Effect of drip irrigation regime and mulching on growth and yield parameters of tomato (*Solanum lycopersicum* L.) varieties

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Agricultural water scarcity poses a serious threat to food and nutrition security in sub-Saharan African countries. Therefore, this study sought to investigate the effect of deficit irrigation and mulching on agronomic traits of two tomato *(Solanum lycopersicum)* varieties. The experimental design was split-split plot. Treatments consisted of two varieties assigned as main plot factor (Mongal F1 and Pectomech), deficit irrigation as subplot factor at three levels: 100, 75 and 50% crop water requirement (ET_c) and rice straw mulch as sub-subplot factor at three levels: 6, 3 and 0 t ha^{-1}. The results showed significant effect of treatments on measured traits. Mild irrigated Mongal F1 mulched with 3 t ha^{-1} rice straw recorded significantly higher leaf chlorophyll concentration of 69.35 µmol/m². Mulching with 3 t ha^{-1} rice straw resulted in higher mean leaf chlorophyll than with 6 or 0 t ha^{-1}. Leaf stomatal conductance was significantly higher (74.10 mmol/m²s) for plants under full irrigation combined with mulch at 6 t ha^{-1} than with medium or no-mulch. Mongal F1 out-yielded Pectomech by a margin greater than 100%, especially when irrigated with higher volumes of water. Full irrigation did not significantly differ from mild deficit irrigation in fruit yield. Mongal F1 mulched at 6 t ha^{-1} gave significantly higher fruit yield of 11.93 t ha^{-1} than un-mulched Pectomech. The mulch effect resulted in significantly higher irrigation water-use efficiency for Mongal F1 that ranged from 2.82 – 3.10 kg m^{-3} compared to un-mulched Pectomech. In addition, 50% deficit irrigated Mongal F1 recorded significantly higher irrigation water-use efficiency of 3.88 kg m^{-3} than full irrigated Pectomech. The integration of mulched Mongal F1 with mild deficit irrigation can improve crop and water productivity of tomatoes under water limiting environments.

Keywords: Deficit irrigation, mulching, fruit yield, irrigation water-use efficiency, tomato

Rainfall variability has posed a negative influence on soil water available for crop production in arid regions (Sylla et al. 2016). The situation is exacerbated by climate change which threatens water resources as well as posing soil water stress conditions (Oyerinde et al. 2014; Sylla et al. 2015). Irrigation mitigates soil water stress conditions and provides the daily water needs of plants. However, there is the need for efficient and sustainable irrigation practices for optimum soil water conditions to improve the soil environment and plant system. Currently, irrigation of most vegetables in Ghana is largely under the traditional furrow irrigation method which is often inefficient in water distribution and increases risk of rootzone soil nitrate leaching due to over irrigation (Popova et al. 2005; Zheng et al. 2015). Consequently, farmers are unable to accurately schedule their irrigations due to the poor technical knowledge on irrigation and often leads to poor yields (Calzadilla et al. 2009). Farmer achievable fruit yield of tomato *(Solanum lycopersicum)* in Ghana stands at a mean of 7.5 t ha^{-1} which contributes to a yield gap of 50% when compared to the national attainable yield of 15 t ha^{-1} (MoFA 2017). However, poor fruit yield of tomato compared to the 7.5 t ha^{-1} farmer achievable yield has been reported under irrigated ecologies of the Guinea Savanna Zone. For instance, farmers in the Bontanga Irrigation Scheme obtain fruit yield between 2.8 - 5.0 t ha^{-1} (Asare-Bediako et al. 2007). Adongo et al. (2016) reported fruit yields of 6.2 t ha^{-1} and 4.2 t ha^{-1} for farmers in Tono and Vea Irrigation Schemes respectively. The poor fruit yield can be attributed to factors that include poor irrigation infrastructure and water management. However, properly utilised drip

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irrigation systems could be an alternative for water scarce environments. The systems have high water-use efficiency of about 95% (Sharma 2001; Pedro and Ferreira 2007) and can contribute to an increase in tomato fruit yield (Xu et al. 2009). Moreover, integrating drip systems with deficit irrigation strategies and resources, such as crop residue mulch, could result in an exponential increase in fruit yield and water savings.

Deficit irrigation is a practice where plants receive volumes of water below their daily needs, especially at less sensitive growth stages (Costa et al. 2007). Biswas et al. (2015) recorded high tomato fruit yields of 79.49 and 81.12 t ha^{-1} on plots with paddy straw and polyethylene mulch respectively, under severely stressed irrigation; they found 50% savings on irrigation water under the drip irrigation system and a 25 – 27 % increase in fruit yield. Kebede (2019) found significantly higher onion bulb yield of 34.71 t ha^{-1} when full irrigation was combined with 6 t ha^{-1} straw; 80% ET_c (crop water requirement) in combination with 6 t ha^{-1} straw gave almost as much yield of 32.52 t ha^{-1} and 60 % ET_c with no mulch had the lowest yield (21.10 t ha^{-1}). Despite the benefits of deficit irrigation, care is needed to maintain optimum soil water conditions for plant use (Sharma et al. 2019; Parkash and Singh 2020). Therefore, research is required to ascertain threshold levels of deficit irrigation that would not have a significant effect on tomato growth and yield. Though literature is available on the effect of crop residue mulch on tomato, there is limited information on the quantity of rice straw to apply and the interactions with irrigation especially under water limiting environments of the Guinea Savanna Zone of Ghana. Plants exhibit different tolerant levels to soil water stress conditions (Mohawesh 2018; Singh et al. 2019), so an in-depth understanding of the interaction effect of deficit irrigation regimes and quantity of rice straw mulch on improved tomato varieties will help to fill the knowledge gap and improve the agronomic performance of tomato.

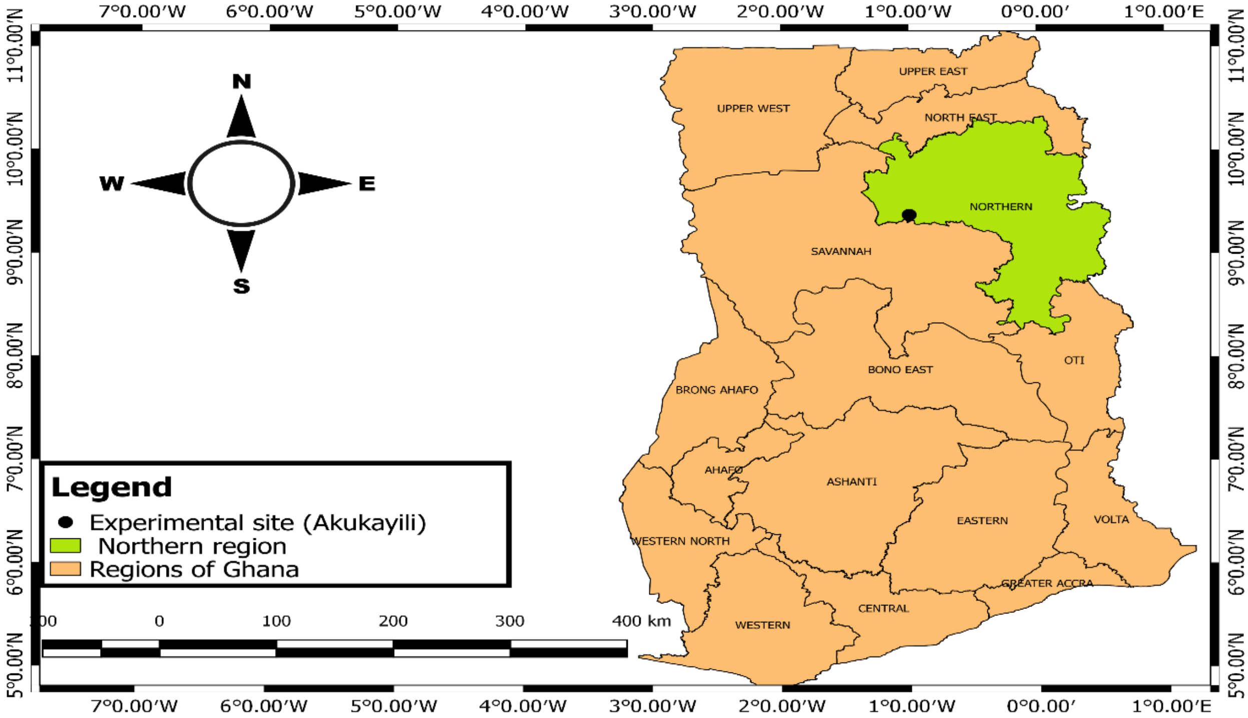

Figure 1: Map of Ghana showing the location of experimental site in the Northern region of Ghana

Materials and methods

Study area description

The experiment was conducted in the two dry seasons of 2020/1 to 2021/2 at the experimental field of CSIR - Savanna Agricultural Research Institute (SARI), Nyankpala, Tamale in the north of Ghana (Figure 1). The site coordinates are; N 09˚ 23' 18", W 001˚ 00' 08" and an altitude of 176 m above sea level. The vegetation is typically of Guinea Savannah, characterised by grassland with interspersed trees; the climatic condition of the area is described as warm and semi-arid with unimodal rainfall of 800 – 1300 mm per annum (Kombiok et al. 2005). In a normal year, the rainy season starts in May and ends in October giving way to the onset of dry season which lasts from November to April, within which irrigation is fully practiced. In this study the cropping period for tomatoes was from December to March; in both years there was no rainfall (Table 1). In the first season, ambient temperatures ranged from 20.9 - 38.5˚C, whereas a range of 19.4 - 37.8˚C was recorded in the second season (Table 1). Wind speed was lowest in December and highest in March for each season and ranged from 0.9 - 2.7 km/h (Table 1). The agroecology experiences an estimated reference evapotranspiration (ET_o) above 1,600 mm/yr (Abdul-Ganiyu 2011). The chemical and physical soil characteristics are given in Table 2, including volumetric water content at field capacity and permanent wilting point for three soil layers to 60 cm depth. The soil is characterised by sandy-loam texture with poor soil fertility status considering the low nitrogen and organic matter content.

Table 1: Weather conditions in the two cropping seasons at the experimental field in Akukayili, Nyankpala, Tamale, Ghana

Month/year	**Rainfall (mm)**	**Wind speed (km/h)**	**Minimum temperature (°C)**	**Maximum temperature (°C)**	**Mean temperature (°C)**	**Mean relative humidity (%)**
	2020/21 dry cropping season					
Dec - 2020	0.0	0.9	21.6	37.2	29.4	60.0
Jan - 2021	0.0	1.4	20.9	37.0	29.0	51.2
Feb - 2021	0.0	1.7	21.5	38.0	29.7	40.6
Mar - 2021	0.0	2.7	26.8	38.5	32.7	53.1
	2021/22 dry cropping season					
Dec - 2021	0.0	1.5	20.6	35.8	30.9	61.4
Jan - 2022	0.0	2.2	19.4	35.4	24.4	49.8
Feb - 2022	0.0	1.9	23.7	37.8	28.4	54.0
Mar - 2022	0.0	2.6	27.3	37.6	41.6	74.6

CSIR-SARI Meteorological Department

Table 2: Pre-experiment soil properties of the site at Akukayili, Nyankpala, Tamale, Ghana

	Units	**Soil layers (cm)**		
Chemical properties		0-20	21-40	
Electrical conductivity (EC)	µS/cm	13.06	8.32	6.98
Acidity or alkalinity (pH)		5.45	5.42	5.42
Organic carbon content (OC)	%	0.98	0.74	0.53
Total nitrogen content (N)	%	0.09	0.07	0.05
Exchangeable phosphorus (P)	mg/kg	3.68	2.35	2.31
Exchangeable potassium (K)	mg/kg	78.0	56.0	44.0
Calcium (Ca)	cmol+/kg	3.40	2.40	2.20
Magnesium (Mg)	cmol+/kg	0.40	1.80	1.60
Cation exchange capacity (CEC)	cmol+/kg	5.80	5.64	4.93
Physical and hydraulic properties				
Soil texture		Sandy-loam	Sandy-loam	Sandy-loam
Total organic matter (OM)	%	2.90	1.44	1.21
Field capacity (θm FC)	% v/v	18.20	18.00	20.40
Permanent wilting point (θm PWP)	% v/v	9.10	8.60	9.60
Saturation (θm SAT)	% v/v	45.80	41.90	38.10
Available water (AWC)	% v/v	9.10	9.40	10.80
Bulk density (BD)	g cm^{-3}	1.48	1.68	1.69
Porosity of soil (P)	%	44.12	36.51	29.97
Saturated hydraulic conductivity (K_{sat})	(cm/min)	0.081	0.044	0.041

Analysed at the CSIR-SARI Soil Chemistry Laboratory, Nyankpala, Tamale, Ghana

Experimental design and field cultural practices

The experimental design was split-splitplot with treatments arranged in a randomised complete block design replicated four times. Treatments consisted of two tomato varieties as the main plot factor: Mongal F1 and Pectomech; deficit irrigation regimes as subplot factor at three levels: full irrigation (100% crop evapotranspiration, ET_c), mild deficit irrigation (75% ET_c) and severe deficit irrigation (50% ET_c), and quantity of rice straw mulch as sub-subplot factor at three levels: 6, 3 and 0 t ha^{-1}. The 100, 75 and 50% ET_c resulted in 1, 2 and 3 days irrigation intervals respectively. The gross plots consisted of three plant rows of 4.5 m length and 1 m alleys to separate plots. Rice straw, obtained from paddy rice fields, was air-dried, and cut with a cutlass into smaller pieces of 1 - 2 cm length. The processed straw was weighed and spread uniformly on the soil surface of plots according to treatment requirement: 6 t ha^{-1} (4.86 kg/plot), 3 t ha^{-1} (2.43 kg/plot) and 0 t ha^{-1} (0 kg/plot). The imposition of irrigation regime treatments started 3 weeks after transplanting (WAT) to allow for proper seedling establishment.

Seeds of the tomato varieties were purchased from AGRISEED Limited, Tamale, Ghana and raised in the nursery. Seedlings were ready by 3 weeks after emergence and transplanted to the plots at a spacing of 0.60 x 0.30 m inter- and intra-rows resulting in a net plot size of 8.1 m^2. Based on a soil test and fertiliser recommendations of 75 kg N/ha, 40 kg P_2O_5/ha and 40 kg K_2O/ha, fertilisers were applied uniformly to all experimental units in a split application. Basal fertiliser (Yara Mila Grower containing 17% N, 10% P, 10% K, 3% S and 0.3% Zn) was applied at 2 WAT by dibbling and burying at 5 cm soil depth around the root system. Plants were top-dressed at 4 WAT using Yara Mila Actyva – 23% N, 10% P, 5% K, 2% MgO, 3% S and 0.3% Zn). Early season insect pests such as aphids and whiteflies were controlled with Tihan (Spirotetramat 75 g L^{-1} and Flubendiamide 100 g L^{-1}) at 200 ml ha^{-1}. Thunder insecticide (Imidacloprid 100 g L^{-1} and Betacyfluthrin 45 g L^{-1}) was applied at

200 ml ha^{-1} to control mid-to-late season insect pests such as fruit sucking flies and larvae. Fungal and bacterial diseases were controlled using Adepa Agro-Organic Pesticide (Ethyl Palmitate, Ethyl Oleate, 9-methyl-Z-10-tetradecen-1-olacetate, 1-Ecosanol, Elcosen-1-ol, cis-9-Trans Squalene) applied at the rate of 100 mls per 15 L of water. The Adepa Agro-Organic Pesticide has an added nutritional benefit that provided the calcium need of plants prior to fruiting.

Drip irrigation system layout and computation of irrigation requirements

Plants were irrigated using a surface drip irrigation system laid out as shown in Figure 2. The characteristics of the driptape consisted of 0.30 m emitter spacing with 1 L h^{-1} discharge rate, 16 mm diameter, 0.20 mm thickness and 1 bar nominal pressure. Each plant was irrigated by one emitter. The system was supported with a 2.5 HP gasoline pump with the following hydraulic properties: maximum flow of 100 L min^{-1}, maximum head of 16 m, and maximum suction head of 7 m.

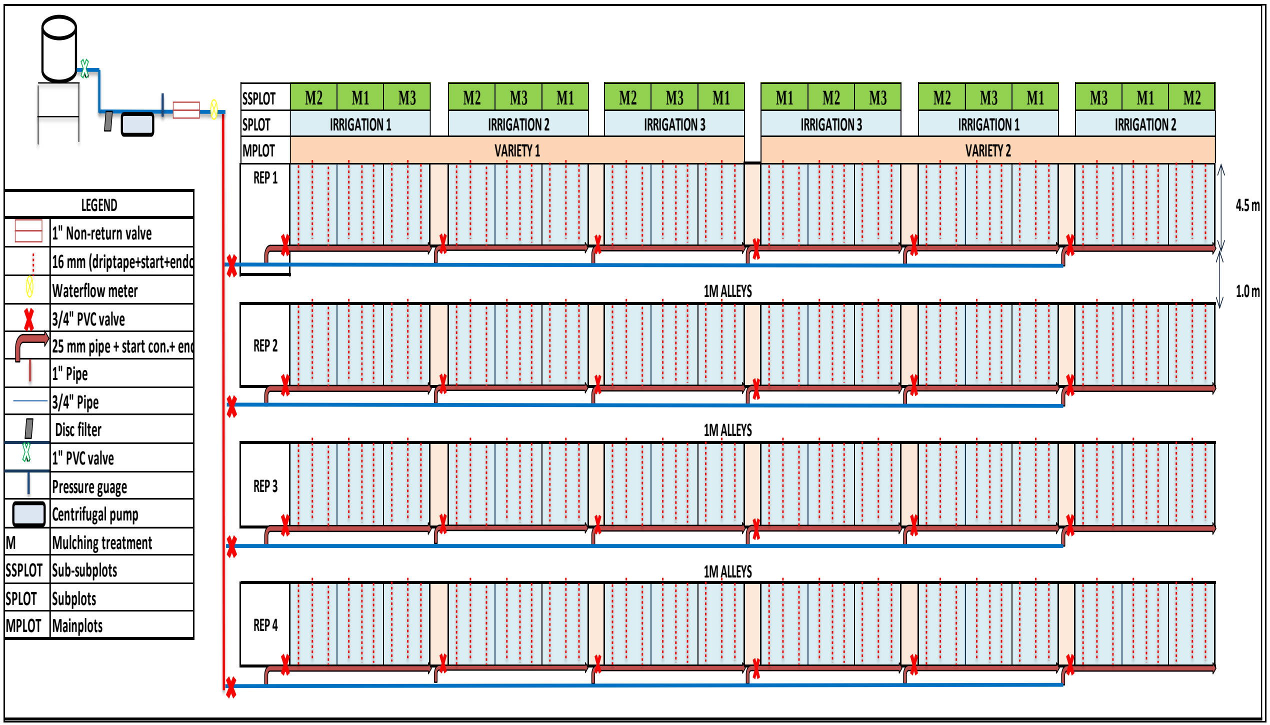

Figure 2: Drip irrigation setup and field layout of treatments

The reference evapotranspiration (ET_o) and crop coefficient (K_c) data were used to compute the daily crop water requirement (ET_c) of tomatoes (*Doorenboos and Pruitt 1977)*. The derived ET_c was further expressed as percentages of irrigation treatments. The ET_o values were calculated from historical weather data (1974 – 2019) acquired from CSIR-SARI Meteorological Department. The computation was done using FAO-CROPWAT Model according to the Penman-Monteith equation (Allen et al. 1998). The weather variables consisted of relative humidity, rainfall, wind speed, minimum and maximum temperatures, sunshine hours, and solar radiation. Crop coefficient (K_c) values of tomato were obtained from the FAO drainage paper No. 56 for the different growth stages and adjusted to meet the local site conditions due to the influence of weather (Annandale and Stockle 1994; Allen et al. 1998). Coefficient factors for crop growth stages are averaged and presented as: (1) initial stage = 0.9; (2) development stage = 1.0; (3) mid-season stage = 1.1; and (4) late-season stage = 0.92.

Net irrigation water applied was determined using the following equation (Savva and Frenken 2002):

$$\mathrm{IRn} = \mathrm{ET_c} - (\mathrm{Pe} + \mathrm{Ge} + \mathrm{Wb}) + \mathrm{LR}$$

IRn – net irrigation; ET$_c$ *- crop water requirement; Pe - effective dependable rainfall; Ge - ground water contribution from water table Wb – rootzone soil water at the beginning of each period; LR - leaching requirement (calculation was in mm).*

In this study, net irrigation water applied was equal to the daily ET$_c$ of tomato since Pe was assumed to be zero under dry season upland conditions and Ge was not considered because of the low ground water table depth (20 m). The irrigation water quality was excellent and soil salinity was very low, hence no leaching requirement was considered.

In order to ascertain soil moisture depletion of rootzone soil, total available water content from previous irrigation, the equation formulated by Waller and Yitayew (2016) was adopted and applied to bring soil water back to conditions of field capacity by irrigation.

$$\text{Soil moisture depletion (\%)} = \frac{\mathrm{FC-M}}{\mathrm{FC-PWP}}\ x\ 100$$

FC - field capacity of the soil; M – soil moisture content before irrigation; PWP-permanent wilting point of the soil (calculation in % v/v).

Soil moisture was monitored within 0 – 30 cm of rootzone soil an hour before and after irrigations using the FieldScout TDR 150 Soil Moisture Meter, Spectrum Technologies, Inc., USA. In both seasons, total water applied amounted to 5492, 4119 and 2746 m^3/ha for 100%, 75% and 50% ET$_c$ irrigation treatments respectively. The irrigation interval was estimated as the ratio of readily available soil water content to the net irrigation requirement and resulted in 1, 2 and 3 day intervals for irrigation regimes of 100%, 75% and 50% ET$_c$ respectively.

Parameters and measurements

Leaf chlorophyll concentration (LCC)

The chlorophyll concentration of tomato leaves was derived by a non-destructive method using the CCM-200 plus Chlorophyll Meter, OPTI-SCIENCES, INC. Measurements were taken between 12.00 and 14.00 local time at weekly intervals starting 4, 5 and 6 WAT. A total of three leaves per plant from ten randomly selected plants, totaling 30 leaves per plot were measured. Plant leaves were randomly selected from the lower, mid, and top portions of the stem for measurement. Chlorophyll measurement per plot was averaged.

Leaf stomatal conductance (LSC)

The stomatal conductance of tomato leaves was monitored and measured using the Steady State Diffusion Porometer Model SC-1, Decagon Devices, INC., USA. Measurement was made by contact with leaves in the direction of sunlight and between 12.00 and 14.00 local time. The instrument was calibrated to meet local field conditions prior to taking measurements. Abaxial measurements were taken weekly in each experimental unit and started 2 WAT that lasted six times. A total of three leaves per plant from five randomly selected plants, totaling 15 leaves per plot were measured. Plant leaves were randomly selected from the portion of canopy receiving more than 70% sunlight. Leaf stomatal conductance (mmol/m^{2}s) readings per plot were averaged.

Fruit yield

The fruit yield was determined by harvesting ripe fruits from each treatment plot. A total of six harvests were carried out in both seasons. Fruits from each harvest were weighed using a digital weighing scale. The total fresh fruit weight per harvest cycle with respect to individual treatment was summed up and recorded. The recorded fruit weight kg/plot was converted to t ha^{-1}.

Irrigation water-use efficiency (IWUE)

IWUE is defined as the ratio of total crop yield (tomato fruit and seed) to the seasonal irrigation water applied to the crop (Howell et al. 2002). The application of water to meet the daily demand of tomato can be from irrigation or precipitation or both. In this study no water was provided by precipitation.

$$\text{IWUE} = \frac{\text{TFY (kg)}}{\text{SIW (m}^3\text{)}}$$

TFY - total fresh fruit yield of tomato,
SIW - seasonal irrigation water applied to the crop.

Statistical analysis

Agronomic data gathered were subjected to analysis of variance using GenStat Statistical Package 12 Edition. Mean separation was performed using the Least Significant Difference (LSD) at P = 0.05. LSC and LCC data are only displayed for weeks within each season that showed significant ($P \leq 0.05$) treatment interactions. Data interpretation of treatment focused initially on the 3-way interaction; if not significant, 2-way treatment interactions were examined. Treatment interaction means were plotted and shown on graphs constructed using Microsoft Office (Excel) 2019 version.

Results and discussion

Effect of variety, deficit irrigation regimes and mulching on leaf chlorophyll concentration (LCC)

The analysis of variance showed a significant (P = 0.029) interaction effect of variety (V), deficit irrigation regimes (I) and quantity of rice straw (M) levels (V x I x M) on LCC at 5 WAT in the first irrigated season. The 3 t ha^{-1} mulch resulted in overall highest mean LCC values than 6 or 0 t ha^{-1} (Table 3). In the second season none of the interactions were significant and the only significant main effect was irrigation regime with 100% ET$_c$ giving the lowest LCC. The first season suggested that Pectomech combined with 100% ET$_c$ and 6 t ha^{-1} mulch resulted in the lowest LCC of 49.92 µmol/m² (Figure 3). However, it was not significantly different from Pectomech combined with 100% ET$_c$ and no-mulch which obtained 51.65 µmol/m². Pectomech combined with 100% ET$_c$ and no-mulch resulted in a non-significant difference in LCC when compared to the following treatment combinations; Mongal F1 x 100% ET$_c$ x 0 t ha^{-1}, Pectomech x 50% ET$_c$ x 6 t ha^{-1}, and Pectomech x 75% ET$_c$ x 0 t ha^{-1} mulch. Mongal F1 in combination with 75 % ET$_c$ and 3 t ha^{-1} mulch recorded the highest LCC of 69.35 µmol/m² followed by Mongal F1 combined with full irrigation and 6 t ha^{-1} mulch with LCC of 66.50 µmol/m²; these values represented increases of 39% and 33.2% respectively over the lowest LCC. The results concur with Medyouni et al. (2021), who found that mild deficit irrigation of 60% soil water stress produced higher chlorophyll florescence for tomato plants, compared to full irrigation. According to Chai et al. (2016), plants growing under soil water stress condition that is triggered by mild deficit irrigation, often experience a shorter stress period, and recover quick after irrigation leading to an increase in growth and physiological development; however, they stated that recovery rate of plants from water stress depends on the species. Plants under mild deficit irrigation increase their root system development, which enhances the uptake of water and essential plant nutrients from the soil (Liu et al. 2011; Li et al. 2013; Chai et al. 2016) and hence, significant improvement in chlorophyll concentration of leaves. Likewise, the application of higher volumes of irrigation water poses risk of soil nitrate leaching that would eventually result in decline in chlorophyll concentration (Popova et al. 2005). Wang et al. (2010a) reported an increase in nitrogen distribution within the middle and upper segments of plant leaf canopy under mild deficit irrigation. Wang et al. (2010b) found that, soil microbial activity was drastically improved under regulated deficit irrigation due to cycles of wetting and drying events and resulted in high substrates available for microbe ingestion, hence enhancing plant net-nitrogen mineralisation. Even more important, in this study the application of rice straw sometimes resulted in improving leaf chlorophyll concentration compared to the no-mulch treatment (Figure 3). This corroborates findings of Lahmod et al. (2019), where the application of wheat straw on *Trigonella foeunm graecum* L. increased the chlorophyll content of leaves with a SPAD value of 58.17 at the maturity stage, when compared to the control of no mulch with a SPAD value of 38.85.

Table 3: Means and interaction effects of variety, deficit irrigation regimes, mulching on mean leaf chlorophyll concentration (LCC), leaf stomatal conductance (LSC), total fruit yield (FY) and irrigation water-use efficiency (IWUE) for two seasons at Akukayili in the Guinea Savanna agroecology of Ghana

Treatment	**2020/21**				**2021/22**			
	LCC (µmol/ m^2) at 5WAT	LSC (mmol/ m^{2}s) at 7 WAT	FY (t ha^{-1})	IWUE (kg m^{-3})	LCC (µmol/ m^2) at 6WAT	LSC (mmol/ m^{2}s) at 2 WAT	FY (t ha^{-1})	IWUE (kg m^{-3})
Tomato variety (V)								
Mongal F1	63.96	61.30	12.08	3.07	46.06	120.10	9.39	2.43
Pectomech	58.54	57.10	4.26	1.07	45.58	125.10	4.08	1.05
LSD $_{(0.05)}$	**6.84^{ns}**	**16.37^{ns}**	**4.72***	**1.30***	**6.36^{ns}**	**11.79^{ns}**	**7.70^{ns}**	**1.91^{ns}**
P Value	**0.09**	**0.48**	**0.01**	**0.02**	**0.83**	**0.27**	**0.12**	**0.11**
Irrigation regimes (%ET$_c$) (I)								
100	57.81	64.70	9.56	1.74	42.17	120.70	7.24	1.32
75	63.91	55.90	8.04	1.95	46.44	121.90	6.87	1.67
50	62.04	57.10	6.91	2.51	48.85	125.30	6.10	2.22
LSD $_{(0.05)}$	**4.17***	**8.61^{ns}**	**1.89***	**0.53***	**2.46*****	**12.89^{ns}**	**2.66^{ns}**	**0.74^{ns}**
P Value	**0.02**	**0.09**	**0.03**	**0.02**	**<.001**	**0.73**	**0.65**	**0.06**
Quantity of rice straw (t/ha) (M)								
6	60.70	64.50	9.42	2.43	45.87	121.40	8.54	2.22
3	63.29	55.10	8.84	2.22	46.36	130.50	7.88	2.04
0	59.76	58.10	6.24	1.56	45.23	116.00	3.80	0.95
LSD $_{(0.05)}$	**2.95***	**5.21****	**0.97*****	**0.27*****	**3.09^{ns}**	**10.36***	**1.20*****	**0.32*****
P Value	**0.05**	**0.003**	**<.001**	**<.001**	**0.76**	**0.02**	**<.001**	**<.001**
Interaction effects (LSD at P = 0.05)								
V x M	6.35^{ns}	15.02^{ns}	4.45^{ns}	1.22^{ns}	6.02^{ns}	14.36^{ns}	7.39*	1.82*
V x I	6.87^{ns}	15.76^{ns}	4.37^{ns}	1.20*	5.88^{ns}	16.57^{ns}	7.10^{ns}	1.76^{ns}
I x M	5.68^{ns}	10.92*	2.25^{ns}	0.63^{ns}	4.89^{ns}	18.83^{ns}	3.05^{ns}	0.84^{ns}
V x I x M	8.66*	17.98^{ns}	4.53^{ns}	1.25^{ns}	7.93^{ns}	25.78*	7.14^{ns}	1.79^{ns}

*V x M - interaction effect of variety and mulch, V x I - interaction effect of variety and irrigation regimes, I x M - interaction effect of irrigation regimes and mulch, V x I x M - interaction effect of variety, irrigation regimes and mulch, ETc - crop water requirement. LSD - least significant difference of means. WAT- weeks after transplanting, *** - $P \leq 0.001$, ** - $P \leq 0.01$, * - $P \leq 0.05$, ns – $P > 0.05$*

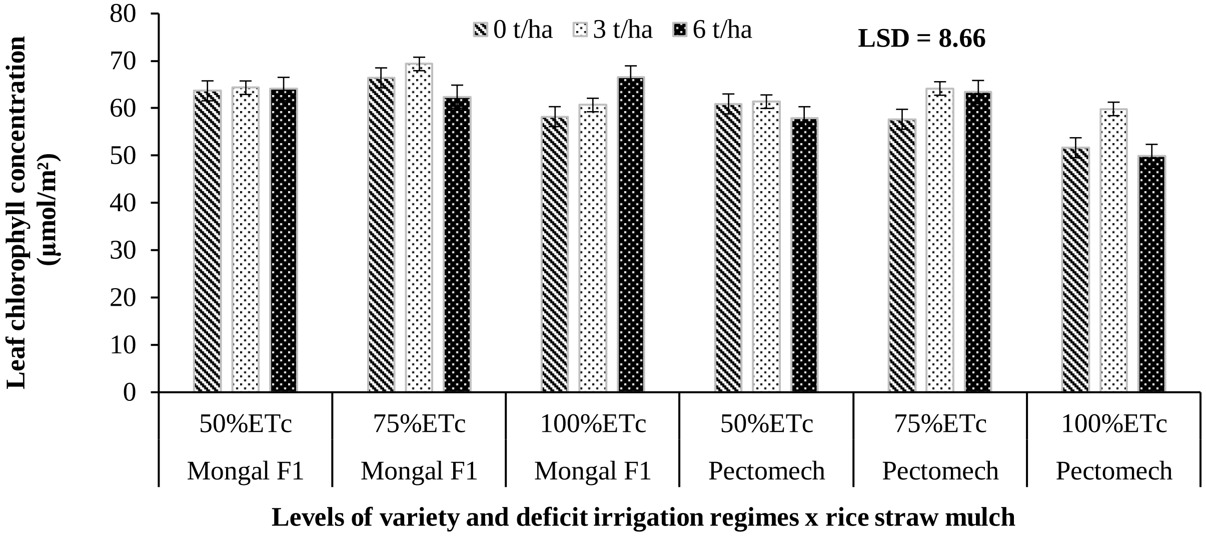

Figure 3: Interaction effect of variety, irrigation regimes and quantity of rice straw mulch (V x I x M) on mean leaf chlorophyll concentration (LCC) of tomato plants at 5 weeks after transplanting (WAT) in the first experimental season.

Bars represent standard error of means (SEM), LSD - least significant difference of means at P = 0.05

Effect of variety, deficit irrigation regimes and mulching on leaf stomatal conductance (LSC)

ANOVA showed a significant (P = 0.032) 2-way interaction effect of deficit irrigation regimes and quantity of rice straw mulch (I x M) on LSC at 7 WAT in the first season. In the second season there was a significant (P = 0.03) 3-way interaction effect of variety, deficit irrigation regimes and quantity of rice straw (V x I x M) on LSC at 2 WAT (Table 3). The first season result showed that the full irrigation regime in combination with 6 t ha^{-1} rice straw recorded the highest LSC of 74.10 mmol/m^{2}s, significantly higher than with medium or no mulch. A similar result occurred with 50% deficit irrigation, but no significant differences were found among mulch treatments with 75% deficit irrigation (Figure 4). Overall, 6 t ha^{-1} mulch gave significantly higher mean LSC values than 3 or 0 t ha^{-1} in the first season. The highest LSC of 143.7 mmol/m^{2}s in the second season was recorded by Pectomech in combination with full irrigation and 3 t ha^{-1}, significantly higher than Pectomech combined with 50% deficit irrigation and no-mulch, Mongal F1 combined with full irrigation and no-mulch, Mongal F1 combined with 75% deficit irrigation and 6 t ha^{-1} mulch, and lastly Mongal F1 combined with 75% deficit irrigation and no-mulch (Figure 5). The significant treatment interaction effect in the second season was present at 2 WAT, and plants were younger at the time with higher leaf area that contributed to the higher values of LSC recorded. On the other hand, plants were much older with curled leaves and reduced leaf area at the time (7 WAT) of measurement in the second season. Liu et al. (2005) observed a significant decrease in LSC for potatoes grown under soil water stress condition posed by an irrigation interval of 14 days compared to a reduced irrigation interval of 9 days and to fully watered plants. Pazzagli et al. (2016) found significantly lower LSC of leaves under deficit irrigation of 70% and 70% partial rootzone drying when compared to the full irrigation regime. The decline in LSC under mild to severe deficit irrigation could be attributed to closure of stomata by plants in response to soil water stress (Parkash and Singh 2020). The closure of stomata results in a retarded transpiration rate and a detrimental effect on physiological performance of plants (Pask et al. 2012). Just as important, the application of rice straw mulch provided a conducive micro-environment around the plants and conserved enough soil water due to reduction in evaporation. The availability of adequate soil water will increase transpiration as well as photosynthesis rate of plants. The no-mulch plots possibly experienced high evaporation of water from the soil which resulted in soil water stress conditions that triggered closure of stomata and led to low conductance. It is worth noting that, Mongal F1 even under severe soil water stress condition increased LSC and transpiration rate which depicted varietal tolerance and fast recovery to water stress. This variety appeared to be less sensitive to soil water stress and is well acclimatised to the local environment when compared to Pectomech (Ochar et al. 2019). Soil water stress can cause a relative increase in soil temperature and influence the performance of Pectomech because of its intolerant nature to heat (Melomey et al. 2019). For both varieties, the inclusion of rice straw mulch improved LSC which reiterates the importance of mulches in soil water conservation (Hochmuth et al. 2001; Kirnak et al. 2001).

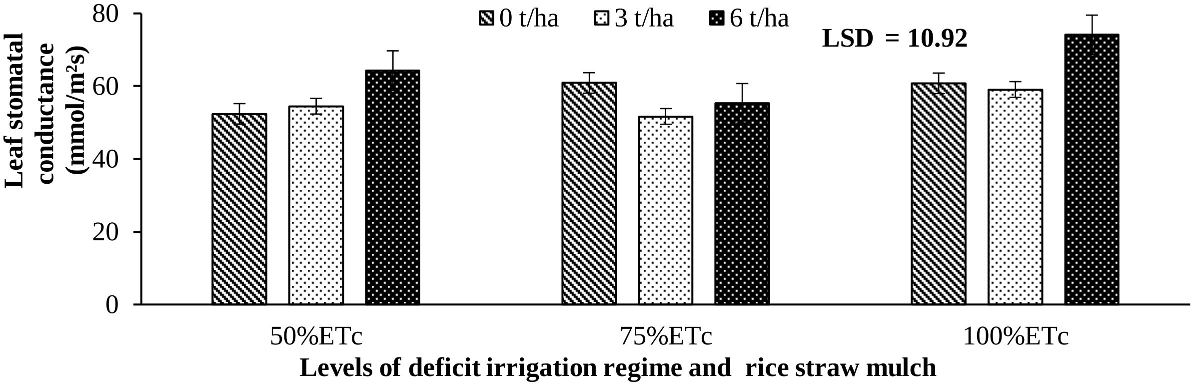

Figure 4: Interaction effect of irrigation regimes and quantity of rice straw (I x M) on leaf stomatal conductance (LSC) of tomato plants at 7 weeks after transplanting (WAT) during the first experimental season.

Bars represent standard error of means (SEM), LSD - least significant difference of means at P = 0.05

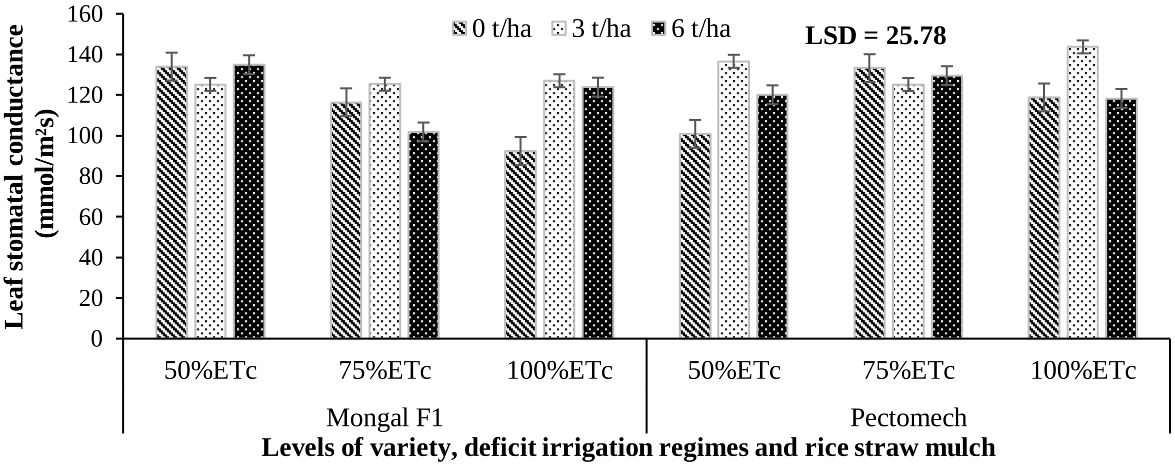

Figure 5: Interaction effect of variety, irrigation regimes and quantity of rice straw mulch (V x I x M) on leaf stomatal conductance (LSC) of tomato plants at 2 weeks after transplanting (WAT) during the second experimental season.

Bars represent standard error of means (SEM), LSD - least significant difference of means at P = 0.05

Effect of variety, deficit irrigation regimes and mulching on total fruit yield

ANOVA showed non-significant interaction effects of treatments on total fruit yield of tomatoes in the first season. In the second season the interaction of variety (V) and mulch (M) was significant. In the first season the effect of variety on fruit yield was significant at P = 0.01 and Mongal F1 was consistently higher in fruit yield over the two seasons, recording 184% more fruit yield than Pectomech in the first season and 130% more in the second season (Table 3). Mongal F1 is reportedly high yielding and tolerant to heat stress (Ochar et al. 2019). Also, the variety is well adapted to local irrigated conditions and efficient in water-use. According to Steduto et al. (2012), ambient temperatures greater than 27°C cause a decline in crop yield due to an increase in plant stresses. This condition of high temperatures was prevalent during the experiment especially at the reproductive stage of crop development. Consequently, several flowers aborted and dropped that led to poor fruit yield. However, the application of high irrigation water increased fruit yield in both seasons, but this was only significant when full irrigation produced 18.9% and 38.4% more fruit yield than the mild and severe deficit irrigation regimes respectively; however, fruit yield recorded by full irrigation was not significantly greater (P>0.05) when compared to that of mild deficit irrigation. Incorporating rice straw mulch at 6 t/ha resulted in a significant increase in fruit yield in the first season.

In the second season, Mongal F1 mulched at 6 t ha^{-1} resulted in significantly higher fruit yield than un-mulched Pectomech, representing an increase of 447% (Figure 6). Mongal F1 mulched at 3 t ha^{-1} also resulted in significantly higher fruit yield than un-mulched Pectomech. The incorporation of 6 t ha^{-1} mulch recorded overall highest mean fruit yields, followed by the 3 t ha^{-1} mulch. Fruit yield was much higher for Mongal F1 when rice straw mulch was applied. Research by Ahmad et al. (2011) on the effect of mulching using rice straw, sugarcane straw and wheat straw on chili pepper found significant gains in fruit weight for mulched plots compared with un-mulched plots. Igbadun et al. (2012), reported that mulching increased bulb yield of onion by 12 – 15% over no-mulch. Malik et al. (2018) in their studies on sugar beet in areas of limited water supply found an increase in root yield from 11.96 - 19.45% for mulched plots compared to no-mulch and an overall improvement in water productivity. Osei-Bonsu and Asibuo (2013) and Kassahun (2017) reported a significant yield increase of 100% for mulch management strategies compared to un-mulched treatment; mulched plots had higher rootzone soil moisture retention than un-mulched plots due to the lower water evaporation rates from the soil surface of mulched plots. Un-mulched plots experience soil water stress conditions that will cause closure of stomata by plants and lead to decline in transpiration and fruit yield (Liu et al. 2003; Parkash and Singh 2020).

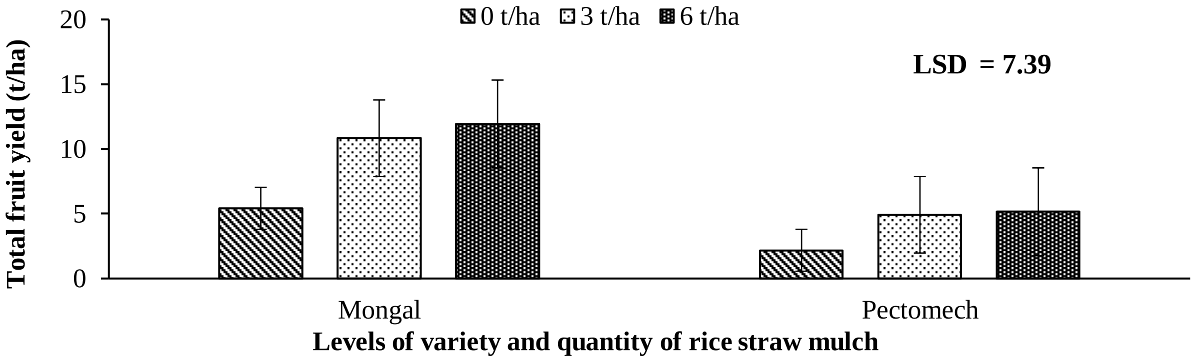

Figure 6: Interaction effect of variety and quantity of rice straw mulch (V x M) on total fruit yield of tomato in the second experimental season.

Bars represent standard error of means (SEM), LSD - least significant difference of means at P = 0.05

Effect of variety, deficit irrigation regimes and mulching on irrigation water–use efficiency (IWUE)

ANOVA showed a significant (P = 0.047) interaction effect of variety and deficit irrigation regimes (V x I) on IWUE in the first season and a significant (P = 0.02) interaction effect of variety and mulch (V x M) in the second season (Table 3).

In the first season IWUE of Mongal F1 in combination with severe deficit irrigation regime increased by 256% from that recorded by Pectomech in combination with severe deficit irrigation regime (Figure 7). Specifically, an IWUE of 3.88 kg m^{-3} was recorded by Mongal F1 in combination with severe deficit irrigation (Figure 7). In contrast, Mongal F1 in combination with mild deficit irrigation and Mongal F1 in combination with full irrigation, recorded a non-significant difference in IWUE. Mongal F1 in combination with mild deficit irrigation recorded a similar IWUE than with full irrigation, but the full irrigation resulted in 25% more water being applied to plants than the mild irrigation treatment. Mubarak and Hamdan (2018) and Ragab et al. (2019) reported a significant decrease in IWUE with the application of higher water deficits. Shammout et al. (2018) assessed deficit irrigation effect on bell pepper yield and water-use efficiency and found that full irrigation gave lower IWUE whereas the severely stressed irrigation of 60% gave higher water-use efficiency. Pazzagli et al. (2016) reported high water-use efficiency for tomatoes under moderately stressed irrigation when compared to full irrigation. According to Taromi et al. (2019), deficit irrigation regimes result in well-developed plant root systems. This enhances the uptake of water and essential plant nutrients, such as nitrogen, to improve fruit yield (Ngouajio et al. 2007). In addition, most plants, including tomatoes experiencing water stress condition recover faster when irrigation is applied. This is due to the increased uptake of water and nutrients by plants, driven by active processes of transpiration and photosynthesis (Yang et al. 2012). Despite the benefits of deficit irrigation, it must be done with caution since the soil water stress conditions posed could result in poor performance of the crop (Yuan et al. 2016; Sharma et al. 2019; Parkash and Singh 2020). The Mongal F1 variety exhibited superiority over Pectomech by producing more fruit yield per unit of water-use. Rashidi and Gholami (2008), in their literature review reported the range of Water Productivity (WP) for tomato to be between 2.58 – 11.88 kg m^{-3}. Based on these WP values, the water productivity of Pectomech in combination with deficit irrigation regime levels fell below this range (Figure 7). However, Mongal F1 in combination with deficit irrigation regime levels, produced water productivity which is well placed within the WP range. There is the need for maximising crop yield per water consumed rather than maximising yield per land area (Evans and Sadler 2008).

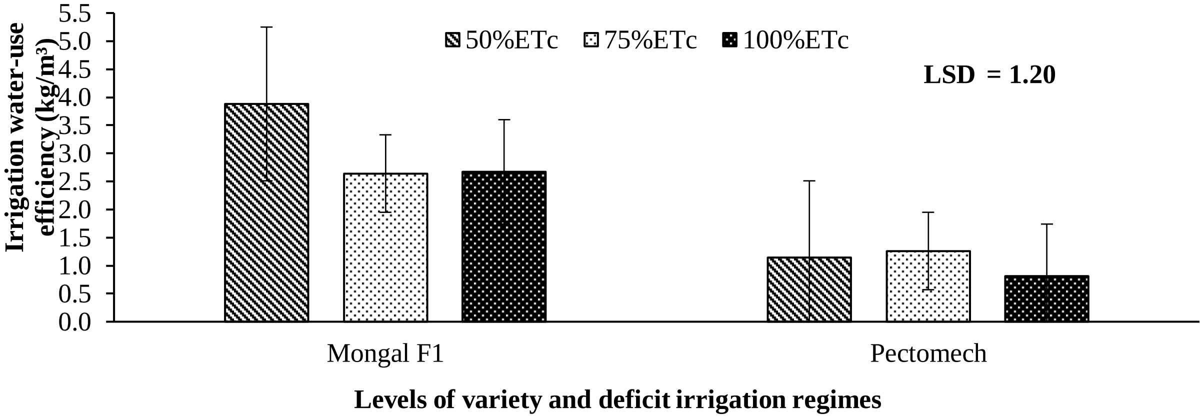

Figure 7: Interaction effect of variety and irrigation regimes on irrigation water-use efficiency (IWUE) of tomato plants in the first experimental season.

Bars represent standard error of means (SEM), LSD - least significant difference of means at P = 0.05

In the second season the IWUE for Mongal F1 was slightly lower than that recorded in the first year due to the lower fruit yield produced. The treatment interaction showed that mulched Mongal F1 treatments had higher mean IWUE than no-mulch Pectomech, but not of no-mulch Mongal F1 or mulched Pectomech (Figure 8). However, the trend is clear and mulched treatments for both varieties increased IWUE by 100 - 150% compared to no-mulch treatments, although not statistically significant. The results corroborate findings by Liang et al. (2011) who reported that IWUE was significantly influenced by mulch materials that is, wheat straw, plastic mulch and combined mulch and resulted in 97.9, 60.1 and 104% respective increases in IWUE over no-mulch. The water productivity of Mongal F1, in combination with 6 t ha^{-1} and 3 t ha^{-1} rice straw, fell within the normal Water productivity range of 2.58 - 11.88 kg m^{-3} for tomatoes as reported by Rashidi and Gholami (2008). Shen et al. (2012) found significant improvement in IWUE when straw mulch was applied to maize growing under arid conditions. The harsh weather conditions of arid and semi-arid regions call for the use of straw materials such as rice straw as protective layers for the soil to help prevent water loss through evaporation (Biswas et al. 2015). Hence, the promotion of rice straw as mulch material in the vegetable farming system of water limiting environments is key to water saving. According to Jain et al. (2000) and Kassahun (2017), the incorporation of straw mulch, with deficit drip irrigation strategies, would contribute immensely to maximising water productivity.

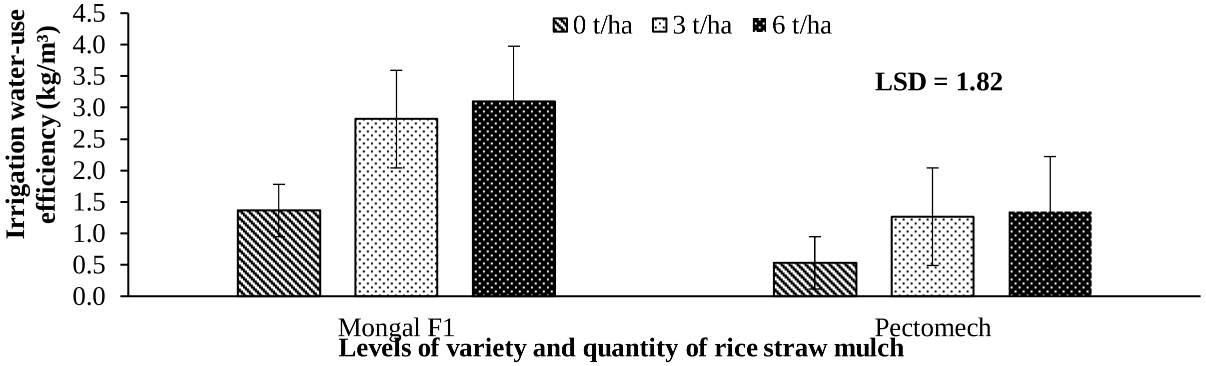

Figure 8: Interaction effect of variety and quantity of rice straw mulch on irrigation water-use efficiency (IWUE) of tomato plants in the second experimental season.
Bars represent standard error of means (SEM), LSD - least significant difference of means at P = 0.05

Conclusion

The agronomic performance exhibited by the selected tomato varieties varied in their interaction with deficit irrigation regimes and rice straw mulch levels. Generally mild deficit irrigation and rice straw improved leaf chlorophyll concentration compared to full irrigation. However, higher levels of irrigation, in combination with rice straw mulch levels, often increased leaf stomatal conductance of plants. The mild deficit irrigation regime produced total fruit yields similar to full irrigation in both seasons, so could be the best option to improve fruit yield and increase water savings in water-limiting environments. Mongal F1, in combination with rice straw mulch levels, at 6 t ha^{-1} and 3 t ha^{-1} increased total fruit yield of tomato by around 100% when compared to no-mulch treatment combinations. There was a similar but smaller effect for Pectomech. However, Pectomech yielded consistently less than Mongal F1, and this corresponded with lower IWUE. Irrigation water-use efficiency of selected varieties was improved under deficit irrigation regime levels. In addition, the inclusion of rice straw mulch at 3 t ha^{-1} and 6 t ha^{-1} improved irrigation water-use efficiency by over 100%, when compared to the no-mulch treatment. The role of regulated deficit irrigation regimes and the inclusion of rice straw as surface mulch is crucial to improving the soil environment as well as the physiological performance of tomato plants, aimed at maximizing water and crop productivity under water limiting environments.

Data availability

The corresponding author will provide available data supporting the findings of this study upon request.

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Conflict of interest

No conflict of interest exists.

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