Radiation Use Efficiency and Growth Parameters of Tomato Plant (*Solanum lycopersicum*) under different Irrigation Management in Screenhouse and Ambient Environment

Johnson Toyin Fasinmirin[1*], Funke Florence Akinola[2], Bolaji Adelanke Adabembe[3]

(1. Department of Agricultural and Environmental Engineering, Federal University of Technology, P.M.B. 704, Akure, Ondo State, Nigeria;
2. Department of Agricultural and Bio-Environmental Engineering, Federal Polytechnic, Ado-Ekiti, P.M.B. 5351, Ado Ekiti, Nigeria;
3. Department of Water Resources Management and Agro-Meteorology, Federal University, Oye –Ekiti, P.M.B. 373, Oye- Ekiti, Nigeria)

Abstract: Studies on radiation use and physiological development such as leaf area of crops planted under screen-house and ambient environments is very scarce in the sub-Saharan part of Africa. This research therefore was aimed at investigating the radiation use of tomato under screen-house and ambient environment to determine its leaf area index (LAI) under different irrigation water treatments: 100% Field capacity (100%FC), 75% FC, 50% FC and rain-fed condition in ambient environment. AccuPAR LAI 80 Ceptometer (Decagon Device) was used for direct measurement of the above and below canopy photosynthetic active radiation, fraction of beam interception (F_b), leaf distribution coefficient (*chi*), leaf area index (*LAI*), zenith angle (θ), and ratio of below canopy PAR and above canopy PAR (τ). The radiation uses efficiency of tomato planted in screen-house and under ambient condition was evaluated from the yield of tomato and fraction of beam intercepted by tomato plant. Result showed RUE values of 0.29 ± 0.02 kg $MJ^{-1}m^{-2}$, 0.56 ± 0.002 kg $MJ^{-1}m^{-2}$, 0.6 ± 0.001 kg $MJ^{-1}m^{-2}$ and 0.21 ± 0.01 kg $MJ^{-1}m^{-2}$ for the tomato plant grown under 50%, 70%, 100% irrigation level, and control sample, respectively. The highest LAI values (0.42) was obtained from tomato under 75% irrigation water level at the ninth weeks after transplanting (9 WAT), which was found to be 22% higher than the tomato under the 100% FC irrigation water level (0.27). The research information has revealed the yield potential and effectiveness of radiation utilization of tomato irrigated to 100% FC in controlled environment when compared with tomato grown under ambient condition.

Keywords: Leaf Area Index, Radiation Use Efficiency, Tomato; Screen-house, Photosynthetic Active Radiation

Citation: Fasinmirin, J. T., F. F. Akinola, and B. A.Adabembe. 2023. Radiation use efficiency and growth parameters of tomato plant (*Solanum lyucopersicum*) under different irrigation management in screenhouse and ambient environment. Agricultural Engineering International: CIGR Journal, 25(4): 46-57.

1 Introduction

Tomato (*Solanum lycopersicum)* is cultivated for its nutritional and medicinal importance. Cooked tomatoes and tomato products are the best sources of lycopene, a very useful antioxidant helpful in preventing the development of many forms of cancer (Mahajan and Singh, 2006). In addition to this versatility, tomatoes are also an important source of vitamins and minerals.

Received date: 2023-01-10 **Accepted date:** 2023-06-28

***Corresponding author: Johnson Toyin Fasinmirin,** Professor, Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure, Nigeria. Phone: +2348069192434. E-mail: jtfasinmrin@futa.edu.ng.

The crop is an excellent source of phosphorus, iron and vitamin A, B and C. They also contain small amounts of the B complex vitamins; thiamin, niacin and riboflavin (Varela.-Moreiras et al., 2013; Naika et al., 2005). The leaf of tomato often serves as indicator to either water stress or poor solar radiation interception. Tomato farming is more successful where there are long sunny periods. The optimum growing temperatures are 21ºC to 24ºC. At these temperatures, good quality seeds will take about seven days to emerge. Temperature also affects flowering and pollination in tomato. The hot and dry weather leads to drying of the flowers and stops pollination. If temperatures are below 15ºC or above 29ºC, pollen release is restricted resulting in incomplete fertilization of ovules. This causes collapsed fruit walls and the formation of deep indentation in the fruit, a phenomenon called cat-face (Bok et al., 2006). The importance of maintaining adequate moisture supply to tomato, most especially through drip system of irrigation cannot be over-emphasized even when other environmental factors are met for optimum growth and yield (Zhai et al., 2010; Mukherjee et al. 2023)

At the crop level, radiation use efficiency (RUE) can be defined as the ratio of dry matter production of the crop to absorbed, intercepted or incident radiation. Improving RUE at both leaf level and crop level contribute to RUE at the level of the production system. RUE can be improved by cultivation methods as well as plant breeding. Improved RUE (expressed as the ratio between total dry matter production and intercepted radiation) is the main factor explaining why modern cultivars have higher production rates than older cultivars (Higashide and Heuvelink, 2009). Studies have shown that plants use diffuse light more efficiently than direct light (Gu et al., 2002; Mercado et al., 2009). This suggests that improved crop RUE in screen-house could be realized through diffusing the incident light in the screen-house. Furthermore, in summer a large amount of solar light is not used for production of shade-tolerant pot plants such as anthodium, orchids and bromeliads, because growers regularly apply shading screens to prevent damage of leaves and flowers. Growers often report that not more than about 5 mol m^{-2} d^{-1} of photosynthetic active radiation (PAR) is realized in the greenhouse (in summer this is about 10-20% of the PAR outside the greenhouse). This severe shading potentially limits crop photosynthesis. This brings the question whether or not we can apply less shading for cultivation of shade-tolerant pot plants without negatively influencing their quality. In winter when solar light levels are low, supplementary light is widely applied in greenhouses at northern latitudes to improve assimilation rate of the crop. Growers apply large quantities of supplementary light, which costs a lot of energy. The question can be raised if these high levels of supplementary light are always efficient. More light may not lead to more production if the crop is sink limited, i.e., the source strength (assimilate production) is larger than the sink strength (ability to utilize assimilates). In these cases, less supplementary light will not reduce crop growth and consequently it will increase crop RUE. For crops such as tomato, the source-sink balance may vary during plant development and between cultivars, which often differ in sink size of the fruits, while fruits are the major sink organs in tomato (Heuvelink et al., 1995). Nevertheless, growers often apply similar lighting regimes for different cultivars and developmental stages. Despite all this developments, relevant data on the radiation use of crops and its attendant effects on leaf areas of crop is very scarce. Therefore, this research is aimed at evaluating the leaf area index of tomato as influence by screen-house and ambient environment under different water management strategies.

2 Materials and methods

2.1 Site description

The study was carried out at the Research and Training Farm of the Department of Agricultural

Engineering, Federal University of Technology, Akure, Nigeria. Akure is located on latitudes $7^0$14'N and $7^0$17´N and within longitudes $5^0$08´E and $5^0$13´E. Akure has a land area of about 2303 km^2 and is situated in the humid rainforest region of southwestern Nigeria. The general elevation is 300 - 700 m above the mean sea level. Local peaks rise to 1000 m; other hill-like structures which are less prominent rise only a few hundred meters above the general elevations (Fasinmirin and Oguntuase, 2008). The pattern of rainfall is bimodal, the first peak occurring in June and July, and the second in September, with a little dry spell in August. The mean annual rainfall ranges from 1300 mm to 1500 mm (Fasinmirin et al., 2018) with an average temperature of 27°C. The relative humidity ranges between 85 and 100% during the rainy season and less than 60% during the dry season. The soils are light textured, fine sandy loam to fine sandy clay loam. The location of experiment within Nigeria and Ondo State is shown in Figure 1.

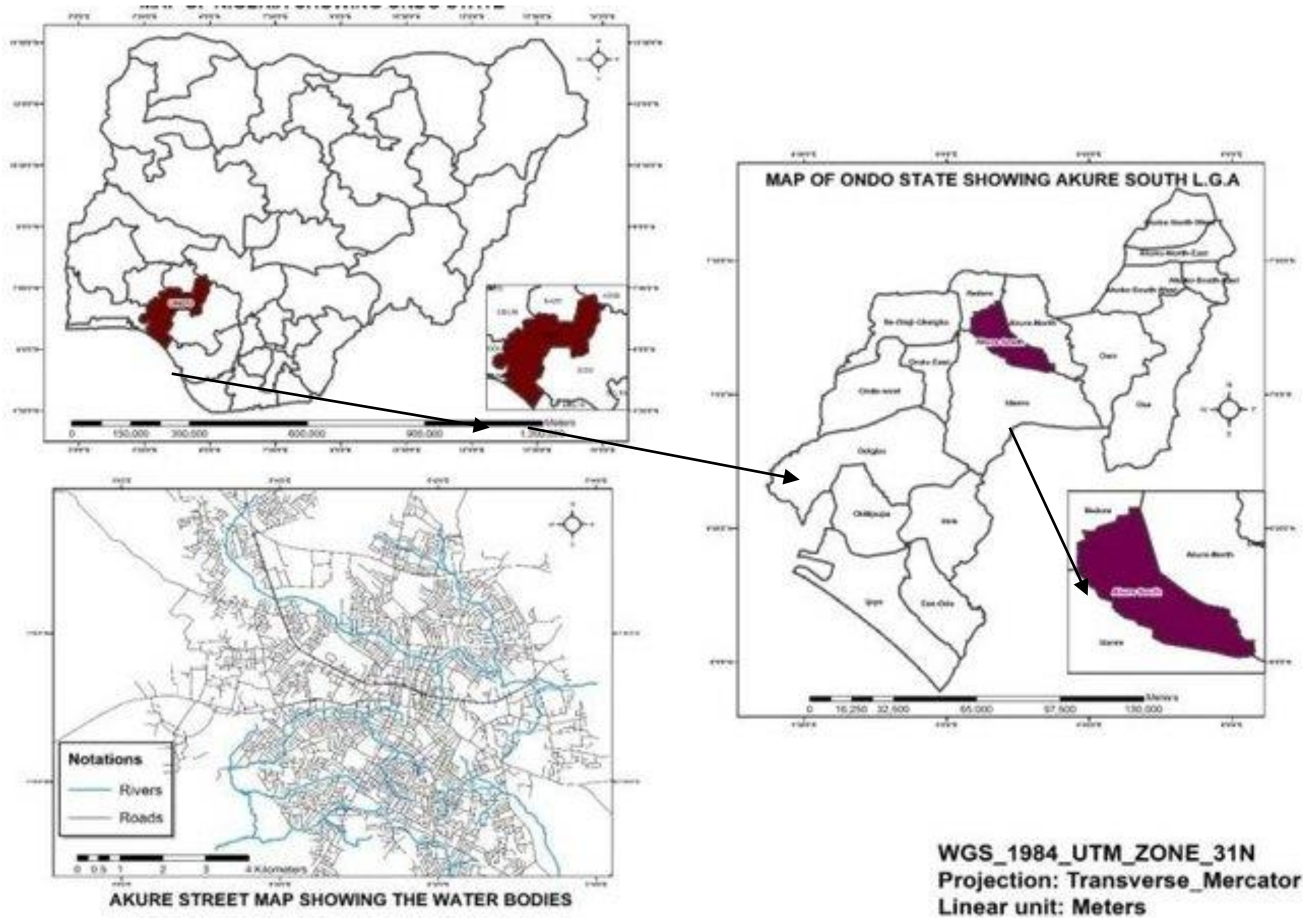


Figure 1 Map showing Akure South (Study Area) in Nigeria.

2.2 Experimental Procedure

The screen-house used for this experiment was 3.4 m high, 4.6 m long and 3.0 m wide, Cherry tomato seedlings was planted in nursery trey and allowed to germinate for four weeks after which it was transplanted into the soil media in the screen house. The experiment was conducted in split plot design of three different treatments i.e. irrigation application to 100% field capacity (100% FC) as treatment 1 (T1), 75% FC as (T2) and 50% FC as (T3) of the soil field capacity, replicated three times in the screen-house, while tomato seedlings were planted under rain-fed condition in three different plots (0.5 × 0.5 m^2) in the ambient environment just beside the screen house (Control experiment, T4) to make a total of twelve plots in all. Drip irrigation was solely used during this experiment and water application to different plots was carried out using drip lines which conducted water from a tank (30 L capacity) placed at a head of 1.2 m to the plots.

2.3 Measurements

2.3.1 Photosynthetic active radiation (PAR)

Above and below canopy PAR of crop under different water management was measured directly on the field using LAI/PAR Ceptometer, model AccuPAR LP-80 (Decagon device). Leaf distribution coefficient (*chi)*, leaf area index (*LAI*), zenith angle (θ), fraction of incident PAR, ratio of below canopy PAR and above canopy PAR (τ) were measured on the field using the LAI/PAR Ceptometer.

2.3.2 Calculation of extinction coefficient (K) and RUE

Based on the measured values of LAI and PAR data (incident PAR above the canopy and incident PAR transmitted through the canopy), the extinction coefficient, K of tomato was determined using the Beer-Lambert equation, which is an exponential form of the Equation (Thornley and France, 2007):

$$I_t/I_0 = e^{-K * LAI} \quad (1)$$

where I_t is the transmitted PAR (TPAR), I_0 is the incident *PAR* and *K* is the light extinction coefficient.

From this equation, we can calculate *IPAR* as:

$$IPAR = I_0(1 - e^{-K * LAI}) \quad (2)$$

RUE was calculated from the slope of the linear regression of cumulative IPAR on cumulative dry biomass obtained from the sequential samplings (Kiniry et al., 2001; Ahmad et al (2008)

$$\text{RUE} = \frac{TDM}{IPAR} \quad (3)$$

where *TDM* is the total dry matter produced (g m^{-2}); *IPAR* is the intercepted photosynthetic active solar radiation (MJ.m^{-2}); and *RUE* is the radiation use efficiency of dry matter produced (g. MJ^{-1}).

2.3.3 Agronomic measurements

Crop agronomic parameters such as tomato plant height, stem girth, fruit height and fruit diameter were determined on function of weeks after transplanting. The tomato plant height was measured using steel meter rule from the soil surface at the base of the plant to the apex of the plant, while the tomato stem girth was determined using digital electronic venier caliper. Also, the height and diameter of fresh harvestable fruits were measured with the aid of venier caliper. All yield parameters were measured from the 8 weeks after transplanting (8WAT).

2.4 Statistical Analysis

All intercepted photosynthetic active radiation and agronomic responses of tomato plant were subjected to statistical analysis such as means, standard deviation and analysis of variance (ANOVA). Models describing the relationship of the intercepted photosynthetic active radiation (IPAR), fraction of intercepted photosynthetic active radiation (FIPAR) and RUE with irrigation levels and time of harvest were established. The relationships between tomato yield components, irrigation levels and growing period were derived using multivariate regression analysis. All statistical analysis were conducted using Minitab 18 software

3 Results and Discussion

3.1 RUE of Tomato

The RUE of the plant is an important factor that influences plant growth (Li et al. 2022). In the absence of stress, RUE is strictly associated to the maximum leaf photosynthetic rate (George-Jaeggli et al., 2013) and correlates well with those effectors that increase the photosynthetic activity such as the leaf nitrogen content (Ding et al., 2021).

The radiation use of the tomato plant was obtained based on the intercepted photosynthetic active radiation (IPAR), fractional of intercepted photosynthetic active radiation (FIPAR) as presented in Figure 2, IPAR values of 3773 MJ m^{-2}, 2230 MJ m^{-2}, 2147 MJ m^{-2}, and 3956 MJ m^{-2} were recorded for tomato plants grown under 50%, 70%, 100% FC, and control samples, respectively. FIPAR values of 8.90, 7.13, 5.79 and 3.33 were observed for tomato plants grown under 50%, 70%, 100% irrigation to FC and the control samples, respectively. The implication of these results is that higher percentage of radiation received in the greenhouse was absorbed by irrigated tomato plants when compared with the tomato grown under ambient condition (control sample). Also, the RUE values of 0.29 ± 0.02 kg $MJ^{-1}m^{-2}$, 0.56 ± 0.002 kg $MJ^{-1}m^{-2}$, 0.6 ± 0.001 kg $MJ^{-1}m^{-2}$ and 0.21 ± 0.01 kg $MJ^{-1}m^{-2}$ were recorded for the tomato plants grown under 50%, 70%, 100% FC, and control samples, respectively (Figure 3). The result clearly shows that plants under 100% FC has the lowest IPAR and FIPAR compared to other treatments in the greenhouse, whereas the highest RUE was recorded from the tomato plant grown under 100% irrigation to field capacity (100% FC).

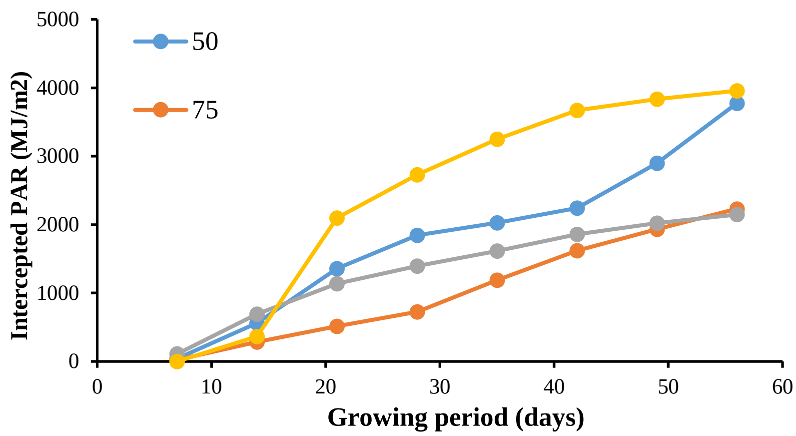
The irrigation water level had no significant effect ($p < 0.05$) on the radiation use of the tomato plant among IPAR, FPAR and RUE (Table 1). Although the result further shows that the combination of the irrigation water level and the growing period can significantly explain the change in the radiation use of the tomato plant. Mathematical relationships were established for the prediction of the radiation use of the tomato plant (IPAR, FPAR and RUE) on function of irrigation water levels and the harvesting period. Model accuracy showed that the combination of the irrigation water level and growing period can predict about 90% ($p<0.001$) of the IPAR, FIPAR and RUE of the tomato plant. The developed model is shown in Equations 4 – 6.

$$IPAR = -606.69 + 576.86t + 5.47I - 2.90tI \quad (4)$$

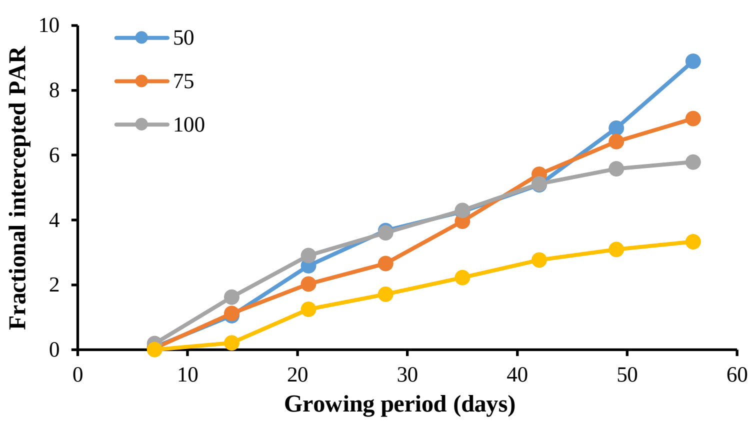
$$FIPAR(MJ) = -1.85 + 1.29t + 0.015I - 0.0039tI \quad (5)$$

$$RUE = 0.016 + 0.006I \quad (6)$$

Where, *IPAR* is the intercepted photosynthetic active radiation, *FIPAR* fractional intercepted photosynthetic active radiation and *RUE* is the radiation use efficiency, t is the harvesting period (weeks) and I is the irrigation level (%).



(a) IPAR



(b) FIPAR

Figure 2 IPAR and FIPAR of tomato under different treatments

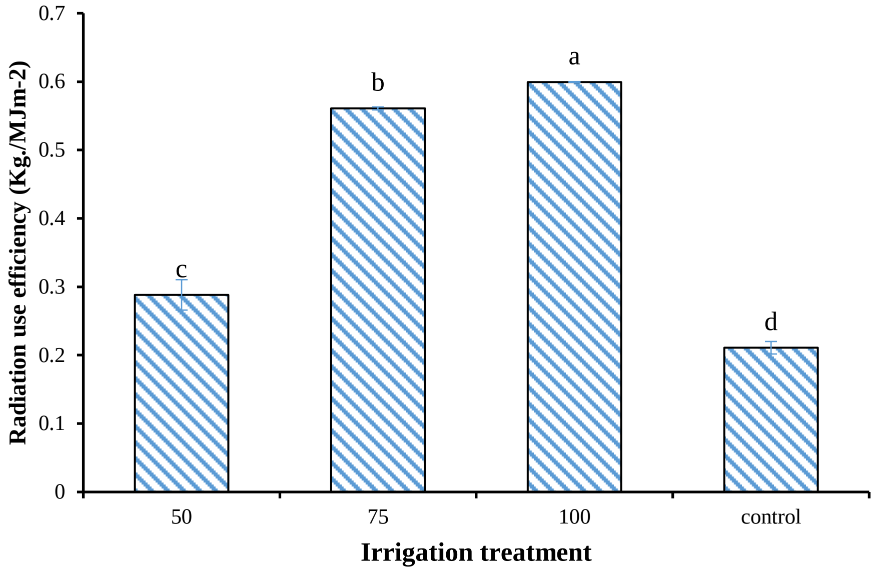


Figure 3 Radiation use of tomato under different treatments

Table 1 Analysis of variance for the radiation use of tomato under different treatments

Radiation use\	Source	DF	Sum of squares	Mean squares	F	p> F
FIPAR	Model	3	84.927	28.309	245.745	< 0.0001
	t	1	9.675	9.675	83.987	< 0.0001
	I	1	0.378	0.378	3.282	0.088
	t*I	1	0.523	0.523	4.541	0.048
	Error	17	1.958	0.115		
	Corrected Total	20	86.885			
IPAR	Model	3	11483142.035	3827714.012	38.024	< 0.0001
	t	1	1927750.483	1927750.483	19.150	0.0004
	I	1	52316.002	52316.002	0.520	0.4808
	t*I	1	293722.002	293722.002	2.918	0.1058
	Error	17	1711307.277	100665.134		
	Corrected Total	20	13194449.312			
RUE	Model	1	0.145	0.1453	35.845	0.0005
	I	1	0.145	0.1453	35.845	0.0005
	Error	7	0.028	0.004		
	Corrected Total	8	0.174			

Photosynthesis in plants depends on various vegetat ive growth factors, such as leaf age, leaf areaand leaf nu mber. Leaf area is related to canopy photosynthesis and production of crops (De Pascale *et al.*, 2015). In terms of fruit quality, the fruit weight is dependent on leaf area index and the higher the RUE, the heavier the fruit weight. All indexes of tomato development in this research point to the fact that the higher the leaf area, the better the radiation use for photosynthesis and consequently, the higher the yield.

3.2 Tomato fruit diameter

The fruit size is a very important factor in tomato processing and production. Thus, the effect of water supply on the fruit size is widely studied; also, the variation in the level of irrigation and its effect on the size of the tomato fruit is a key factor for enhancing its production. The size of the tomato fruit was obtained based on the fruit diameter, fruit height, tomato stem girth and height. Weekly measurements under the different irrigation water levels (100% FC, 75% FC, 50% FC and control) are presented in Figures 4 and 5. Tomato fruit diameter ranges from 34.03 mm - 35.63 mm, 33.73 mm - 35.1 mm, 33.53 mm - 35.73 mm and 33.57 mm - 34.27 mm for the tomato fruit harvested under 100%, 70%, 50% and control sample respectively, while fruit height ranges from 37.9 mm - 41.33 mm, 37.83 mm - 40.47 mm, 37.83 mm - 40.6 mm, 37.83 mm - 38.67 mm for the tomato fruit harvested under 100%, 70%, 50% and control sample, respectively. This clearly shows that the tomato fruits obtained from the 100% irrigation are bigger in size in terms of length when compared with other treatments. Based on the result of the analysis of variance shown in Table 2, the irrigation water level had no significant effect ($p< 0.05$) on the size of tomato fruit (fruit diameter and length), although the result further shows that the combination of the irrigation water level and the harvesting period can significantly explain the change in fruit size.

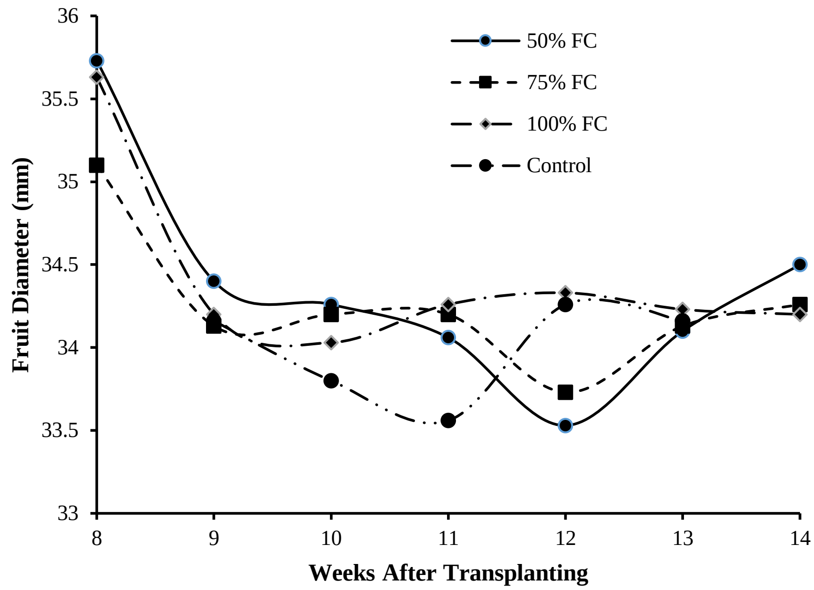


Figure 4 Tomato fruit diameter on function of weeks after transplanting

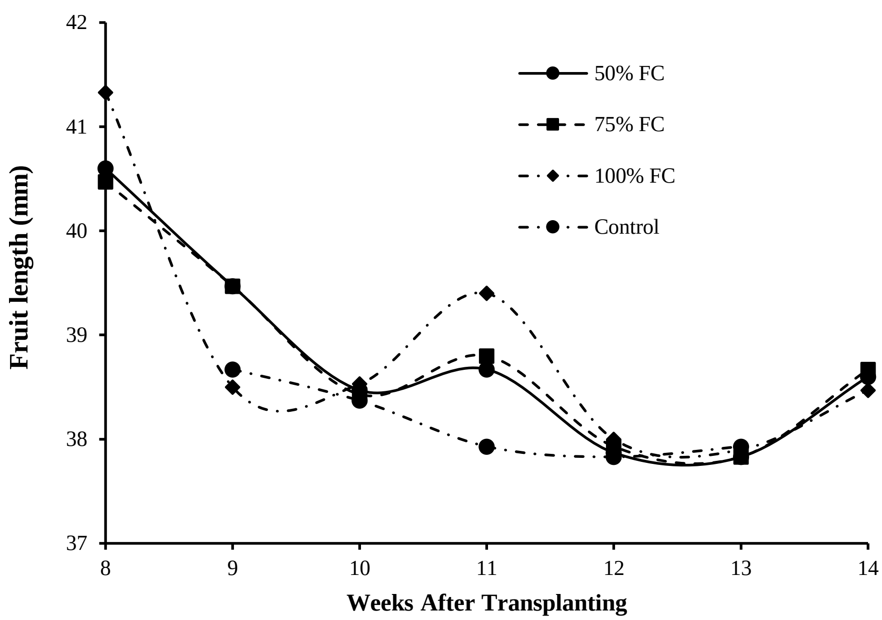


Figure 5 Tomato fruit length on function of weeks after transplanting

However, a mathematical relationship was established for the prediction of the fruit size (fruit diameter and fruit height) on function of the irrigation water level and the harvesting period. The model accuracy showed that the combination of the irrigation water level and harvesting period can predict fruit diameter and fruit height to the 5% level of significance ($p = 0.0135$)

The developed model is presented in Equations 7 and 8 for fruit diameter and fruit height respectively.

$$FD = 35.39 - 0.32t - 0.0057I + 0.00206It \quad (7)$$

$$FH = 40.38 - 0.472t - 0.0012I + 0.0013It \quad (8)$$

where, FD is the fruit diameter (cm), FH is the fruit height (cm), t is the harvesting period (weeks) and I is the irrigation level (%).

Table 2 Analysis of variance (ANOVA) for the variation in the fruit size

Fruit size	Source	DF	Sum of squares	Mean squares	F	p> F
Diameter	Model	3	6.297	2.099	3.883	0.014
	t	1	1.459	1.459	2.700	0.106
	I	1	0.161	0.161	0.298	0.587
	I*t	1	0.388	0.388	0.718	0.400
	Error	57	30.811	0.541		
	Corrected Total	60	37.108			
Height	Model	3	32.737	10.912	12.138	< 0.0001
	T	1	3.256	3.256	3.622	0.062
	I	1	0.007	0.007	0.008	0.928
	I*t	1	0.155	0.155	0.172	0.679
	Error	57	51.246	0.899		
	Corrected Total	60	83.983			

3.3 Tomato Plant Height and Stem Girth

Tomato stem girth and plant height as affected by the variation in irrigation level over the growing period is graphically presented in Figures 6 and 7, respectively. The growth of the tomato plant under different irrigation levels (100%, 75%, and 50%) was significantly different (p= 0.05) from the control, while the values under 100% FC irrigation treatment were not significantly different comparatively with both 75% and 50% FC irrigation treatments. Posthoc test carried out on tomato growth parameters showed significantly lower stem girth and plant height. These variations can be attributed to the contribution of the use of screen-house. Giuliani *et al.* (2016) reported a significant difference in the values for the treatments restoring 100% FC and 70% FC and this might be due to the fact that the water was only supplied at extreme water stress of the tomato plant, while predetermined schedule was available to irrigate the soil to a desired field capacity in the greenhouse.

The relationships between tomato yield components, irrigation levels and growing period were derived using multivariate regression analysis and the relationship with two-factor interaction have a better prediction of over 90% degree of accuracy at $p \leq 0.05$ significance level (Table 3). From the regression analysis, the plant growth parameters significantly depend on the growing period after transplanting followed by the irrigation water level, while the interaction between the growing period and irrigation water level has no significant effect (p<0.05) on the plant growth.

Nonetheless, some researchers suggested that the optimal water supply might be around 60 –70% of crop evapotranspiration in the future because the predicted effects of climate change and heat stress identification will reduce irrigation water availability. The study emphasized the beneficial effects of moderate water stress during the ripening stage of tomato (Giuliani et al., 2019). The increment in growth rate induced by water deficit can be genotype-dependent as well and not only the effect of water deficit (Arbex de Castro Vilas Boas et al., 2017).

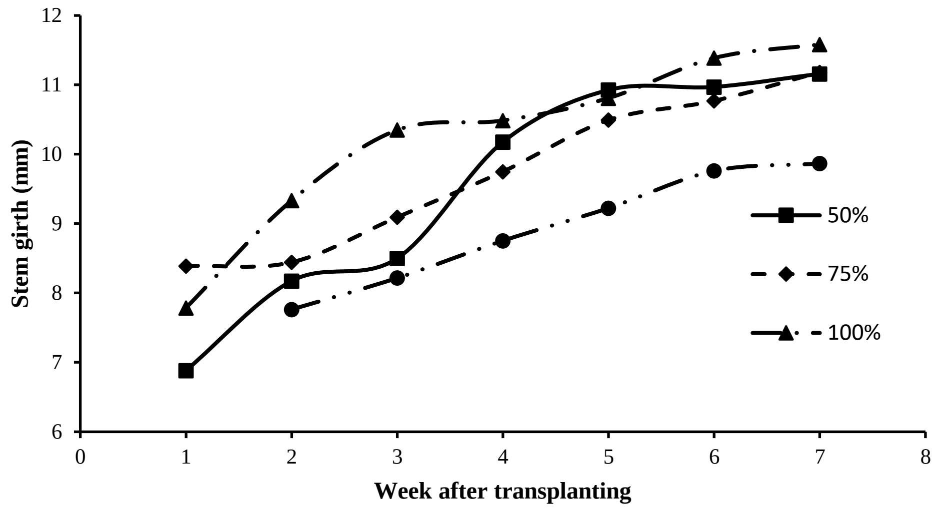


Figure 6 Tomato Stem Girth on function of Weeks after Transplanting

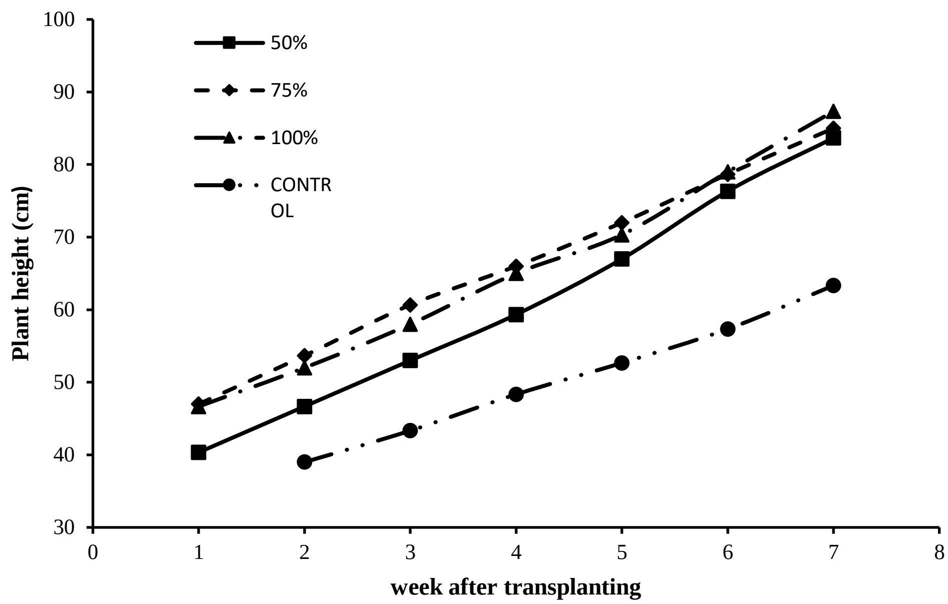


Figure 7 Tomato Plant Height on function of Weeks after Transplanting

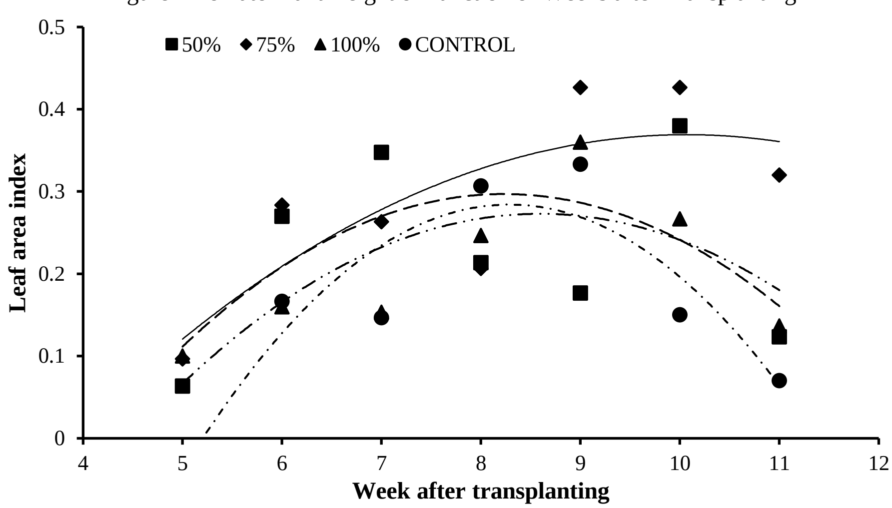


Figure 8 Leaf area index of tomato plant under different irrigation water levels

Table 3 Analysis of variance for yield components

Plant growth	Source	DF	Sum of squares	Mean squares	F	p> F
Stem girth	Model	3	33.432	11.144	55.144	< 0.0001
	t	1	31.256	31.256	154.669	< 0.0001
	I	1	1.748	1.748	8.649	0.009
	tI	1	0.428	0.428	2.116	0.164
	Error	17	3.435	0.202		
	Corrected Total	20	36.867			
Plant height	Model	3	3904.411	1301.470	324.550	< 0.0001
	t	1	3827.250	3827.250	954.408	< 0.0001
	I	1	73.143	73.143	18.240	0.001
	tI	1	4.018	4.018	1.002	0.331
	Error	17	68.171	4.010		
	Corrected Total	20	3972.582			

3.4 Leaf area index (LAI) of tomato

Effect of irrigation water level on LAI progression is graphically presented in Figure 8. The highest LAI value (0.42) was obtained in tomato irrigated to 75% FC during the 9 weeks after transplanting. At this point the LAI of tomato irrigated to 75% FC was 22% higher than the tomato under 100% FC (0.27). Similar observation was made by Harmanto et al. (2005) who reported maximum tomato LAI of 4.8 in plots irrigated to 75% of ETc (actual evapotranspiration) for greenhouse grown tomato. Campillo et al. (2010) also reported highest LAI for greenhouse grown tomato and cucumber to be 3.7 and 3.66, respectively which is consistent with the present study. However, in this study, LAI values for crops irrigated to 50% and 75% FC were found to be higher when compared with crops irrigated to Field capacity (FC 100).

The LAI ceptometer gave reliable readings for tomato in this study. Moisture status with the gas exchange is favourable for the development of leaves' stomata density, which functions in response to leaf water status and has a correlation with specific leaf area corresponding to LAI (Xu and Zhou, 2008). Moreover, soil nutrients, climate and other factors like location and management practices may have influenced LAI.

4 Conclusion

The research suggested effective management of scarce water resources based on the fact that the irrigation application up to the 75% FC gave highest LAI when compared with irrigation application to 100% FC. The combination of the irrigation water level and the growing period can significantly influence the radiation use of the tomato plant. However, tomato irrigated to 100% FC had greater yield comparatively with other levels of irrigation during the research. The research provided a mathematical model for the prediction of tomato fruit diameter and height on function of irrigation water level and harvesting period.

References

Ahmad, S., M. Zia-ul-Haq, H. Ali, S.A. Shad, A. Ahmad, M. Maqsood, M.B. Khan, S. Mehmood and A. Hussain. 2008. Water and radiation use efficiencies of transplanted rice (Oryza sativa L.) at different plant densities and irrigation regimes under semi-arid environment. Pak. J. Bot., 40(1): pp199-209

Arbex de Castro Vilas Boas, A., Page, D., Giovinazzo, R., Bertin, N. and Fanciullino, A.-L. 2017. Combined effects of irrigation regime, genotype, and harvest stage determine tomato fruit quality and aptitude for processing into puree. *Front. Plant Sci.*, 8: 1725.

Bogale, A., Nagle, M., Latif, S., Aguila, M. and Müller, J. 2016. Regulated deficit irrigation and partial root-zone drying irrigation impact bioactive compounds and antioxidant activity in two select tomato cultivars. *Sci. Hortic. (Amsterdam)*, 213: pp115–124.

Bok, I M., Madisa, D. Machcha, M. Moamogwe & More, K. 2006. Manual for vegetable production in Botswana (ed). Department of Agricultural Research Gaborone. Botswana.

Campillo, C., García, M. I., Daza, C., & Prieto, M. H. 2010. Study of a non-destructive method for estimating the leaf area index in vegetable crops using digital images. . *HortScience*, pp1459-1463.

De Pascale, S. Maggio, A.,, Orsini, F. Stanghellini, C., Heuvelink, E. 2015. Growth response and radiation use efficiency in tomato exposed to short-term and long-term salinized soils. *Scientia Horticulturae*, 189:139-149.

Ding, D., Naijiang Wang, N., Zhang, Xi, Zou, Y., Zhao, Y.,, Xu, Z., Chu, X., Liu, J., Bai, Y., Feng, S, Feng H., Siddique, K.H.M., Wendroth, O. 2021. Quantifying the interaction of water and radiation use efficiency under plastic film mulch in winter wheat. *Science of the Total Environment.* Volume 794, 10 November 2021, 148704.

Fasinmirin J.T., Olorunfemi, I.E., Oguntunde, P.G., Reichert, J.M. 2018. Hydraulic Conductivity and Penetration Resistance of a Tropical Rainforest Alfisol under Different Land Uses in Akure, Southwestern Nigeria, *Journal of Experimental Agriculture International*, pp1-12

Fasinmirin, J.T. and Oguntuase, A. 2008. Soil moisture distribution pattern in Amaranthus cruentus field under drip irrigation system. *African Journal of Agricultural Research*, pp486 – 493.

George-Jaeggli, B., Jordan, D.R., van Oosterom, E.J. , Broad, I.J., Hammer, G.L. 2013. Sorghum dwarfing genes can affect radiation capture and radiation use efficiency, *Field Crop Research* 149: 283 – 290.

Giuliani, M.M., Gatta, G., Nardella, E., Tarantino, E., 2016. Water saving strategies assessment on processing tomato cultivated in Mediterranean region. Ital. J. Agron. 11, 69–76. https://doi.org/10.4081/ija.2016.738.

Giuliani, M.M.; Gatta, G.; Cappelli, G.; Gagliardi, A.; Donatelli, M.; Fanchini, D.; De Nart, D.; Mongiano,G.; Bregaglio, S. Identifying the most promising agronomic adaptation strategies for the tomato growing systems in Southern Italy via simulation modeling. Eur. J. Agron. 2019, 111, 125937,doi:10.1016/j.eja.2019.125937

Gu, L., Baldocchi, D. D., Verma, S. B., Black, T. A., Vesala, T., Falge, E. M., et al. (2002). Advantages of diffuse radiation for terrestrial ecosystem productivity. J. Geophys. Res. 107, 2–1. doi: 10.1029/2001JD001242

Harmanto, V. M., Salokhe, B. M., & Tantau, H. J. 2005. Water requirement of drip irrigated tomatoes grown in greenhouse in tropical environment *Agricultural Water Management*, pp225 - 242.

Heuvelink, E., and Buiskool, R. P. M. 1995. Influence of sink-source interactionon dry matter production in tomato. Ann. Bot. 75, 381–389. doi: 10.1006/anbo.1995.103.

Heuvelink, E., Bakker, M., Elings, A., Kaarsemaker, R., & Marcelis, L. 2005. Effect of leaf area on tomato yield. . *Acta horticultura*, 43-50.

Higashide, T., & Heuvelink, E. 2009. Physiological and morphological changes over the past 50 years in yield components in tomato. *Journal of the American Society for Horticultural Science*, 460-465.

Jo, W.J. and Shin J.H. 2020. Effects of leaf area management on tomato plant growth in greenhouses. *Horticulture, Environment, and Biotechnology* (2020) 61:981–988

Kiniry, J. R., McCauley, G., Xie, Y. and Arnold, J. G., 2001, “Rice parameters describing crop performance of four US cultivars”, Agron. J., 93, pp1354-1361.

Li Y.C, Dai H.Y, Chen H. 2022. Effects of plant density on the aboveground dry matter and radiation-use efficiency of field corn. *PLoS ONE* 17(11): e0277547. https://doi.org/10.1371/journal. pone.0277547

Mahajan, G., & Singh, K. 2006. Response of greenhouse tomato to irrigation and fertigation. *Agricultural Water Management*, 202 – 206.

Mercado, L. M., Bellouin, N., Sitch, S., Boucher, O., Huntingford, C., Wild, M., 2009. Impact of changes in diffuse radiation on the global land carbon sink. Nature 458, 1014–1017. doi: 10.1038/nature07949

Mukherjee S., Dash, P. K., Das, D., Das, S. (2023). Growth, Yield and Water Productivity of Tomato as Influenced by Deficit Irrigation Water Management. *Environmental Processes* (2023) 10:10.

Naika, S., de Jeude, J., de Goffau, M., Hilmi, M., van Dam, B. 2005. Cultivation of tomato production, processing and marketing. 4th Edition, Digigrafi, Wageningen, Netherlands

Thornley, J.H.M, France, J. 2007. Mathematical models in agriculture: quantitative methods for the plant, animal and ecological sciences, 2nd ed. CABI, Wallingford. https://doi.org/10.1079/9780851990101.0000。

Urban, O., Klem, K., Ac, A., Havránková, K., Holišová, P., Navrátil, M. 2012. Impacts of clear and cloudy sky conditions on the vertical distribution of photosynthetic CO2 uptake within a spruce canopy. Funct. Ecol. 16, 46–55. doi: 10.1111/j.1365-2435.2011.01934.x

Valcárcel, M., Lahoz, I., Campillo, C., Martí, R., Leiva-Brondo, M., Rosello, S. and Cebolla-Cornejo, J. 2020. Controlled deficit irrigation as a water-saving strategy for processing tomato. *Sci. Hortic. (Amsterdam),* 261, 108972.

Varela-Moreiras G., Ruiz E., Valero T., Avila J.M., del Pozo S. The Spanish Diet: An Update. *Nutr. Hosp.* 2013;28 (Suppl. S5): pp13–20.

Viol, M. A., Carvalho, J. d., Lima, E. M., Mattos, R. W., Rezende, F. C., and Rodrigues, J. L. 2017. Déficit hídrico e produção do tomate cultivado em ambiente protegido. . *Revista Brasileira de Agricultura Irrigada*, pp1244-1253.

Xu, Z and Zhou, G. 2008. Responses of leaf stomatal density to water status and its relationship with photosynthesis in a grass. *Journal of Experimental Botany,* Vol. 59, 12: 3317–3325.

Zhai, Y.M., Shao, X.H., Xing, W.G., Wang, Y., Hung, T.T., Xu, H.L. 2010. Effects of drip irrigation regimes on tomato fruit yield and water use efficiency. *Journal of Food, Agriculture & Environment* Vol.8 (3&4): 709-713.