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Research Article

Enhancing the Productivity and Water Productivity of Lemon Using Partial Root Drying and Adding Biochar

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Abstract

Background and Objective: Enhancing the sustainable management of irrigation deficit is the main goal for all dry areas that suffer from limited irrigation water. The aim of this study was to study the performance of the partial root drying technique (PRD) for providing 50% of the water needs required to irrigate lemon using the addition of organic biochar to sandy soils as sustainable materials. **Materials and Methods:** Two field experiments were carried out during the 2019 and 2020 seasons, at the experimental farm of Al-Nubariya area in Beheira Governorate, Egypt, for studying the impact of partial roots drying (PRD) technique and the addition of biochar (made from corn straws) on the efficiency of adding irrigation water (WAE), Water stress within the roots zone of lemon trees, productivity, water productivity (WP) and the impact of these factors on some quality characteristics of lemon fruits under the conditions of dry sandy areas. The PRD technique was applied with the study of the impact of five biochar rates [0 (control), 4, 6, 8 and 10 t ha^{-1}]. **Results:** The yield of lemon (LY), WP, vitamin C (VC) and total soluble solids (TSS) of lemon was increased and improved with increasing rates of biochar under the PRD technique. Whereas, the highest values for the productivity of lemon trees were obtained at 50% of the necessary irrigation water using PRD technique, compared to the full irrigation under drip irrigation system. So, despite the increase in moisture stress on one side of roots spread area in exchange with the other side when irrigating by PRD technique and consequently water application efficiency (WAE) was decreased, there were many advantages of applying this technique. Significant differences were obtained between PRD and full irrigation (FI) in terms of production values. Increasing the biochar rate led to enhancing soil water holding capacity within the root zone hence, improving WAE. Also, biochar degradation has increased the availability of nutrients. **Conclusion:** Results indicated that using of irrigation with 50% of FI using PRD with a biochar application rate of 10 t ha^{-1} is considered to be the most effective treatment because it provides 50% of the water requirement for irrigating lemon trees and thus can be recommended for application with the highest rate of biochar in the same dry sandy soil conditions in Egypt.

Key words: Deficit irrigation, biochar, corn straw, PRD technique, water productivity, lemon

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Scarcity of water sources and its limitation is one of the most important challenges facing the production of the crops in Egypt, which is an improvement of new methods and techniques that can help to benefit from these precious inputs positively and effectively that is greatly required to reduce and rationalization of the water consumption in the irrigation[1,2]. The gap between crop production and the growing population consumption can be minimized by developing and modernizing agricultural practices in arid regions such as irrigation methodology in Egypt[3]. Water productivity of crops (WP) is extremely important due to limited water resources in dry areas. Water scarcity is the fundamental cause of crop yield reduction worldwide. Therefore, using the irrigation water must be appropriate and the principles of under-irrigation with a small level of yield reduction must be accepted[4,5]. Defective irrigation has been widely evaluated as a beneficial and sustainable production technique in arid areas and the practice aims to maximize the crops water productivity. The results of previous research and experiments confirm that the irrigation deficit is positive and successful in improving and increasing the productivity and water productivity of many crops without causing a sharp and unnoticeable decline in yield[6].

Deficient irrigation (DI), including partial roots drying, is a good strategy for saving and irrigation rationalization which involves reciprocal irrigation of each side plant roots system[7-9]. This strategy results in moderate water stress in the plant, which results in partial closure of the stomata and reduced transpiration loss without significantly affecting photosynthesis and crop productivity. A promising strategy has also been found in several crops suggested that PRD can protect and stimulate roots growth, while under deficit irrigation some roots may die if dry conditions persist[10,11]. Next, it was decided to investigate whether regulated deficit irrigation "RDI" and PRD might be effective and promising irrigation strategies for their application to the cultivation of maize in sandy soils of Egypt. The theoretical background of the PRD technique is that irrigation of one part of the plant roots system maintains the upper side of the crops in favourable water conditions, while dehydration of the other part of roots leads to the formation of radical chemical signals (mainly hormones). Chemical signals generated by the plant root are transmitted to the upper part of plants roots to stimulate and activate low stomata conduction and bud growth[12]. Orally administered partial rehydration prevents dangerous water loss by transpiration and reduces the absorption of carbon dioxide that can occur under dry conditions[13].

Numerous data from the literature have shown that under-irrigation techniques, especially PRD, may increase water use efficiency "WUE" and maintain or improve the productivity of irrigated plants. A wide range of positive PRD-specific responses of plants could explain these effects. Changes in the stomata morphological characteristics observed in PRD root plants (smaller protecting cells, lower stomatal density) and lower conductivity affected transpiration and contributed to increased water productivity, in addition, enhanced photosynthetic capacity which has a positive effect on net photosynthesis[14-16]. Reducing vegetative activity and canopy area for grains/fruits also allowed better exposure to solar radiation (more light penetrating the canopy) and led to the transfer of mimic animals from plant tissues to fruit/grains which may thus improve crops yield and the quality traits[17-21]. In addition, enhanced the roots growth and also, development and increased roots biomass in PRD conditions increase plant water uptake and hydraulic conductivity[22]. Several literature data also indicated that PRD increases the activity of soil microorganisms and also, a higher ability to uptake the roots nutrients[23]. Recently showed an increase in nitrogen and phosphorous uptake of various PRD-treated crops with the so-called 'birch effect[24]. This effect is named in honour of Birch, who discovered that re-wetting previously dry soil leads to increased nitrogen mineralization. According to Dodd, the "birch effect" is caused by changes in physical processes (disruption of soil aggregation and consequent P-shaped release), biological processes (stimulation of soil microbial biomass and activities in the mineralization of soil organic compounds) and both processes are coupled. However, much research effort should be done with different soil types to determine when the rate of nutrient uptake increases under PRD.

In sandy soils, the availability of nutrients and low carbon content in organic soils are among the major agricultural limitations. In addition, due to the above limitations, there are other indicators for soils properties such as reduced water holding capacity, concentrated mineralization of the soil organic matter, in addition, leaching of soil nutrients etc. Due to these limitations, cultivation on sandy soils in dry regions relies heavily on the addition and use of external inputs. The importance of covering rice straw and using it as a sustainable material in mitigating the harsh water deficit conditions under the conditions of dry areas was noted. Conversely, organic amendments in the sandy soil experience a high decomposition rate and the added organic matter is usually mineralized only during young growing seasons[25]. Hence, organic fertilizers must be added frequently and frequently to maintain and improve water productivity and productivity in sandy soils. The importance of manure in relieving water stress has been recommended and reported in dry and arid sandy soil conditions. One of the most important sustainable technology techniques is to rely on organic materials more than others because of their high ability to maintain the healthy environment of sandy soils and biochar can also be a very good and useful option to replace easily degradable organic fertilizers[26,27]. A biochar material was defined as biomass-derived black carbon that is produced after 300-500°C of pyrolysis of carbonaceous materials under the limitations and constraints of hypoxia[28]. The addition of biochar to soils has overcome some limitations encountered while cultivating sandy soils, allowing providing and giving an additional option for soil management and also, other sustainable and organic components such as compost, manure and mineral fertilizers. There are many more environmental and sustainable benefits of biochar over the compost. It is a porous material with a high internal surface area that can support retaining and keeping more moisture and also increase the saturated hydraulic conductivity of the topsoil[29]. Biochar has been added at different rates to sandy soils. Where the application rates significantly and morally affected the properties of the soil, the higher application rates had greater effects. Hence, interest in the use and application of biochar as a sustainable technology to reduce and mitigate the impacts of global warming[30,31]. The physical and chemical properties of biochar can stimulate and cause significant changes in the availability of carbon and soil nutrients and provide physical protection for soil microorganisms against predators and drought. This may alter soil microbial diversity[32]. Biochar derived from low-temperature pyrolysis is called an increasingly volatile content that readily and simply contains biodegradable substrates, which can help support plant growth[33,34]. Pyrolysis is termed high temperature and is characterized by a big surface area and aromatic carbon content that might increase the adsorption capacity, in addition, the inhibitory character (carbon sequestration)[35].

The study aimed at enhancing the sustainable management of irrigation deficit by raising the performance of the partial root drying technique (PRD) and providing 50% of the water needs required to irrigate lemon under the conditions of dry areas using the addition of organic biochar to sandy soils.

MATERIALS AND METHODS

Location and climate of the experimental site: Field experiments were carried out during the 2019 and 2020 seasons on the lemon farm located in the North of Cairo, Egypt on sandy soil at Al-Nubariya Region, Al-Beheira Governorate (latitude 30°26’28’’N, longitude 30°18’0’’E and mean altitude above sea level 21 m. The selected area is characterized by an arid climate, cool winters and hot dry summers. The data of maximum and minimum temperature, relative humidity and wind speed were obtained from the local weather station at El-Nubaria farm.

Physical and chemical properties of soil and irrigation water: Fresh irrigation water source from channel passing through the farm and the experimental area was irrigated by drip irrigation system equipped by solenoid valves to control irrigation rotation. The supplied water had an average pH of 7.6 and 0.55 dS m^{-1} as electrical conductivity (EC). The soil was characterized as sandy soil according to the mechanical analysis of randomly collected samples from the experimental farm. The main physical and chemical characteristics of the soil illustrated in Table 1, were determined in situ and laboratory at the beginning of the experiment.

Biochar production: Pyrolysis experiments, it was made by simple reactors to produce biochar from corn straw using scrap metal drums. The feedstock (corn straw) was put into the reactor for pyrolysis at low temperatures. After pyrolysis, the reactor was left inside the furnace to cool to room temperature. The biochar and ash obtained were weighed. Equation (1)[36] and Fig. 1 include full descriptions of biochar production stages from corn straw. The biochar was added with the maximum wet surface area under the drippers for each lemon tree by mixing it with the upper 30 cm of the soil profile and it was added each year. Chemical analysis of corn stalks biochar was presented in Fig. 2:

$$\text{Yield (\%)} = \frac{\text{Mass of biochar (kg)}}{\text{Dry mass of feedstock (kg)}} \times 100 \qquad (1)$$

Experimental design: The experimental design was split-plot includes two levels of irrigation water deficit [100% and PRD (50% from full irrigation) for irrigating lemon trees (Percy variety grafted on Volca Mariana and the planting distances between lemon trees were 4×5 m and lemon trees are at least 10 years old)] plotted in the main plot and five application rates of biochar [0 (control), 4, 6, 8 and 10 t ha^{-1}] plotted in the sub-main plot as shown in Fig. 3.

Fertilizer addition: Recommended doses of NPK were applied to all treatments according to the recommendation of the ministry of agriculture for lemon trees under drip irrigation system as shown in Table 2.

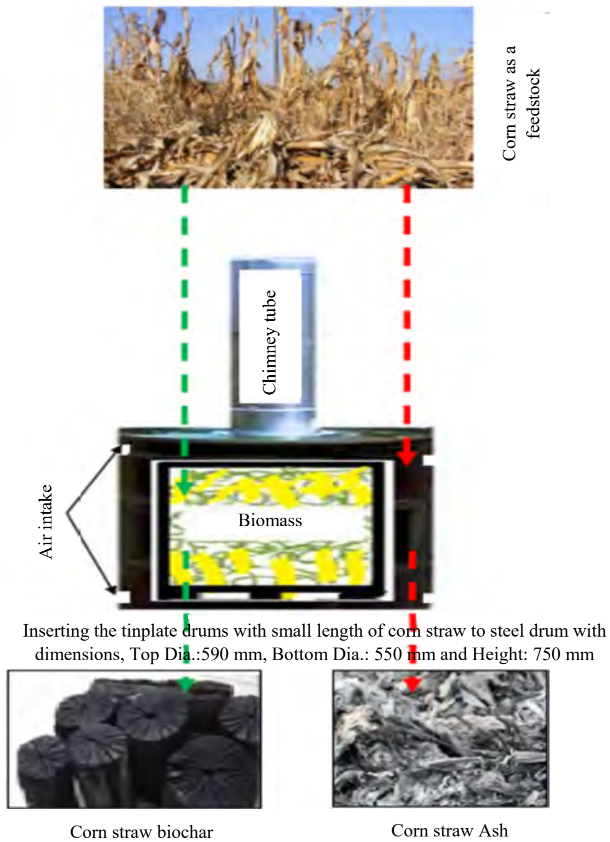

Fig. 1: Using metal scrap drums for producing the biochar from corn straw

Table 1: Physical and chemical characteristics of the soil of the experimental area

	Soil depth (cm)		
Soil characteristics	0-30	30-60	60-90
Texture	Sandy	Sandy	Sandy
Course sand (%)	46.00	45.25	44.99
Fine sand (%)	51.48	49.56	50.44
Silt+clay (%)	2.52	5.19	4.57
Bulk density (t m^{-3})	1.65	1.69	1.71
Organic matter (%)	0.66	0.45	0.22
EC (dS m^{-1})	0.55	0.53	0.50
pH (1:2.5)	8.4	8.6	8.9
Total $CaCO_3$ (%)	7.25	4.46	4.68

Irrigation requirements for lemon: Daily irrigation water was calculated by following Equation (2) and seasonal irrigation water was calculated for 2019 and 2020 under drip irrigation system:

$$IRg = \frac{ETO \times Kc \times Kr}{Ei} - R + LR \quad (2)$$

Where:

IRg = Gross irrigation requirements (mm/day)

ET_o = Reference evapotranspiration (mm/day)

Kc = Crop factor

Kr = Ground reduction factor and the values of Kr measured by Keller equation:

$$Kr = GC\% + 0.15\ (1\text{-}GC\ \%)$$

Where:

Ei = Irrigation efficiency %

R = Water received by the plant from sources other than irrigation, mm (for example rainfall)

LR = Volume of water required for the leaching of salts (mm)

Table 2: Recommended doses of fertilizers for lemon trees applied to all treatments kg per hectare per year

Before flowering			Beginning of fruition			The end of the natural fall of the fruits		
N	P	K	N	P	K	N	P	K
129.6	72	144	129.6	72	192	172.8	0	144
NH_4NO_2 33.5%	H_3PO_4 75%	K_2SO_4 52%	NH_4NO_2 33.5%	H_3PO_4 75%	K_2SO_4 52%	NH_4NO_2 33.5%	H_3PO_4 75%	K_2SO_4 52%
387	96	277	387	96	369	516	0	277

$$\text{Each tree's share of NPK fertilizer} = \frac{\text{Total amount of fertilizers}}{\text{Number of trees per hectare}}$$

Hectare = 2.4 Fadden, $\text{Number of trees per hectare} = \frac{10000}{5\times 4} = 500\ \text{trees}$

Table 3: Total water volumes under partial root drying technique and biochar application rates for each treatment and the irrigation were done two times per week

	Irrigation volumes, $m^3\ ha^{-1}$			
Deficit irrigation, m^3	2019	2020	Biochar application rates, t ha^{-1} (2019)	Biochar application rates, t ha^{-1} (2020)
100% FI	7704	7632	0	0
PRD	3852	3816	4	4
			6	6
			8	8
			10	10

FI: Full irrigation and PRD: Partial root drying

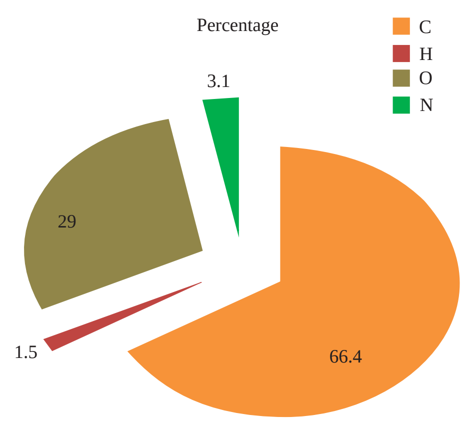

Fig. 2: Ultimate analysis of corn stalks biochar

Total water volumes for each treatment and biochar rate were reported in Table 3.

Evaluation parameters

Water stress in the roots zone of lemon trees: Soil moisture was measured in the effective roots zone before irrigation and the field capacity and wilting point were taken as evaluation lines in consideration as an evaluation parameter for exposure range of roots trees to water stress "WS"[2]. Measurements were taken at soil depths at the mid-growth stage. Soil moisture was measured by a profile probe device.

Water application efficiency "WAE": Water application efficiency relates to the storage depth of irrigation water inside the root zone of lemon trees divided by the depth of the added irrigation water. According to another study[37] WAE was calculated using the following relation (3):

$$\text{WAE (\%)} = \frac{Ds}{Da}\times 100 \qquad (3)$$

Where:

WAE = Water application efficiency (%)

Ds = Depth of stored water in the root zone (cm) calculated by equation:

$$Ds = (\theta_1 - \theta_2)\times d\times \rho$$

Where:

Da = Depth of applied water (cm)

D = Soil layer depth (cm)

θ_1 = Soil moisture content after irrigation (%)

θ_2 = Soil moisture content before irrigation (%)

ρ = Relative bulk density of soil (dimensionless)

Lemon yield: At harvest time, the fruits were collected and weighed and then the fruit yield was determined and calculated by ton per hectare for each treatment.

Water productivity of lemon "WP_{Lemon}" was calculated by equation (4) as follows:

$$WP_{Lemon} = \frac{Ey}{Ir} \qquad (4)$$

Where:

WP_{Lemon} = Water productivity of lemon (kg $_{lemon}$ $m^{-3}{}_{water}$)

Ey = Economical yield (kg ha^{-1})

Ir = Applied amount of irrigation water ($m^3{}_{water}$/ha/season)

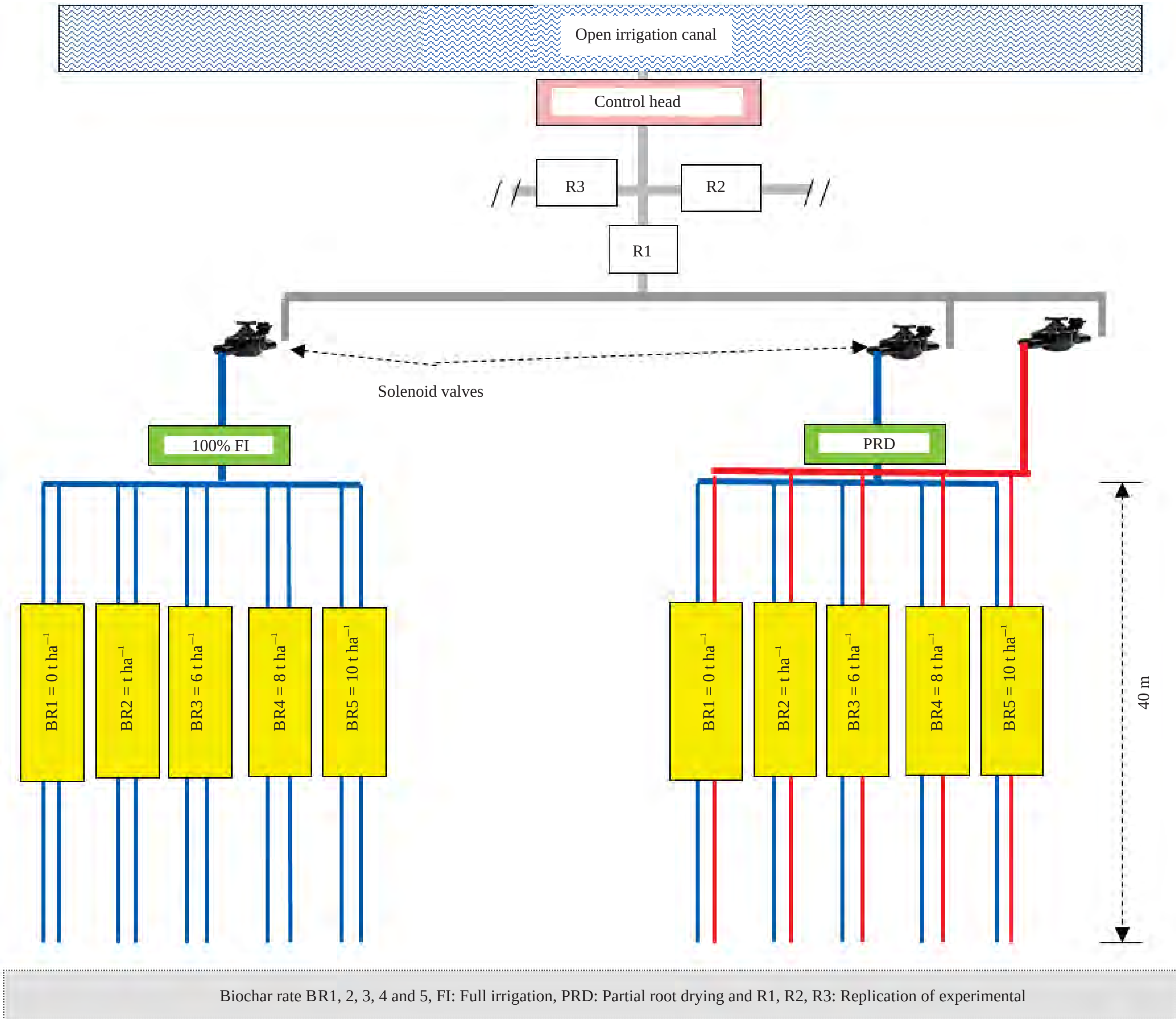

Fig. 3: Layout of experimental design

Fruits quality of lemon: Representative samples of lemon fruits were randomly chosen from each treatment to determine some of the quality parameters of lemon fruits (i.e., fruit diameter (cm), peel thickness (cm), fruit wt (gm), Vitamin C and total soluble solids (T.S.S.) using a hand refractometer[38].

Statistical analysis: The data obtained were subjected to Analysis of Variance (ANOVA)[39] using Co-Stat Software Program Version 6.303 (2004) and LSD at 0.05 level of significance was used for the comparison between means.

RESULTS

Water stress inside root-zone of lemon trees

Impact of PRD on the water stress "W_{stress}": There is a big impact of deficit irrigation on the decrease in Soil Moisture Content (SMC) within the root zone. SMC values decreased by reducing the amount of irrigation water added before irrigation by PRD. The highest values of SMC (10 and 9.4% for seasons 2019 and 2020, respectively) were in irrigation with 100% FI and the lowest values (6.3 and 6% for seasons 2019 and 2020, respectively) were with PRD at 50% FI.

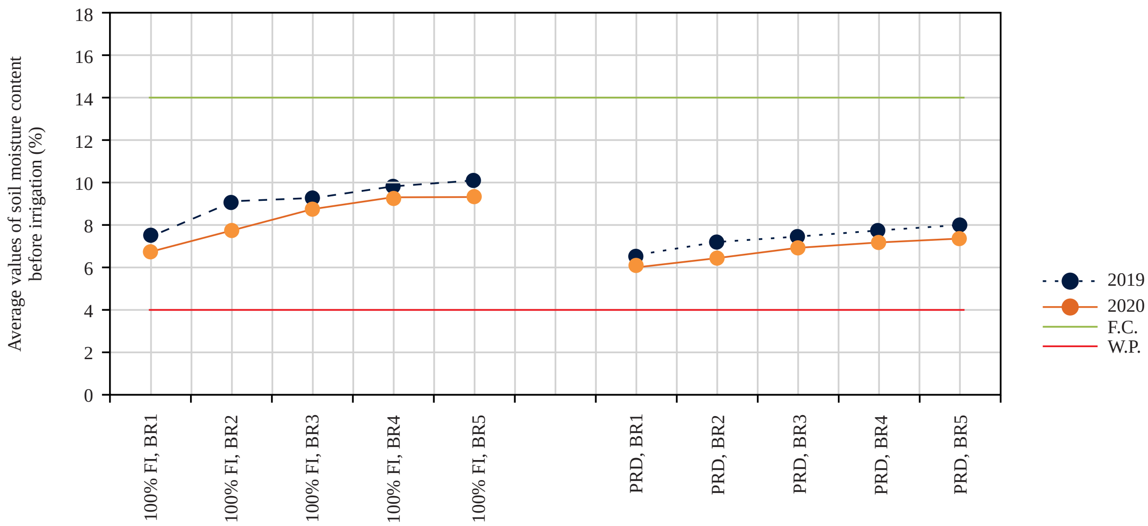

Fig. 4: Impact of partial roots drying (PRD) technique and biochar application rate (BR1-BR5) on water stress during seasons of 2019 and 2020

Impact of biochar rate on W_{stress}: It was also clear from the given Fig. 4 that there were differences in soil moisture content in the root propagation zone after adding different rates of biochar materials to the sandy soil compared to no addition. SMC values were increased by increasing the amount of biochar application rate. The highest values of SMC were at 10 t ha^{-1} and the lowest values were when no addition (at the zero rates).

Impact of the interaction between PRD and biochar rate on W_{stress}: Through Fig. 4, the effect of the interaction between the deficit of irrigation and the addition of biochar was shown, where they found that the highest values of the soil moisture content were when irrigating with 100% FI with the addition of the largest rate of biochar, while the lowest values were when applying the partial root drying technique without adding biochar.

Water application efficiency

Impact of PRD on the water application efficiency "WAE": WAE decreased with applying PRD technique compared to irrigation with 100% FI (control treatment) and this was done during the 2019 and 2020 seasons.

Impact of biochar rate on WAE: The impact of the rate of biochar on WAE was shown in Table 4. WAE values differed significantly according to biochar rate use. The values of the WAE increased with the increase in the rate of adding biochar to sandy soil. The highest values of WAE were recorded under the treatment of adding 10 tons of hectares, while the lowest values were recorded under the treatment without the addition of biochar during the 2019 and 2020 seasons, respectively.

Impact of the interaction between PRD and biochar rate on WAE: The results obtained indicate a negative impact of irrigation by PRD and the positive effect of increasing biochar rate on WAE. However, the WAE was decreased in both seasons as a result of reducing the applied amount of irrigation water by PRD and decreasing the rate of biochar use. The highest value of WAE was below 100% FI with an addition of 10 t ha^{-1} for the 2019 and 2020 seasons.

Lemon yield

Impact of PRD on the lemon yield "LY": The impact of the PRD technique on LY is shown in Table 4. The results indicated that LY under water shortage was not affected by reducing the amount of irrigation water added at the level of 50% (PRD) and 100% of full irrigation and this was done during the 2019 and 2020 seasons. There was a significant difference between the LY values under 100% FI and PRD during the 2019 and 2020 seasons. Whereas, the highest values for the productivity of lemon trees (21.57 and 22.95 t ha^{-1} for seasons 2019 and 2020, respectively) were when 50% of the necessary irrigation water was added by applying the PRD technique, compared to the full irrigation using the traditional method.

Table 4: Impact of partial roots drying technique and biochar rate on the yield and water productivity of lemon

Irrigation deficit	Biochar rate, (t ha^{-1})	The yield of fruits, (t ha^{-1}) 2019	The yield of fruits, (t ha^{-1}) 2020	Water productivity (kg_{lemon} m^{-3}_{water}) 2019	Water productivity (kg_{lemon} m^{-3}_{water}) 2020
Impact of PRD on the yield and water productivity lemon					
100% FI		21.09	22.11	2.73	2.90
PRD		21.57	22.95	5.60	6.02
LSD at 5%		0.47	0.80	0.10	0.17
Impact of biochar rates on the yield and water productivity lemon					
	0	17.42	19.25	3.38	3.80
	4	19.23	20.27	3.70	3.98
	6	22.07	21.88	4.33	4.30
	8	23.33	24.73	4.58	4.92
	10	24.58	26.50	4.82	5.30
LSD at 5%		0.63	0.68	0.14	0.14
Impact the interaction of PRD and biochar rates on the yield and water productivity of lemon					
100% FI	0	17.40	18.93	2.23	2.47
	4	19.87	20.27	2.57	2.67
	6	21.37	21.77	2.77	2.83
	8	22.73	24.13	2.93	3.17
	10	24.07	25.43	3.13	3.37
PRD	0	17.43	19.57	4.53	5.13
	4	18.60	20.27	4.83	5.30
	6	22.77	22.00	5.90	5.77
	8	23.93	25.33	6.23	6.67
	10	25.10	27.57	6.50	7.23
LSD at 5%		0.89	0.97	0.20	0.20

FI: Full irrigation and PRD: Partial root drying

Impact of biochar rate on LY: The impact of the rate of biochar on LY was shown in Table 4. LY values differed significantly according to biochar rate use. During the 2019 and 2020 seasons, the best values of LY (24.58 and 26.50 t ha^{-1} for seasons 2019 and 2020, respectively) were recorded under the treatment of adding 10 t ha^{-1}, while the lowest values were recorded under the treatment without the addition of biochar during the 2019 and 2020 seasons, respectively.

Impact of the interaction between PRD technique and biochar rate on LY: The interaction impact of PRD technique and biochar rate was shown in Table 4. Applying PRD and increasing rate of biochar had a positive impact on LY as the LY values improved during the 2019 and 2020 seasons where, the highest values of LY (25.10 and 27.57 for seasons 2019 and 2020, respectively) with PRD with the addition of 10 t ha^{-1} of biochar for the 2019 and 2020 seasons.

Water productivity of lemon fruits

Impact of PRD on the water productivity of lemon "WP_{lemon}: Table 4 showed the impact of PRD on WP_{lemon}. The results showed that the water productivity increased with the increase in the productivity of the lemon and the decrease in the amount of added irrigation water. This is what happened when irrigating at a level of 50% of full irrigation (PRD) compared to 100% for full irrigation, where the highest values of water productivity for lemon were at irrigation by PRD (50% full irrigation).

Impact of biochar rate on WP_{lemon}: The impact of biochar application rate on WP_{lemon} was presented in Table 4 where the values of WP_{lemon} differed significantly according to the rate of biochar usage during the 2019 and 2020 seasons. The best water yield values for lemon were recorded when 10 t ha^{-1} were added, while the lowest values were recorded when not added during the 2019 and 2020 seasons, respectively.

Impact of the interaction between PRD and biochar rate on WP_{lemon}: The interaction impact between PRD and biochar rate is shown in Table 4. Appling PRD and increasing the biochar rate had a positive impact on increasing WP_{lemon} values, the water productivity values of lemon were improved during the 2019 and 2020 seasons, where the lowest values were when irrigated with 100% of full irrigation and without adding biochar, while the highest values were recorded with irrigation at PRD (50% FI) and the addition of 10 t ha^{-1} of biochar for the 2019 and 2020 seasons, respectively.

Table 5: Impact of partial roots drying technique and biochar rate on the fruit diameter, peel thickness and fruit wt of lemon

		Fruit diameter (cm)		Peel thickness (cm)		Fruit wt (g)	
Irrigation deficit	Biochar rate (t ha^{-1})	2019	2020	2019	2020	2019	2020
Impact of PRD on the yield and water productivity lemon							
100% FI		6.6	6.9	0.47	0.45	155.7	164.0
PRD		6.5	6.9	0.47	0.46	180.5	189.6
LSD at 5%		NS	NS	NS	NS	3.045	1.5
Impact of biochar rates on the yield and water productivity lemon							
	0	5.4	5.4	0.53	0.52	141.1	152.9
	4	6.3	6.5	0.50	0.50	157.9	164.6
	6	6.9	7.1	0.50	0.48	175.1	182.6
	8	7.0	7.5	0.42	0.38	180.1	186.9
	10	7.1	7.8	0.40	0.40	186.1	196.9
LSD at 5%		0.4	0.35	0.04	0.05	3.4	3.1
Impact the interaction of PRD and biochar rates on the yield and water productivity of lemon							
100% FI	0	5.3	5.5	0.57	0.53	131.3	143.4
	4	6.3	6.6	0.50	0.47	142.9	147.3
	6	6.8	7.3	0.50	0.50	161.5	168.2
	8	7.2	7.3	0.40	0.37	169.7	174.1
	10	7.2	7.7	0.40	0.40	173.1	186.8
PRD	0	5.4	5.3	0.50	0.50	151.0	162.5
	4	6.3	6.5	0.50	0.53	173.0	181.8
	6	6.9	6.9	0.50	0.47	188.8	197.1
	8	6.9	7.8	0.43	0.40	190.6	199.8
	10	7.0	7.8	0.40	0.40	199.0	207.1
LSD at 5%		NS	NS	NS	NS	4.8	4.4

FI: Full irrigation and PRD: Partial roots drying

Physical properties of lemon fruits

Impact of PRD on fruit diameter "FD", peel thickness"PT" and fruit wt "FW" of lemon: The impact of PRD on FD, PT and FW of lemon are presented in Table 5. The results indicate that, in general, the best values of FD, PT and FW of lemon were achieved under irrigation by PRD (50% from FI) in both seasons of 2019 and 2020.

Impact of biochar rate on fruit diameter "FD", peel thickness "PT" and fruit wt "FW" of lemon: The impact of application rate of biochar on FD, PT and FW of lemon are presented in Table 5. The FD, PT and FW of lemon values were significantly varied according to biochar rate. The best values of FD, PT and FW of lemon were recorded under the treatment of adding 10 t ha^{-1}, while it recorded the worst values under the treatment of no adding of biochar during 2019 and 2020 seasons, respectively.

Impact of the interaction between PRD and biochar rate on FD, PT and FW of lemon: The interaction impact of PRD and biochar rate is shown in Table 5 were PRD and increasing of biochar rate had a positive impact on FD, PT and FW of lemon. FD, PT and FW of lemon values were improved through 2019 and 2020 seasons where, FD, PT and FW of lemon values were recorded as the best values with PRD (50% FI) with adding 10 t ha^{-1} in 2019 and 2020 seasons, respectively.

Chemical properties of lemon fruits

Impact of PRD on the vitamin C " VC" and total soluble solids "TSS" of lemon juice: The impact of PRD on VC and TSS of lemon juice are presented in Table 6. The results indicate that, in general, the highest values of VC and TSS of lemon juice were achieved under irrigation by PRD (50% from FI) in both seasons of 2019 and 2020 whereas it recorded the lowest values in 2019 and 2020 season, respectively with irrigating by100% FI and there were significant differences.

Impact of biochar rate on VC and TSS of lemon juice: The impact of biochar rate on VC and TSS of lemon juice are presented in Table 6. The VC and TSS of lemon juice values were significantly varied according to biochar rate. The highest values of VC and TSS of lemon juice were recorded under the treatment of adding 10 t ha^{-1}, while it recorded the lowest values under the treatment of no adding of biochar during the 2019 and 2020 seasons, respectively.

Impact of the interaction between PRD and biochar rate on VC and TSS of lemon juice: The interaction impact of PRD and biochar rate is shown in Table 6 were PRD and increasing of biochar rate had a positive impact on VC and TSS of lemon juice. VC and TSS of lemon juice values were improved through the 2019 and 2020 seasons where, VC and TSS of

Table 6: Impact of partial roots drying technique and biochar rate on the total soluble solids (TSS) and vitamin C of lemon

		Total soluble solids (%)		Vitamin C mg/100 mL juice	
Irrigation deficit	Biochar rate, (t ha^{-1})	2019	2020	2019	2020
Impact of PRD on the yield and water productivity lemon					
100% FI		7.11	7.59	30.34	32.11
PRD		8.04	8.63	32.10	33.71
LSD at 5%		0.50	0.56	0.95	1.42
Impact of biochar rates on the yield and water productivity lemon					
	0	6.40	7.02	28.40	30.12
	4	7.13	7.68	30.88	32.22
	6	7.63	7.97	31.92	32.98
	8	8.07	8.67	32.30	34.10
	10	8.65	9.23	32.60	35.15
LSD at 5%		0.23	0.20	1.01	0.89
Impact the interaction of PRD and biochar rates on the yield and water productivity of lemon					
100% FI	0	5.83	6.40	27.43	28.37
	4	6.43	6.77	30.10	31.90
	6	7.03	7.37	31.20	32.40
	8	7.90	8.53	31.53	33.73
	10	8.37	8.90	31.43	34.17
PRD	0	6.97	7.63	29.37	31.87
	4	7.83	8.60	31.67	32.53
	6	8.23	8.57	32.63	33.57
	8	8.23	8.80	33.07	34.47
	10	8.93	9.57	33.77	36.13
LSD at 5%		0.32	0.28	NS	1.25

FI: Full irrigation, TSS: Total soluble solids, PRD: Partial root drying and VC: Vitamin C

lemon juice were recorded the highest values with PRD (50% FI) with adding 10 t ha^{-1} in 2019 and 2020 seasons respectively.

DISCUSSION

Soil moisture content "SMC" values decreased by reducing the amount of irrigation water added before irrigation by PRD. This makes sense, because the average moisture content of a large volume of water (100% of full irrigation) is greater than the average moisture content of a small volume of water (50% of full irrigation) within root-zone and that means more water stress when watering with less than FI. It was also clear from the given figure that there were differences in soil moisture content in the root propagation zone after adding different rates of biochar materials to the sandy soil compared to no addition. SMC values were increased by increasing the amount of biochar application rate. This is due to the ability of biochar materials to retain soil moisture within the root-zone region and thus with increasing the rate of this biochar (sustainable materials) and average moisture content within the root-zone region, thus helping to reduce water stress within the root zone of lemon trees. These results are consistent with previous studies[25-27,29].

The decrease in WAE with PRD may be attributed to the interaction of two factors, because as we know that the mechanism of roots drying technique when irrigation, it irrigates one side of tree roots and leaves the other dry and in next irrigation, it exchanges with the other offender that was not previously irrigated, so it irrigates it and leaves the other side dry, which exposes the non-irrigated side to severe drought for a long period, which led to a rise the temperature on the non-irrigated side, in addition to the rapid decomposition of organic matter that collects the grains of sandy soil, which led to a decrease in the ability of soil to hold the added irrigation water inside the root spread area. Based on the above, the low WAE with the PRD technique compared to regular irrigation on 100% of the water needs of lemon trees is due to the high temperature of the un-irrigated area for these trees, which led to a decrease in the viscosity of the water and thus easy escape from the area of spread roots with deep percolation. The increase in the temperature of the soil also increased the rate of decomposition of organic matter in it, which led to the lack of interconnection between the sand grains, which helped the irrigation water escape below the effective area for the spread of the roots by deep seepage. The values of the WAE increased with the increase in the rate of adding biochar to soil, as it was proven by many previous studies that the biochar contains large and high pores, which led to the mechanical storage of the added irrigation water and its retention in the area of root spread and not escaping by deep percolation. These results are consistent with those of[29,35].

There was a significant difference between the LY values under 100% FI and PRD during the 2019 and 2020 seasons. Whereas, the highest values for the productivity of lemon trees were when 50% of the necessary irrigation water was added by applying the PRD technique, compared to the full irrigation using the traditional method. So, despite the increase in moisture stress on one side of the root spread area in exchange with the other side when irrigating by the method of root drying, as well as a decrease in the WAE, the many advantages of applying this technique, which were mentioned above in the introduction, led to significant differences between them and the production values when irrigating with 100% of lemon tree irrigation needs. Increasing in LY by increasing the biochar rate may be due to two reasons, Increasing rate of adding biochar, which led to an increase in the ability of the sandy soils to retain water within the root zone and thus improving the WAE, which led to a reduction of water stress within root-zone of lemon trees, Enrichment of the growing medium with available nutrients as a result of mechanical retention of moisture and mineral fertilizers added within the pores and pockets of the biochar. Applying PRD and increasing the rate of biochar had a positive impact on LY as the LY values improved during the 2019 and 2020 seasons. The main reasons for the erosion and increase of LY under PRD and 10 t ha^{-1} may be attributed to the many advantages resulting from the application of the radical drying technique for the roots in addition to the importance of increasing the addition of biochar in the area of the roots spread because of its great importance in retaining the added irrigation water, which reduces the moisture stress to which the roots of lemon trees are exposed, in addition to the high ability of biochar to retain and hold the nutrients, making it available for a longer duration of absorption by the roots of lemon trees. These results are in agreement with previous study[29,35,40].

The results showed that the water productivity increased with the increase in the lemon productivity and the decrease in the amount of added irrigation water. This is what happened when irrigating at a level of 50% of full irrigation (PRD) compared to 100% for full irrigation, where the highest values of water productivity for lemon were at irrigation by PRD (50% full irrigation). The increase in the WP_{lemon} by increasing of biochar rate may be due to the same reasons as the increase in the yield of lemon.

The increasing of FD, PT, FW, VC and TSS of lemon fruits by increasing of biochar rate might be due to the interaction of two constants, increasing the biochar rate which caused increasing of water holding capacity inside the root zone and then enhancing the WAE hence, mitigation the water stress within the root zone, enriching the growing media with the available nutrients as a result of biochar degradation. The main causes of enhancing the FD, PT, FW, VC and TSS of lemon fruits under PRD and 10 t ha^{-1} might be attributed to the same causes of improving the lemon yield. These results are in agreement with previous study[17-21,23].

CONCLUSION

Many advantages are resulting from the application of the PRD technique for the roots in addition to the importance of increasing the addition of biochar in the area of the roots zone because of its great importance in retaining the added irrigation water, which reduces the moisture stress to which the roots of lemon trees are exposed, in addition to the high ability of biochar to retain and hold the nutrients, making it available for a longer duration of absorption by the roots of lemon trees. Appling of PRD technique and increasing biochar rate had a positive impact on LY, WP and some of the quality traits of lemon. The highest values with PRD (50% FI) and adding 10 t ha^{-1} for seasons of 2019 and 2020, respectively. It could be concluded from the obtained results that using PRD by using 50% FI with biochar rate 10 t ha^{-1} was the most effective treatment where it saved 50% from water requirements for lemon trees and consequently, it can be recommended for application in the same arid Egyptian conditions.

SIGNIFICANCE STATEMENT

This study discovered an improvement in the cultivation of lemon farms using the drip irrigation system under dry climatic conditions and an increase in the yield, water productivity and quality of lemon by using the PRD technique and adding the highest rate from biochar as sustainable materials to sandy soils. This study will help the farmers to choose the appropriate irrigation system technique (PRD) with increasing the adding of corn straw biochar for maximizing and improving the crop yields, water productivity and quality of cultivated crops with minimum additional costs.

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