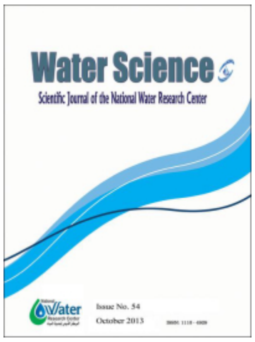

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Improving mango production using partial root drying technique and organic fertilisation: Field and modeling study

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ABSTRACT

The decreasing in water availability due to climate change can affect agricultural production. The water shortage problem led to the development of several water saving techniques. One of the waters saving techniques in irrigation is the partial root-zone drying (PRD) method. Tow field experiments accompanied by a modeling study were carried out during seasons 2020/2021 and 2021/2022, respectively, using four deficit irrigation strategies [FI (100% of full irrigation), DI1 (0.75FI), DI2 (0.5FI) where water was supplied to both sides of the mango trees and DI3 (Partial Root-zone Drying, PRD = 0.5FI) where water was supplied to a single side of each tree in an alternating manner)]. The four irrigation methods were designated as the study's major plots. Then, for the purpose of adding compost, each main plot was divided into four smaller plots [NC (No-Compost), C12 (12 ton ha^{-1}), C18 (18 ton ha^{-1}) and C24 (24 ton ha^{-1})] to investigate the effects of such treatments on increasing water productivity, yield, and the quality of mango fruits. The results indicated that adding compost with PRD irrigation method decreased water stress throughout the root zone and increased the yield, water productivity and fruit quality. Compost addition C24 (24 ton ha^{-1}) with PRD irrigation increased the amount of soil organic matter and microorganism activity when compared to other treatments. Additionally, C24 treatment improved mango quality under both FI and PRD treatments, the PRD technique enhanced fruit yields by 3.8% and 7.3% and water productivity by 51.6% and 53.8% for 2021 and 2022 seasons, respectively, compared to FI, while reducing the applied irrigation water by 50% for each season. In comparison to other irrigation strategies, the PRD strategy had shown superior outcomes in enhancing the yield, water productivity, and quality of mango yield. With the use of compost "C24" as organic matter fertilizer, PRD proved to be an effective dual technique to save water and increase productivity. Under both current and future water scarcity caused by climate change, it could be a successful adaptation technique. The SALTMED model produced accurate simulations of the soil moisture content, mango production, and water productivity during the two seasons.

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Introduction

Food production globally needs to increase by almost 70% by 2050 in order to feed and fulfill the demands of the 9.1 billion people (FAO Food and Agriculture Organization, 2009). One of the key climatic elements that can reduce agricultural output is drought. Therefore, for the most effective use of irrigation water, the development and adoption of new irrigation strategies are required to cope with situations of water scarcity brought on by existing and future climate change (Abdelraouf & Abuarab, 2012; Hozayn, Abd El-Wahed, Abd El-Monem, Abdelraouf, & Ebtihal, 2016).

The partial root drying irrigation technique (PRD) divides a crop's root zone into two sides. In general, the procedure includes irrigating the vertical half of a crop's root system while leaving the other half to dry. The dry side of the root system is irrigated in the subsequent irrigation, while the previously watered side is left to dry (Adu, Yawson, Armah, Asare, & Frimpong, 2018). Through osmotic adjustment, deficit irrigation (DI) techniques like PRD also improve drought tolerance. Some investigations indicated that PRD has outperformed DI. Crop productivity and drought tolerance have both been proven to increase with the production of antioxidants and osmotic adjustment during PRD (Raza et al., 2017). Water-saving irrigation techniques like DI and PRD reduce agricultural irrigation needs without significantly reducing productivity (Abdelraouf & Ragab, 2018). The process of wetting and drying in PRD results in a partial closure of the stomata, which reduces water losses by transpiration while allowing sufficient CO_2 flow for photosynthesis and growth (Iqbal et al., 2020).

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In recent years, PRD irrigation has been experimented using several agricultural crops all around the world, these studies showed that in PRD, compared to full irrigation (FI), irrigation water use would be reduced by around 30–50% without significantly reducing the yield. However, there have only been a few studies looking at how PRD affects mango (Spreer et al., 2007; Spreer, Müller, Hegele, & Ongprasert, 2009). PRD technique is a type of deficit irrigation that has been applied and used with many fruit trees (Jovanovic & Stikic, 2018). In the PRD approach, certain roots are exposed to dry circumstances, while others receive adequate irrigation, then an exchange of both parts occurs with each irrigation process. As a result of this alternation, biochemical responses and signals occur, resulting in an equilibrium between reproductive and vegetative development (Sepaskhah & Ahmadi, 2010). Water stress on the dry side of the root system leads to the release of abscisic acid (ABA) signals, which in turn regulate the opening and closing of stomata of leaves, reducing transpiration losses and allowing sufficient CO_2 for photosynthesis. Satienperakul, Manochai, Ongprasert, Spreer, and Müller (2009), found that PRD technology has high potential to produce high quality and exportable mango fruits.

There are a lot of organic matters and nutrients such as nitrogen and phosphorus in animal manure. Several studies have confirmed that the addition of compost increases and enhances the microbial activities of the soil, which improve crop growth (Zhen et al., 2014). Organic fertilizers have been comprehensively tested and shown to be effective in increasing nutrient availability to crops, thereby improving grain yield in a cost-effective and environmentally friendly manner (Leite, Oliveira, Araújo, Galvão, & Lemos, 2010). Organic fertilization also increases levels of organic matter and improves soil porosity, stability and structure. Moisture as well as nutrients increase the number and biological activity of microorganisms (Wang, Niu, Zhou, & Wang, 2011). Intense microbial activity that results from employing compost accelerates the breakdown and humification of organic waste (Nikaeen, Nafez, Bina, Nabavi, & Hassanzadeh, 2015). Additionally, harmful organic components are broken down, producing stabilized and sterilized compost (Poluszyńska, Jarosz-Krzemińska, & Helios-Rybicka, 2017).

Mangoes are the fifth most widely grown and cultivated fruit in the world (Normand, Lauri, & Legave, 2015). It is widely eaten and consumed in the form of fresh fruit or other processed forms, and its importance is due to the content of its bioactive compounds such as polyphenols, enzymes, carotenoids, vitamins E and C, cellulose, fiber, hemicellulose, protein, fats, enzymes and pectin (Jahurul et al., 2015). Mango is a fruit that is well-liked all around the world because of its distinctive flavor, and nutritious values. Mangoes are commercially grown in over 90 countries and are produced at a rate of over 28.5 Mt annually. 77% of the global mangoes are produced in Asia, 13% in America, and 9% in Africa (FAO, 2022).

Models are excellent tools for managing irrigation water in agriculture. They could be useful in estimating agricultural water needs, scheduling irrigation, forecasting yields, and detecting soil salinization. A complete model that can be used to various irrigation systems, soil types, crops, and tree species is the SALTMED model as well as various water application methods and water qualities. The model has a number of sub-models (Ragab et al., 2015) such as water and solute flow, crop growth dependent on temperature/degree days, crop rotations, nitrogen dynamics, soil temperature, dry matter, and yield, subsurface irrigation, deficit irrigation, including partial root drying (PRD), evapotranspiration (ET) using Penman-Monteith equation. The current version allows for the simultaneous operation of up to 20 fields or treatments (Ragab, Choukr-Allah, Nghira, & Hirich, 2016).

However, few researchers have looked at combining the PRD irrigation technology with compost application. Therefore, this research will focus on the combined impacts of PRD with compost application for mango production in order to support farmers and agricultural stakeholders with the knowledge they need for the optimal management strategies to enhance mango water use efficiency. The purpose of this study is to ascertain, by field work and modeling using the SALTMED model, the effects of PRD and compost application on mango production, water productivity, and quality in arid environments.

Materials and methods

Location and climate of experimental site

Mango trees were the subject of field tests on sandy soil in the Al-Nubariya Region of Al Buhayra Governorate, Egypt (latitude 30° 30’ 1.4”‘N, longitude 30° 19’ 10.9”‘E, and mean altitude above sea level 21 m), as shown in Figure 1. Figure 2 depicts the neighborhood weather station at El-Nubaria Farm.

Physical and chemical properties of soil, irrigation water and compost

The irrigation water source was a canal that was close to the experimental region and had an electrical conductivity (EC) of 0.45 dS m^{-1} and an average

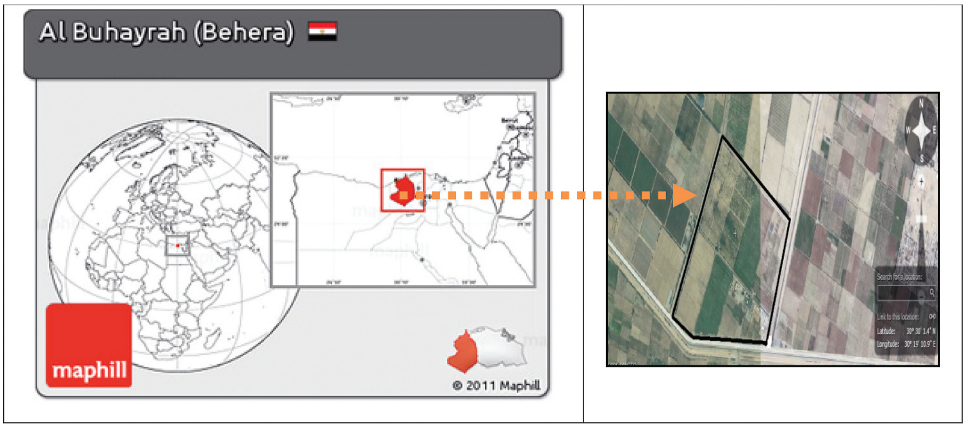

Figure 1. Location of the study site, al-Nubariya region, Egypt.

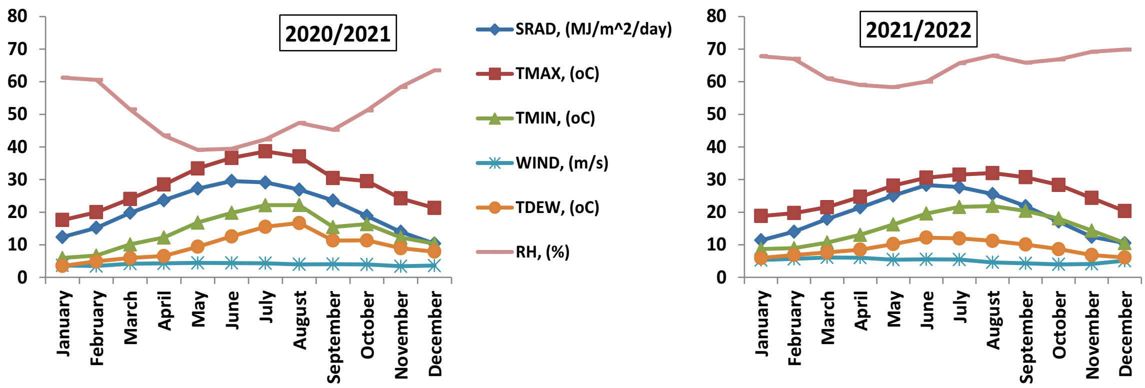

Figure 2. Climate data for the study site. SRAD: Solar Radiation, TMAX: Maximum Air Temperature, TMIN: Minimum Air Temperature, WIND: Wind Speed, TDEW: Dew/Frost Point Temperature, RH: Average Relative Humidity.

Table 1. The soil's physical and chemical properties for the testing area.

	Soil depth (cm)		
Soil properties	0–30	30–60	60–90
Texture	Sandy	Sandy	Sandy
Course sand (%)	46.47	45.25	44.94
Fine sand (%)	40.48	49.63	51.59
Silt (%)	7.05	3.02	2.04
Clay (%)	6.00	2.10	1.43
Bulk density (g cm^{-3})	1.67	1.66	1.65
Organic matter (%)	1.1	0.90	0.72
EC (dS m^{-1})	0.65	0.58	0.55
pH (1:2.5)	7.7	7.6	7.4
Total $CaCO_3$ (%)	4.8	4.28	4.31

Table 2. Chemical analysis of organic fertilizer.

Item		Compost, 2020/2021	Compost, 2021/2022
pH		5.87	5.91
EC (dS m^{-1})		0.75	0.64
Anions (mg./l)	HCO_3^-&CO_3^{2-}	1.36	1.25
	Cl^-	3.52	3.37
	SO_4^{2-}	2.88	2.86
Cation (mg./l)	Ca^{++}	2.12	1.96
	K^+	2.23	2.15
	Mg^{++}	1.06	1.14
	Na^+	2.35	2.23
Organic Matter (%)		25.8	28.7
Moisture Content (%)		20	20
Nitrogen (%)		0.90	0.93
Compost C/N ratio		20:1	19:1
Phosphorus (%)		0.18	0.19
Potassium (%)		0.54	0.57

C/N ratio (compost's carbon-to-nitrogen ratio).

pH of 7.4. The main physical and chemical characteristics of the soil at the beginning of the experiment are listed in Table 1. The data in Table 2 indicate the chemical analysis of organic fertilizer. The compost was made from crop residues and animal waste in a ratio of 1:1.

Irrigation system description

The main line was a PVC pipe, 110 mm in diameter, and the manifold lines with a diameter of 63 mm, these were connected to the laterals through a 2” control valve. A 16 mm diameter by 50 m long emitter with an 8 liter per hour discharge rate was installed into the laterals and operated at 1.0 bar operating pressure. The PRD irrigation there were two lateral lines and each line is 40 cm away from the mango tree trunk and not between the two drip lines. A second option was to operate one of the two lines (each with three drippers per tree) in alternation with the other line to irrigate every 4 days.

Experimental design

The experimental layout was arranged in a split-plot design using three replicates. Four deficit irrigation strategies [FI (100% of full irrigation), DI1(0.75FI), DI2 (0.5FI) were supplied to both sides of the tree and DI3 (PRD = 0.5FI) was partial root-zone drying irrigation technique (PRD) which divides a crop's root zone into two sides. In general, the procedure includes irrigating the vertical half of a crop's root system while leaving the other half to dry. In the following irrigation, the dry side of the root system is watered, while the previously watered side is allowed to dry (Adu, Yawson, Armah, Asare, & Frimpong, 2018)] were assigned as main plots. Then, each main plot was divided into sub main plots, each of which received one of four compost treatments (NC, or No Compost), C12, C18, or C24). The means of these two trees were used for statistical analysis after each treatment was reproduced three times with two trees per replicate.

Irrigation requirements for mango

Equation (1) was used for calculating daily irrigation water, and the seasonal irrigation water was 9850 and 9810 m^3/ha/season for 100% full irrigation "FI" during seasons 2020/2021 and 2021/2022, respectively, using drip irrigation system. Because the rainfall amount was insignificant, it was not included in the calculation across the two seasons. FI received 100% of the irrigation volume required demand for the irrigation period.

$$FI = \left[\frac{ETo\ x\ Kc\ x\ Kr}{Ei}\right] - R + LR \qquad (1)$$

Where ETo is the reference evapotranspiration (mm/day) and FI is the full irrigation demand (mm/day) using the Penman – Monteith equation; According to Durán, Rodríguez, Gálvez, Gutiérrez, and García-Tejero (2019), the crop coefficient (Kc) averaged 0.43, 0.67, and 0.63; Kr is the ground cover reduction factor, and its values are calculated using the Keller equation: Kr = GC% + 0. 15 (1 - GC%), where GC (ground cover); Ei (Irrigation efficiency, %) assumed to be 90%; R (Water received by the plant from rainfall, mm); LR (Water required for leaching salts). Irrigation frequency was for every 4 days. The irrigation requirements of mango were shown as in Table 3.

Mango trees

All experimental plots were treated by the recommended mango growing N-P-K fertilizers requirements as recommended by the instructions of the Ministry of Agriculture of Egypt (Bulletin No. 857, 2004). The study was carried out using 15-year-old mango trees (*Mangifera indica L.* cv. "zibdia" grafted onto "sukari") and spaced at 3 × 5 m, with an average of 600 trees per ha. All fieldwork was completed per local recommendations using the same fertilization (240 kg N, 71 kg P_2O_5, and 212 kg K_2O) and standard cultivation methods for disease and pest management (Bulletin, No., 857, 2004).

Soil moisture distribution

Soil moisture distribution was determined by measuring soil moisture content by profile probe device at maximum water availability (2 h after irrigation) and at different locations at 0–10, 10–20 and 20–30 cm on the horizontal direction (X- direction) and at depth of 0–30, 30–60 and 60–90 cm on the vertical direction (Y- direction). By using Surfer 13 Golden software program, the contouring maps can be obtained as shown in Figure 3.

Table 3. Irrigation requirements of mango.

	2020/2021				2021/2022			
	Init. stage	Dev. stage	Mid. stage	late stage	Init. stage	Dev. stage	Mid. stage	late stage
ET_O, mm/day (from weather station)	4.90	2.63	5.50	5.23	4.88	2.61	5.47	5.22
Kc (Durán, Rodríguez, Gálvez, Gutiérrez, & García-Tejero, 2019)	0.43	0.55	0.67	0.65	0.43	0.55	0.67	0.65
Kr: Kr = GC% + 0. 15 (1 - GC%)	0.62	0.79	1	0.94	0.60	0.80	1	0.93
Ei,% (assumed)	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
R, mm/day	0.10	0.68	0.20	0	0.12	0.71	0.24	0
LR,(5%), mm/day	0.07	0.03	0.19	0.18	0.08	0.04	0.19	0.17
IRg, mm/day	1.42	0.62	4.08	3.73	1.36	0.75	4.02	3.68
Days of each age stage (FAO 56)	60	90	120	95	60	90	120	95
FI, mm/stage	85.2	55.7	489.6	354.4	81.6	67.5	482.4	349.6
FI, mm/season	985				981			
FI, m^3/ha^{-1}/season	9850				9810			
DI1, m^3/ha^{-1}/season, (0.75FI)	7388				7358			
DI2, m^3/ha^{-1}/season, (0.5FI)	4925				4905			
DI3, m^3/ha^{-1}/season, (PRD = 0.5FI)	4925				4905			

ETo: reference evapotranspiration, Kc: crop coefficient, Ei: irrigation efficiency, R: Rainfall, LR: the ratio of irrigation water salinity to drainage water salinity, FI: Full Irrigation, DI: Deficit irrigation, PRD: partial root-zone drying.

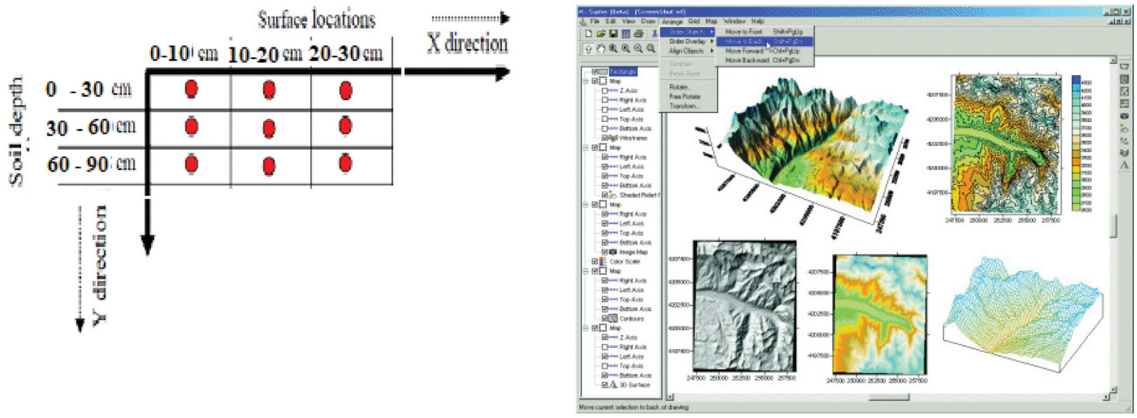

Figure 3. Contouring maps of moisture levels obtained by SURFER software.

Root-zone water stress

The average moisture content before and after irrigation was measured for each treatment. The difference between the current soil moisture and the wilting point (W.P.) is used to assess the amount of water stress in the root zone. Field capacity (F.C.) soil moisture content was 15%, while water potential (W.P.) was 4%.

Soil organic matter content

Measuring soil organic matter content in the root zone in response to the compost under deficit irrigation strategies was investigated as an indicator of nutritional status. Samples were taken from the soil at the beginning of the season and every month until the end of the season.

Mango yield

Fruit yield was estimated when a certain number of fruits from each tree in each treatment were gathered, weighed, and harvested as kg per tree then converted to ton ha^{-1}.

Mango water productivity "WP_{mango}"

WP_{mango} was determined Using Equation (2), James (1988) states the following

$$WP_{mango} = \frac{Ey}{Ir} \tag{2}$$

WP_{mango} is the mango's water production (kg_{mango}/$m^3{}_{water}$); The fruit yield is Ey (kg/ha). Ir stands for irrigation water volume ($m^3{}_{water}$/ha/season).

The SALTMED model

The International Commission on Irrigation and Drainage website, located at https://icid-ciid.org/inner_page/41, offers the SALTMED model for free download. (FI) + (NC) for season 2020/2021 was chosen for calibration. The hydraulic characteristics of sandy soils, for example, were changed until a very close match was made between the observed and simulated values. The farmed crop's properties were also changed, as indicated in Table 4. The coefficient of determination (R^2), root mean square error (RMSE), and coefficient of variation (CV) were used to assess the model's goodness of fit as a performance indicator and the coefficient of residual mass (CRM) and by Equations (3), (4), and (5), respectively (Abdelraouf, El-Sayed, Alaraidh, Alsahli, & El-Zaidy, 2020; Ragab et al., 2015).

$$RMSE = \sqrt{\frac{\sum (y_o - y_s)^2}{N}} \tag{3}$$

Table 4. The input parameters of mango for SALTMED model calibrating using FI and NC treatments during the 2020/2021 season.

Parameter	Growth Stage	Mango
Number of days to harvest		320
Growth stages of mango fruit	Initial	60
	Development	90
	Middle	120
	Late	95
Crop coefficient "Kc" Kc (Durán, Rodríguez, Gálvez, Gutiérrez, & García-Tejero, 2019)	Initial	0.43
	Middle	0.67
	End	0.63
Leaf area index "LAI"	Initial	1.16
	Middle	3.54
	End	4.47
Minimal root depth, m		0.40
Maximal root depth, m		0.90
Un-stressed crop yield, ton ha^{-1}		7.8
Water uptake threshold, %	Initial	0.85
	Middle	0.67
	End	0.58
Field capacity, m^3 m^{-3}		0.15
Saturated soil moisture content, m^3 m^{-3}		0.26
Wilting point, m^3 m^{-3}		0.04
Root width factor		0.35
Residual water content, m^3 m^{-3}		0.00
Lambda pore size distribution index		0.22
Bubbling pressure (soil air entry value), cm		10.14
Maximum depth for evaporation, mm		52

Where, y_o is the observed value; y_s is the simulated value; and N is the total number of observations.

$$R^2 = \left\{ \frac{1}{N} \frac{\sum \left(y_o - y_o^-\right)\left(y_s - y_s^-\right)}{\sigma y_o - \sigma y_s} \right\} \tag{4}$$

Where: y_o^- = averaged observed value, y_s^- = averaged simulated value, σy_o = observed data standard deviation, σy_s = simulated data standard deviation.

$$CRM = \frac{\left(\sum y_o - \sum y_s\right)}{\sum y_o} \tag{5}$$

The RMSE, CRM, and R^2 values should be equal to 0.0, 0.0, and 1.0, respectively, for complete agreement between the observed and simulated data.

Mango fruit quality

In order to measure some of the quality parameters of mango fruits, such as the total soluble solids, T.S.S., using a Carl Zeiss hand refractometer according to Singh (1988), the total acidity of fruit juice estimated as g citric acid/100 ml juice, and Vitamin C (mg/100 ml juice), determined according to A.O.A.C (1990), representative samples of mango were randomly selected from each treatment.

Statistical analysis

According to Snedecor and Cochran (1980), all the data collected over the course of the two research seasons

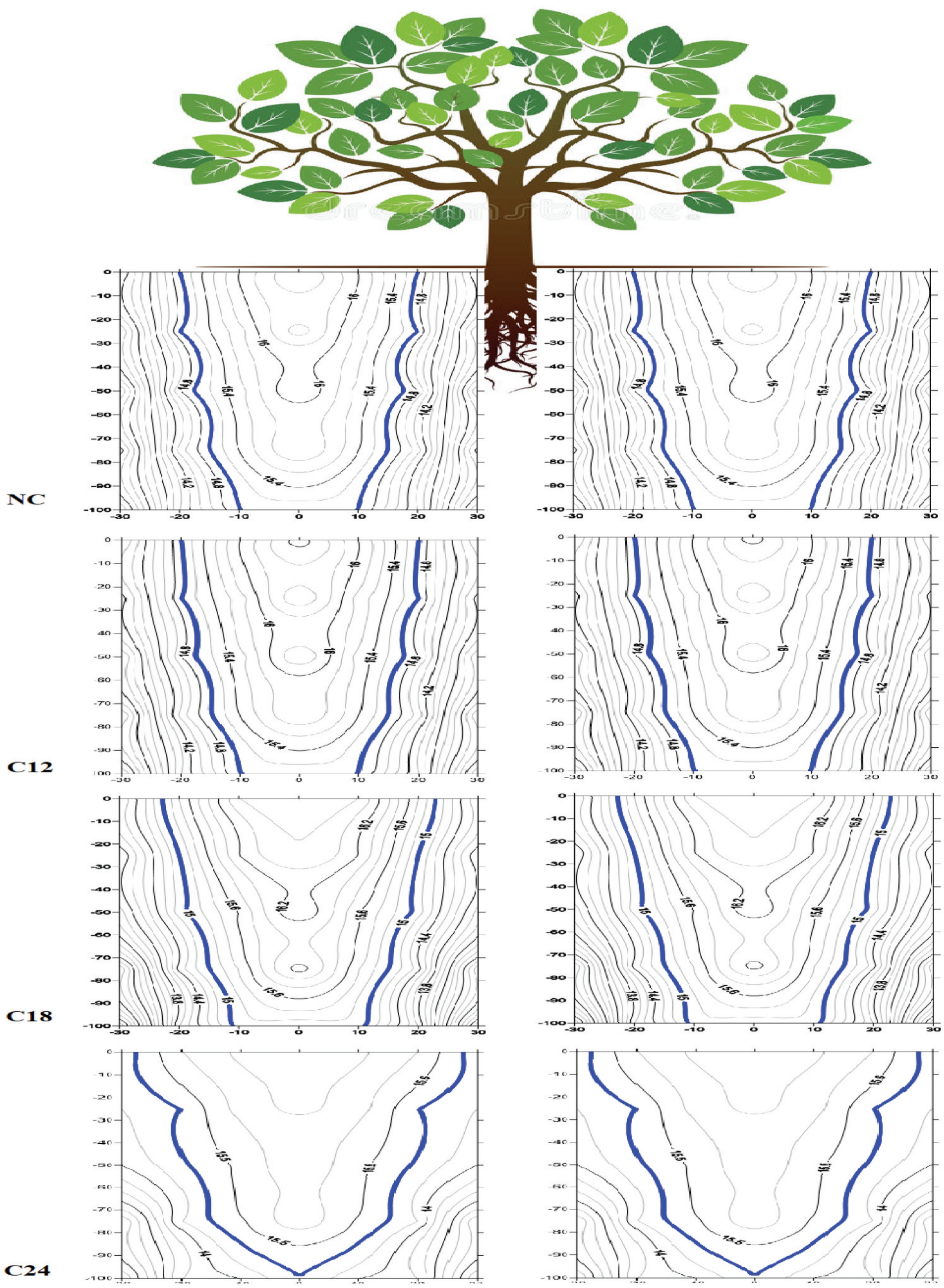

Figure 4. Effect of compost addition rate [NC (no-compost), C12 (12 ton ha-1), C18 (18 ton ha-1) and C24 (24 ton ha-1)] on soil moisture distribution within the root zone (90 cm in depth & 60 cm in diameter) under FI (100% Full irrigation) during season 2020/2021 (Blue line represents the soil moisture at field capacity), (Soil moisture distribution is uniform on both sides of the roots of mango trees).

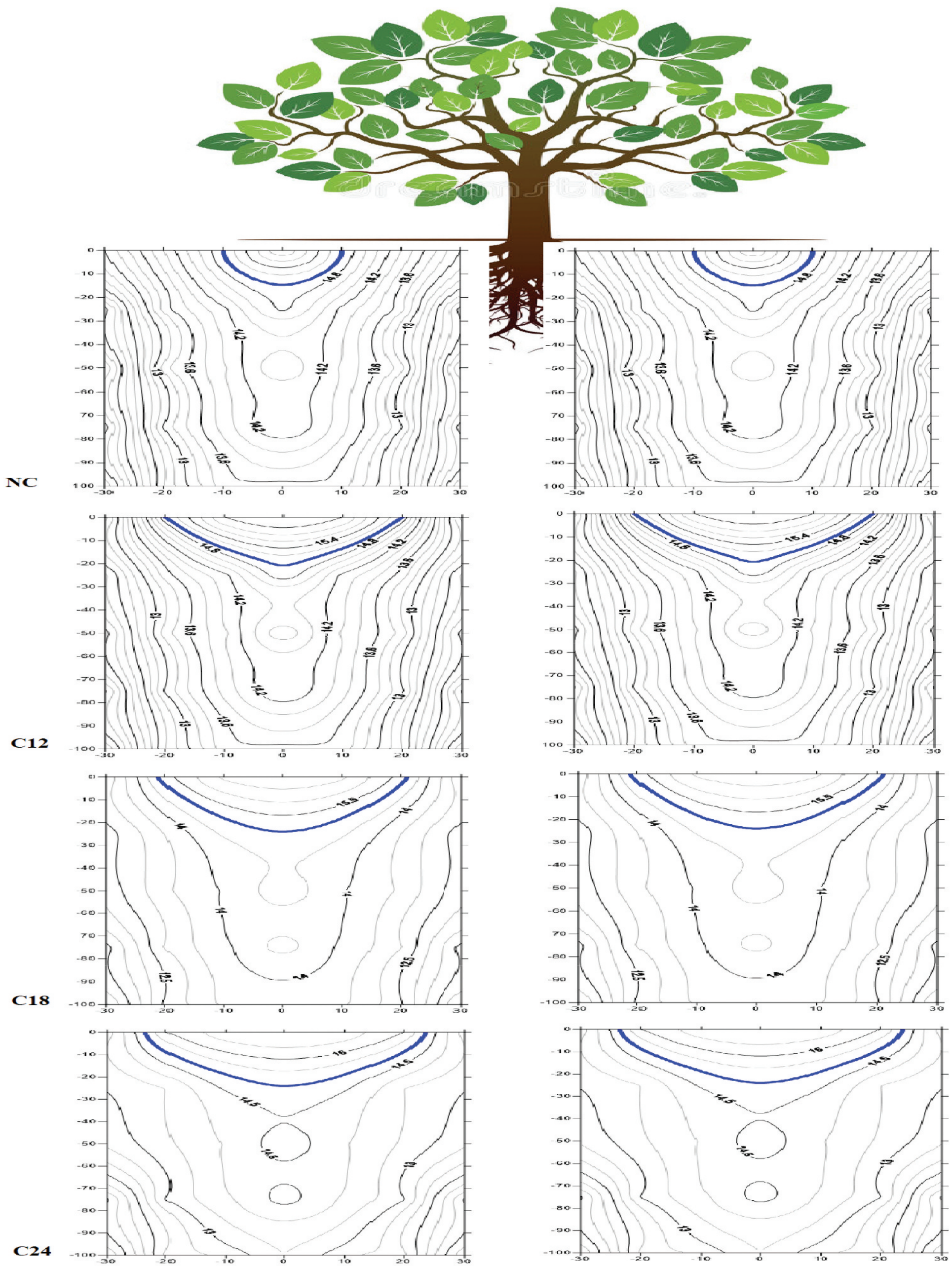

Figure 5. Effect of compost addition rate [NC (no-compost), C12 (12 ton ha^{-1}), C18 (18 ton ha^{-1}) and C24 (24 ton ha^{-1})] on soil moisture distribution within the root zone (90 cm in depth & 60 cm in diameter) under FI (100% Full irrigation) during season 2020/2021 (Blue line represents the soil moisture at field capacity), (Soil moisture distribution is uniform on both sides of the roots of mango trees).

were statistically analyzed using the analysis of variance (ANOVA) procedure with a split plot design and three replications. Using least significant differences (LSD) tests to compare treatment means of the measured parameters, differences were deemed significantly at p 0.05.

Results and discussion

Soil moisture distribution

The impact of deficit irrigation methods on the distribution of soil moisture content inside the root zone is depicted in Figures 4–6. When the amount of irrigation water delivered is reduced, the values of soil moisture content “SMC” also fall, however in the scenario depicted in Figure 7, the values of SMC were high on one side of the tree, similar to the case of irrigation with 100% FI, while low on the other side of the tree, similar to the case of irrigation by 50% FI (Irrigation on for one of the drip lines and irrigation off with the other drip line alternately).

Figure 4 shows that, by increasing the rate of compost addition when irrigating by 100% FI, the most soil moisture-containing area increased, subsequently the roots were only subjected to a minimum water stress. When the maximum rate of (24 ton ha^{-1}) compost applied compared to the control treatment (NC), there was a significant increase in the moisture within the root

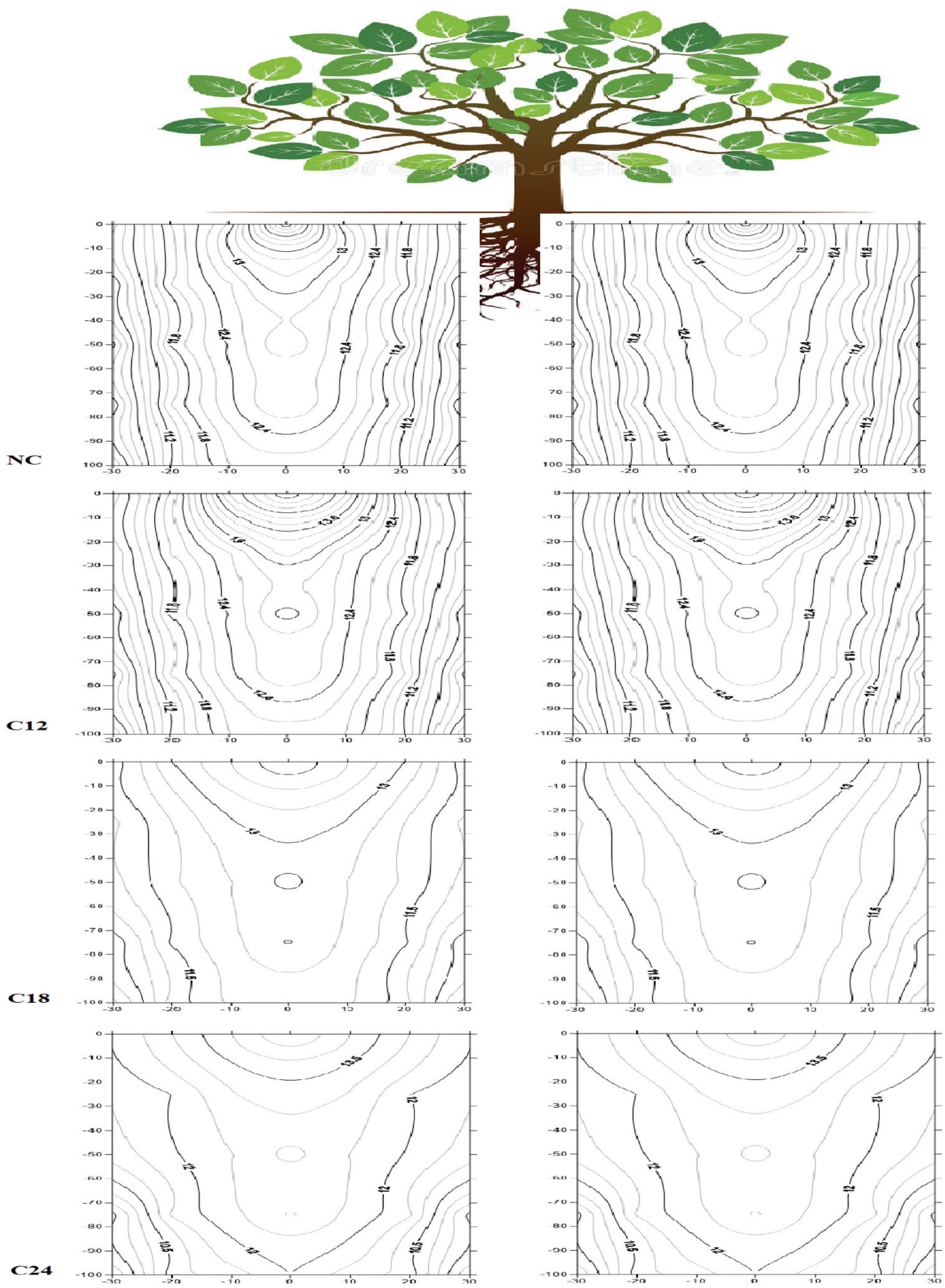

Figure 6. Effect of compost addition rate [NC (no-compost), C12 (12 ton ha-1), C18 (18 ton ha-1) and C24 (24 ton ha-1)] on soil moisture distribution within the root zone (90 cm in depth & 60 cm in diameter) under deficit irrigation (DI2 = 0.5 Full irrigation) during season 2020/2021 (No blue line appears here as the moisture content did not reach the moisture content at the field capacity due to the high water stress in the root zone), (Soil moisture distribution is uniform on both sides of the roots of mango trees).

zone. In (DI1 = 0.75 FI), the size of the area with the highest SMC was increased, but to a lower amount than with full irrigation, as shown in Figure 5. Increasing the rate of compost application resulted in increasing SMC and reducing the water stress in the root zone. This result was also noticed in the (DI2 = 0. 5 FI), although the condition was relatively more water stressful, Figure 6.

Figure 7 also demonstrated the extent to which increasing the compost addition rates increased SMC when DI3 (PRD) strategy was used, with higher water stress on one side of the roots of mango trees while no water stress on the other.

The root-zone water stress

The data of irrigation at 100% FI and NC during the 2020/2021 treatment was considered for SALTMED calibration. Figures 8–10 showed the extent of the significant and accurate correlation between the actual observed values of SMC and the simulated values before or after the irrigation application, using the SALTMED model.

The water stress "WS" is considered here as a deviation from the soil moisture capacity of the root zone. The results shown in Figure 11 and Table 5 demonstrate the significant impact of

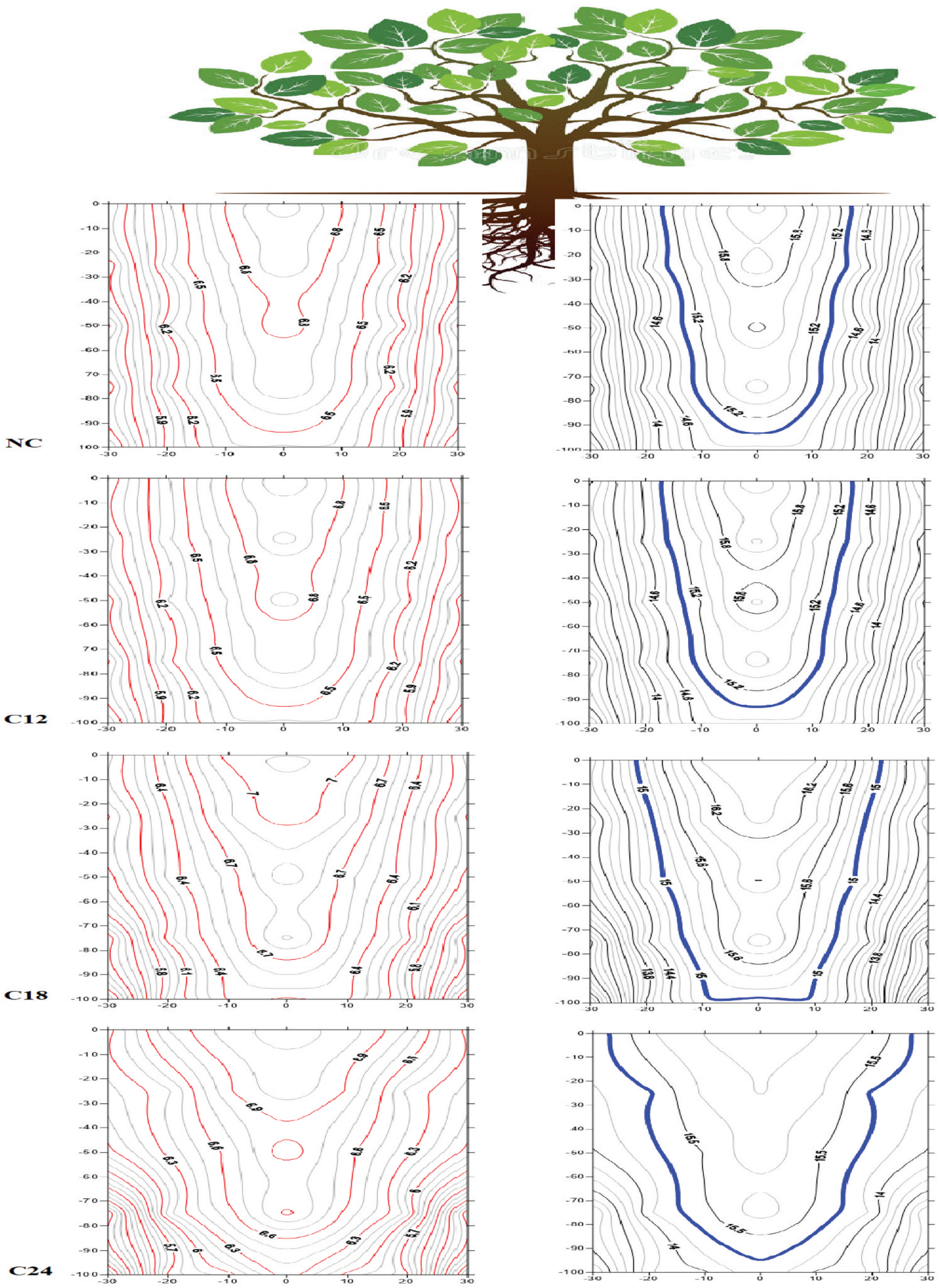

Figure 7. Effect of compost addition rate [NC (no-compost), C12 (12 ton ha-^{1}), C18 (18 ton ha-^{1}) and C24 (24 ton ha-^{1})] on soil moisture distribution within the root zone (90 cm in depth & 60 cm in diameter) under deficit irrigation (DI3= PRD= 0.5 Full irrigation) during season 2020/2021(Blue line represents the soil moisture at field capacity while the red lines indicate an increase in the water stress of the non-irrigated part, i.e. approaching the soil moisture of the wilting point), (Soil moisture distribution is not uniform on both sides of the roots of mango trees).

irrigation deficiency strategies and the rate of compost addition on the WS of the root zone of mango tree as well as the precision of the simulation of the results achieved using the SALTMED simulation model. The results shown in Figure 11 indicate how much the reduced irrigation increased the WS in the root zone (the status of the SMC before and after irrigation). However, the situation was different under PRD irrigation. During PRD irrigation, the irrigated side of the tree experiences no WS while the dry side of the tree experiences WS. This situation alternates between the two sides in the following irrigation.

Figure 11 demonstrates the beneficial impact of increasing the application rate of organic compost materials on decreasing the WS in the root zone. It was noticed that by increasing the amount of compost materials, moisture content values increased, thus, reducing the amount of moisture stress of the root zone. The capacity of organic compost materials to retain irrigation water within the root zone of such sandy soil led to

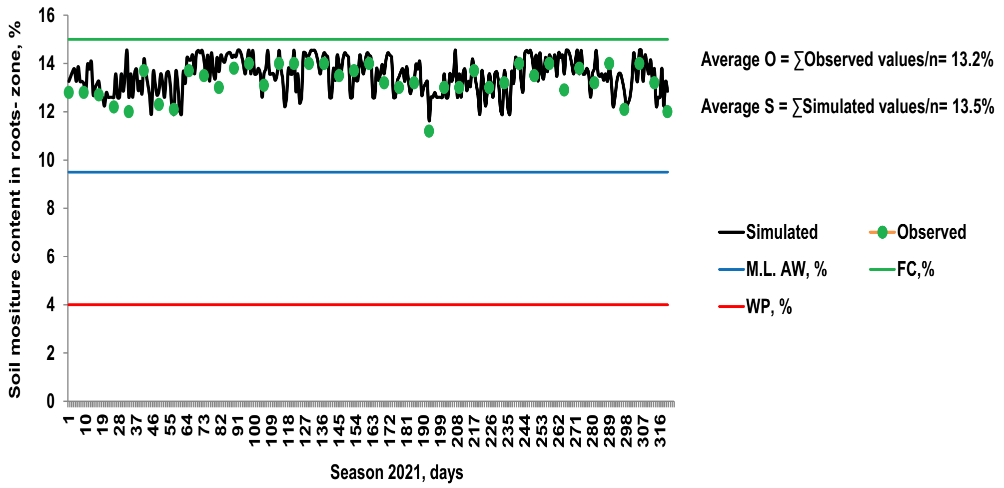

Figure 8. SALTMED calibration using (100%FI and NC during 2020/2021) treatment data (after irrigation).

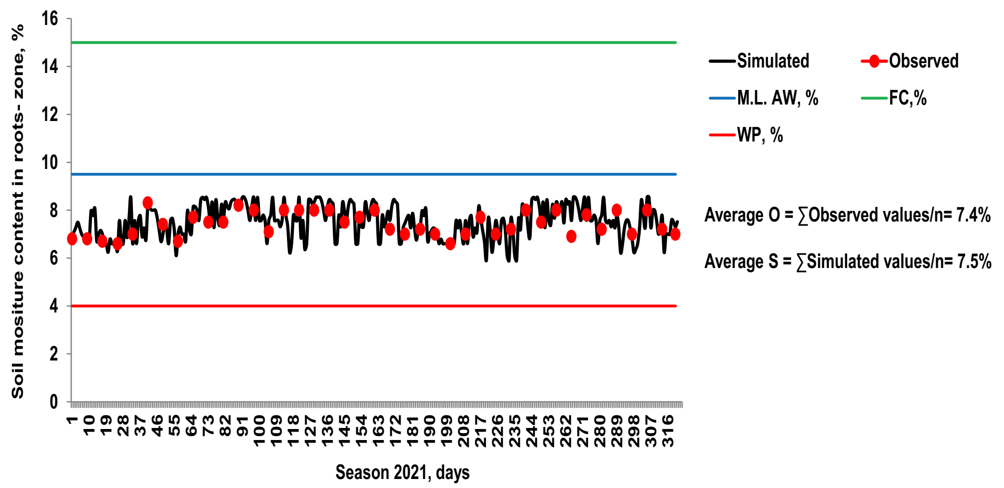

Figure 9. SALTMED calibration using (100%FI and NC during 2020/2021) treatment data (before irrigation).

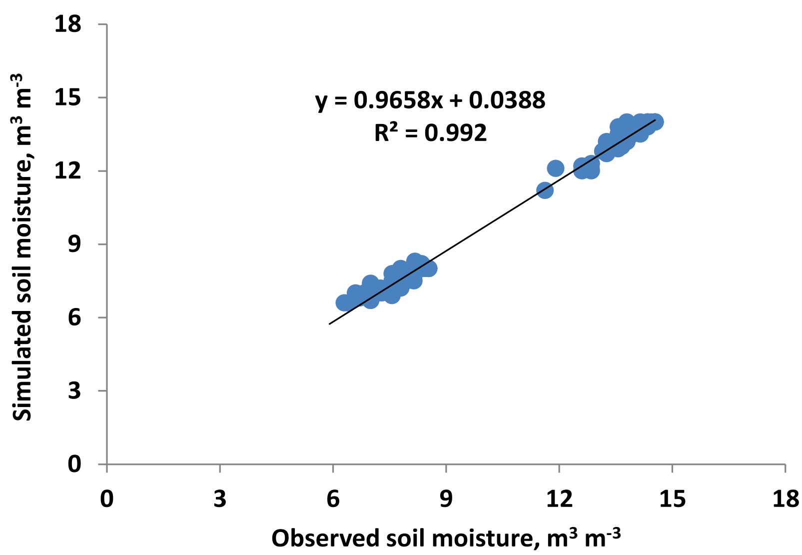

Figure 10. Observed versus SALTMED model simulated values (calibration) of the soil moisture content after and before irrigation for (100%FI and NC during 2021).

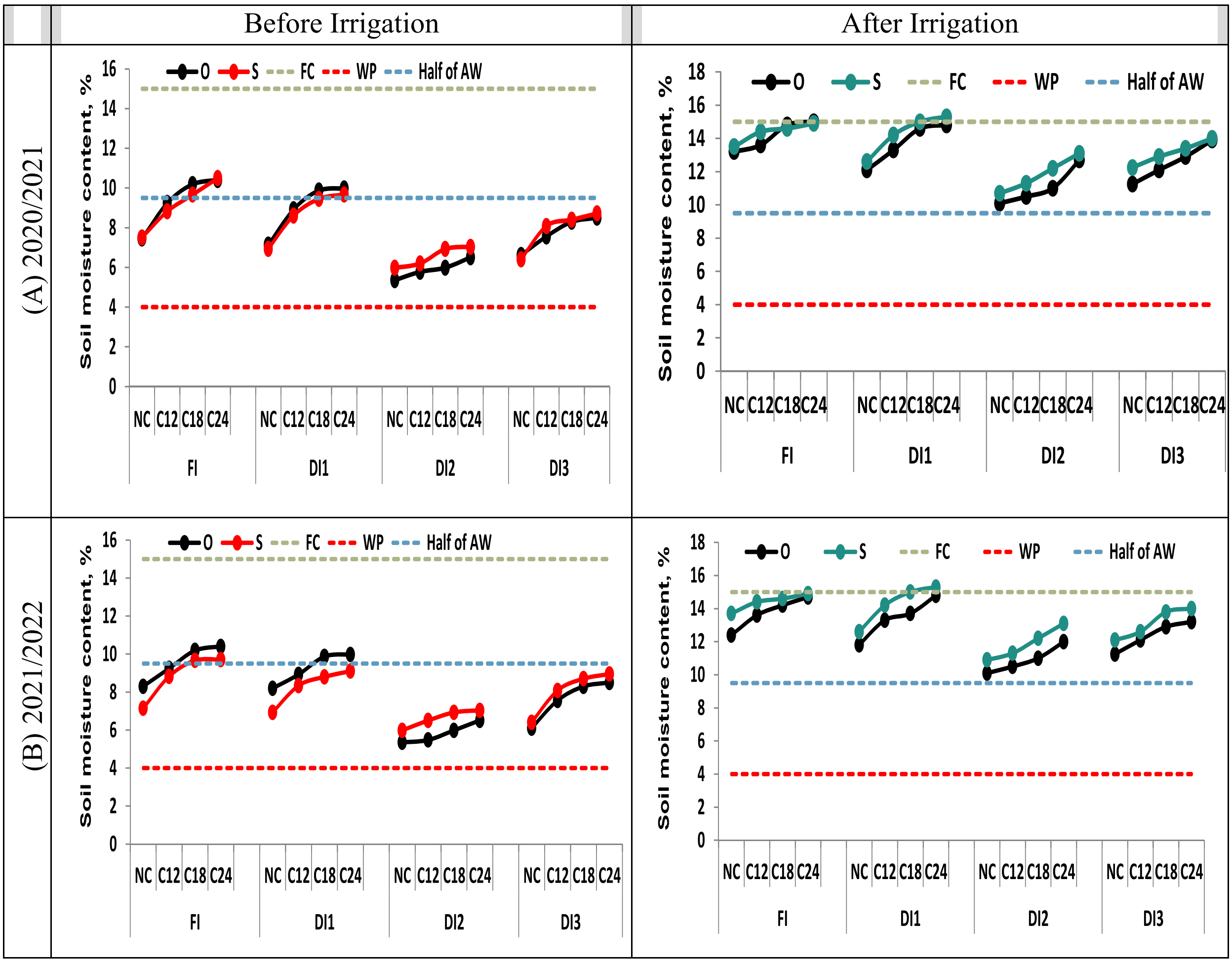

Figure 11. Effect of deficit irrigation strategies and compost addition rate on the water stress of the root-zone [FI (100% of full irrigation), DI1 (0.75FI), DI2 (0.5FI), DI3 (PRD = 0.5FI), NC (no-compost), C12 (12 ton ha^{-1}), C18 (18 ton ha^{-1}) and C24 (24 ton ha^{-1}), PWP (permanent wilting point), FC (field capacity), O (Observed values), S (Simulated values), DI (Deficit Irrigation) and AW (available water)].

Table 5. R^2, RMSE, and CRM coefficients of determination for soil moisture in a single layer (0–40 cm) for all treatments.

		2020/2021			2021/2022		
Deficit irrigation strategies	Compost addition rate	R^2	RMSE	RCM	R^2	RMSE	RCM
FI	NC (calibration)	0.992	0.007	−0.014	0.942	−0.013	−0.015
	C12	0.932	0.004	0.024	0.942	0.008	0.036
	C18	0.973	−0.011	0.028	0.981	0.001	0.031
	C24	0.965	0.005	0.038	0.964	0.005	0.022
DI1	NC	0.987	0.008	0.021	0.973	0.014	−0.014
	C12	0.974	0.003	0.031	0.977	0.004	0.039
	C18	0.969	−0.011	−0.024	0.974	0.011	0.023
	C24	0.956	0.001	0.025	0.955	0.001	0.024
DI2	NC	0.944	0.005	−0.015	0.942	0.006	0.006
	C12	0.972	0.005	0.027	0.964	0.007	0.034
	C18	0.941	0.009	0.026	0.943	0.005	0.028
	C24	0.937	0.004	0.031	0.938	0.001	−0.015
DI3	NC	0.914	−0.013	0.027	0.925	0.007	0.045
	C12	0.975	0.004	0.024	0.976	0.031	−0.024
	C18	0.983	0.008	0.033	0.984	0.032	−0.014
	C24	0.948	0.012	0.031	0.955	−0.011	0.009
Overall Average		0.960	0.003	0.020	0.958	0.007	0.013

[FI (100% of full irrigation), DI1 (0.75FI), DI2 (0.5FI), DI3 (PRD = 0.5FI), NC (No-compost), C12 (12 ton ha^{-1}), C18 (18 ton ha^{-1}), C24 (24 ton ha^{-1}), and DI (Deficit Irrigation)].

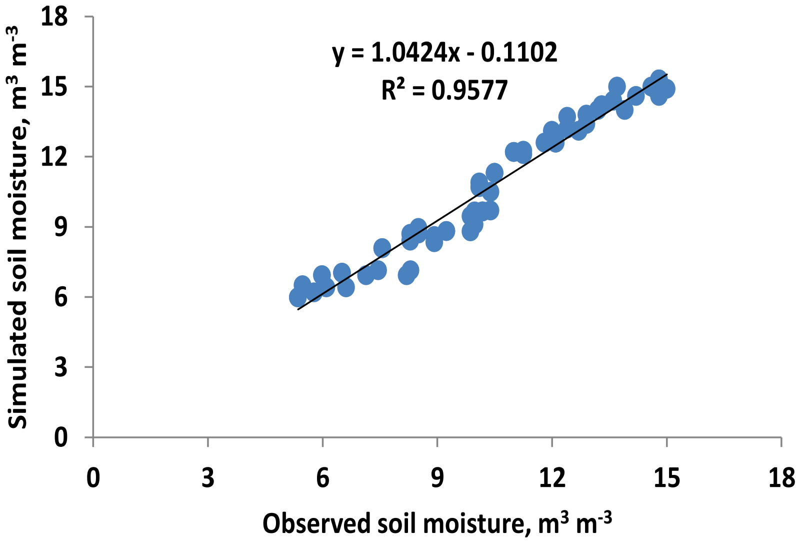

Figure 12. Overall observed versus SALTMED model simulated values (validation) of the soil moisture content for all treatments.

a reduction in WS and increased the SMC compared to no-adding compost (NC) treatment (Iqbal et al., 2020).

Overall, it is evident from Figure 11 that the lowest WS was attained when irrigating at 100% of FI and adding 24 ton ha^{-1} of organic compost, whereas the highest WS was attained when irrigating at 50% FI and without adding compost. WS affects plant's photosynthesis rate and stomatal conductance, subsequently, the biomass and fruit yield (Abdelraouf & Ragab, 2018; Abdelraouf, El-Sayed, Alaraidh, Alsahli, & El-Zaidy, 2020).

Figures 11, 12 and Table 5 show that the values of soil moisture observed in the field were close to soil moisture simulated using the SALTAMD model at the four irrigation strategies FI, DI1, DI2, and DI3. Moreover, statistical analysis in Figure 12 and Table 5 shows that the determination coefficient R^2 was higher between soil moisture measured in the field and the simulated by the SALTMAD model. R^2 was 0.957 for overall soil moisture observed and those results agreed with Abdelraouf and Ragab (2017), Marwa, Abdelraouf, Wahba, El-Bagouri, and El-Gindy (2017).

Soil organic matter content

The soil organic matter in the root zone, the effects of compost application rate and irrigation deficit levels have been evaluated. Figure 13 demonstrates that each of the treatments had an impact on the amount of organic matter in the soil.

As SMC increases, microorganism activity increases as well. These microorganisms decompose the soil's organic matter and this releases nutrients for plant

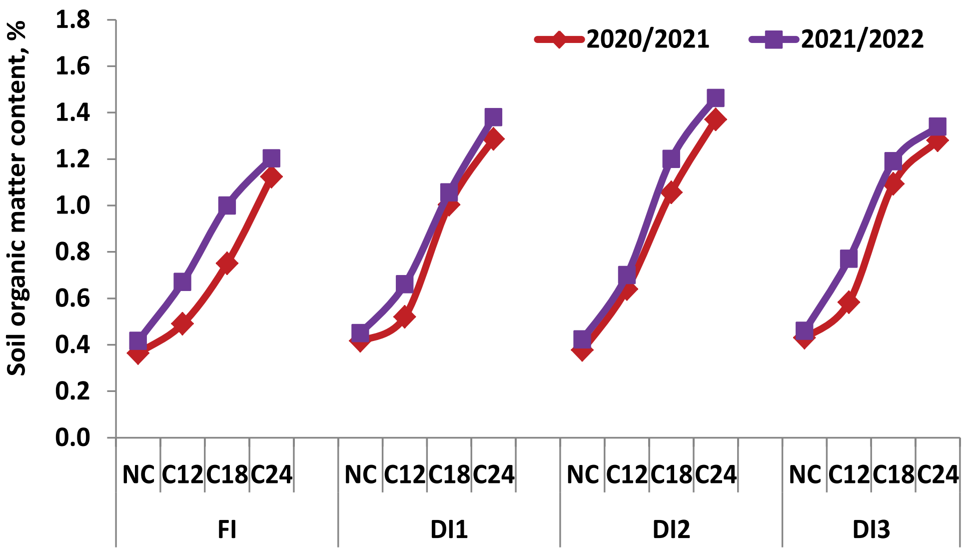

Figure 13. Effect of deficit irrigation strategies and compost addition rate on the soil organic matter content [FI (100% of full irrigation), DI1 (0.75FI), DI2 (0.5FI), DI3 (PRD = 0.5FI), NC (No-Compost), C12 (12 ton ha-^{1}), C18 (18 ton ha-^{1}), C24 (24 ton ha-^{1}) and DI (Deficit Irrigation)].

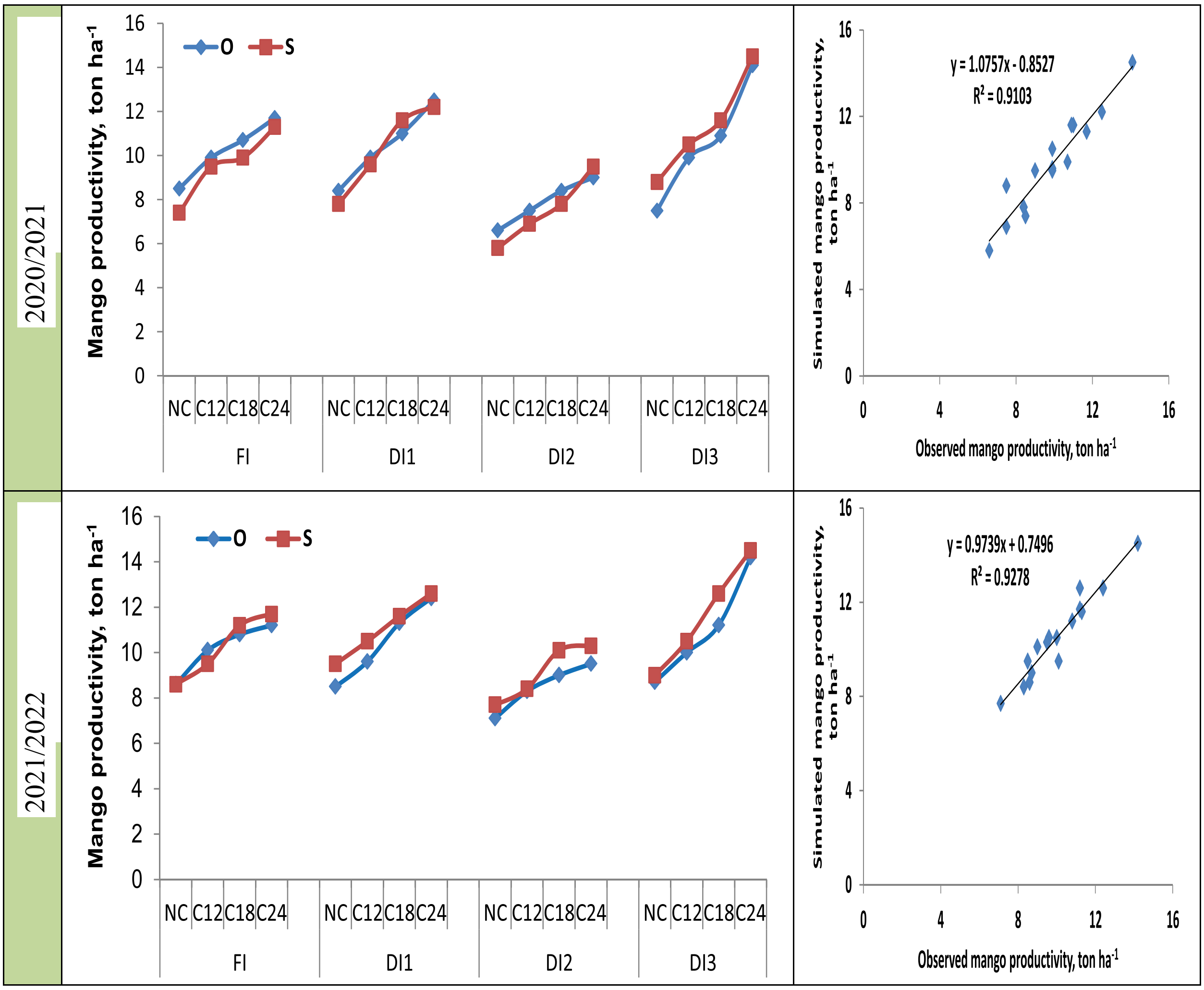

Figure 14. Effect of deficit irrigation strategies and compost addition rate on the on yield of mango [FI (100% of full irrigation), DI1 (0.75FI), DI2 (0.5FI), DI3 (PRD = 0.5FI), NC (no-compost), C12 (12 ton ha-^{1}), C18 (18 ton ha-^{1}) and C24 (24 ton ha-^{1}), O (Observed values), S (Simulated values), DI (Deficit Irrigation)].

uptake. However, some of these nutrients might be leached beyond the root zone under excess irrigation. Although the additional irrigation volume is the same when employing the PRD root drying technique or 50% FI, it has been found that the root drying technique's irrigation reduced the amount of organic matter in the soil. This can be a result of subjecting both sides of the tree's root to cycles of wetting and drying.

Figure 13 demonstrates the impact of the increasing rate of compost on increasing the soil's organic content. More application leads to more soil organic matter content, which is vital for water and nutrient retention particularly for sandy soil (Khurshid, Iqbal, Arif, & Nawaz, 2006). Moreover, compost slow release of those nutrients makes them available for mango tree roots for a longer period of time.

Mango yield productivity

When analyzing the factors separately, the first factor (deficit irrigation strategies) had a positive and significant effect on mango yield, which was also significantly affected by the second factor (compost addition rate) for the two seasons as represented in Figure 14 and Table 6.

Among the deficit irrigation strategies, the highest yield values were obtained under PRD followed by DI1 (0.75FI) and then FI, while the lowest values were under DI2 (0.5FI) for the two seasons. The highest mango yield values were 10.6 and 11 tons per hectare when using PRD for 2020/2021 and 2021/2022, respectively, and there was no-significant difference between PRD, DI1(0.75FI) and FI on mango yield. However, there was a significant difference between DI2 (0.5FI) and other treatments. The lowest values of mango yield were 7.9 and 8.5 ton ha^{-1} obtained when applying DI2 (0.5FI) for 2020/2021 and 2021/2022, respectively. With the same techniques by using PRD and DI in field experiments, it was revealed that PRD was significantly increased crop production (Du, Kang, Zhang, Li, & Yan, 2008). According to Shahabian, Samar, Talaie, and Emdad (2012), DI treatments decreased fruit yields for orange trees by 30%

Table 6. Effect of deficit watering techniques and the rate of compost addition on mango yield and water productivity.

		Yield of fruits, ton ha^{-1}				Water productivity, $kg_{mango}\ m^{-3}{}_{water}$			
		2020/2021		2021/2022		2020/2021		2021/2022	
Deficit irrigation strategies	Compost addition rate	O	S	O	S	O	S	O	S
FI		10.2	9.5	10.2	10.3	1.04	0.97	1.04	1.05
DI1		10.5	10.3	10.5	11.1	1.42	1.40	1.42	1.50
DI2		7.9	7.5	8.5	9.1	1.6	1.52	1.73	1.86
DI3		10.6	11.4	11	11.7	2.15	2.31	2.25	2.38
LSD at 5%		0.7		0.7		0.11		0.13	
	NC	7.8	7.5	8.2	8.7	1.22	1.20	1.32	1.39
	C12	9.3	9.1	9.5	9.7	1.47	1.45	1.52	1.56
	C18	10.3	10.2	10.6	11.4	1.63	1.63	1.69	1.84
	C24	11.8	11.9	11.8	12.3	1.89	1.92	1.92	1.99
LSD at 5%		0.7		1.3		0.12		0.17	
	NC, (calibration)	8.5	7.4	8.6	8.6	0.86	0.75	0.88	0.88
FI	C12	9.9	9.5	10.1	9.5	1.01	0.96	1.03	0.97
	C18	10.7	9.9	10.8	11.2	1.09	1.01	1.10	1.14
	C24	11.7	11.3	11.2	11.7	1.19	1.15	1.14	1.19
	NC	8.4	7.8	8.5	9.5	1.14	1.06	1.16	1.29
DI1	C12	9.9	9.6	9.6	10.5	1.34	1.30	1.30	1.43
	C18	11	11.6	11.3	11.6	1.49	1.57	1.54	1.58
	C24	12.5	12.2	12.4	12.6	1.69	1.65	1.69	1.71
	NC	6.6	5.8	7.1	7.7	1.34	1.18	1.45	1.57
DI2	C12	7.5	6.9	8.3	8.4	1.52	1.40	1.69	1.71
	C18	8.4	7.8	9	10.1	1.71	1.58	1.83	2.06
	C24	9	9.5	9.5	10.3	1.83	1.93	1.94	2.10
	NC	7.5	8.8	8.7	9	1.52	1.79	1.77	1.83
DI3	C12	9.9	10.5	10	10.5	2.01	2.13	2.04	2.14
	C18	10.9	11.6	11.2	12.6	2.21	2.36	2.28	2.57
	C24	14.1	14.5	14.2	14.5	2.86	2.94	2.90	2.96
LSD at 5%		1.4		2.5		0.22		0.34	

[FI (100% full irrigation), DI1 (0.75FI), DI2 (0.5FI), DI3 (PRD = 0.5FI), NC (No-Compost), C12 (12 ton ha^{-1}), C18 (18 ton ha^{-1}) and C24 (24 ton ha^{-1}), O (Observed values), S (Simulated values) and DI (Deficit Irrigation)].

when compared to FI; however, PRD treatments had no effect on fruit yields at all. Furthermore, Hutton and Loveys (2011), demonstrated that PRD had no impact on citrus trees' fruit production.

In terms of compost application rate, a higher mango yield (11.8 and 11.8 ton ha^{-1}) was recorded in C24 followed by the C18 treatment (10.3 and 10.6 ton ha^{-1}), and C12 treatment (9.3 and 9.5 ton ha^{-1}). There was a significant difference between C24 and other treatments, given that the minimum yield (7.8 and 8.2 ton ha^{-1}) was recorded in NC for 2020/2021 and 2021/2022, respectively. Mango yield increased with the C24 treatment as a result of enhanced growth, and eventually greater yield compared to other treatments. Similar findings were noted by Ahmad et al. (2022), who discovered that composting improved stomatal conductance in plants because more soil moisture was available and leaf turgor was maintained, keeping the stomata open.

Among the interaction between the two factors, the interaction also had a statistically significant effect on mango yield for the two seasons as indicated in Figure 14 and Table 6. The greatest mango yield values were 14.1 and 14.2 tons per hectare under PRD together with C24 during 2020/2021 and 2021/2022, respectively.

There were no-significant differences between applying DI3 (PRD+C24) and DI1 (0.75FI+C24), but these treatments and the other treatments differed significantly from one another. But these treatments and the other treatments differed significantly from one another. The lowest values of mango yield were 6.6 and 7.1 ton ha^{-1} obtained by applying DI2 (0.5FI) under NC for 2020/2021 and 2021/2022, respectively.

There was a positive impact with the PRD strategy when compared with FI, DI1 (0.75FI) and DI2 (0.5FI), especially with C24. The positive impact of PRD with C24, is possibly caused by two factors: first, the beneficial effects of the PRD strategy, which alternately waters the plant's root systems on opposite sides. Second, the great capacity of compost to hold water and nutrients, making them available for longer length of time, results in partial stomatal closure and a decrease in transpiration losses without significantly reducing photosynthesis and yield when used in conjunction with this technique. These observations are matching the findings of Ahmad et al. (2022); Abdelraouf, El-Sayed, Alaraidh, Alsahli, and El-Zaidy (2020); El-Habbasha, Okasha, Abdelraouf, and Mohammed (2014), who indicated that the production might be improved and drought stress reduced by combining two strategies (adding compost and PRD).

Figure 14 and Table 6 also show the yield productivity results obtained through the SALTMED simulation model, where the correlation coefficient R^2 was 0.91 for the season 2020/2021 and it was 0.93 for season 2021/2022.

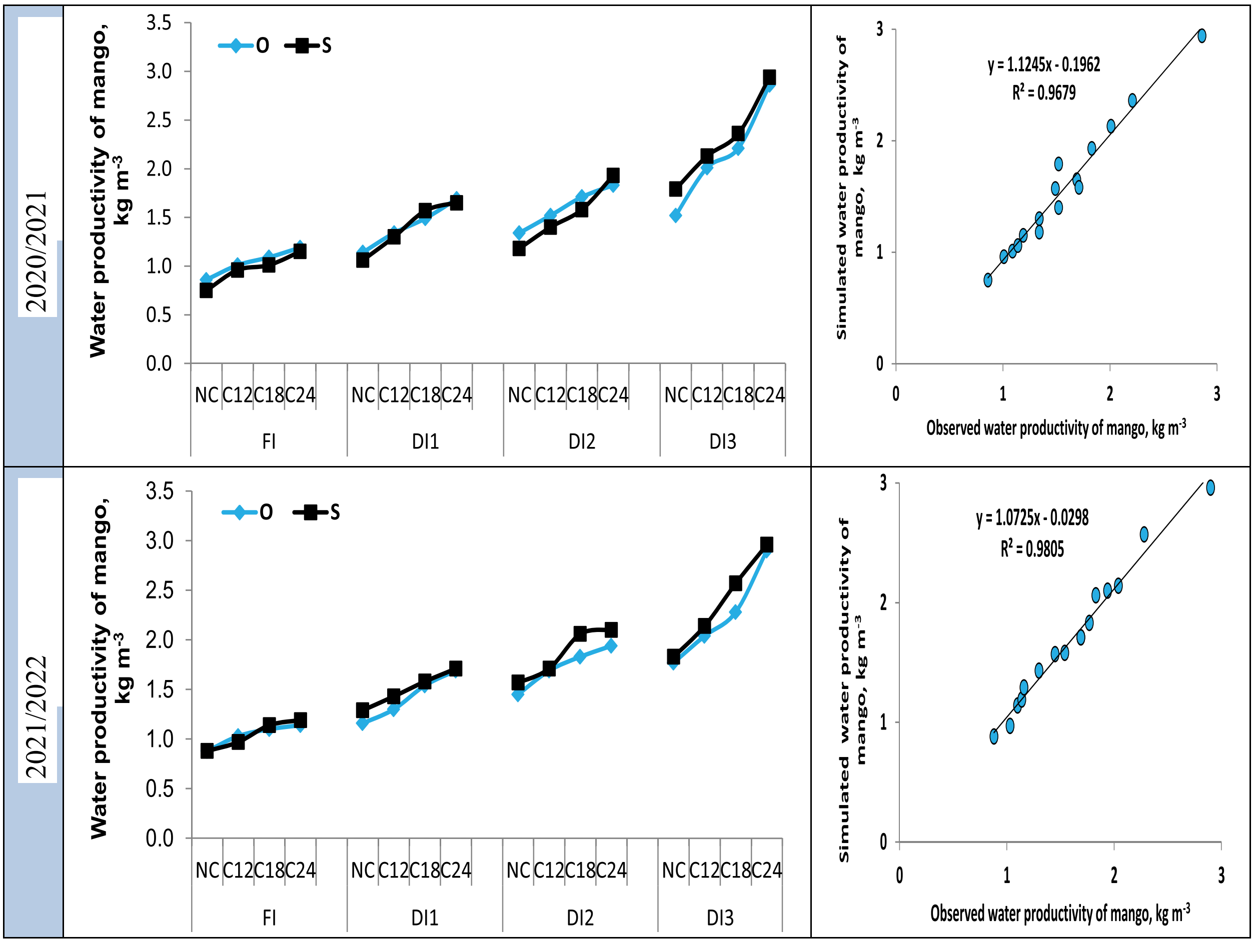

Figure 15. Effect of deficit irrigation strategies and compost addition rate on the on-water productivity of mango [FI (100% of full irrigation), DI1 (0.75FI), DI2 (0.5FI), DI3 (PRD =0.5FI), NC (no-compost), C12 (12 ton ha-[1]), C18 (18 ton ha-[1]), C24 (24 ton ha-[1]), O (Observed values), S (Simulated values) and DI (Deficit Irrigation)].

Table 7. Effect of deficit irrigation strategies and compost addition rate on some quality traits of mango.

Deficit irrigation strategies	Compost addition rate	T.S.S., (%)		Total Acidity, (%)		vitamin C, (mg/100 ml juice)	
		2020/2021	2021/2022	2020/2021	2021/2022	2020/2021	2021/2022
FI		10.2	11.1	0.87	0.90	35.0	37.4
DI1		10.6	11.3	0.90	0.93	36.6	39.0
DI2		8.4	9.0	0.89	0.92	33.8	36.8
DI3		10.9	11.7	0.88	0.95	35.7	38.4
	NC	8.7	9.6	0.77	0.82	28.9	31.6
	C12	9.4	10.0	0.84	0.88	31.6	34.2
	C18	10.1	10.9	0.92	0.94	37.2	39.4
	C24	11.9	12.7	1.01	1.06	43.4	46.5
FI	NC	8.6	10.5	0.73	0.79	26.9	29.3
	C12	9.8	10.4	0.80	0.86	29.1	31.7
	C18	10.1	11.1	0.89	0.89	38.4	40.5
	C24	12.1	12.5	1.06	1.07	45.7	48.0
DI1	NC	9.4	9.9	0.84	0.87	32.0	34.1
	C12	9.9	10.7	0.86	0.89	34.5	36.8
	C18	11.0	11.6	0.89	0.92	36.9	39.3
	C24	12.0	13.1	1.01	1.05	43.1	45.9
DI2	NC	7.0	7.6	0.80	0.82	29.7	32.7
	C12	7.8	8.2	0.84	0.86	32.7	35.6
	C18	9.0	9.6	0.94	0.97	34.4	36.6
	C24	9.9	10.7	0.97	1.03	38.5	42.1
DI3	NC	9.8	10.4	0.71	0.81	27.2	30.1
	C12	10.1	10.7	0.86	0.92	30.1	32.7
	C18	10.1	11.4	0.94	0.97	39.4	41.2
	C24	13.4	14.5	1.02	1.10	46.2	49.8

[FI (100% full irrigation), DI1(0.75FI), DI2 (0.5FI), DI3 (PRD = 0.5FI), NC (no-compost), C12 (12 ton ha^{-1}), C18 (18 ton ha^{-1}), C24 (24 ton ha^{-1}) and DI (Deficit Irrigation)].

Water productivity of mango

Divide the yield by the total irrigation volume used over the season to get water productivity per unit of farmed area.

Figure 15 and Table 6 show clearly the effect of deficit irrigation strategies on the water productivity of the mango crop. As the amount of irrigation water decreased, the water productivity values increased. Additionally, Figure 15 demonstrates that the water productivity values improved as the rate of compost addition increased. This may be as a result of the increase in water and nutrient retention in the root zone.

According to the experiment's findings, the partial root drying technique (PRD) with the addition of 24 ton per ha^{-1} compost produced the maximum water productivity and mango production values. Findings of the current research have similarity with many studies such as Ahmad et al. (2022) who noted that the PRD method greatly increased WP as compared to FI. The same findings were reported by Abdelraouf, El-Shawadfy, Dewedar, and Hozayn (2021); Shahabian, Samar, Talaie, and Emdad (2012); El-Metwally et al. (2015).

Figure 15 and Table 6 show the water productivity results obtained through the SALTMED simulation model, where the seasons 2020/2021 and 2021/2022 have correlation coefficients R^2 of 0.96 and 0.98, respectively.

Quality of mango fruit

Table 7 shows the impact of deficit irrigation techniques with compost addition on the total soluble solids (T.S.S.), total acidity, and vitamin C content of mango fruits over the duration of two seasons. Generally, the use of the PRD technique with the compost addition rate over the two seasons increased the quality of mango fruits. Composting had a beneficial impact on the quality traits of mango fruits over the two seasons of deficit irrigation strategies. Mango fruit quality performed well when employing the PRD strategy with compost, and lowest when using the DI2 (0.5FI) strategy and no compost treatment. Numerous studies have shown that PRD irrigation has increased the quality of the production (Shahnazari, Liu, Andersen, Jacobsen, & Jensen, 2007). According to earlier research on a variety of field crops, the PRD technique produced higher WP and even better fruit quality than DI1 and DI2 techniques under the same level of water deficit (Wang, Liu, Andersen, & Jensen, 2010). The same findings were reported by Abdelraouf, El-Sayed, Alaraidh, Alsahli, and El-Zaidy (2020).

The maximum percentage of organic compost added to the irrigation water while partially drying the roots produced the best results for mango fruit quality, according to Table 7. This was attributed to the method's successful creation of an active state within the root zone and the stomata control process. The addition of organic compost to the soil had a favorable impact on increasing water and nutrient retention and reducing water stress in the root zone.

It is worthwhile noting that various crop species respond to water stress management techniques in different ways. PRD seems to be a very effective irrigation strategy with many potential future applications.

To properly expand, use, and apply this procedure under various soil types, climatic conditions, and cultivars, further study is required. In order to use this irrigation correctly, it is necessary to calculate the duration that the dry and wet sides alternate, as well as the cultivar's growth stages.

Conclusions

There is a need to implement strategies that improve agricultural productivity in water stressed regions. Enhancing agricultural production can be achieved by the adoption of water-saving strategies and drought-tolerant cultivars. The PRD irrigation technique is a novel approach that has been applied over the past 10 years to a variety of horticultural and agronomic crops, allowing for yield and water productivity increase, improving the efficiency of water and nutrient use, improving the nutritional status of various agricultural species, and improving yield and fruit quality. This study showed that the best strategy for increasing mango quantity and quality in a dry climate and sandy soils is to apply irrigation using the Partial root Drying Method, PRD accompanied by application of organic compost. In this study, the partial root-zone drying technique (PRD) with the addition of 24 ton ha^{-1} compost gave the best results. This strategy can be recommended to local mango producers and those of similar conditions to implement PRD + C24 as a feasible adaptation strategy to achieve high mango output and conserve water by at least 50%. The study proved that PRD + C24 enhanced yield, water productivity, and the quality of mango fruits. Under various deficit irrigation strategies. Furthermore, the SALTMED model could simulate and forecast changes in soil moisture, yield, and water productivity.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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