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MAXIMIZING IRRIGATION WATER USE EFFICIENCY FOR PEPPER BY USING SANDY SOIL COMPRESSION TECHNIQUE UNDER EL-TAL EL-KABIR CONDITIONS

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Optimal management of water and soil is critical for efficiency and productivity in arid and semi-arid areas. This experiment was conducted over two summer seasons (2023 and 2024) in a private farm in El-Tal El-Kabir, Ismailia Governorate, Egypt, using surface drip irrigation with three irrigation levels (IR 100, 75, and 50% of the ETc). The study evaluated the combined effects of soil amendment treatments (T0= clay: 0, humic acid: 0, biochar: 0; T1= clay: 8, humic acid: 10, biochar: 4; T2= clay: 16 t fed^{-1}, humic acid: 20 kg fed^{-1}, biochar: 8 t fed^{-1}) and compression soil levels (0, 4 and 8 passes with a 10 ton roller, at 11% moisture content), on some soil physical properties, quality of peppers, marketable yield, water use efficiency (WUE), irrigation water use efficiency (IWUE) and yield response factor (Ky). The best values for available water, quality parameters and marketable yield were observed at T1, with CP= 4 passes and IR= 100%. While the highest values of WUE and IWUE were 4.04 and 3.55 kg m^{-3} for 2023, 4.16 and 3.64 kg m^{-3} for 2024 under T1, CP= 4 passes, and IR= 75%. The lowest Ky values, 0.23 and 0.21, occurred under the same treatment, revealing the crop's resilience to preserve productivity with deficit irrigation water. This study demonstrates that it is possible to save 33% in irrigation water and increase marketable yield by 11% compared to the control treatment when growing summer pepper with T1, CP= 4 passes and IR= 75%. These results underscore the importance of optimizing soil management and irrigation practices to maximize water use efficiency, marketable yield and agricultural sustainability.

Keywords: soil compression, soil amendments, irrigation water levels

INTRODUCTION

In water-limited regions such as arid and semi-arid regions, water demand is relatively high and scarcity is considered an agricultural issue (Rost et al., 2018) and therefore, water management practices and adaptation strategies to manage agricultural water use is important (Biswas et al., 2025). Effective management of irrigation water and conservation of water resources are essential for sustainable crop production and food security. Improving the hydraulic and physical properties of sandy soils; which dominate many dry areas will also help to improve irrigation water use efficiency (IWUE). Sandy soils are often characterized by poor water retention and high permeability, which often results in substantial water losses due to deep percolation and evaporation (Hillel, 2018). Consequently, soil physical improvement measures such as controlling soil compression and the use of amendments can significantly improve soil water holding capacity and plant water uptake, resulting in less need for irrigation water (Blanco-Canqui and Lal, 2020 and Glab and Gondek, 2025). There is growing interest in complementary strategic approaches targeting issues associated with scarcity, namely improved irrigation decisions and improved agronomic management of soils (Fereres and Soriano, 2007) and effective precision water management for achieving sustainable development goals (Roy et al., 2025).

Some light mechanical compression and the addition of organic amendments of sandy soils may improve soil structure and moisture retention for additional water use efficiency (WUE) without reducing crop yields (Ahmed et al., 2023) and may enhance moisture availability in the root zone, decrease water loss and improve irrigation performance which are important for promoting sustainable agriculture in water-limited systems (Wang et al., 2022).

Soil compression is an important physical process influencing soil structure, especially in sandy soils that have low levels of porosity and water holding capacity; mechanical compressions such as compression (10-ton rollers), with passes at oddly (0, 3, 6 and 9), can dramatically influence soil physical property such as bulk density, compact porosity, or available water (Wang et al., 2022 and Zhang et al., 2023). Moderate levels of compression have been shown to enhance soil particle contact, as well as reducing macro-pores; enhancing water retention capacity while still allowing adequate responses for root growth (Li et al., 2021 and Ahmed et al., 2023). Intensive compression increases bulk density, decreases air-filled soil that limits plant growth and slows water infiltration capacity (Chen et al., 2020). Specifically, Ahmed et al. (2023) suggested that 3-6 passes of a 10-ton roller along with clay, humic acid and biochar amendment prior to planting improved the bulk density, porosity and water retention capacities that still permitted crop growth. Similarly, Liu et al. (2022) concluded that applying organic amendments (gypsum biochar and clay) and moderately compacting soil (about three passes) would enhance the physical properties of soil and initially available water prior to harvesting. Wang et al. (2022) noted that three to six roller passes of compression improved both porosity and water-holding capacity while reducing root permeability damage. Recently, Kumar et al. (2022) reported that three passes were optimal for improving soil structure and avoiding damaging excessive compression levels.

However, Zhang et al. (2023) also pointed out that more than six passes with a roller could cause damaging excess compression with poor crop growth. Also, Zhang et al. (2023) would recommend moderation with 3 to 6 passes with various roll plow designs. Various soil amendments, such as clay (Naylor et al., 2022), along with humic acid and biochar, have now received much attention due to their positive abilities to improve sandy soil properties by increasing the fine particle size component, organic matter and micro-porosity of sandy soils (Singh et al., 2021 and Kumar et al., 2022). Applying and incorporating the addition of these organic amendments can help neutralize the damaging potential of compression by improving soil aggregation, moisture retention, and nutrient availability (Yuan et al., 2021 and Li and Wang, 2023). Studies that combined mechanical compression with amendment rates have indicated a synergistic response when modest compression was combined with higher rates of amendments had a maximum bulk density, where porosity and water holding capacity increased, which may be necessary for crop success for arid and semi-arid climates (Ahmed et al., 2023).

Irrigation management was found to play an important role in adjusting soil physical properties with crop productivity. Increased irrigation levels (full irrigation at 100%) and deficit irrigation with irrigation at 85%, 70% and 55% of crop evapotranspiration) would improve soil moisture availability and plant water status, which directly affect yields and WUE (Fathy et al., 2020 and Zhao et al., 2022). Evidence suggests that applying deficit irrigation combined with moderate compression and amendment rates would not only produce satisfactory yields but also improve WUE and IWUE (Omar and Salem, 2021). The actual evapotranspiration (ETa) and crop yield response factor (Ky) are both perfect parameters to determine crop sensitivity to water deficit under both management conditions (Mahmoud et al., 2021). In sandy soils where pepper is grown, the compression scenarios, together with amendment rates and irrigation levels, can have a substantial effect on growth parameters, yield quality parameters (e.g., fruit size or soluble solids) and water productivity (Wang et al., 2022 and Li et al., 2023). In addition, the results of many studies have reported no or limited response to multiple passes by a roller (3-6) on soil physical quality, crop productivity and water productivity when combined with relatively high amendment rates and regulated deficit irrigation (85%) as earlier indicated (Ahmed et al., 2023 and Zhang et al., 2023).

Moderate soil compression was achieved with three passes with a 10-ton roller and three amendments (clay, humic acid and biochar). This treatment modifies the physical properties of the sandy soil to make it better, through reducing overly high porosity and increasing the bulk density to an optimal density, thus improving the water holding capacity of the soil (Liu et al., 2022 and Kumar et al., 2023). The combination of soil compression with associated amendments helps to hold moisture, which can improve WUE and IWUE by reducing non-beneficial water losses such as surface evaporation and/or deep percolation (Wang et al., 2022 and Ahmed et al., 2023). Additionally, the enhanced water supply promotes better physiological processes in crops, thus improving productivity and quality, at least under partial water stress (Mahmoud et al., 2021 and Omar and Salem, 2021). These findings stress the significance of including soil compression, organic soil management and effective irrigation scheduling to achieve productive crops while using suboptimal water resources in arid sandy soils.

This study aimed to evaluated the impact of different numbers of passes with a 10-ton roller (0, 4 and 8), four rates of soil amendments (clay, humic acid and biochar) and four levels of added irrigation water (IR= 100%, 75% and 50%) using drip irrigation on soil physical properties, yield and quality of peppers, WUE, IWUE, actual ETa and the Ky.

MATERIALS AND METHODS

1. Experiments Layout

Field trials were conducted at the El-Tal El-Kabir, Ismailia Governorate, Egypt, at a private farm (30°29′42″ N; 31°45′18″ E; 17 m a.s.l.) during two consecutive summer seasons (2023 and 2024). The experiment was developed with a split-split plot design with three replications, Summer pepper (*Capsicum annuum, local chili*) was irrigated with a surface drip irrigation system with three levels of irrigation (IR =100%, 75% and 50% of crop evapotranspiration) the three soil amendments (T0: 0 t fed^{-1} clay, 0 kg fed^{-1} humic, 0 t fed^{-1} biochar; T1: 8 t fed^{-1} clay, 10 kg fed^{-1} humic, 4 t fed^{-1} biochar; T2: 16 t fed^{-1} clay, 20 kg fed^{-1} humic, 8 t fed^{-1} biochar) were organized as the sub-plot. The compression treatments (CP = 0, 4 and 8 passes) were applied to the other experimental units and every compression treatment was performed using a 10-ton, 2.17 m wide smooth-wheel roller that was loaded at the optimum moisture content of 11%. Each experimental plot (40 m^2) was separated from adjacent plots by a barren strip (2 m wide) between neighbouring treatments to avoid horizontal water infiltration. Sandy soil physical properties such as bulk density (ρb, g cm^{-3}), total porosity (Pt, %), saturated hydraulic conductivity (Ks, cm h^{-1})

and available water (AW, %) were measured to assess the interactive effects of soil compression (CP), soil amendment treatments (SAT) and levels of irrigation water (IR) on sandy soil physical properties. For the summer pepper crop, measurements were taken for fruit length (L), fruit diameter (D), total soluble solids (TSS), pH, and marketable yield (MY, Mg ha^{-1}) along with calculations of actual (ETa, mm), (WUE, kg m^{-3}), (IWUE, kg m^{-3}), and the yield response factor (Ky, -). Statistical analysis was performed using the CoStat software program, following the methods of Snedecor and Cochran (1989).

2. Soil Characteristics

Before planting, soil samples were taken for determination of some selected physic-chemical properties according to Page et al. (1982) and Klute (1986) (Tables 1 and 2).

Table (1). Some physical characteristics of experimental soil.

Soil depth (cm)	Particle size distribution %					Textural class	OM %	ρ_b g cm^{-3}	P_t %	Ks cm h^{-1}	FC %	WP %	AW %
	C. sand	M. sand	F. sand	Silt	Clay								
0-20	63.35	18.51	11.23	4.19	2.72	S	0.26	1.56	41.31	19.31	13.34	6.58	6.76
20-40	62.42	18.23	10.85	5.04	3.46	S	0.23	1.57	40.75	18.53	12.59	6.75	5.84
40-60	61.69	17.86	10.49	5.72	4.24	S	0.21	1.59	40.00	17.78	11.91	6.83	5.08

C: coarse; M: medium; F: fine; OM: organic matter; ρb: bulk density; Pt: total porosity; Ks: saturated hydraulic conductivity; FC: field capacity; WP: wilting point; AW: available water.

Table (2). Some chemical characteristics of experimental soil.

Soil depth (cm)	EC (dS m^{-1})	pH	$CaCO_3$ %	CEC cmole kg^{-1}	Soluble ions (meq/l) in the saturated soil paste extract							
					Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	CO_3^{--}	SO_4^{--}
0-20	2.17	7.89	17.35	8.51	11.87	1.39	6.93	1.51	8.63	2.71	-	10.36
20-40	2.32	7.75	16.91	9.73	12.39	1.53	7.61	1.67	9.37	3.19	-	10.64
40-60	2.49	7.63	15.87	10.05	12.91	1.76	8.34	1.89	10.21	3.57	-	11.12

3. Quality of Irrigation Water

The chemical analysis of the IR used was conducted according to the methods illustrated by Ayers and Westcot (1994), as shown in (Table 3).

Table (3). Some chemical analysis for irrigation water.

Sample	pH	EC dS m^{-1}	SAR	Soluble cations, meq l^{-1}				Soluble anions, meq l^{-1}			
				Na^+	K^+	Ca^{++}	Mg^{++}	CL^-	HCO_3^-	$CO_3^=$	$SO_4^=$
Mean	7.57	1.83	4.56	8.71	2.29	4.87	2.43	4.35	6.84	-	7.11

4. Soil Amendments Specifications

4.1. Clay (Bentonite) characteristics

The bentonite clay quarries in Kom Oshim, located in Fayoum Governorate, are situated adjacent to the El-Fath industrial area, about 15 km southwest of Fayoum city. This area is regarded as a major source of bentonite clay deposits. The bentonite clay sample was air-dried at 60°C for 48 hours, followed by crushing in a jaw crusher until 100% passed through a 5 mm sieve. Mineralogical analyses were conducted using X-ray diffraction (XRD), shown in Fig. (1).The phases were ordered by their abundance and comprised clay minerals in the following order: Montmorillonite, Kaolinite and Illite. The clay minerals, Quartz and Calcite, were found in small amounts as non-clay minerals. At the same time, the absolute units of the primary fraction sizes of the studied sample had an assessment of the semi-quantitative percentage of observed clay minerals using X-ray fluorescence (XRF). The sample showed a percentage of clay minerals based on the abundance of 83% Montmorillonite and 17% Kaolinite minerals. The physical and chemical analyses were performed for bentonite clay using techniques following the methods described by Page et al. (1982), Klute (1986) and Rivers and Komosa (2016) as shown in Tables (4 and 5).

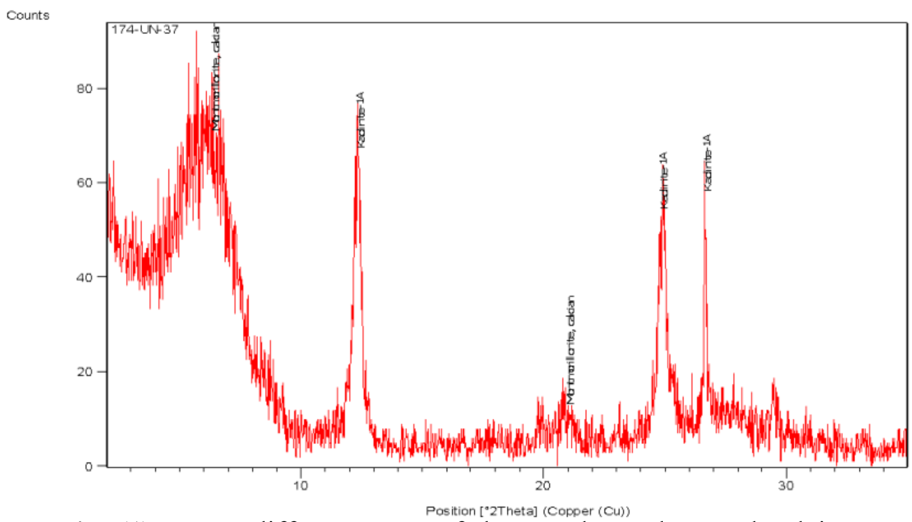


Fig. (1). X-ray diffractograms of the powder and treated calcic Bentonite clay fraction of sample.

4.2. Humic acid characteristics

Physical and chemical characteristics of humic acid powder used in soil amendment are listed in Table (6).

4.3. Biochar characteristics

The Physical and chemical characteristics of biochar used in soil amendment are shown in Table (7).

Table (4). Physical characteristics of the clay (Bentonite) sample.

Particle size distribution %			ρ_b	FC	WP	AW	FSI
Sand	Silt	Clay	g cm^{-3}	%	%	%	ml g^{-1}
6.23	12.31	81.46	0.73	43.16	14.31	28.85	6.53

Table (5). Chemical characteristics of the clay (Bentonite) sample.

EC (dS m^{-1})	pH	CEC cmole kg^{-1}	Cations and anions of soluble salts, %							
			Na^+	K^+	Ca^{++}	Mg^{++}	Cl^-	HCO_3^-	CO_3^{--}	$SO4^{--}$
0.75	7.81	112.37	0.69	0.36	3.94	2.51	0.73	2.28	-	4.49

Table (6). Physical and chemical characteristics of humic acid powder used in soil amendment.

Appearance	Dark brown powder
Humic acid content	74 % (w/w)
Fulvic acid content	18% (w/w)
pH (1:1.5)	6.91
Moisture content	7%
Total organic matter	68%
Organic carbon	52%
Nitrogen (N)	1.54%
Bulk density	0.41 g cm^{-3}

Table (7). Physical and chemical characteristics of biochar used in soil amendment.

Appearance	Black, granular
Organic carbon content	76 % (w/w)
pH	8.13
Moisture content	9%
Total organic matter	82%
Cation exchange capacity	39 cmol kg^{-1}
Ash content	17%
Bulk density	0.53 g cm^{-3}
Surface area	320 m^2 g^{-1}

5. Mineral Fertilization Program

The Ministry of Agriculture provides fertilization rate recommendations for optimal pepper production in the Tel Kabir area of

Ismailia to promote plant growth and obtain high yields. Because of the sandy soil in this area, plants require a well-balanced fertilization program, which supplies the most needed nutrients. The following fertilization recommendations were provided:

- Superphosphate (100 kg fed^{-1}) - Phosphorus as a nutrient for root establishment and early growth.
- Ammonium Nitrate (150 kg fed^{-1} supplied in 3 splits) - For vegetative growth when the plant is in active growth stage.
- Potassium Fertilizer (100 kg fed^{-1}) - For fruit development and resistance against diseases during flowering and fruit set.
- Calcium Fertilizer (50 kg fed^{-1}) - Ensures fruit set, keeps blossom-end rot from occurring, and improves fruit quality.

6. Measurement of Soil Physical Properties

6.1. Total porosity

$$P_t = 1 - (\rho_b / \rho_s) \text{ X } 100 \quad (\%) \text{ (Brady, 1974)}$$

Where:

ρ_b: bulk density, g cm^{-3}

ρ_s: particle density, 2.65 g cm^{-3}

6.2. Saturated hydraulic conductivity

$$Ks = Q.L / A.\ \Delta H \quad (\text{cm } h^{-1}) \text{ (Hillel, 2013)}$$

Where:

Q: steady state discharge, $cm^3\ h^{-1}$

L: distance between upper and lower points of the sample, cm

ΔH: change of the hydraulic head, cm

A: cross-sectional area of the sample, cm^2

6.3. Available water

$$AW = \theta_{fc} - \theta_{wp} \qquad (\%) \text{ (Brady and Weil, 2008)}$$

Where:

θ_{fc}: field capacity at a suction pressure of (− 0.33 bar), (%)

θ_{wp}: wilting point at a suction pressure of (− 15 bars), (%)

7. Reference Evapotranspiration (ETo)

The reference evapotranspiration (ETo) values from Table (8) were generated using CropWat 8 software and the FAO-56 Penman-Monteith equation (Allen et al., 1998).

Table (8). Calculated reference evapotranspiration (mm day^{-1}) through summer pepper growth period.

Month	Mar	Apr	May	Jun	Jul
ETo mm day^{-1}	3.03	3.57	5.24	6.49	6.95

8. Crop Evapotranspiration (ETc)

The crop evapotranspiration (ETc) delivered in Table (9) was estimated using the following equation:

$$ETc = Kc_{FAO} \cdot ETo \quad (mm\ day^{-1})$$ (Allen et al., 1998)

Where:

Kc_{FAO}: crop coefficient from FAO No. (56)

ETo: reference crop evapotranspiration, mm day^{-1}

9. Applied Irrigation Water Levels (IR)

The amounts of applied IR levels for summer pepper crop revealed in Table (10) were calculated by using the equation:

$$IR_{100,\ 75,\ 50\%} = (ETc - pe)Kr / Ea) + LR \quad (mm\ period^{-1})$$

(Keller and Karmeli, 1974)

Where:

Kr: correction factor for limited wetting according to the 80% pepper canopy coverage, Kr = 0.90. (Smith, 1992).

Ea: irrigation efficiency for surface drip irrigation system 85% (Allen et al., 1998).

Pe: effective rainfall, 10 mm $season^{-1}$.

LR: leaching requirements, (0.19 x ETc), mm.

Table (9). Calculated crop evapotranspiration (mm day^{-1}) through summer pepper growth period.

Stages Planting date	Initial 13/03 to 11/04	Develop. 12/04 to 16/05	Mid 17/05 to 25/06	Late 26/06 to 15/07	Seasonal 13/03 to 15/07
Period length (day)	30	35	40	20	125
Kc_{FAO} (-)	0.60	0.83	1.05	0.90	--------
ETo (mm)	96.84	151.67	240.85	136.70	626.06
$ETc_{100\%}$ (mm)	58.10	125.89	252.89	123.03	559.91
Eff. Rainfall (mm)	6.00	4.00	0.00	0.00	10.00

Table (10). Calculated added irrigation water levels (IR), mm through pepper plant growth period.

IR (%)	Applied irrigation water (mm) Growth stages				
	Initial	Development	Mid	Late	Seasonal
100	66.01	152.55	314.97	153.23	686.76
75	49.51	114.41	236.23	114.92	515.07
50	33.01	76.28	157.49	76.62	343.39

10. Actual Evapotranspiration

$$ETa = (M2\% - M1\%) / 100 \cdot db \cdot D \quad (mm)$$

(Doorenbos and Pruitt, 1984)

Where:
M_2: moisture content after irrigation %
M_1: moisture content before irrigation %
d_b: specific density of soil
D: mean depth, mm

11. Water Use Efficiency

$$WUE = MY / ETa$$ (Howell et al., 2001)

Where:
MY: marketable yield of summer pepper crop, (Ma ha^{-1}).

12. Irrigation Water Use Efficiency

$$IWUE = MY / IR \quad (kg\ m^{-3})$$ (Michael, 1978)

Where:
IR: seasonal applied irrigation water, (m^3), Table (10).

13. Yield Response Factor (Ky)

$$(1- MY/ Ym) = Ky\ (1- ETa/ ETm)$$ (Allen et al., 1998)

Where:
ETa: actual evapotranspiration, mm $season^{-1}$
ETm: crop evapotranspiration (without stress), mm $season^{-1}$
Ym: maximum yield at $IR_{100\%}$, Ma ha^{-1}

RESULTS

1. Impact of CP and IR on Some Physical Characteristics of Sandy Soil under Various SAT Treatments

1.1. Bulk density

Across all treatments, bulk density (bp) was significantly increased with higher CP and IR (Table 11). This was consistent during the 2023 and 2024 growing seasons in the 20 cm depth. The ρb was the lowest under the T2, CP = 0 passes and IR = 50% treatment, which reached 1.48 and 1.47 g cm^{-3} for the 2023 and 2024 seasons, respectively. The highest ρb values were recorded under T2, CP = 8 passes and IR = 100% treatment, where ρb measurements reached 2.12 and 2.09 g cm^{-3} for each respective growing season.

1.2. Total porosity

Table (11) illustrates the impacts of SAT, Soil Compression (CP) and applied Irrigation (IR) water levels on the total porosity (Pt) of sandy soil during the 2023 and 2024 growing seasons. In general, Pt declines as CP and IR increase across all treatments. The nature was similar at the 20.0 cm depth for both the 2023 and 2024 growing seasons. The lowest average Pt was associated with treatment T2, CP = 8 passes, IR = 100%, with values of 20.00 and 21.13% during the two growing seasons, respectively. The highest average Pt was associated with T2, CP = 0 passes, and IR = 50% treatment with values of 44.15 and 44.53 %, respectively.

1.3. Saturated hydraulic conductivity

Table (11) reveals the relationship between SAT, CP and IR levels on saturated hydraulic conductivity (Ks) in sandy soils. Overall, the Ks measurements decreased with increased CP but increased with higher IR regardless of treatment in this study. This pattern of decreasing Ks with increased CP and increased Ks with higher irrigation (IR) was consistent at 20 cm for both the growing seasons (2023 and 2024). The lowest Ks measurements were under treatment T2, CP = 8 passes (12.63 MPa) and IR = 50% with values of 4.15 and 4.06 cm h^{-1} in 2023 and 2024, respectively. The higher Ks (T0, CP = 0 passes (0.01 MPa), IR = 100%; values of 19.38 and 18.95 cm h^{-1} in 2023 and 2024, respectively.

1.4 Available water

The impact of SAT, CP and IR on the available water (AW) in sandy soil showed that the highest AW values were 12.94 and 12.68% for the 2023 and 2024 seasons respectively, under T1, CP = 4 passes and IR = 100% treatment (Table 11). In contrast, the lowest AW values were recorded under treatment T2, CP = 8 passes and IR = 50%, with 2.79 and 2.73% for the respective seasons.

2. Impact of CP and IR on Pepper Quality Parameters under Various SAT Treatments

The values in Tables (12 and 13) show the combined effects of SAT, CP and IR on the quality parameters of the summer pepper crop (i.e., fruit length (L), fruit diameter (D), total soluble solids (TSS) and juice pH (pH). The quality indicators of fruit increased overall with irrigation levels and SAT treatments whereas the addition of CP generally decreased fruit quality. The highest values of fruit L and D were obtained under T1, CP = 4 passes and IR = 100% treatment with lengths of 16.78 and 4.96 cm for season 2023 and 17.11 and 5.06 cm for season 2024, respectively. The lowest values were observed under T2, CP = 8 passes, and IR = 50% treatment with lengths of 5.37 and 2.31 cm for season 2023 and 5.49 and 2.35 cm for season 2024, respectively. The highest TSS were observed under T1, CP = 4 passes and IR = 100% treatment at 9.72 and 9.94%, for both seasons, respectively, while the lowest TSS were taken from T2, CP = 8 passes and IR = 50% treatment at 4.69 and 4.79% for both seasons, respectively. The highest juice pH values were obtained under treatment T2, CP = 0 passes and IR = 100% treatment at 6.07 and 6.19 for both seasons, respectively. In contrast, the lowest juice pH was obtained under treatment T2, CP = 8 passes, and IR = 50% at 4.13 and 4.21 for both seasons, respectively. Moderate CP and soil amendments (i.e., clay, humic acid and biochar) in the T1 treatment improved soil structure this enhancing water retention and root development and improving the quality of the fruit, particularly in terms of fruit size and total soluble solids (TSS).

Table (11). Impact of soil compression (CP) and irrigation levels (IR) on bulk density (ρb), total porosity (Pt), saturated hydraulic conductivity (Ks), and available water (AW) for sandy soil under different soil amendment treatments (SAT) at a depth of 20 cm during the 2023 and 2024 seasons.

SAT	CP (passes)	IR (%)	ρb ($g\ cm^{-3}$)		Pt (%)		Ks ($cm\ h^{-1}$)		AW (%)	
			1st	2nd	1st	2nd	1st	2nd	1st	2nd
T0	0	100	1.58n	1.56n	40.38e	41.13d	19.38a	18.95a	6.75g	6.61g
		75	1.56o	1.54o	41.13d	41.89d	17.54b	17.16b	5.06i	4.96i
		50	1.53p	1.52p	42.26c	42.64c	13.46e	13.17e	4.38k	4.29k
	4	100	1.64l	1.62m	38.11g	38.87g	17.38b	17.00b	7.61f	7.45f
		75	1.61m	1.60m	39.25f	39.62f	14.54d	14.23d	5.72h	5.60h
		50	1.59n	1.57n	40.00e	40.75e	12.46f	12.19f	4.82j	4.72j
	8	100	1.89f	1.87g	28.68o	29.43o	11.41g	11.16g	5.81h	5.69h
		75	1.86g	1.85g	29.81n	30.19n	9.65h	9.43h	4.89j	4.79j
		50	1.84h	1.83h	30.57m	30.94n	7.23j	7.07j	3.57m	3.50m
T1	0	100	1.56o	1.54o	41.13d	41.89d	17.56b	17.18b	8.91e	8.73e
		75	1.53p	1.52p	42.26c	42.64c	15.62c	15.28c	7.68f	7.52f
		50	1.51q	1.50q	43.02b	43.40b	12.34f	12.07f	4.46k	4.37k
	4	100	1.72j	1.71k	35.09j	35.47j	13.38e	13.08e	12.94a	12.68a
		75	1.69k	1.67l	36.23i	36.98i	11.54g	11.29g	11.89b	11.65b
		50	1.66l	1.65l	37.36h	37.74h	8.46i	8.27i	5.57h	5.46h
	8	100	1.99d	1.98d	24.91r	25.28r	9.63h	9.42h	5.19i	5.08i
		75	1.97d	1.95e	25.66q	26.42q	7.81j	7.64j	4.07l	3.98l
		50	1.94e	1.92f	26.79p	27.55p	5.36l	5.25l	3.23n	3.16n
T2	0	100	1.53p	1.52p	42.26c	42.64c	15.42c	15.08c	10.23c	10.02c
		75	1.51q	1.49q	43.02b	43.77b	13.75e	13.46e	9.42d	9.23d
		50	1.48r	1.47r	44.15a	44.53a	11.51g	11.27g	5.62h	5.51h
	4	100	1.83h	1.81h	30.94m	31.70m	11.38g	11.13g	11.86b	11.62b
		75	1.81h	1.79i	31.70l	32.45l	9.54h	9.34h	10.18c	9.98c
		50	1.79i	1.76j	32.45k	33.58k	6.46k	6.32k	4.91j	4.81j
	8	100	2.12a	2.09a	20.00u	21.13u	8.27i	8.09i	4.87j	4.77j
		75	2.09b	2.06b	21.13t	22.26t	6.59k	6.45k	3.65m	3.57m
		50	2.05c	2.03c	22.64s	23.40s	4.15m	4.06m	2.79o	2.73o

T0: (0 t fed^{-1}clay, 0 kg fed^{-1} humic acid, 0 t fed^{-1} biochar)
T1: (8 t fed^{-1}clay, 10 kg fed^{-1} humic acid, 4 t fed^{-1} biochar)
T2: (16 t fed^{-1}clay, 20 kg fed^{-1} humic acid, 8 t fed^{-1} biochar)

3. Impact of CP and IR On MY For Pepper Performance under Various SAT Treatments

Combined effects of SAT, CP and IR on summer pepper marketable yield (MY) increased with increases in irrigation levels and SAT treatments (Fig. 2 and 3). The study showed that it was likely that over-compression of the soil decreased MY production. The highest values of MY were 19.37 and 19.71 Mg ha^{-1} for the 2023 and 2024 seasons, respectively, under T1, CP = 4 passes, and IR = 100% treatment. In contrast, the lowest MY values were 2.43 and 2.59 Mg ha^{-1} for both seasons, respectively, under T2, CP = 8 passes, and IR = 50% treatment.

Table (12). Impact of soil compression (CP) and irrigation levels (IR) on fruit length (L), fruit diameter (D), total soluble solids (TSS), and juice pH of pepper crop under different soil amendment treatments (SAT) during the 2023 season (Average ± standard deviation).

SAT	CP (passes)	IR (%)	L (cm)	D (cm)	TSS (%)	pH (-)
T0	0	100	14.24d ± 0.36	4.31h ± 0.14	8.35f ± 0.21	5.81e ± 0.15
		75	12.62f ± 0.31	4.08i ± 0.13	8.03h ± 0.19	5.63i ± 0.14
		50	7.49l ± 0.24	2.67s ± 0.10	6.49l ± 0.17	5.29m ± 0.12
	4	100	14.98c ± 0.34	4.41f ± 0.13	8.57e ± 0.20	5.87d ± 0.14
		75	13.71e ± 0.31	4.29h ± 0.11	8.25g ± 0.18	5.68h ± 0.13
		50	8.53k ± 0.28	2.93p ± 0.09	6.72k ± 0.16	5.34l ± 0.11
	8	100	12.27f ± 0.36	3.35j ± 0.12	5.69m ± 0.18	5.16n ± 0.14
		75	9.85h ± 0.31	2.98o ± 0.11	5.41n ± 0.17	4.89p ± 0.13
		50	7.53l ± 0.29	2.63t ± 0.07	5.13p ± 0.12	4.53r ± 0.08
T1	0	100	15.81b ± 0.39	4.68d ± 0.15	8.87d ± 0.21	5.93c ± 0.17
		75	13.95e ± 0.34	4.35g ± 0.13	8.61e ± 0.19	5.71g ± 0.15
		50	8.46k ± 0.27	2.97o ± 0.08	6.98j ± 0.14	5.35l ± 0.12
	4	100	16.78a ± 0.41	4.96a ± 0.17	9.72a ± 0.23	5.98b ± 0.18
		75	15.53b ± 0.39	4.71c ± 0.15	9.39b ± 0.21	5.76f ± 0.16
		50	9.37i ± 0.31	3.25k ± 0.11	7.57i ± 0.17	5.42j ± 0.13
	8	100	11.92g ± 0.38	3.16l ± 0.12	5.45n ± 0.18	4.98o ± 0.14
		75	9.15i ± 0.32	2.84q ± 0.08	5.23o ± 0.14	4.71q ± 0.09
		50	6.74m ± 0.28	2.49u ± 0.06	4.96q ± 0.12	4.37s ± 0.07
T2	0	100	16.09a ± 0.42	4.82b ± 0.19	9.12c ± 0.25	6.07a ± 0.21
		75	14.21d ± 0.31	4.57e ± 0.12	8.85d ± 0.19	5.84e ± 0.14
		50	8.74j ± 0.29	3.01n ± 0.08	7.21i ± 0.15	5.41j ± 0.12
	4	100	15.52b ± 0.36	4.65d ± 0.13	8.84d ± 0.20	5.92c ± 0.14
		75	14.87c ± 0.34	4.43f ± 0.10	8.47f ± 0.17	5.71g ± 0.12
		50	8.61j ± 0.29	3.07m ± 0.07	6.95j ± 0.14	5.37k ± 0.11
	8	100	9.79h ± 0.38	3.07m ± 0.09	5.17p ± 0.16	4.75q ± 0.13
		75	7.54l ± 0.33	2.75r ± 0.07	4.91q ± 0.14	4.49r ± 0.11
		50	5.37n ± 0.26	2.31v ± 0.05	4.69r ± 0.12	4.13t ± 0.09

T0: (0 t fed^{-1}clay, 0 kg fed^{-1} humic acid, 0 t fed^{-1} biochar)
T1: (8 t fed^{-1}clay, 10 kg fed^{-1} humic acid, 4 t fed^{-1} biochar)
T2: (16 t fed^{-1}clay, 20 kg fed^{-1} humic acid, 8 t fed^{-1} biochar)

Table (13). Impact of soil compression (CP) and irrigation levels (IR) on fruit length (L), fruit diameter (D), total soluble solids (TSS), and juice pH of pepper crop under different soil amendment treatments (SAT) during the 2024 season (Average ± standard deviation).

SAT	CP (passes)	IR (%)	L (cm)	D (cm)	TSS (%)	pH (-)
T0	0	100	14.52e ± 0.34	4.39h ± 0.12	8.53g ± 0.19	5.92d ± 0.13
		75	12.87g ± 0.29	4.16i ± 0.11	8.21i ± 0.17	5.74g ± 0.12
		50	7.64m ± 0.23	2.72s ± 0.09	6.63n ± 0.16	5.39j ± 0.11
	4	100	15.26d ± 0.32	4.50f ± 0.11	8.76e ± 0.18	5.98d ± 0.13
		75	13.98f ± 0.30	4.38h ± 0.10	8.43h ± 0.16	5.79f ± 0.12
		50	8.70l ± 0.26	2.99p ± 0.08	6.87m ± 0.14	5.45i ± 0.10
	8	100	12.51g ± 0.35	3.42j ± 0.11	5.82o ± 0.16	5.26k ± 0.12
		75	10.03i ± 0.29	3.04o ± 0.10	5.53p ± 0.15	4.98m ± 0.11
		50	7.67m ± 0.27	2.68s ± 0.06	5.25r ± 0.11	4.62o ± 0.07
T1	0	100	16.12b ± 0.38	4.76d ± 0.13	9.07d ± 0.19	6.04c ± 0.15
		75	14.23f ± 0.32	4.43g ± 0.11	8.80e ± 0.17	5.82f ± 0.13
		50	8.62l ± 0.25	3.02o ± 0.07	7.14l ± 0.12	5.45i ± 0.11
	4	100	17.11a ± 0.39	5.06a ± 0.14	9.94a ± 0.21	6.09b ± 0.16
		75	15.82c ± 0.37	4.80c ± 0.13	9.60b ± 0.19	5.87e ± 0.14
		50	9.54j ± 0.30	3.31k ± 0.10	7.74j ± 0.15	5.52h ± 0.12
	8	100	12.17h ± 0.36	3.21l ± 0.11	5.57p ± 0.16	5.07l ± 0.13
		75	9.34j ± 0.30	2.89q ± 0.07	5.35q ± 0.12	4.80n ± 0.08
		50	6.89n ± 0.27	2.54t ± 0.05	5.07s ± 0.11	4.45p ± 0.06
T2	0	100	16.40b ± 0.41	4.91b ± 0.17	9.32c ± 0.23	6.19a ± 0.19
		75	14.49e ± 0.29	4.65e ± 0.11	9.04d ± 0.17	5.95d ± 0.13
		50	8.91k ± 0.27	3.07n ± 0.07	7.37k ± 0.13	5.51h ± 0.11
	4	100	15.84c ± 0.35	4.74d ± 0.11	9.03d ± 0.18	6.03c ± 0.13
		75	15.16d ± 0.32	4.52f ± 0.09	8.65f ± 0.16	5.82f ± 0.11
		50	8.78l ± 0.28	3.13m ± 0.06	7.10l ± 0.13	5.47i ± 0.10
	8	100	10.01i ± 0.37	3.12m ± 0.07	5.28r ± 0.14	4.84n ± 0.11
		75	7.72m ± 0.31	2.80r ± 0.06	5.02s ± 0.12	4.58o ± 0.09
		50	5.49o ± 0.24	2.35u ± 0.04	4.79t ± 0.10	4.21q ± 0.07

T0: (0 t fed^{-1}clay, 0 kg fed^{-1} humic acid, 0 t fed^{-1} biochar)
T1: (8 t fed^{-1}clay, 10 kg fed^{-1} humic acid, 4 t fed^{-1} biochar)
T2: (16 t fed^{-1}clay, 20 kg fed^{-1} humic acid, 8 t fed^{-1} biochar)

4. Impact of CP and IR on ETa for Pepper Performance under Various SAT Treatments

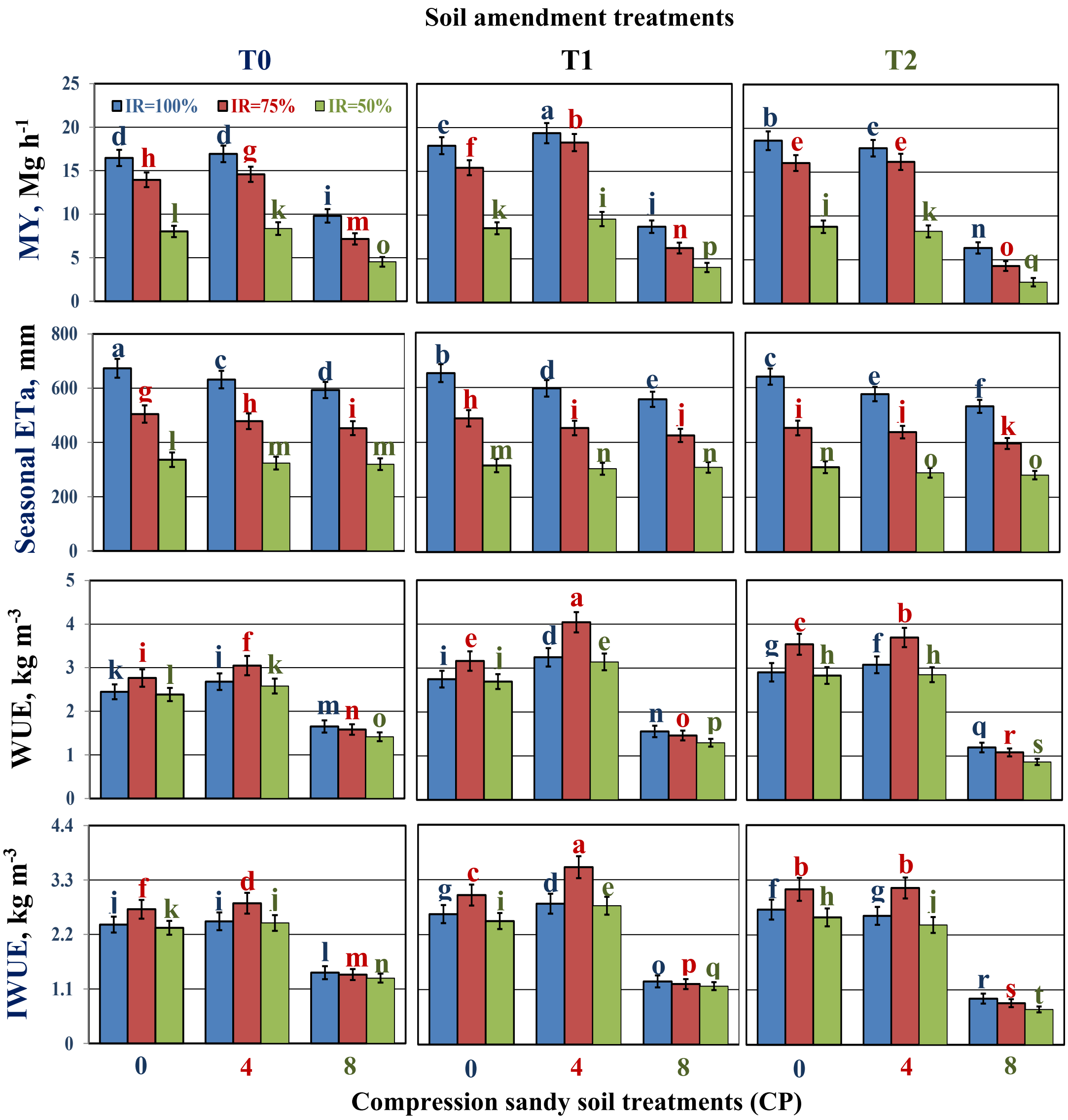
Similar to MY, the combined effects of SAT, CP and IR on the actual ETa for summer pepper increased with increases in irrigation levels while decreasing with increases in SAT treatments and over compression of the soil (Fig. 2 and 3). The lowest ETa values were 280.65 and 278.07 mm for the 2023 and 2024 seasons, respectively, under T2, CP = 8 passes, and IR = 50% treatment. Conversely, the highest ETa values were 673.12 and 671.36 mm season^{-1}, respectively, under T0, CP = 0 passes and IR = 100% treatment for both seasons.

5. Impact of CP and IR on WUE and IWUE for Pepper Performance under Various SAT Treatments

The maximum values of WUE and IWUE that showed the joint effects of SAT, CP and IR on WUE and IWUE for summer pepper were 4.04 and 3.55 kg m^{-3} for the 2023 season and 4.16 and 3.64 kg m^{-3} for the 2024 season, under treatment T1, CP = 4 passes, and IR = 75%. However, the minimum values of WUE and IWUE were 0.87 and 0.71 kg m^{-3} for the 2023 season and 0.93 and 0.75 kg m^{-3} during the 2024 season, under treatment T2, CP = 8 passes and IR = 50%. Moreover, the WUE and IWUE values under treatment T1, CP = 4 passes and IR = 75%, revealed a substantial increase of about 65 and 48 % during the 2023 season and 66 and 49 % during the 2024 season, compared to the control treatment T0, CP = 0 passes and IR = 100%.

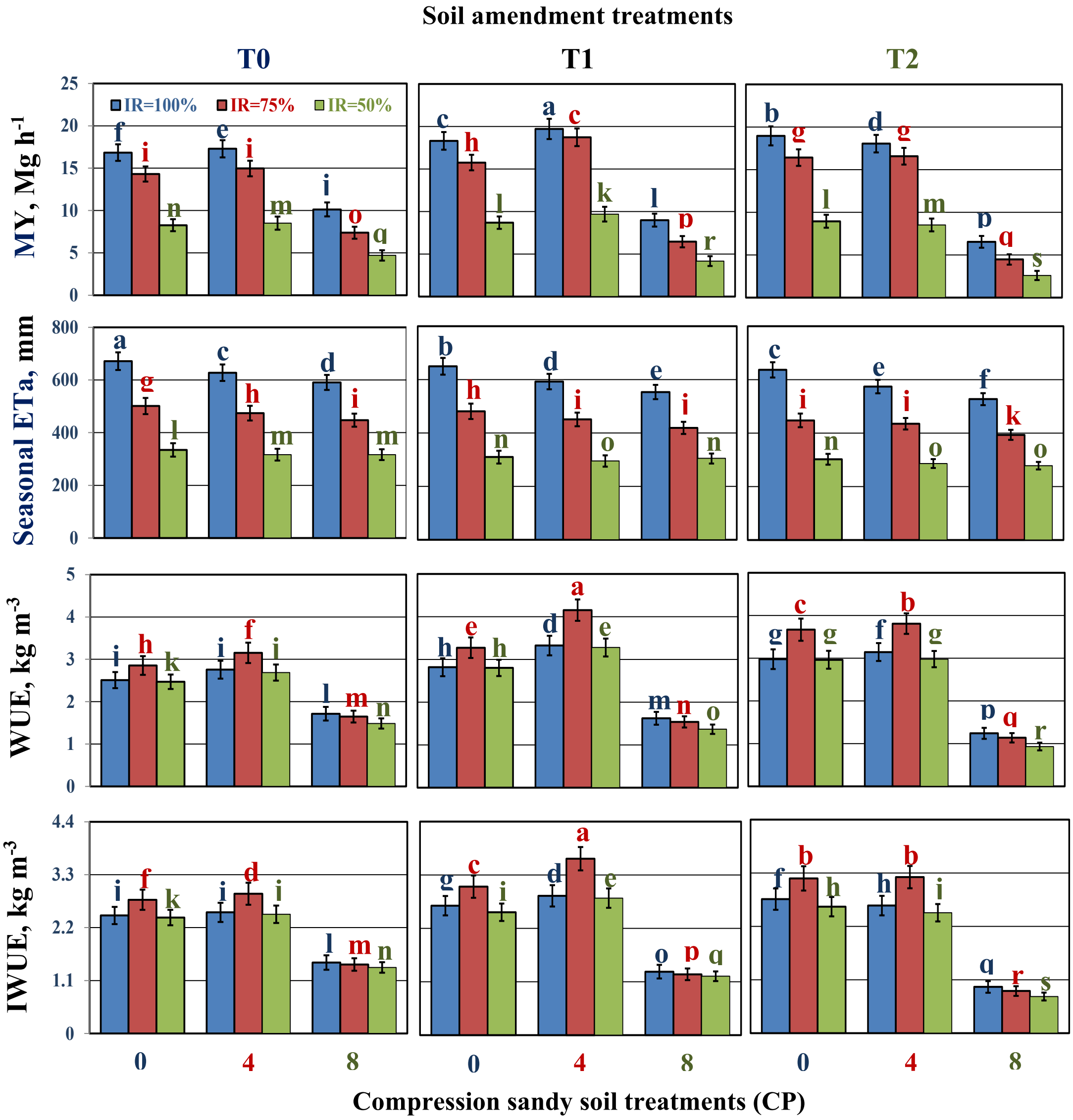
6. Impact of CP and IR on Ky for Pepper Performance under Various SAT Treatments

Ky for summer pepper, revealed a linear relationship (Fig. 4) between the relative reduction in actual evapotranspiration (1-(ETa/ETmax)) and the relative reduction in yield (1-(Ya/Ymax). For the 2023 season, the measure of correlation for Ky was highly significant and positive. The Ky values of the CP and under the (SAT = 10) for the 0, 4 and 8 levels were: r = 0.969**, 0.962** and 1.00** respectively. Also, The Ky values for the T1 treatment for CP levels of 0, 4, and 8 were (r = 0.962, 0.897** and 1.00**). The Ky values for T2 treatment for CP levels of 0, 4, and 8 were (r = 0.932**, 0.925**, and 1.00**). In addition, the relationships between 1-(ETa/ETmax) and 1-(Ya/Ymax) for the 2024 season followed the same pattern across all CP levels under T0, T1, and T2 treatments (Fig. 4). Furthermore, Ky values for summer pepper decreased as IR and SAT increased for all CP passes under T0, T1, and T2 treatments (Fig. 5). The lowest Ky values were recorded for the T1, CP =4 passes, and IR =75% treatment of 0.23 and 0.21 for the 2023 and 2024 seasons, respectively, while the highest Ky values were recorded for T2, CP = 8 passes, and IR = 50% treatment with 1.31 and 1.28 for the first and second season respectively.



T0: (0 t fed^{-1}clay, 0 kg fed^{-1} humic acid, 0 t fed^{-1} biochar)
T1: (8 t fed^{-1}clay, 10 kg fed^{-1} humic acid, 4 t fed^{-1} biochar)
T2: (16 t fed^{-1}clay, 20 kg fed^{-1} humic acid, 8 t fed^{-1} biochar)

Fig. (2). Impact of sandy soil compression treatments (CP) and irrigation water levels (IR) on marketable yield (MY), seasonal actual evapotranspiration (ETa), water use efficiency (WUE) and irrigation water use efficiency (IWUE) of pepper crop under different soil amendment treatments (SAT) during the 2023 season.



T0: (0 t fed[-1]clay, 0 kg fed[-1] humic acid, 0 t fed[-1] biochar)
T1: (8 t fed[-1]clay, 10 kg fed[-1] humic acid, 4 t fed[-1] biochar)
T2: (16 t fed[-1]clay, 20 kg fed[-1] humic acid, 8 t fed[-1] biochar)

Fig. (3). Impact of sandy soil compression treatments (CP) and irrigation water levels (IR) on marketable yield (MY), seasonal actual evapotranspiration (ETa), water use efficiency (WUE) and irrigation water use efficiency (IWUE) of pepper crop under different soil amendment treatments (SAT) during the 2024 season.

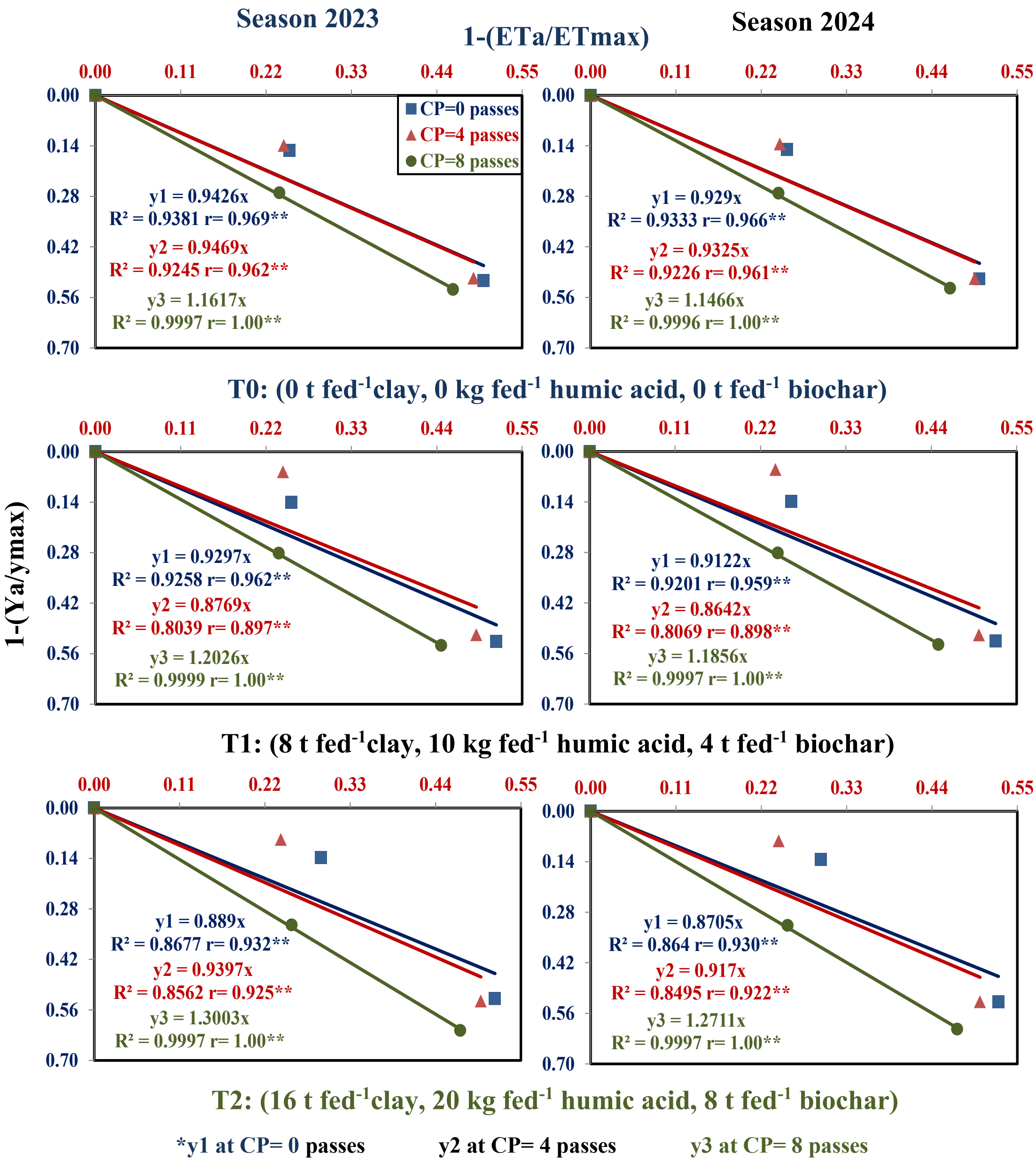


Fig. (4). Relationship between the decrease in marketable yield (MY) and actual evapotranspiration stress (ETa), mm season^{-1}, of pepper crop under different soil amendment treatments (SAT), sandy soil compression treatments (CP), and irrigation water levels (IR) for seasons 2023 and 2024.

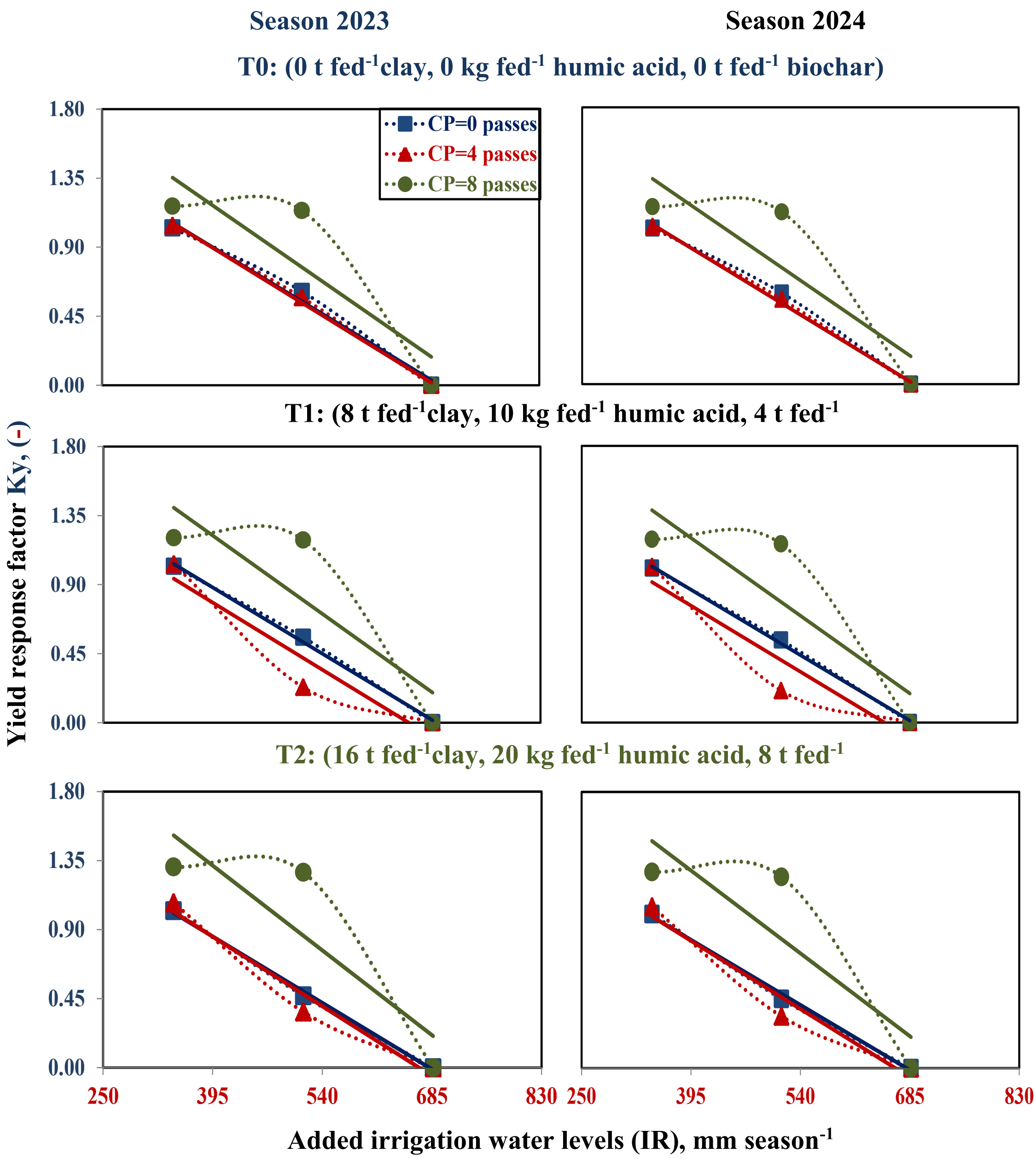


Fig. (5). Impact of irrigation water levels (IR) and sandy soil compression treatments (CP) on the yield response factor (Ky) of pepper crop under different soil amendment treatments (SAT) for seasons 2023 and 2024.

DISCUSSION

This study has indicated a significant effect of irrigation water and soil compression (CP) on major physical properties of sandy soils (bulk density (ρb), total porosity (Pt). The example of irrigation and the volumetric water contents are expected to be higher. Therefore, the wet weight is most likely higher. Therefore, the bulk density delivered is greater. This is consistent with Hillel (2018) findings as they note that irrigation increases soil moisture, and in turn, soil moisture leads soil bulk density to be higher.

Furthermore, soil compression led to a reduction in porosity and, hence, increased bulk density. This is documented and consistent with Wang et al. (2022) and Ahmed et al. (2023) as they document that compression leads to a decrease in macro-porosity, decreases water infiltration, or reduces water retention (areal extension). The findings from the study provide a good advice to Egyptian farmers since water resources are scarce and limited, and soils are generally sandy soils to maintain irrigation and manage compression in order to maintain soil health and contribute to their water holding capacity or improve it (Hillel, 2018 and Blanco-Canqui and Lal, 2020).

Soil amendments, such as clay, humic acid and biochar, had an impactful combination of effective plant growth with T2 treatment, resulting in significant increases in ρb. Soil amendments improve soil aggregation, which then leads to improved soil structure. Conversely, enhanced soil structure increases soil stability and, ultimately, soil's ability to hold water. Overall, this improves structure and mitigates the factors that cause CP to support improved sustainability of farming practices wherever possible (Singh et al., 2021 and Li and Wang, 2023). Blanco-Canqui and Lal (2020) stated that at moderate CP levels, implementing compression could increase water retention by increasing bulk density and limiting macro-porosity. Given this, soil amendments benefits Egyptian farmers aiming at improvement of soil condition and water-holding capacity is especially important in a water-limited situation such as Egypt (Li et al., 2021 and Yuan et al., 2021).

This study suggests that soil amendments, like clay, humic acid and biochar, improve micro-porosity and water-holding capacity and augment root growth. This was significant when considering moderate compression, with soil amendments allowing water-holding potential at a greater porosity. The results of this study are in line with Yuan et al. (2021) and Li and Wang (2023), where soil amendments can form fine particle fractions providing better soil structure and reduced degradation from farmers with useful excessive CP. For Egyptian farmers cultivating sandy soils, results of this study are useful in the field of fast-drying water profile, evaporation of soil water and limited water supply, that typically face farmers in arid lands (Fathy et al., 2020 and Zhao et al., 2022).

Irrigation management was identified as another critical area for improving WUE and IWUE. The study showed that the effective management of irrigation (applied at 75% of crop evapotranspiration) in combination with moderate CP and organic amendment resulted in improvement for WUE and IWUE by approximately 65% and 48% improvements, respectively. This result supports the theories of Fathy et al. (2020) and Zhao et al. (2022) who stated that deficit irrigating crops, along with good practices of soil management, could improve water productivity since loss to non-beneficial forms of water reductions could be minimized, using less water to produce the same yields effectively. The information provided here is helpful practical pathway for farmers and decision-makers throughout Egypt to develop strategies to use water more efficiently while maintaining or increasing their yield while likewise facing challenges of decreased water availability (Hillel, 2018 and Ahmed et al., 2023).

The Ky is a widely recognized measure of crop resilience to water stress (Boyacı et al., 2025). The T1, CP = 4 passes IR = 75% treatment in this study had low Ky values to indicate that the crops in that treatment were more resilient to water stress. This is in line with Mahmoud et al. (2021), who stated that Ky values less than 1.0 reflect greater tolerance to water stress and enhanced development in water-limited conditions. The higher Ky values were from the T2, CP = 8 passes IR = 50% treatment, which reinforces the importance of managing CP and irrigation to reduce crop yield losses when plants are under water stress. This study is very relevant for Egyptian agriculture with the increased risk of drought and low water availability and lays the groundwork for developing crop resilience (Mahmoud et al., 2021 and Omar and Salem, 2021).

The results showed that soil amendments and moderate soil compression, in addition to selected irrigation management practices, have resulted in greater crop quality as a result of increased fruit size and total soluble solids. The benefits of the practices in this study are consistent with Li et al. (2021) and Ahmed et al. (2023), who showed similar improvements to soil structure and nutrient availability. The advantages of the practices for farmers in Egypt would help support water conservation and better quality produce for local consumption and export, which enhances the economy (Li et al., 2021 and Ahmed et al., 2023).

The combined use of moderate CP (4 passes), soil amendments, and full irrigation (IR = 100%) resulted in the greatest MY produced. Therefore, it is clear that in addition to soil amendments, CP and irrigation have a noteworthy effect on crop productivity. Conversely, severe CP (8 passes) and limiting irrigation, compared to 50%, produced a poor MY. For Egypt's policymakers, the findings are pertinent; improved crop productivity is vital for food security as the population continues to increase and climate change impacts affect agriculture (Fereres and Soriano, 2007 and Ahmed et al., 2023).

As discussed in the study, it highlights that moderate CP, along with soil amendments and irrigation, provided the greatest gain in integrated water use efficiency, crop productivity and sustainability effects in arid and semi-arid environments. The importance of this research for Egyptian agriculture is that the growing water scarcity and severe loss of soil quality in arid regions is an issue that needs addressing. These results affirm previous work conducted by Fereres and Soriano (2007) and Ahmed et al. (2023) that an integrated soil management strategy can effectively improve water productivity while maintaining yield. This study provides local Egyptian producers and agricultural leaders with specific advice to advance soil conservation-based irrigation practices to achieve sustainable agriculture in water-stressed regions.

Future research should consider effective compression level acquisition, soil amendments and irrigation schedules for different soils and crops in Egypt. The original soil, especially where there is high sand content, common throughout Egypt, will be served by pre-planting practices of soil amendment such as clay, humic acid, Biochar and even composted manure, improving soil structure, water retention and root retention. In addition to optimizing the long-term economic impacts of our recommended practices for their acceptance, it is the more definitive economic benefits that demonstrate that enhanced crop production along with decreased irrigation costs provides a solid case for investment in sustainable agriculture over CP or amended compressed soils alongside its investment into compression practices. Furthermore, we need to define how many of these practices could roll out across climatic zones throughout Egypt.

Soil-specific approaches targeting specific climates will enhance overall crop production efficiency and water use efficiency across the country. Responsiveness clearly highlights the relevance of this topic for Egyptian policymakers and, as well, the farmers themselves. They are facing sustained agrarian pressures posed by reduced water supply. Implementing improved water-efficient soil management practices will help mitigate the threats of decreasing water resources and will represent a more sustainable food supply system, making these results very relevant to the agricultural strategy of Egypt.

CONCLUSION

Generally, this study found that applying medium soil amendment (T1), moderate soil compression (4 passes by roller), and irrigating water added at 75% of ETc resulted in saving 33% of IR added, increasing 11% of marketable yield, and improved soil physical properties compared control treatment, also, this combination increased water use efficiency and IWUE while, decreased the yield response factor, revealing greater crop flexibility under water-limited conditions. These conclusions provide a reasonable and sustainable opportunity for producers and decision-makers to improve productivity in regions that are arid and semi-arid conditions. This study also recommends field verification to support more widespread performance.

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تعظيم كفاءة الاستهلاك الأروائى للفلفل باستخدام تقنية أنضغاط التربة الرملية تحت ظروف التل الكبير

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تعد الإدارة المثلى للمياه والتربة أمرًا حيويًا لتحقيق الكفاءة والإنتاجية في المناطق الجافة والشبه جافة. لذا تم إجراء هذه التجربة على مدار موسمين صيفيين ٢٠٢٣ و٢٠٢٤ في مزرعة خاصة بمنطقة التل الكبير، محافظة الإسماعيلية، مصر، باستخدام نظام الري بالتنقيط السطحي؛ حيث تم ري الفلفل الصيفي بثلاثة مستويات من مياه الرى المضافة (١٠٠، ٧٥، ٥٠٪ محسوبة من البخرنتح للمحصول) تم دراسة التأثيرات المشتركة لثلاثة معدلات من محسنات التربة المضافة T0 بدون إضافة (طين ٠ طن/ فدان، حامض الهيوميك ٠ كجم/ فدان، فحم حيوى ٠ طن/ فدان) وT1 أضافة متوسطة (طين ٨ طن/ فدان، حامض الهيوميك ١٠ كجم/ فدان، فحم حيوى ٤ طن/ فدان) وT2 إضافة مرتفعة (طين ١٦ طن/ فدان، حامض الهيوميك ٢٠ كجم/ فدان، فحم حيوي ٨ طن/ فدان) مع ثلاثة مستويات من انضغاط التربة (٠، ٤، ٨ مرات مرور) تم تطبيقها باستخدام هراس وزنه ١٠ طن عند مستوى رطوبة ١١٪ على بعض الخواص الطبيعية للتربة وكذلك المحصول القابل للتسويق ومعايير الجودة لمحصول الفلفل، كما تم حساب الإستهلاك المائى الفعلى وكفاءة الإستهلاك المائى والأروائى ومعامل المحصول للفلفل. أظهرت النتائج أن أعلى قيم للماء المتاح ومعايير الجودة والمحصول القابل للتسويق تم الحصول عليها عند تطبيق المعاملة التي تضمنت إضافة متوسطة لمحسنات التربة (الطين ٨ طن/ فدان، الهيوميك أسيد ١٠ كجم/ فدان، الفحم الحيوي ٤ طن/ فدان) مع مستوى معتدل لإنضغاط التربة (٤ مرات مرور بالهراس) والري الكامل ١٠٠٪. كما تم تسجيل أعلى قيم لكفاءة الإستهلاك المائى والأروائى لمحصول الفلفل حيث بلغت ٤,٠٤ و٣,٥٥ كجم/ م[3] فى موسم ٢٠٢٣ و٤,١٦ و٣,٦٤ كجم/ م[3] فى موسم ٢٠٢٤ وذلك عند تطبيق المعاملة التى تضمنت إضافة متوسطة لمحسنات التربة (الطين ٨ طن/ فدان، الهيوميك أسيد ١٠ كجم/ فدان، الفحم الحيوي ٤ طن/ فدان) مع مستوى معتدل من إنضغاط التربة (٤ مرات مرور بالهراس) و٧٥٪ من مياه الرى المضافة. كما سجلت أقل قيم لمعامل المحصول حيث كانت ٠,٢٣ و٠,٢١ في كلا الموسمَين عند نفس المعاملة وهو مؤشر جيد على مرونة المحصول وعدم تراجعه بشكل كبير نتيجة لاستخدام كميات مياه أقل. أظهرت هذه الدراسة أن زراعة الفلفل الصيفي بإستخدام معدلات متوسطة من محسنات التربة المضافة مع مستوى معتدل من انضغاط التربة يمكن أن يوفر حوالي ٣٣٪ من مياه الري المضافة وكذلك يزيد المحصول القابل للتسويق بنسبة ١١٪ مقارنة بالمعاملة التقليدية (بدون إضافة المحسنات وبدون إنضغاط للتربة وعند تطبيق الري الكامل١٠٠٪).
تؤكد النتائج على أهمية تحسين إدارة التربة وممارسات الري لتعظيم كفاءة استخدام المياه، وزيادة العوائد، وتعزيز الاستدامة الزراعية.