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Improving the Soil Physical and Hydraulic Properties by Irrigation with Wastewater under Different Soil Tillage Management

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Abstract: Irrigation with recycled wastewater increases the organic substance of the soil. Thus, the effect of the increased organic substance on the physical and hydraulic properties of the soil can be developed with different irrigation water quantities and soil tillage treatments. In this study, the effect of increased organic matter was determined after a two-year study carried out on a silage maize field irrigated at varying irrigation water levels of recycled wastewater (RWW) (100%, 67%, and 33% irrigation levels with RWW) and freshwater (FW) (100% irrigation level with FW) under direct sowing (DS) and conventional tillage (CT). RWW is compared to FW, the bulk density at 100% irrigation level was 1.5% lower, while porosity, aggregate stability, field capacity, wilting point, and available water were significantly higher by 1.9%, 12.0%, 2.8%, 2.2%, and 3.6%, respectively. Bulk density, aggregate stability, field capacity, wilting point, and available water were 1.5%, 4.3%, 3.3%, 2.2%, and 4.2% were significantly higher in DS according to CT, respectively, while porosity was 1.5% lower. These effects can be attributed to the RWW irrigation under DS due to the organic matter content in DS which was 1.1% higher than with CT, while RWW increased the organic matter content by 17% according to FW between full irrigations. As a result of the study, it was concluded that 100% irrigation levels using RWW directly within the scope of DS may be a practical approach to improve the physical and hydraulic properties of the silage maize field.

Keywords: Conventional tillage, Direct sowing, Irrigation, Recycled wastewater, Soil organic matter

Farklı Toprak İşleme Yönetimi Kapsamında Atık Su ile Sulama Yapılarak Toprağın Fiziksel ve Hidrolik Özelliklerinin İyileştirilmesi

Öz: Geri dönüştürülmüş atık su ile sulama yapmak, toprağın organik maddesini artırmaktadır. Böylece artan organik maddenin toprağın fiziksel ve hidrolik özelliklerine etkisi farklı sulama suyu miktarları ve farklı toprak işleme uygulamaları ile geliştirilebilir. Bu çalışmada, artan organik maddenin etkisi, doğrudan ekim (DS) ve geleneksel toprak işleme (CT) altında değişen geri dönüştürülmüş atık su (RWW) (RWW ile %100, %67 ve %33 sulama seviyeleri) ve temiz suyla (FW) (FW ile %100 sulama seviyesi) sulama seviyelerinde sulanan bir silajlık mısır tarlasında gerçekleştirilen iki yıllık bir çalışmanın ardından belirlenmiştir. %100 sulama düzeyinde; RWW, FW ile karşılaştırıldığında, hacim ağırlığı %1.5 daha düşük olmuşken, porozite, agregat stabilitesi, tarla kapasitesi, solma noktası ve kullanılabilir su kapasitesi sırasıyla %1.9, %12.0, %2.8, %2.2 ve %3.6 oranında önemli ölçüde artış göstermiştir. Hacim ağırlığı, agregat stabilitesi, tarla kapasitesi, solma noktası ve kullanılabilir su kapasitesi CT'ye göre DS'de sırasıyla %1.5, %4.3, %3.3, %2.2 ve %4.2 seviyesinde anlamlı derecede artış göstermişken, porozite %1.5 daha düşük olmuştur. Bu etkiler, DS'deki organik madde içeriğinin CT'ye göre %1.1 daha yüksek olması nedeniyle DS altında RWW ile sulamaya ilişkin açıklanabilirken, tam sulamalar arasında; RWW, FW'ye göre organik madde içeriğini %17 arttırmıştır. Çalışma sonucunda DS kapsamında RWW kullanılarak %100 sulama seviyelerinin silajlık mısır tarlasının fiziksel ve hidrolik özelliklerini iyileştirmede pratik bir yaklaşım olabileceği sonucuna ulaşılmıştır.

Anahtar Kelimeler: Geleneksel toprak işleme, Doğrudan ekim, Sulama, Geri dönüştürülmüş atık su, Toprak organik maddesi

1. Introduction

Although provoking various environmental and health problems, sustaining the agricultural or drinking water requirements of the ever-increasing population on a global scale in an environment exposed to increasing freshwater scarcity encourages producers to reuse wastewater in crop production, especially in areas with severe arid, because of the many essential inorganic and organic nutrients it contains (Shahid et al., 2020). While the untreated, often diluted, partly reclaimed wastewater in agriculture areas covers 30 million hectares worldwide, agriculture areas irrigated with reclaimed wastewater are estimated to be about one million hectares (Drechsel et al., 2022). The reuse of recycled wastewater in irrigation water is seen as one of the main ways to avoid future water scarcity and to reduce the damage caused by water pollution to the environment.

Recycled wastewater improves the structural properties of soil with its high organic matter content because organic matter is an effective binding matter for increasing soil aggregation (Tunc & Sahin, 2016). Cakmakci and Sahin (2021) determined that the physical properties of the soil improved with the contribution of dissolved organic matter in recycled wastewater irrigation, supporting productivity in silage maize. Similarly, Dogan Demir and Sahin (2019) reported that increasing the organic matter of soil by irrigating with recycled wastewater increased the aggregate stability of soil by about 4% compared to irrigation with freshwater.

The mechanism of soil water retention, which indicates the balance of the water in the profile of the soil including field capacity and permanent wilting point, shows how much water the crop will consume from the soil. Water retention which is one of the general hydraulic soil properties could be increased by increasing organic matter content. Water retention in the soil occurs as a result of soil organic matter improving the soil pore size distribution and structure (Ors et al., 2015). Mujdeci et al. (2017) stated that organic matter increases porosity in favor of useful water retention by increasing the space rates among soil aggregates.

Soil tillage can cause differences in the hydraulic properties of soil by changing the structural properties of the soil. In intensive soil tillage conditions, the soil bulk density decreases with decreased soil compaction. However, since no interference is made with the soil in direct sowing, the bulk density may increase, and thus porosity can decrease (Gozubuyuk et al., 2014). However, organic matter stocks in the soil can be increased in direct sowing conditions, both physically due to less interference with the soil and biochemically due to less mineralization as a result of less oxygen input compared to intensive tillage treatments. The intensive size of tillage can increase the decomposition rate of crop residues and cause significant decreases in soil organic matter content, while the oxidation of organic matter is reduced in direct sowing since the soil is handled less (Malhi et al., 2018). Thus, increasing organic matter in the soil can support the increase of soil and crop productivity by improving the physical and hydraulic properties of the soil.

In previous studies, the effects of either irrigation with recycled wastewater or different tillage practices on the physical and/or hydraulic properties of the soil have been investigated and discussed. However, no integrated study has been found in the literature examining the physical and hydraulic properties of soil irrigated at changed levels with recycled wastewater under different tillage practices. With a significant contribution of soil organic matter that may be increased in these conditions, further improvement in soil physical and hydraulic conditions can be expected. Thus, this study aimed was to evaluate and discuss the changes in the physical and hydraulic properties of silage maize soil irrigated at varying irrigation water levels with recycled wastewater under conventional and direct sowing practices compared to fully irrigation with freshwater. Therefore, this study hypothesizes that full irrigation with recycled wastewater under direct sowing practice can provide considerable contributions to improve the physical and hydraulic properties of the soil.

2. Materials and Methods

2.1. Experimental area climate and soil properties

This experiment was carried out in the experimental area of Van Yuzuncu Yil University Faculty of Agriculture (38°34′35″ N, 43°17′26″ E) in East Turkey during two silage maize (*Zea mays* L. cultivar OSSK-644) crop vegetation periods between May and September in 2020-2021. The area where the experiment was conducted has a semi-arid climate with an annual average precipitation of 410 mm for many years (1991-2020) (TSMS, 2022). According to the experimental area weather station (iMETOS-2) data (Cakmakci & Sahin, 2021; Yerli et al., 2023 and 2024), the mean temperature and total precipitation in 2020 (May 15 - September 13) in 2021 (May 11 - September 4) were 22.4°C and 37.0 mm – 22.8°C and 52.1 mm, respectively.

The soil texture in the surface layer of 0–30 cm of the experimental field is classified as sandy clay loam. The determined main properties in the surface layer, as the mean of three replicates were: pH 8.2, electrical conductivity (EC) 0.34 dS m^{-1}, organic matter 1.4%, total nitrogen 0.08%, $CaCO_3$ 11%, field capacity 0.384 m^3 m^{-3}, permanent wilting point 0.225 m^3 m^{-3}, available water content 0.159 m^3 m^{-3}, particle density 2.7, bulk density 1.31 g cm^{-3}, total porosity 52%, and aggregate stability 44%.

2.2. Experimental design and treatments

The main treatments used in the study were conventional tillage (CT) and direct sowing (DS), while the sub treatments were 100% (RWW100), 67% (RWW67), and 33% (RWW33) irrigations with recycled wastewater and %100 (FW100) irrigation with freshwater (Figure1). The three-replication experiment was designed according to the split-plots study design, and randomized blocks study design. The total number of plots in the experimental field was 24, each plot was organized with a size of 3.5 × 7.2 m and five rows (Figure 1).

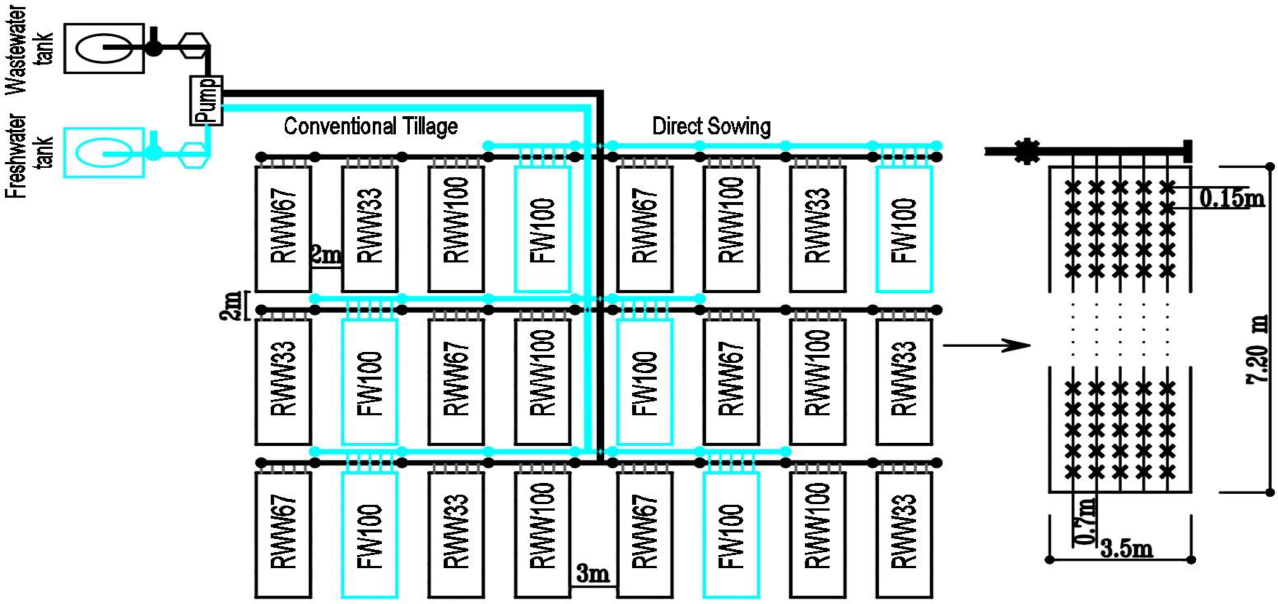

Figure 1. The experimental design. FW100: irrigation at 100% level with freshwater, RWW100: irrigation at 100% level with recycled wastewater, RWW67: irrigation at 67% level with recycled wastewater, RWW33: irrigation at 33% level with recycled wastewater.

Şekil 1. *Deneme deseni. FW100: Temiz su ile %100 düzeyinde sulama, RWW100: Geri dönüştürülmüş atık su ile %100 düzeyinde sulama, RWW67: Geri dönüştürülmüş atık su ile %67 düzeyinde sulama, RWW33: Geri dönüştürülmüş atık su ile %33 düzeyinde sulama.*

2.3. Irrigation water

While freshwater was delivered from the tap water network, the recycled wastewater was transferred to tanks in the experimental field from the Biological Treatment Plant of wastewater positioned in the Edremit district of Van province, Turkey before each irrigation via a water tanker with 20 tones. The applied waters were sampled to determine their characteristics each month during irrigation periods. The properties of the freshwater and recycled wastewater used are given in Table 1.

Considering the guidelines of the Food and Agriculture Organization of the United Nations (FAO) on the interpretation of water quality for irrigation purposes, according to the pH, which should be between 6.5-8.4, and the electrical conductivity (EC) classification values (low < 0.7 dS m^{-1}, medium 0.7-3.0 dS m^{-1}, high > 3.0 dS m^{-1}), the pH and EC values of the used fresh water and recycled wastewater were in the non-problematic class (Pescod, 1992; Ayers & Westcot, 1994). SAR values of the applied waters less than 3, when evaluated together with EC, do not pose any risk in terms of soil degradation considering FAO guidelines. Suspended solid matter content, which can cause clogging in the drip irrigation equipment (e.g. driplines, drippers), had no restriction on the use since it did not exceed the limit value of 50 mg L^{-1} given by Ayers and Westcot (1994). Boron content with less than 0.7 mg L^{-1} was also no toxicity problem according to the same guideline. The heavy metal contents of recycled wastewater were below the maximum allowable values considering the phytotoxic threshold levels of trace elements mentioned by FAO resources (Pescod, 1992; Ayers & Westcot, 1994). Total nitrogen and phosphorus contents of recycled wastewater, which have important contributions to soil fertility and crop development, were high. However, total nitrogen content in wastewater was appropriate considering the threshold value (10 mg L^{-1}) in the agricultural reuse mentioned in many international regulations and guidelines (Shoushtarian & Azar, 2020). Biochemical oxygen demand (BOD) reflecting organic pollutants that can be degraded by microorganisms indicates organic content load in water, and is mostly used as five-day biochemical oxygen demand (BOD_5). Chemical oxygen demand (COD) as another parameter in the measurement of organic pollution shows the organic compound oxidized by the oxidant (Zhao et al., 2022). While EPA (2012) did not suggest a value for COD, the wastewater quality was appropriate considering the BOD_5 value, which should be less than 30 mg L^{-1} in irrigation waters for non-food crops. The wastewater contained only domestic waste since there is no major industrial facility in the region. As a result, it was concluded that there is no harm in using irrigation water for irrigation (Yerli & Sahin, 2022).

Table 1. The properties of freshwater and recycled wastewater used in the study
Çizelge 1. *Çalışmada kullanılan temiz su ve geri dönüştürülmüş atık suyun özellikleri*

Properties	Freshwater		Recycled wastewater	
	2020	2021	2020	2021
pH	8.10 ± 0.08	8.20 ± 0.05	7.44 ± 0.04	7.72 ± 0.07
EC (dS m^{-1})	0.348 ± 0.01	0.358 ± 0.02	1.108 ± 0.05	1.139 ± 0.01
Sodium adsorption rate	0.89 ± 0.02	0.75 ± 0.05	2.54 ± 0.05	2.51 ± 0.08
Total phosphorus (mg L^{-1})	–	–	1.69 ± 0.10	1.18 ± 0.03
Total nitrogen (mg L^{-1})	–	–	10.9 ± 0.9	10.8 ± 0.5
SSM (mg L^{-1})	–	–	21.9 ± 1.5	29.9 ± 1.4
COD (mg L^{-1})	–	–	36.3 ± 0.6	38.7 ± 3.2
BOD_5 (mg L^{-1})	–	–	22.0 ± 0.5	24.3 ± 1.5
B (mg L^{-1})	–	0.55 ± 0.03	-	0.46 ± 0.04
Fe (mg L^{-1})	0.054 ± 0.005	0.412 ± 0.009	0.053 ± 0.005	0.419 ± 0.007
Cu (mg L^{-1})	–	0.011 ± 0.001	-	0.011 ± 0.001
Mn (mg L^{-1})	0.009 ± 0.001	0.071 ± 0.006	0.007 ± 0.001	0.095 ± 0.004
Zn (mg L^{-1})	–	0.015 ± 0.001	–	0.015 ± 0.000
Pb (mg L^{-1})	–	0.002 ± 0.001	–	0.002 ± 0.001
Cd (mg L^{-1})	–	0.001 ± 0.001	–	-
Cr (mg L^{-1})	–	0.001 ± 0.000	–	0.001 ± 0.001
Ni (mg L^{-1})	–	0.038 ± 0.001	–	0.047 ± 0.002

– : not determined, ± : standard error of mean, EC: electrical conductivity, SSM: suspended solid matter COD: chemical oxygen demand, BOD_5: biological oxygen demand

2.4. Irrigation treatments

Considering the root development and water need of silage maize vegetation period, the irrigations were carried out in two separate periods 1st (until the crop height 40-50 cm of silage maize, that is, until the 4-6 leaf period) and 2nd (after the period of 4-6 leaves) (Yerli et al., 2023). The irrigation dates in the 1st and 2nd periods were determined with an approach that the sum of the difference between crop evapotranspiration (ETc) and precipitation (P) values. The irrigations were made when this sum value formulated as the $\sum(ETc - P)$ was reached to 40% of the available water at a soil layer of 0.30 m (19 mm) in 1st period and 0.90 m (60 mm) in 2nd period (Allen et al., 1998). ETc was calculated by multiplying (ETc = kc × ETo) crop coefficient (kc) and reference evapotranspiration (ETo) values. While kc was obtained from Crop Water Consumption Guide for Irrigated Crops in Turkey, ETo was calculated by using daily climate data measured at the weather station (Imetos 2) in the study area with the CROPWAT program. In the 1st period, the depleted moisture at the 0.3 m soil layer in the freshwater plots in each irrigation was completed to the field capacity by freshwater applied equally to all plots with a 30% wetting percentage. The irrigations in the 2nd period were carried out with different irrigation quantities (RWW100, RWW67, RWW33, FW100) using a 65% wetting percentage (Cakmakci & Sahin, 2021). In each irrigation during this period, water amounts sufficient to replenish the decreasing moisture amount in the 0.90 m soil layer in the freshwater plots of each tillage sowing treatments to the field capacity were applied to the full irrigation plots. RWW67 and RWW33 plots were irrigated at a rate of 67% and 33% of the full irrigation amounts, respectively.

Field capacity, wilting point, and available water values in the experimental plots were determined according to the approach principles specified in the soil sampling and analysis section after the study. The soil moisture measurements at certain times during the vegetation period (sowing, before each irrigation, and harvesting) were carried out at a distance of about 15-20 cm from the drippers, between two crops in the middle of plots. While the water content at 0-30 cm soil layer was directly measured with a portable TDR (Trime-Pico, IPH/T3, IMKO) calibrated to experimental field conditions, gravimetric sampling was applied in the soil layers of 30-60 and 60-90 cm. The soil moisture content in gravimetric sampling was expressed in terms of weight as the ratio of weight difference between wet and dry soil to the weight of dry soil. Equation 1 was used to determine the volumes of irrigation water applied, and the confirmation of the water volumes was also provided by the readings on the water meters located at the beginning of each plot.

$$V = (FC - CM) \times BD \times SD \times WP \times IP \times PA \quad (1)$$

Where V is the irrigation quantity (L), FC and CM are the field capacity and current moisture (% of weight), BD is the bulk density of the soil (g cm^{-3}), SD is the soil depth (0.30 m and 0.90 m for 1st and 2nd periods, respectively), WP is the wetting ratio (0.30 and 0.65 for 1st and 2nd periods, respectively), IP is the irrigation ratio (1.0, 0.67, and 0.33 for 100%, 67% and 33% irrigation levels, respectively), PA is the plot area (25.2 m^2). Seasonal irrigation quantities as a two-year average were between 351-327 mm, 242-227 mm, and 129-122 mm for 100%, 67%, and 33% irrigation treatments in conventional tillage, while the quantities in direct sowing were 319-294 mm, 220-204 mm, and 118-111 mm.

2.5. Tillage sowing treatments and cultural processes

In the conventional tillage, the field was plowed, a cultivator-rotary harrow was used, and finally, seeding was done with a pneumatic seeder, respectively. However, plots without tillage were seeded with a direct sowing machine. In conventional tillage, the hoeing was carried out at 2 separate times when the crop height was 15-20 cm and 40-50 cm (4-6 leaf stage), while in direct sowing, an herbicide for weed removal was applied without hoeing. During the 1st year, 100 and 150 kg ha^{-1} of urea and TSP were applied together with the sowing, and the 2nd urea fertilization was carried out equally to the first dose in the 4-6 leaf period. In the 2nd year, fertilization was applied only in the freshwater plots to supplement the missing nitrogen and phosphorus considering the first-year residual effect incurred by recycled wastewater.

2.6. Soil sampling and analysis

The disturbed and undisturbed soil samples were taken from three layers (0-30 cm, 30-60, and 60-90 cm) in each plot. Organic matter content, particle and bulk densities, wet aggregate stability, field capacity, and permanent wilting point were determined during the harvest periods of the two experimental years. The Walkley-Black method was applied to determine soil organic matter content (Nelson & Sommers, 1982). The particle density was determined with the pycnometer method (Blake & Hartge, 1986a). The bulk density was obtained by dividing the undisturbed soil samples with dry weight (g) taken with a cylinder after drying in the oven to the volume (100 cm^3) of the cylinder (Blake & Hartge, 1986b). Wet aggregate stability was obtained according to the wet sieving method using soil fraction with a diameter of 1-2 mm (Kemper & Rosenau, 1986). Field capacity corresponds to the upper limit of available water in the soil and indicates the moisture of the soil after drainage of the water retained in the macro pores by gravity effect, and represents the moisture balanced with tension of practically 0.033 MPa suction. The permanent wilting point represents the inferior limit of available water for crop in the soil and corresponds to the moisture balanced with tension usually around 1.5 MPa. Therefore, using undisturbed soil samples taken with an approximate volume of 100 cm^3 soil core sample rings for field capacity and disturbed soil samples sieved through a 2 mm mesh for wilting point were used. The amounts of moisture retained at field capacity and wilting point were determined by applying a tension of 0.033 MPa and 1.5 MPa to the saturated samples, respectively with a pressure plate apparatus in the laboratory (Klute, 1986). The available water (AW) was calculated as the difference between the water content at field capacity and wilting point. Porosity was calculated via Equation 2 (Danielson & Sutherland, 1986).

$$P = [(1 - (BD / (PD \times \gamma_w))] \times 100 \quad (2)$$

Where P is the porosity (% of volume), BD is the bulk density of the soil (g cm^{-3}), PD is the particle density of the soil, and γ_w is the volume weight of pure water at +4°C (1 g cm^{-3}).

2.7. Statistical analysis

The statistical analyses of all data were carried out with the SPSS program. ANOVA analysis was performed for all parameters to determine the differences between soil layers (0–30 cm, 30–60 cm, and 60–90 cm), and the results showed that there was a general similarity for all parameters in the soil layers. In addition, considering that the surface soil layer is more critical in crop production (Yerli et al., 2024), the evaluations were carried out in the 0-30 cm soil layer. Thus, by accepting the variables of tillage sowing and irrigation treatments as constant, the results were evaluated with the General Linear Model, and significant means were classified with the Duncan multiple comparison test at a 5% probability level. In addition, the RStudio program was used to show correlative relationships.

3. Results and Discussion

The results showed that all physical and hydraulic properties (except particle density) and organic matter content values were significantly ($p < 0.01$) affected by irrigation and tillage sowing treatments in the 0-30 cm soil layer, considering the two-year averages (Table 2).

Table 2. Variance analysis results
Çizelge 2. *Varyans analizi sonuçları*

Year	Source	df	Particle density mean square	F	P	Bulk density mean square	F	P
2020	tillage sowing	1	0.000	1.029	0.326	0.002	33.333	0.000
	irrigation	3	0.000	1.524	0.247	0.000	8.222	0.002
	tillage sowing × irrigation	3	6.111E-005	0.419	0.742	1.111E-005	0.222	0.880
	error	16	0.000			5.000E-005		
2021	tillage sowing	1	0.000	0.000	1.000	0.003	16.447	0.001
	irrigation	3	0.000	2.222	0.125	0.001	6.763	0.004
	tillage sowing × irrigation	3	1.111E-005	0.178	0.910	0.000	1.079	0.386
	error	16	6.25E-005			0.000		
2020 2021	tillage sowing	1	6.667E-005	1.000	0.332	0.002	44.000	0.000
	irrigation	3	7.778E-005	1.167	0.353	0.001	15.636	0.000
	tillage sowing × irrigation	3	1.111E-005	0.167	0.917	5.000E-005	1.091	0.381
	error	16	6.667E-005			4.583E-005		
Year	Source		Porosity			Wet aggregate stability		
2020	tillage sowing	1	2.982	23.216	0.000	25.010	240.100	0.000
	irrigation	3	0.878	6.837	0.004	32.017	307.364	0.000
	tillage sowing × irrigation	3	0.034	0.268	0.848	0.510	4.900	0.013
	error	16	0.128			0.104		
2021	tillage sowing	1	3.550	12.599	0.003	26.670	110.551	0.000
	irrigation	3	1.394	4.949	0.013	66.083	273.918	0.000
	tillage sowing × irrigation	3	0.278	0.985	0.425	0.744	3.083	0.057
	error	16	0.282			0.241		
2020 2021	tillage sowing	1	3.241	47.417	0.000	25.834	340.665	0.000
	irrigation	3	1.036	15.152	0.000	47.463	625.665	0.000
	tillage sowing × irrigation	3	0.080	1.171	0.352	0.630	8.313	0.001
	error	16	0.068			0.076		
Year	Source		Field capacity			Permanent wilting point		
2020	tillage sowing	1	1.127	58.783	0.000	0.184	11.919	0.003
	irrigation	3	1.407	73.391	0.000	0.738	47.883	0.000
	tillage sowing × irrigation	3	0.013	0.696	0.568	0.008	0.532	0.667
	error	16	0.019			0.015		
2021	tillage sowing	1	2.100	11.457	0.004	0.240	3.600	0.076
	irrigation	3	5.212	28.427	0.000	0.583	8.750	0.001
	tillage sowing × irrigation	3	0.050	0.275	0.843	0.008	0.117	0.949
	error	16	0.183			0.067		
2020 2021	tillage sowing	1	1.550	28.189	0.000	0.220	12.595	0.003
	irrigation	3	3.025	54.997	0.000	0.629	35.960	0.000
	tillage sowing × irrigation	3	0.017	0.311	0.817	0.007	0.405	0.752
	error	16	0.055			0.018		
Year	Source		Available water content			Organic matter		
2020	tillage sowing	1	16.467	62.156	0.000	0.008	10.243	0.006
	irrigation	3	0.431	1.627	0.223	0.235	298.878	0.000
	tillage sowing × irrigation	3	0.389	1.468	0.261	0.001	1.256	0.323
	error	16	0.265			0.001		
2021	tillage sowing	1	33.112	8.864	0.009	0.002	1.449	0.246
	irrigation	3	24.282	6.500	0.004	0.323	281.820	0.000
	tillage sowing × irrigation	3	1.912	0.512	0.680	0.000	0.203	0.893
	error	16	3.735			0.001		
2020 2021	tillage sowing	1	24.080	24.779	0.000	0.004	9.062	0.008
	irrigation	3	7.404	7.619	0.002	0.276	585.404	0.000
	tillage sowing × irrigation	3	0.921	0.948	0.441	0.000	0.637	0.602
	error	16	0.972			0.000		

df – degree of freedom, F – F-ratio score, P – P-value

3.1. Soil organic matter content

Organic matter content increased in all irrigation and tillage sowing treatments compared to the pre-experiment value (1.36%), and the highest values were observed in the RWW100 and direct sowing treatments (Figure 2), and the 2nd year values were found to be higher than the first-year values. In the 2nd year, the RWW100 and RWW67 treatments increased organic matter content by 19.0% and 1.7%, respectively compared to the FW100 treatment, while the RWW33 treatment resulted in a 12.6% lower content with decreasing in the irrigation quantity.

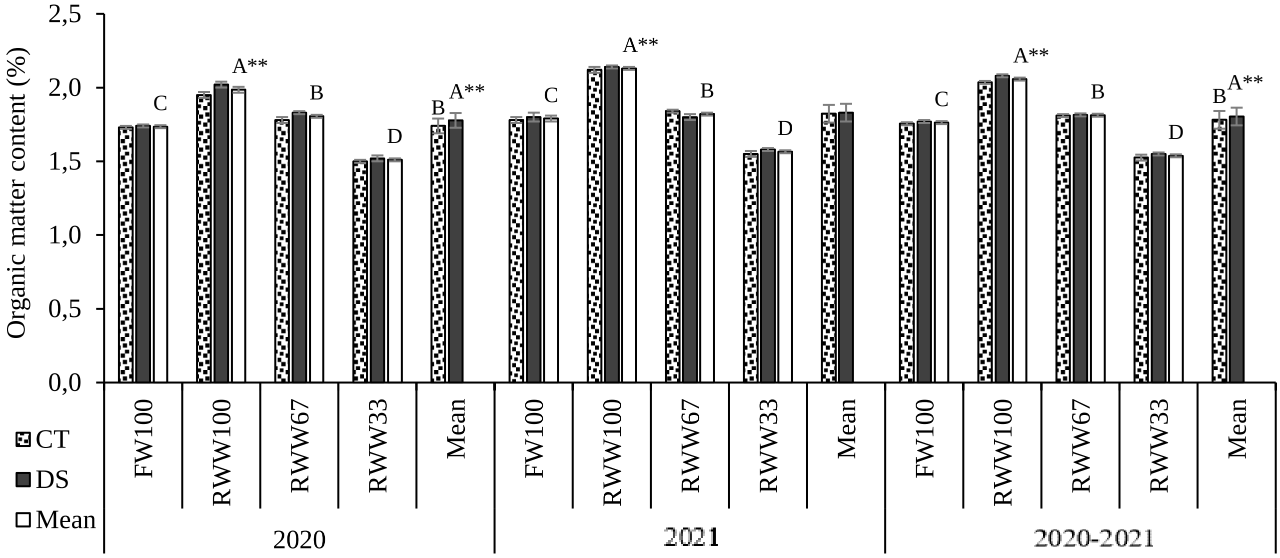

Figure 2. Organic matter contents in 0-30 cm soil layer in different tillage sowing and irrigation treatments. CT: conventional tillage, DS: direct sowing, FW100: irrigation at 100% level with freshwater, RWW100: irrigation at 100% level with recycled wastewater, RWW67: irrigation at 67% level with recycled wastewater, RWW33: irrigation at 33% level with recycled wastewater; **: p < 0.01; the significance comparisons are between both irrigation treatments and tillage sowing treatments in each experiment year.

Şekil 2. *Farklı toprak işleme ekim ve sulama uygulamalarında 0-30 cm toprak tabakasındaki organik madde içerikleri. CT: geleneksel toprak işleme, DS: doğrudan ekim, FW100: temiz su ile %100 düzeyinde sulama, RWW100: geri dönüştürülmüş atık su ile %100 düzeyinde sulama, RWW67: geri dönüştürülmüş atık su ile %67 düzeyinde sulama, RWW33: geri dönüştürülmüş atık su ile %33 düzeyinde sulama; **: p < 0,01; istatistik karşılaştırmalar her iki deneme yılı için hem sulama hem de toprak işleme ekim uygulamaları arasındadır.*

The significant ($p < 0.001$) positive correlation between the irrigation quantity and soil organic matter content (Figure 3) showed that the RWW33 treatment with less wastewater quantity limited the effect of organic matter on the soil from wastewater (Figure 2). This also explained the high organic matter content in the RWW100 treatment irrigated with a high quantity of wastewater. Bedbabis et al. (2015) have determined that organic matter in the soil increases with the effect of high chemical oxygen demand and biological oxygen demand contents of wastewater. Therefore, the suspended organic matter based on high chemical oxygen demand and biological oxygen demand values (37.5 and 23.2 mg L^{-1} as two-year averages, respectively) found in the wastewater used in this study resulted in a significant increase in organic matter of the soil especially in the RWW100 treatment (Figure 2). Many researchers have also reported that with the reuse of wastewater, there are significant increases in the organic matter content of the soil due to the organic components of the water (Tunc & Sahin, 2016; Abd-Elwahed, 2019; Dogan Demir & Sahin, 2020; Cakmakci & Sahin, 2021).

Minimal stirring of soil in direct sowing can protect organic matter stock because the intensive process in conventional soil tillage increases decomposition of organic matter because of oxidation in highly aerated soil (Malhi et al., 2018). In addition, crop residues left on the soil in direct sowing contribute to soil organic matter (Gozubuyuk et al., 2020). Denardin et al. (2019), Yang et al. (2019), and Kan et al. (2020) have also reported that the organic matter content of the soil was enriched in direct sowing according to intensive tillage practices.

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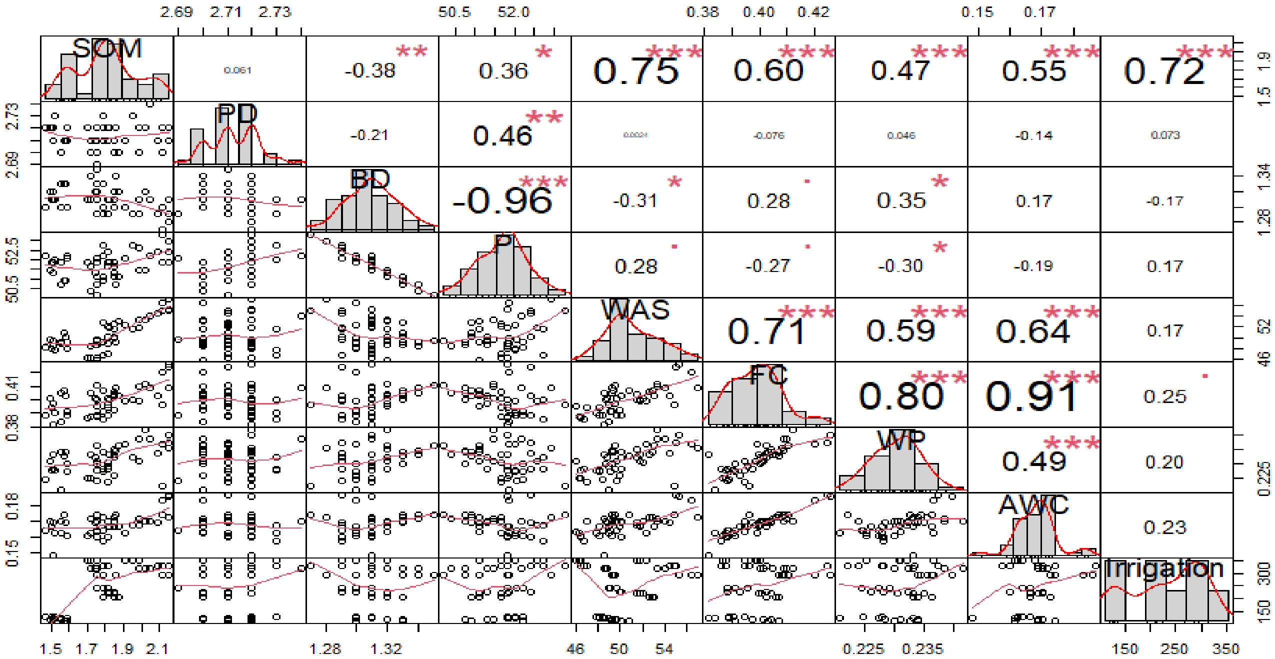

Figure 3. Correlation matrix for data in 0-30 cm soil layer. SOM: soil organic matter content, PD: particle density, BD: bulk density, P: porosity, WAS: wet aggregate stability, FC: field capacity, WP: permanent wilting point, AWC: available water content, Irrigation: irrigation quantity; ***, **, *: significant at 0.001, 0.01 and 0.05 level, respectively.

Şekil 3. *0-30 cm toprak tabakasındaki veriler için korelasyon matrisi. SOM: toprağın organik madde içeriği, PD: özgül ağırlık, BD: hacim ağırlık, P: porozite, WAS: ıslak agregat stabilitesi, FC: tarla kapasitesi, WP: devamlı solma noktası, AWC: kullanılabilir su kapasitesi, Sulama: sulama miktarı; ***, **, *: sırasıyla 0,001, 0,01 ve 0,05 düzeyinde önemlidir.*

3.2. Particle and bulk densities, and porosity

Bulk density in the RWW100 in the 2nd year was found to be less in both tillage sowing practices compared to the pre-experiment value (1.31 g cm^{-3}) (Figure 4). Considering the significant ($p < 0.01$) changes in bulk density between treatments (Table 2), it has been observed that porosity significantly ($p < 0.01$) increased in treatments in which bulk density values were low (Figure 3). Therefore, a significant ($p < 0.001$) negative correlation between porosity and bulk density was determined (Figure 3). Furthermore, the linear increase of porosity with particle density was determined to be statistically significant ($p < 0.01$).

Since the variation in particle density is mostly related to soil organic carbon, it could be said that the organic matter content did not reach a level that affected particle density considering the non-significant relationship among organic matter content and particle density in the study (Figure 3). Moreover, as a general approach, it is stated that particle density may not change significantly in short periods. In general, the formation of more stable aggregates and a lower bulk density are attributed to the presence of organic matter (Ramezani et al., 2019). Therefore, the limitation in the decrease in bulk density in the RWW67 and RWW33 treatments was attributed to less organic matter content in the soil (Figure 2). A significant negative correlation ($p < 0.01$) of bulk density with soil organic matter content also confirmed these findings (Figure 3). Moreover, it could be said that strong aggregation decreases bulk density considering the significant ($p < 0.05$) negative correlation between bulk density and wet aggregate stability (Figure 3). Similarly, many researchers have also stated that the bulk density of soils irrigated with the reuse of the wastewater decreased due to the enriched in organic matter (Biswas et al., 2017; Dogan Demir & Sahin, 2019; Cakmakci & Sahin, 2021).

Bulk density was low in conventional tillage due to the loose soil structure and was found to be higher with the effect of soil compaction with the direct sowing treatment. Similarly, Gozubuyuk et al. (2014) determined that conservation tillage practices cause soil compaction and thus increase bulk density according to conventional tillage. Many researchers have also stated that bulk density was higher in direct sowing according to intensive tillage or conventional tillage (Gozubuyuk et al., 2014; Blanco-Canqui & Ruis, 2018).

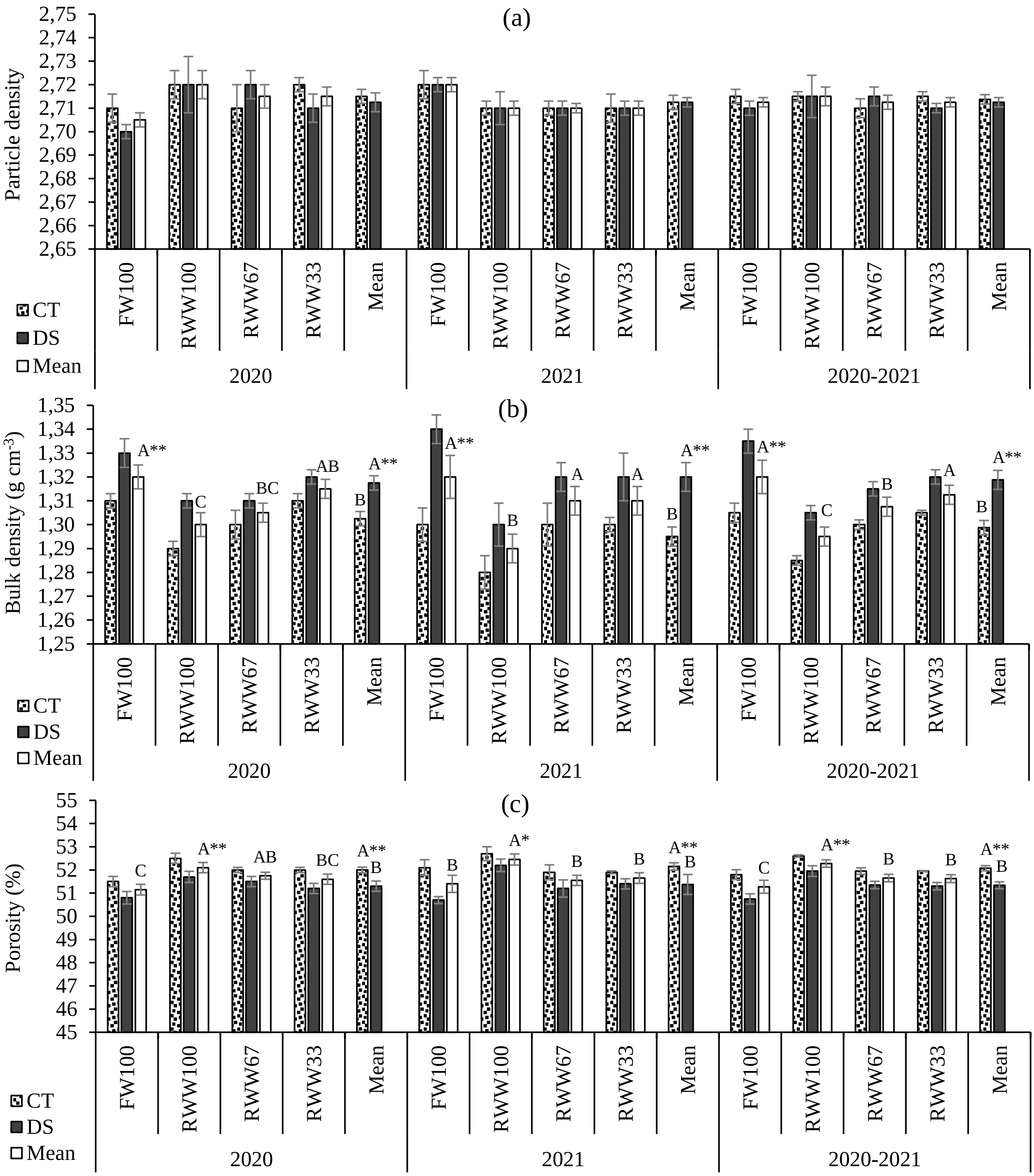

Figure 4. Particle density (a), bulk density (b), and porosity values (c) in 0-30 cm soil layer in different tillage sowing and irrigation treatments. CT: conventional tillage, DS: direct sowing, FW100: irrigation at 100% level with freshwater, RWW100: irrigation at 100% level with recycled wastewater, RWW67: irrigation at 67% level with recycled wastewater, RWW33: irrigation at 33% level with recycled wastewater; **: $p < 0.01$; the significance comparisons are between both irrigation treatments and tillage sowing treatments in each experiment year.

Şekil 4. *Farklı toprak işleme ekim ve sulama uygulamalarında 0-30 cm toprak tabakasındaki özgül ağırlık (a), hacim ağırlık (b) ve porozite değerleri (c). CT: geleneksel toprak işleme, DS: doğrudan ekim, FW100: temiz su ile %100 düzeyinde sulama, RWW100: geri dönüştürülmüş atık su ile %100 düzeyinde sulama, RWW67: geri dönüştürülmüş atık su ile %67 düzeyinde sulama, RWW33: geri dönüştürülmüş atık su ile %33 düzeyinde sulama; **: p < 0,01; istatistik karşılaştırmalar her iki deneme yılı için hem sulama hem de toprak işleme ekim uygulamaları arasındadır.*

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The porosity values in the RWW100 treatment under conventional tillage and direct sowing in the 2nd year were higher by 1.7% and 0.8% than the pre-experimental value (51.8%), respectively. The approach that organic matter added to soil increases porosity under irrigation conditions with wastewater is supported by Biswas et al. (2017) who stated that porosity in irrigation with wastewater was 6% higher than with freshwater. Similarly, increases in porosity have been detected in wastewater irrigation conditions in many studies (Tunc & Sahin, 2015; Dogan Demir & Sahin, 2019; Cakmakci & Sahin, 2021). The porosity decreased with the increase in bulk density due to the decrease of organic matter entering the soil in deficit irrigation treatments (Figures 2 and 4). Compared to conventional tillage, the higher bulk density in direct sowing also revealed lower porosity values. Kucukalbay and Akbolat (2015) indicated that low porosity values were determined in direct sowing (53.1%) among different tillage practices, while high porosity values were determined in conventional tillage (56.7%) and reduced tillage (53.7%).

3.3. Wet aggregate stability

RWW100 under direct sowing resulted in significantly ($p < 0.01$) higher wet aggregate stability values by 14.2% and 17.3% compared to the FW100 treatment under direct sowing and conventional tillage, respectively, considering 2nd year values which were higher than for the 1st year (Table 2 and Figure 5). While all treatments increased wet aggregate stability compared to the pre-experimental value (43.8%), RWW100 treatment in the 2nd year resulted in a 26.9% higher value. Direct sowing in the 2nd year also increased this value by 18.9%.

Soil organic matter mediates better aggregation by flocculation and cementation of particles (Alhassan et al., 2018). It has been clarified that adding organic matter to the soil with recycled wastewater irrigation contributes positively to aggregate stability, and therefore, the decrease in the organic matter with the decrease in the amount of irrigation also reduces aggregate stability. The significant ($p < 0.001$) positive correlation between wet aggregate stability and organic matter content also supports this (Figure 3). Dogan Demir and Sahin (2020) stated that the aggregate stability increased under the conditions of using wastewater for irrigation. Cakmakci and Sahin (2021) confirmed a similar situation and reported that aggregate stability increased at lower levels due to deficit irrigation with wastewater.

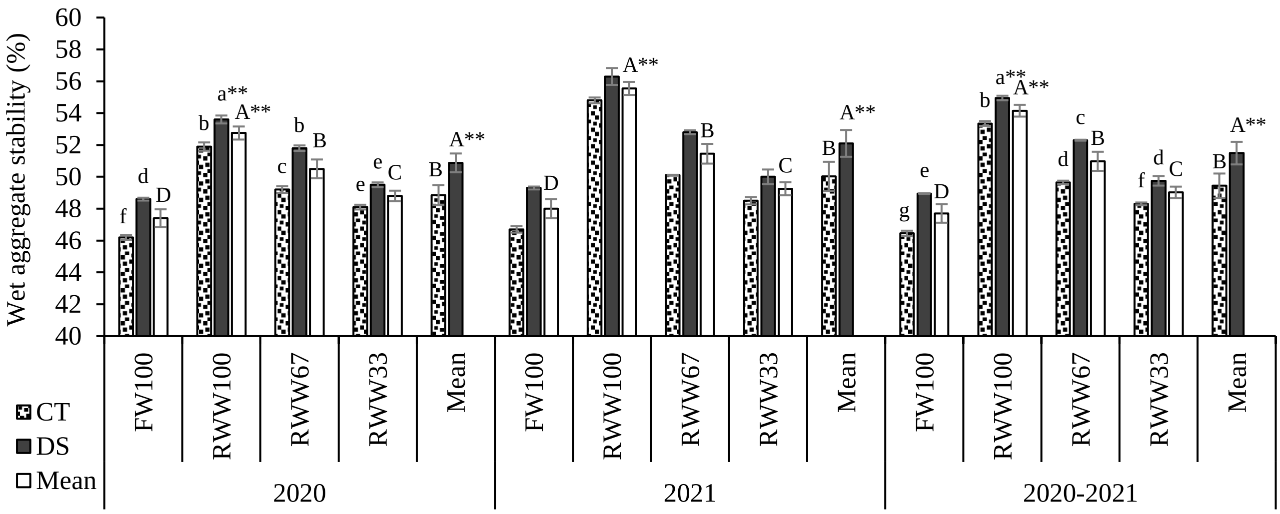

Figure 5. Wet aggregate stability values in 0-30 cm soil layer in different tillage sowing and irrigation treatments. CT: conventional tillage, DS: direct sowing, FW100: irrigation at 100% level with freshwater, RWW100: irrigation at 100% level with recycled wastewater, RWW67: irrigation at 67% level with recycled wastewater, RWW33: irrigation at 33% level with recycled wastewater; **: $p < 0.01$; the significance comparisons are between both irrigation treatments and tillage sowing treatments in each experiment year.

Şekil 5. *Farklı toprak işleme ekim ve sulama uygulamalarında 0-30 cm toprak tabakasındaki ıslak agregat stabilitesi değerleri (c). CT: geleneksel toprak işleme, DS: doğrudan ekim, FW100: temiz su ile %100 düzeyinde sulama, RWW100: geri dönüştürülmüş atık su ile %100 düzeyinde sulama, RWW67: geri dönüştürülmüş atık su ile %67 düzeyinde sulama, RWW33: geri dönüştürülmüş atık su ile %33 düzeyinde sulama; **: p < 0,01; istatistik karşılaştırmalar her iki deneme yılı için hem sulama hem de toprak işleme ekim uygulamaları arasındadır.*

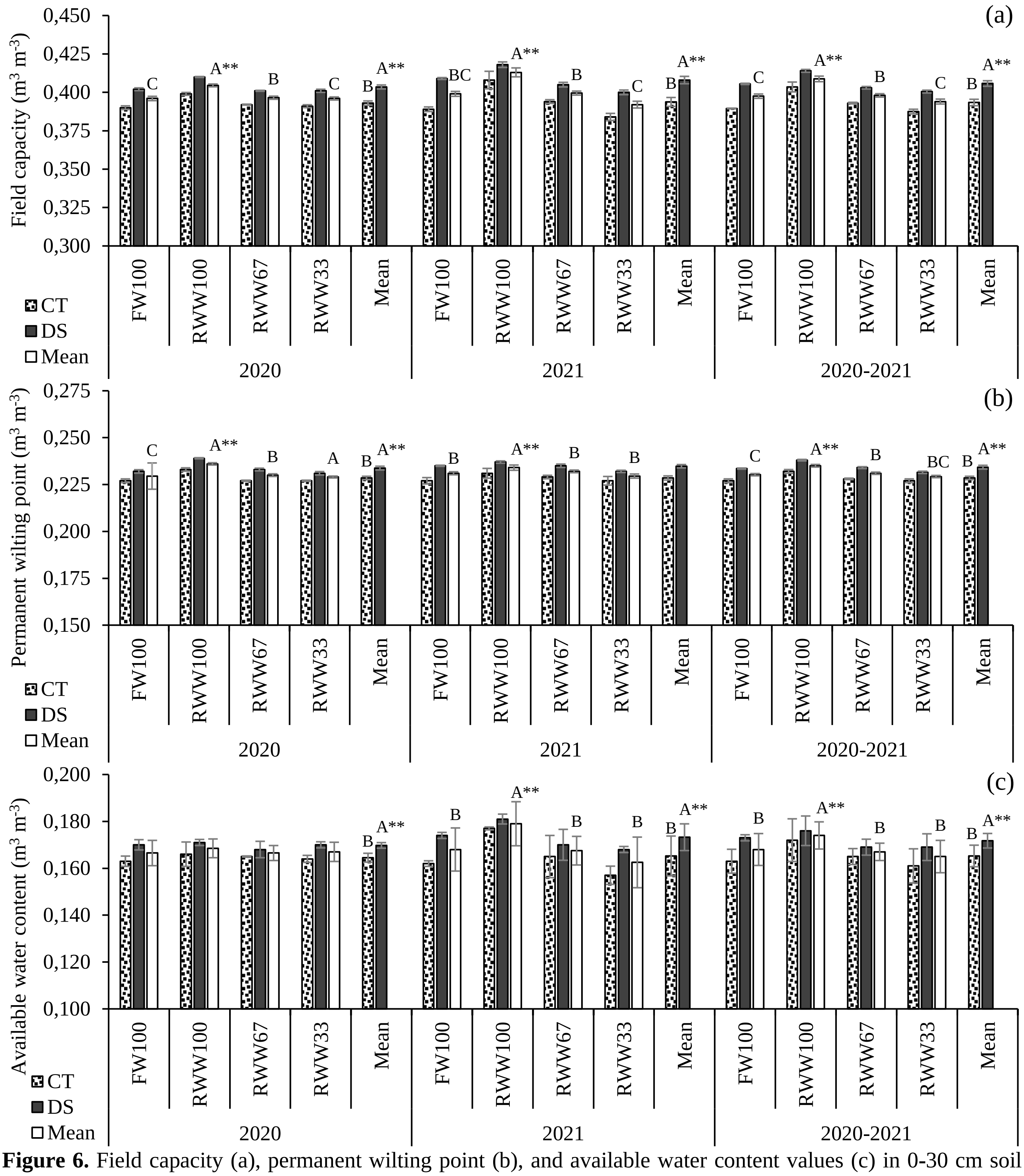

Figure 6. Field capacity (a), permanent wilting point (b), and available water content values (c) in 0-30 cm soil layer in different tillage sowing and irrigation treatments. CT: conventional tillage, DS: direct sowing, FW100: irrigation at 100% level with freshwater, RWW100: irrigation at 100% level with recycled wastewater, RWW67: irrigation at 67% level with recycled wastewater, RWW33: irrigation at 33% level with recycled wastewater; **: p < 0.01; the significance comparisons are between both irrigation treatments and tillage sowing treatments in each experiment year.

Şekil 6. *Farklı toprak işleme ekim ve sulama uygulamalarında 0-30 cm toprak tabakasındaki tarla kapasitesi (a), devamlı solma noktası (b) ve kullanılabilir su tutuma kapasitesi değerleri (c). CT: geleneksel toprak işleme, DS: doğrudan ekim, FW100: temiz su ile %100 düzeyinde sulama, RWW100: geri dönüştürülmüş atık su ile %100 düzeyinde sulama, RWW67: geri dönüştürülmüş atık su ile %67 düzeyinde sulama, RWW33: geri dönüştürülmüş atık su ile %33 düzeyinde sulama; **: p < 0,01; istatistik karşılaştırmalar her iki deneme yılı için hem sulama hem de toprak işleme ekim uygulamaları arasındadır.*

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The higher aggregate stability of direct sowing according to conventional tillage can be attributed to residues of the crop adding organic matter to the soil in direct sowing and organic matter conservation is better since the soil is less disturbed. Similarly, Sithole et al. (2019) reported that aggregate stability was found to be higher in direct sowing and this was associated with the longer preservation of organic matter and slower mineralization in direct sowing according to intensive tillage. In addition, many researchers have stated that aggregate stability is higher in direct sowing according to conventional tillage (Du et al., 2013; Gozubuyuk et al., 2014; Nouwakpo et al., 2018).

3.4. Field capacity, permanent wilting point, and available water

The RWW100 and the direct sowing treatments significantly ($p < 0.01$) increased field capacity, permanent wilting point, and available water content compared to the FW100 treatment and conventional tillage (Table 2 and Figure 6) and were also higher than pre-experiment values: field capacity 0.384 $m^3\ m^{-3}$, permanent wilting point 0.225 $m^3\ m^{-3}$, available water content 0.159 $m^3\ m^{-3}$.

The physical properties of the soil such as bulk density and porosity highly influence water retention with hydraulic behavior changes in the soil (Hartmann et al., 2020). Many studies have reported that positive developments in soil hydraulic properties occur with the improvements in soil properties brought about by irrigation with recycled wastewater (Tunc & Sahin, 2015; Musazura et al., 2019; Badaou & Sahin, 2021). The significant ($p < 0.05$) correlations of bulk density and porosity values with field capacity and permanent wilting point in this study also confirmed this opinion (Figure 3). Moreover, more significant ($p < 0.001$) correlations of field capacity, permanent wilting point, and available water content with organic matter content were determined. Therefore, it could be said that the higher level of field capacity and permanent wilting point values in recycled wastewater irrigation conditions compared to freshwater irrigation can be related to the organic matter contribution of recycled wastewater to soils. This also explains the reducing effect of declining content of organic matter on the water holding capacity in deficit irrigation treatments. Mujdeci et al. (2017) stated that the increase in voids and stabilization of soil aggregates with the addition of organic matter increases porosity in favor of water holding capacity. Ors et al. (2015) indicated that the water holding capacity of the soil is directly dependent on the pore distribution of the soil and soil organic matter can improve the pore size distribution in the soil in favor of better water retention. In addition, Abdelfattah (2013) reported that the high amount of organic matter in the soil, especially in areas suffering from drought, supports the increase in the amount of available water. Many studies have indicated that the addition of organic matter to soil improves field capacity and wilting point (Ors et al., 2015; Kadioglu & Canbolat, 2019; Alaboz & Cakmakci, 2020).

As a similar approach, the increases in water holding capacity in direct sowing according to conventional tillage can be explained by the contribution of organic matter by direct sowing into the soil (Figure 2). Gozubuyuk et al. (2014) stated that higher available water values in the surface soil layer were obtained in direct sowing according to conventional and reduced soil tillage treatment. In addition, the increase in the amount of available water in no-tillage conditions may be related to the micro and macro pore distribution. This study also indicated the possible positive effects of higher aggregate stability values on the pore size distribution and thus water retention in direct sowing practice. Furthermore, another study examining the effects of tillage sowing practices on the hydraulic properties of soil has reported that better values were obtained in no-till conditions (Somasundaram et al., 2018).

4. Conclusion

As a result of the study, it was concluded that full irrigation with recycled domestic wastewater under direct sowing can be good practice and contribute to the development of the soil, considering that full irrigation with wastewater under direct sowing improves the physical and hydraulic properties of the soil in silage maize cultivation and that the use of domestic wastewater in irrigation, saving freshwater, as well as reducing the risk of environmental pollution by waste disposal. Thus, it can be suggested that the silage maize field be operated under direct sowing by irrigation with recycled domestic wastewater, but it should be considered that short-term findings should be supported by long-term data to see the sustainable effect on soil.

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