Soil Science Society of American Journal*, 62: 847–855. <https://doi.org/10.2136/sssaj1998.03615995006200040001x>
- Singh, R. P., Prasad, P. V. V., & Reddy, K. R. (2015). Climate change: implications for stakeholders in genetic resources and seed sector. *Advances in Agronomy*, 129, 117-180. <https://doi.org/10.1016/bs.agron.2014.09.002>
- Teklu, L. (2017). Effect of furrow irrigation methods and deficit levels on soil properties and yield of tomato (*Solanum lycopersicum* L.) at Dugda District, Central Rift Valley, Ethiopia. *Central Rift Valley, Ethiopia*, 6(04).
- Tolomio, M., & Casa, R. (2020). Dynamic crop models and remote sensing irrigation decision support systems: a review of water stress concepts for improved estimation of water requirements. *Remote Sensing*, 12(23), 3945. <https://doi.org/10.3390/rs12233945>

Usman, M., Nichol, J. E., Ibrahim, A. T., & Buba, L. F. (2018). A spatio-temporal analysis of trends in rainfall from long-term satellite rainfall products in the Sudano Sahelian zone of Nigeria. *Agricultural and forest meteorology*, 260, 273-286. <https://doi.org/10.12691/ajwr-10-3-1>

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, 44: 892–898. <https://doi.org/10.2136/sssaj1980.03615995004400050002x>

van Genuchten, M. T., Leij, F. J. and Yates, S. R., (1992). The RETC code for quantifying the hydraulic functions of unsaturated soils. Project summary, EPA' Robert . Kerr Environmental Research Lab., Ada, OK, USA.

van Genuchten, M. T., Leij, F. J., and Yates, S. R. (1991). The RETC code for quantifying the hydraulic functions of unsaturated soils. EPA/600/2-91/065. R.S. Kerr Environ. Res. Lab., U.S. Environmental Protection Agency, ADA, OK, pp93

Wang, X., Fan, J., Xing, Y., Xu, G., Wang, H., Deng, J., ... & Li, Z. (2019). The effects of mulch and nitrogen fertilizer on the soil environment of crop plants. *Advances in agronomy*, 153, 121-173. <https://doi.org/10.1016/bs.agron.2018.08.003>

Zhang, J., Sun, A., Duan, J., Wang, X., Shen, and Liu, X. (2007). Effects of different planting patterns on water use and yield performance of winter wheat in the Huang-Huai-Hai plain of China. *Agricultural Water Management*, 92:41-47. <https://doi.org/10.1016/j.agwat.2007.04.007>