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Short-Term Effect of Different Doses Of Sewage Sludge on Soil Physical and Hydraulic Properties with Different Irrigation Regimes in a Silage Maize Field

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Abstract: Soil physical and hydraulic properties may be affected significantly from stabilized sewage sludge, and irrigation regimes may change the magnitude of these effects. Therefore, we examined the effects of different sewage sludge doses (D0: 0 t/ha, D1: 30 t/ha, D2: 60 t/ha, D3: 90 t/ha) and irrigation regimes (S1, S2, S3) on the soil physical and hydraulic properties with two-year study in a silage maize cultivated soil. The experiment was carried out in a completely random factorial design with three replications. In the S1, S2 and S3 irrigation regimes, when the sum of estimated crop evapotranspiration by FAO-Penman-Monteith approach and effective precipitation difference were 25 mm, 50 mm and 75 mm, respectively, irrigations were carried out and the moisture deficit in the soil was completed to field capacity. While moisture regimes did not have significant effects on soil physical and hydraulic properties, sewage sludge doses resulted in significant effects. Compared to D0, 3.1% lower bulk density, 1.9% lower particle density, 14.9% higher wet aggregate stability and 2.6% higher gravimetric field capacity values were determined at the D3 treatment. It was determined that these improvements were due to the high organic matter content of the sewage sludge, which increased the organic matter content in the soil with increasing doses, and it was also supported by significant linear relationships between the organic matter and these parameters. As a conclusion, although the importance of the positive effects of increasing dose can be emphasized, it can be stated that longer-term studies are needed to see more permanent and effective results.

Keywords: Aggregate stability, bulk and particle densities, municipal sewage sludge, water retention capacity

Silajlık Mısır Tarlasında Farklı Sulama Rejimlerinde Farklı Dozlarda Arıtma Çamurunun Toprağın Fiziksel ve Hidrolik Özelliklerine Kısa Süreçte Etkisi

Öz: Stabilize arıtma çamuru, toprağın fiziksel ve hidrolik özelliklerini önemli ölçüde etkileyebilir ve sulama rejimleri bu etkilerin büyüklüğünü değiştirebilir. Bu nedenle, farklı arıtma çamuru dozlarının (D0: 0 t/ha, D1: 30 t/ha, D2: 60 t/ha, D3: 90 t/ha) ve sulama rejimlerinin (S1, S2, S3) toprak fiziksel ve hidrolik özellikleri üzerindeki etkilerini, silajlık mısır yetiştirilen bir toprakta iki yıllık bir çalışma ile incelenmiştir. Deneme, üç tekrarlamalı tamamen rastgele faktöriyel deneme düzeninde yürütülmüştür. S1, S2 ve S3 sulama rejimlerinde, FAO-Penman-Monteith yaklaşımı ile tahmini ürün evapotranspirasyonunun ve etkili yağış farkının toplamı sırasıyla 25 mm, 50 mm ve 75 mm olduğunda, sulamalar yapılmış ve topraktaki nem açığı tarla kapasitesine tamamlanmıştır. Nem rejimlerinin toprak fiziksel ve hidrolik özellikleri üzerinde önemli etkileri olmazken, arıtma çamuru dozları önemli etkilere yol açmıştır. D0 ile karşılaştırıldığında D3 uygulamasında %3.1 daha düşük kütle yoğunluğu, %1.9 daha düşük tane yoğunluğu, %14.9 daha yüksek ıslak agregat stabilitesi ve %2.6 daha yüksek gravimetrik tarla kapasitesi değerleri belirlenmiştir. Bu iyileşmelerin arıtma çamurunun yüksek organik madde içeriğinden kaynaklandığı, bu nedenle de artan dozlarla topraktaki organik madde içeriğinin arttığı belirlenmiş ve organik madde ile bu parametreler arasında önemli doğrusal ilişkiler bulunması da bunu desteklemiştir. Sonuç olarak, artan dozun olumlu etkilerinin önemi vurgulanabilse de, daha kalıcı ve etkili sonuçlar görmek için daha uzun süreli çalışmalara ihtiyaç olduğu söylenebilir.

Anahtar Kelimeler: Agregat stabilitesi, kütle ve tane yoğunluğu, kentsel arıtma çamuru, su tutma kapasitesi

1. Introduction

With increasing urbanization and industrialization, the number of wastewater treatment plants is increasing rapidly, and this causes an increase in sewage sludge wastes (Nahar & Hossen, 2021). Treatment sludge is a by-product formed as a result of the treatment of industrial, domestic and municipal wastewater, and consists of water, organic matter and biosolids (Yuan & Dai, 2016). These wastes, which should be disposed of without harming the environment, are generally used for fertilizer and soil conditioner in agriculture. The use of controlled and appropriate doses of sewage sludge in agricultural areas is one of the simplest disposal methods (Mondal et al. 2015; Çakır & Çimrin, 2018). Municipal sewage sludge with low heavy metal content that has undergone the stabilization process is preferred mostly in agriculture due to its properties as both an economic fertilizer source and soil improvement.

Organic components in sludge increase the stability of soil aggregates, improve water holding capacity and total soil porosity (Ors et al. 2015; Abdallh & Sahin, 2020; Sahin et al. 2020; Badaou & Sahin, 2022; Yerli et al., 2024). Many studies have shown significant improvements in the physical, hydraulic and chemical properties of soils enriched with sewage sludge, such as aggregate stability, water holding capacity, bulk density, particle density, total porosity, aeration capacity, water permeability, cation exchange capacity and exchangeable Ca content (Mondal et al. 2015; Ors et al. 2015; Cherfouh et al. 2018; Norouzian et al. 2018). Mujdeci et al. (2017) also indicated that organic matter improves the available pore distribution among soil aggregates in favor of improving water retention.

Maize is an important agricultural crop that can be effectively grown on almost every continent in the world, except Antarctica, and can adapt to various climatic conditions (Özkan & Bayhan, 2022). The wide adaptability of this plant makes it an option that can successfully integrate into different climates and soil types. Silage maize is an important food source in the livestock sector worldwide. It plays a critical role in nutrition, especially for dairy cattle. This versatility of maize, together with the advantages it provides for the agricultural sector, contributes to the diversification and sustainability of food production. Maize also need to frequent irrigation higher yield (Cakmakci & Sahin, 2021; Yerli et al., 2023). Fast microbial decomposition of organic matter and microbially derived carbon under frequent irrigation iss also known to promote aggregation (Rabbi et al., 2024; Yerli et al., 2024).

Considering findings previous studies, there is a need examining the short-term effects of physical and hydraulic properties of soil irrigated at changed intervals with irrigation regimes under different sewage sludge dose in silage maize field. In this study, it was aimed to improve soil physical and hydraulic properties with irrigation regime management of different doses of stabilized sewage sludge obtained from domestic waste. In Erzurum ecology in Türkiye, moisture regimes were created at various irrigation levels with real-time water consumption approach and available sewage sludge dose was researched.

2. Material and Methods

2.1. Study area and experimental design

The study was carried out in 2021 (May 7 - September 9) and 2022 (May 13 - September 10) at the experimental field of Atatürk University Plant Production Application and Research Center in Erzurum province, Turkey (39.933° N and 41.236° E, 1780 m a.s.l). The average air temperature and total precipitation during the vegetation period were 18.2 °C and 80.1 mm in the first year, and 17.6 °C and 111.2 mm in the second year, respectively. According to the US Soil Taxonomy, the experimental area soil is aridisol (Soil Survey Staff 1992). Prior to the experiment, the texture of the surface layer (0-30 cm) of the experimental field was clay loam, pH and EC values, and organic matter and lime contents were determined as 7.61, 0.163 dS/m, 1.73% and 0.47%, respectively. Irrigation water was applied using groundwater with an average pH value of 7.43 and an EC value of 0.286 dS/m, with a surface drip irrigation system, one lateral to each plant row.

The experiment was carried out with four different sewage sludge doses (D0: 0 t/ha, D1: 30 t/ha, D2: 60 t/ha, D3: 90 t/ha) and three different irrigation regime applications (S1, S2, S3) in a completely random 4x3 factorial design, with doses as the main plots, with 3 replications in a total of 36 plots. Each plot with an area of 25.2 m^2 was arranged as measured of 3.5 m × 7.2 m in 5 rows. DKC 6777 silage maize variety in FAO 700 group was planted with a pneumatic seeder on the soil processed with a vertical rotovator before sowing, with 70 cm row spacing and 15 cm plant distance on the rows.

2.2. Mixing of sewage sludge into soil and other cultural processes

Stabilized sewage sludge was supplied from the wastewater treatment plant located in Erzurum, Türkiye. pH and EC values and organic matter content, Ca content and dry matter ratio of the stabilized sewage sludge before the experiment were determined as 6.72, 6.51 dS/m, 38.6%, 40.96 cmol/kg, and 29.9% respectively. Heavy metal content in sewage sludge was below the limit values specified in the Regulation on the Use of Domestic and Urban Sewage Sludge in Soil in Türkiye (Official Gazette, 2010).

Stabilized sewage sludge was brought to the experimental area in the autumn period (end of September 2020) before the first planting year, spread homogeneously on the surface of the plowed plots and was mixed to a depth of 15 cm with a hoe machine. No additional chemical fertilizer was applied to the plots where sewage sludge was applied in either year. However, considering the results of the fertility analysis in the 0-30 cm soil layer in the D0 plots without sewage sludge, the deficient nitrogen and phosphorus fertilizer amounts were determined, and the deficient amounts were applied to the plots manually according to the doses of 100 kg/ha urea (% 45-46 N) and 150 kg/ha triple super phosphate (% 43-46 P_2O_5). All of the phosphorus and half of the nitrogen were applied immediately after planting. The remaining half of the nitrogen was given when the plants reached 40-50 cm in height (with 4-6 leaves). The selection of current fertilizer doses and the applications were made by considering previous studies on silage maize in this and similar regions (Ors et al., 2015; Cakmakci & Sahin, 2021; Yerli et al., 2023). The first and second hoeing for weed control was done when the plants reached 15-20 cm and 40-50 cm height, respectively.

2.3. Determination of irrigation time and amount

When the total of the difference between estimated crop evapotranspiration (ETc) and effective rainfall (Peff) in S1, S2 and S3 irrigation regimes [$\sum$ (ETc – Peff)] was 25 mm, 50 mm and 75 mm, respectively, irrigations were applied and the moisture deficit according to the field capacity in the soil was completed to the field capacity. In 2021, a total of 310.2 mm, 293.2 mm and 277.9 mm of irrigation water was applied in the S1, S2 and S3, respectively. In 2022, a total of 336.8 mm, 323.9 mm and 297.4 mm of irrigation water was applied. The applied water quantities were calculated according to wetting rates of 0.30 and 0.65, respectively, considering 30 cm soil depth until the 4-6 leaf stage of the plants and then 90 cm soil depth. While the moisture at 30 cm was measured with a field-calibrated moisture meter (TDR, Trime-Pico, IPH/T3, IMKO), and the moisture in the lower layers was measured gravimetrically.

The ETc value was calculated with the following Equation.!

$$ETc = ETo \times kc \quad (1)$$

"kc" values were obtained from the Evapotranspiration Guide for Irrigated Crops in Türkiye (TAGEM, 2017). Reference evapotranspiration (ETo) values were also calculated with the Penman-Monteith (FAO) approach using the CROPWAT program. The climate data required for the calculations were obtained from the Erzurum Airport Meteorological Station near to the experimental area. Rainfall data were also obtained from the pluviometer located in the experimental area since all the precipitation stored in the effective root zone of silage maize, all of it is considered effective precipitation (Peff).

2.4. Determination of soil physical and hydraulic properties

After harvest in the experimental years, disturbed and undisturbed soil samples were taken from 0-30 cm depth from all plots. Particle density was determined by Pycnometer method (Blake & Hartge, 1986a). Bulk density was calculated by dividing the oven dry weights of samples taken with undisturbed soil sampling cylinder by the total sample volume (Blake & Hartge, 1986b). Porosity was calculated using particle and bulk density values (Danielson & Sutherland, 1986). Wet aggregate stability was determined by Yoder type wet sieving device (Kemper & Rosenau, 1986). The amount of water retained at field capacity (- 0.033 MPa) and permanent wilting point (-1.5 MPa) were determined by using ceramic plates in a pressure chamber. (Klute, 1986). Available water content was calculated from the difference between field capacity and permanent wilting point (Cassel & Nielsen, 1986). Soil organic matter content was determined by the Smith-Weldon method (Nelson & Sommers, 1982). Exchangeable Ca was measured by ICP-MS using samples subjected to high pressure wet digestion process (U.S. EPA, 2007).

The initial bulk density, particle density, porosity, wet aggregate stability, field capacity, permanent wilting point and available water content were 1.29 g/cm^3, 2.66, 51.9%, 46.8%, 23.2% of weight, 13.3% of weight, and 38.3 mm, respectively. Exchangeable Ca content was 15.84 cmol/kg, and organic matter content was 1.73%.

2.5. Statistical Analysis

The experimental data were analyzed with General Linear Model approach in the SPSS statistics program. Considering significant effects of sewage sludge doses, irrigation regimes and their interactions, the means at the $p < 0.05$ significance level were classified using the multiple comparison test. In addition, Pearson correlation analyses were applied to determine the binary relationships between some parameters.

3. Results and Discussion

3.1. Soil physical properties

Sewage sludge doses significantly ($p<0.01$) increased bulk and particle densities and wet aggregate stability values in both year and average of years, significant ($p < 0.01$) effect on porosity was determined in the first year only (Table 1). Bulk density decreased with increasing dose, and 3.1% lower bulk density was determined in the D3 treatment compared to the D0 treatment (Table 2). With the increase in the sewage sludge dose, the particle density also decreased and a 1.9% lower value was determined in the D3 dose compared to D0. In porosity, the D3 treatment provided a 0.8% higher value compared to D0 in the first trial year. The aggregate stability value of the D3 treatment was also 14.9% higher compared to D0.

Table 1. Variance analysis results
Çizelge 1. Varyans analizi sonuçları

Parameter	Year	Variance Sources	df	Mean Square	F	P
Bulk density	2021	Dose	3	0.002	18.758	0.000
		Irrigation	2	0.000	0.175	0.841
		Dose × Irrigation	6	7.870E-05	0.708	0.646
		Error	24	0.000E+00		
	2022	Dose	3	0.002	20.444	0.000
		Irrigation	2	0.000	0.576	0.570
		Dose × Irrigation	6	4.907E-05	0.535	0.776
		Error	24	9.167E-05		
	2021-2022	Dose	3	0.002	37.526	0.000
		Irrigation	2	0.000	0.684	0.514
		Dose × Irrigation	6	3.611E-05	0.684	0.664
		Error	24	5.278E-05		
Particle density	2021	Dose	3	0.004	57.538	0.000
		Irrigation	2	0.000	2.423	0.110
		Dose × Irrigation	6	1.417E-04	1.962	0.112
		Error	24	0.000		
	2022	Dose	3	0.004	53.544	0.000
		Irrigation	2	0.000	1.900	0.171
		Dose × Irrigation	6	9.537E-05	1.144	0.368
		Error	24	0.000		
	2021-2022	Dose	3	0.004	56.718	0.000
		Irrigation	2	0.000	1.654	0.212
		Dose × Irrigation	6	1.157E-04	1.603	0.190
		Error	24	0.000		
Porosity	2021	Dose	3	0.953	6.141	0.003
		Irrigation	2	0.230	1.480	0.248
		Dose × Irrigation	6	2.900E-01	1.869	0.128
		Error	24	1.550E-01		
	2022	Dose	3	0.350	1.801	0.174
		Irrigation	2	0.233	1.201	0.318
		Dose × Irrigation	6	1.260E-01	0.650	0.690
		Error	24	1.940E-01		
	2021-2022	Dose	3	0.350	1.801	0.174
		Irrigation	2	0.233	1.201	0.318
		Dose × Irrigation	6	1.260E-01	0.650	0.690
		Error	24	1.940E-01		
Wet aggregate stability	2021	Dose	3	93.330	662.696	0.000
		Irrigation	2	0.054	0.384	0.685
		Dose × Irrigation	6	1.800E-02	0.128	0.992
		Error	24	1.410E-01		
	2022	Dose	3	89.472	496.701	0.000
		Irrigation	2	0.196	1.088	0.353
		Dose × Irrigation	6	6.300E-02	0.348	0.904
		Error	24	1.800E-01		
	2021-2022	Dose	3	91.400	1445.252	0.000
		Irrigation	2	0.067	1.064	0.361
		Dose × Irrigation	6	1.300E-02	0.212	0.969
		Error	24	6.300E-02		
Organic matter	2021	Dose	3	0.074	956.131	0.000
		Irrigation	2	0.006	78.429	0.000
		Dose × Irrigation	6	0.000E+00	3.667	0.010
		Error	24	7.778E-05		
	2022	Dose	3	0.148	321.789	0.000
		Irrigation	2	0.002	4.934	0.016
		Dose × Irrigation	6	0.000E+00	0.331	.914
		Error	24	4.611E-04		
	2021-2022	Dose	3	0.105	665.889	0.000
		Irrigation	2	0.004	23.211	0.000
		Dose × Irrigation	6	0.000E+00	0.871	0.530
		Error	24	1.583E-04		

Table 1. (continued)
Çizelge 1. (devam)

Parameter	Year	Variance Sources	df	Mean Square	F	P
Exchangeable Ca	2021	Dose	3	5.451	36.986	0.000
		Irrigation	2	0.027	0.184	0.833
		Dose × Irrigation	6	0.087	0.592	0.734
		Error	24	0.147		
	2022	Dose	3	1.832	11.902	0.000
		Irrigation	2	0.087	0.565	0.576
		Dose × Irrigation	6	0.053	0.344	0.906
		Error	24	0.154		
	2021-2022	Dose	3	3.324	45.690	0.000
		Irrigation	2	0.052	0.714	0.500
		Dose × Irrigation	6	0.027	0.371	0.890
		Error	24	0.073		
Field capacity	2021	Dose	3	0.697	2.879	0.057
		Irrigation	2	0.008	0.032	0.968
		Dose × Irrigation	6	2.400E-02	0.098	0.996
		Error	24	2.420E-01		
	2022	Dose	3	0.782	6.821	0.002
		Irrigation	2	0.003	0.029	0.971
		Dose × Irrigation	6	3.300E-02	0.291	0.936
		Error	24	1.150E-01		
	2021-2022	Dose	3	0.748	5.894	0.004
		Irrigation	2	0.005	0.042	0.959
		Dose × Irrigation	6	2.900E-02	0.228	0.963
		Error	24	1.270E-01		
Permanent wilting point	2021	Dose	3	0.063	0.453	0.717
		Irrigation	2	0.004	0.026	0.974
		Dose × Irrigation	6	2.000E-03	0.013	1.000
		Error	24	1.380E-01		
	2022	Dose	3	0.041	1.086	0.374
		Irrigation	2	0.008	0.207	0.814
		Dose × Irrigation	6	2.300E-02	0.612	0.718
		Error	24	3.800E-02		
	2021-2022	Dose	3	0.045	0.772	0.521
		Irrigation	2	0.002	0.033	0.968
		Dose × Irrigation	6	9.000E-03	0.159	0.985
		Error	24	5.900E-02		
Available water content	2021	Dose	3	1.055	0.132	0.940
		Irrigation	2	0.385	0.048	0.953
		Dose × Irrigation	6	3.190E-01	0.040	1.000
		Error	24	7.984E+00		
	2022	Dose	3	2.459	1.409	0.265
		Irrigation	2	0.028	0.016	0.984
		Dose × Irrigation	6	8.400E-01	0.481	0.816
		Error	24	1.745E+00		
	2021-2022	Dose	3	1.649	0.578	0.635
		Irrigation	2	0.974	0.341	0.714
		Dose × Irrigation	6	3.056E+00	1.070	0.407
		Error	24	2.855E+00		

*$p < 0.05$

Bulk density decreased with increasing dose, and 3.1% lower bulk density was determined in the D3 treatment compared to the D0 treatment (Table 2). With the increase in the sewage sludge dose, the particle density also decreased and a 1.9% lower value was determined in the D3 dose compared to D0. In porosity, the D3 treatment provided a 0.8% higher value compared to D0 in the first trial year. The aggregate stability value of the D3 treatment was also 14.9% higher compared to D0.

Considering the initial values of particle density as 2.66, bulk density as 1.29 g/cm^3, porosity as 51.9% and wet aggregate stability as 46.8%, at the end of the second trial year, D3 treatment decreased bulk density by 4.7% and particle density by 1.5%, while increasing porosity by 1.9% and wet aggregate stability by 22.2%.

Table 2. Bulk density, particle density, porosity and wet aggregate stability values in 0-30 cm soil layer at different sewage sludge dose and irrigation regimes

Çizelge 2. Farklı arıtma çamuru dozları ve sulama rejimlerinde 0-30 cm toprak tabakasında kütle yoğunluğu, tane yoğunluğu, porozite ve ıslak agrega stabilitesi değerleri

Parameter	Year	Irrigation treatment	D0	D1	D2	D3	Mean
Bulk density (g/cm^3)	2021	S1	1.27±0.01	1.26±0.00	1.25±0.01	1.23±0.01	1.25±0.01
		S2	1.27±0.01	1.26±0.00	1.25±0.00	1.24±0.01	1.26±0.00
		S3	1.26±0.01	1.26±0.01	1.26±0.01	1.23±0.01	1.25±0.00
		Mean	1.27±0.00 A*	1.26±0.00 AB	1.25±0.00 B	1.23±0.00 C	
	2022	S1	1.27±0.01	1.26±0.00	1.24±0.00	1.23±0.00	1.25±0.00
		S2	1.27±0.00	1.26±0.00	1.25±0.01	1.23±0.01	1.25±0.00
		S3	1.26±0.01	1.27±0.00	1.25±0.01	1.24±0.01	1.25±0.00
		Mean	1.27±0.00 A*	1.26±0.00 A	1.25±0.00 B	1.23±0.00 C	
	2021-2022	S1	1.27±0.00	1.26±0.00	1.25±0.00	1.23±0.00	1.25±0.00
		S2	1.27±0.01	1.26±0.00	1.25±0.00	1.23±0.00	1.25±0.00
		S3	1.26±0.00	1.27±0.00	1.25±0.01	1.24±0.01	1.25±0.00
		Mean	1.27±0.00 A*	1.26±0.00 A	1.25±0.00 B	1.23±0.00 C	
Particle density	2021	S1	2.67±0.01	2.66±0.01	2.64±0.00	2.63±0.00	2.65±0.01 A*
		S2	2.67±0.01	2.64±0.00	2.63±0.00	2.62±0.00	2.64±0.01 B
		S3	2.68±0.00	2.64±0.00	2.63±0.00	2.62±0.00	2.64±0.01 B
		Mean	2.67±0.00 A*	2.65±0.00 B	2.63±0.00 C	2.62±0.00 D	
	2022	S1	2.68±0.01	2.66±0.00	2.65±0.00	2.62±0.01	2.65±0.01
		S2	2.67±0.01	2.65±0.00	2.64±0.00	2.62±0.01	2.65±0.01
		S3	2.68±0.00	2.65±0.00	2.63±0.00	2.63±0.01	2.65±0.01
		Mean	2.67±0.00 A*	2.65±0.00 B	2.64±0.00 C	2.62±0.00 D	
	2021-2022	S1	2.67±0.01	2.66±0.01	2.64±0.00	2.62±0.00	2.65±0.01
		S2	2.67±0.00	2.65±0.00	2.64±0.00	2.62±0.00	2.64±0.01
		S3	2.68±0.00	2.64±0.00	2.63±0.00	2.63±0.01	2.64±0.01
		Mean	2.67±0.00 A*	2.65±0.00 B	2.64±0.00 C	2.62±0.00 D	
Porosity (%)	2021	S1	52.4±0.12	52.5±0.24	52.8±0.26	53.2±0.21	52.7±0.13
		S2	52.6±0.24	52.1±0.20	52.3±0.06	52.7±0.32	52.4±0.12
		S3	53.0±0.28	52.1±0.28	52.0±0.17	53.2±0.25	52.6±0.18
		Mean	52.6±0.14 AB	52.3±0.13 B	52.4±0.14 B	53.0±0.15 A*	
	2022	S1	52.7±0.43	52.8±0.11	53.0±0.19	52.9±0.16	52.9±0.11
		S2	52.6±0.22	52.4±0.07	52.6±0.17	53.1±0.29	52.6±0.111
		S3	52.8±0.32	52.1±0.16	52.7±0.29	52.8±0.38	52.6±0.15
		Mean	52.7±0.17	52.4±0.12	52.8±0.13	52.9±0.15	
	2021-2022	S1	52.5±0.17	52.7±0.15	52.9±0.16	53.1±0.11	52.8±0.09
		S2	52.6±0.23	52.3±0.10	52.5±0.05	52.9±0.05	52.5±0.09
		S3	52.9±0.17	52.1±0.16	52.3±0.29	53.0±0.29	52.6±0.14
		Mean	52.7±0.11	52.4±0.11	52.6±0.10	53.0±0.10	
Wet aggregate stability (%)	2021	S1	49.7±0.24	52.0±0.07	54.5±0.29	57.2±0.30	53.4±0.84
		S2	49.7±0.21	51.9±0.14	54.4±0.27	57.0±0.16	53.2±0.83
		S3	49.6±0.27	51.7±0.09	54.5±0.21	57.2±0.21	53.3±0.86
		Mean	49.7±0.12 D	51.9±0.06 C	54.5±0.13 B	57.1±0.12 A*	
	2022	S1	50.0±0.59	52.0±0.08	54.6±0.17	57.0±0.04	53.4±0.80
		S2	49.7±0.37	51.9±0.10	54.4±0.22	57.3±0.21	53.3±0.86
		S3	50.0±0.28	52.2±0.10	54.6±0.09	57.4±0.07	53.5±0.83
		Mean	49.9±0.22 D	52.0±0.07 C	54.5±0.09 B	57.2±0.09 A*	
	2021-2022	S1	49.9±0.28	52.0±0.03	54.5±0.16	57.1±0.15	53.4±0.82
		S2	49.7±0.08	51.9±0.05	54.4±0.13	57.1±0.10	53.3±0.84
		S3	49.8±0.24	52.0±0.06	54.6±0.13	57.3±0.11	53.4±0.84
		Mean	49.8±0.11 D	51.9±0.03 C	54.5±0.07 B	57.2±0.07 A*	

Due to the high organic matter content of the sewage sludge of 38.6%, the organic matter content of the soil increased with the increase in the applied dose, and the highest values were determined in the D3 treatment, and infrequent irrigation regime, which reduced organic matter mineralization (Figure 1). Organic matter in the soil supports microorganism activities and strengthens the bonds between soil mineral materials, thus ensuring that aggregates are more durable and stable (Lu et al., 2021). Therefore, mostly, the presence of organic matter increases aggregate stability and decreases bulk density (Ramezani et al., 2019). Similarly, Asadu et al. (2008), Delibacak et al. (2020) and Aksakal and Cambaztepe (2022) reported that organic matter, bulk density, porosity and aggregate stability in the sewage-amended soil were improved significantly compared to the without sewage soil. Although Sharma (2024) reported that porosity increases as the organic matter content of the soil increases, as parallel to our porosity results, Sort and Alcañiz (1999) reported that although sludge application caused an increase in both fine micro and coarse porosity of the soil, this effect was transient as no significant difference was detected compared to the control one year after application. Simões-Mota et al. (2022) also reported the significant effect on porosity of long-term sewage sludge application. However, Camps-Sagué et al. (2024) indicated that the potential improvement benefits on soil structure of sewage sludge are limited to their use within a certain dose range, and reported no significant differences between sewage sludge application of twenty years and mineral treatment for total porosity were found.

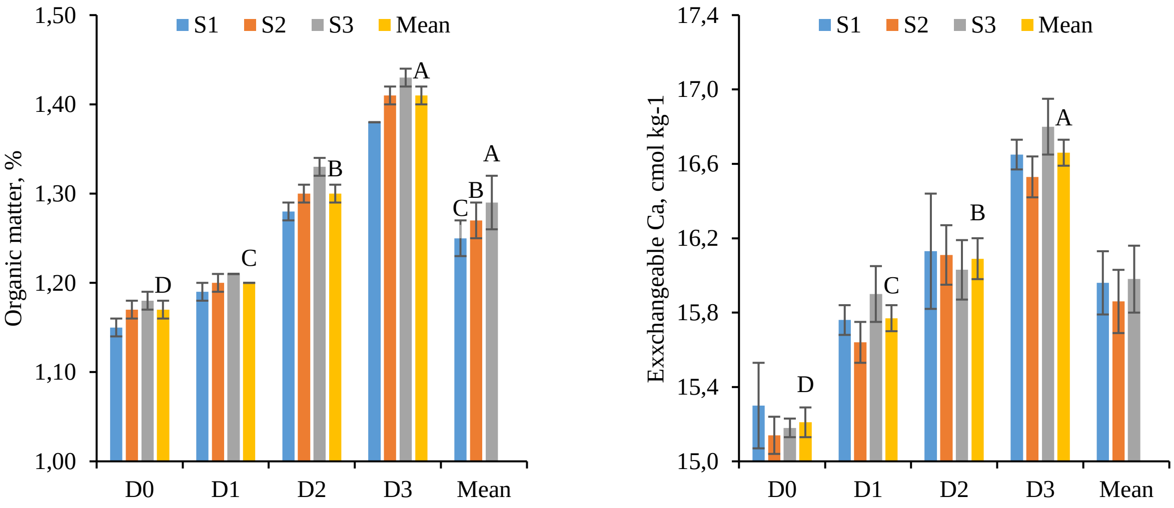

Fig 1. Experimental years averages of organic matter and exchangeable Ca contents in 0-30 cm soil layer under different irrigation regimes with different sewage sludge doses. D0: 0 t/ha, D1: 30 t/ha, D2: 60 t/ha, D3: 90 t/ha. S1, S2, and S3: irrigation when sum of the difference between estimated evapotranspiration and effective precipitation equals to 25 mm, 50 mm and 75 mm, respectively. *: $p < 0.05$

Şekil 1. Farklı sulama rejimleri ve farklı arıtma çamuru dozları altında 0-30 cm toprak katmanındaki organik madde ve değiştirilebilir Ca içeriklerinin deneysel yıl ortalamaları. D0: 0 t/ha, D1: 30 t/ha, D2: 60 t/ha, D3: 90 t/ha. S1, S2 ve S3: tahmini buharlaşma ve etkili yağış arasındaki farkın toplamı sırasıyla 25 mm, 50 mm ve 75 mm'ye eşit olduğunda sulama. *: $p < 0.05$

The binary relationships of particle density, bulk density and wet aggregate stability with the soil organic matter content were significantly ($p < 0.01$) linear (Figure 2). Similarly, Yerli et al. (2024) indicated that while the decrease in bulk density and increases in wet aggregate stability was mostly related to soil organic matter content, organic matter content did not reach a level that affected particle density significantly.

Biswas et al. (2017) indicated that the increase in the organic matter content of the soil leads to a decrease in bulk density. Usman et al. (2012) also stated that as the sewage sludge ratio increases, the bulk density decreases due to increased porosity. Sabtow and Kızıloğlu (2022) reported that the particle density decreases with the increase in dose in soils where organic materials are applied. (Ojeda et al. (2008) reported that aggregate stability generally has a good correlation with soil organic matter content, soil has a higher organic carbon content and greater aggregate stability than the control two years after the surface application of the sludge. Gülser and Candemir (2015) determined significant positive correlations between organic matter and aggregate stability in a soil treated with agricultural wastes. While the many other studies also indicated that the increase in organic matter content significantly increases aggregate stability (Dong et al., 2023; Sun et al., 2023; Halder et al., 2024), many studies also reported a positive relationship between organic matter content and aggregate stability (Sarker et al., 2018; Mbanjwa et al., 2022; Sonsri et al., 2023).

Exchangeable Ca contents in soil in D0 and D1 treatments were lower than the initial value of soil (15.84 cmol/kg) based on probably crop consumption (Figure 1). However, exchangeable Ca contents in soil increased with increasing dose due to high Ca content of sewage sludge (40.96 cmol/kg) in D2 and D3 treatments compared to the initial value of soil. The effect of Ca on aggregate stability is related to the ability of soil colloids to neutralize surface charges. Calcium interacts with negatively charged soil colloids, neutralizes surface charges and increases aggregate stability by allowing soil particles to adhere better to each other. Therefore, it is known that soils with sufficient Ca content generally have higher aggregate stability. Researches show that there is a positive relationship between soil aggregate stability and exchangeable Ca content. As exchangeable Ca content increases, aggregate stability also increases; this relationship is explained by Ca acting as a bridge between clay particles and supporting aggregate formation (Gümüş et al., 2016). These experiment results stated a significant ($p < 0.01$) positive relationship between soil aggregate stability and exchangeable Ca content (Figure 2). Similarly, Bedel et al. (2018) and Yao et al. (2022) also determined a positive relationship between aggregate stability and exchangeable Ca content in their studies.

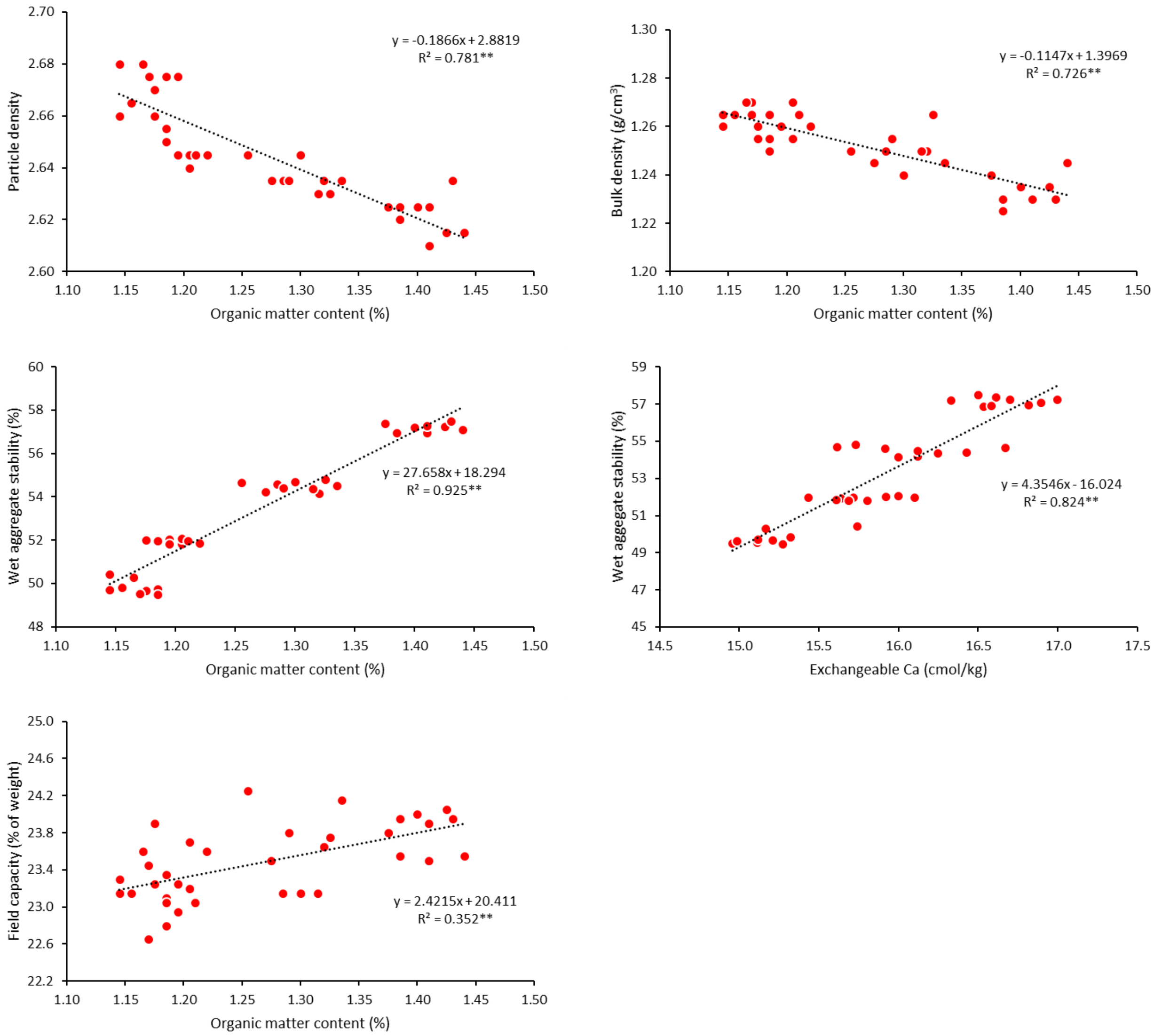

Fig 2. The binary relationships between some soil properties (n=36; **$p < 0.01$)
Şekil 2. Bazı toprak özellikleri arasındaki ikili ilişkiler (n=36; **$p < 0.01$)

3.2. Soil hydraulic properties

The effect of sewage sludge application on field capacity was significant ($p < 0.01$; $p < 0.05$ in the first year) (Table 1). In the two-year average, when compared to D0, gravimetric field capacity values increased by 0.85%, 2.1% and 2.6% in D1, D2 and D3 treatments, respectively (Table 3). Moreover, D3 treatment provided a 2.6% improvement compared to the initial value (23.2% of weight) in the experiment. Sewage sludge, with its high organic matter content, enriches the soil in terms of organic matter and increases its water holding capacity at low tension. Studies show that soils with high organic matter content have higher field capacities. In this study, a significant ($p < 0.01$) positive relationship was found between gravimetric field capacity and organic matter content (Figure 2). Lal (2020) and Ramirez et al. (2023) also stated that the increase in organic matter increases field capacity and that there is a linear relationship between these two parameters. Many other studies have also shown that the increase in organic matter in the soil causes a significant increase in field capacity values (Tunc & Sahin, 2015; Kadıoğlu & Canbolat, 2019; Alaboz & Çakmakcı, 2020; Yerli et al., 2024).

Table 3. Field capacity, permanent wilting point and available water content values in 0-30 cm soil layer at different sewage sludge dose and irrigation regimes

Çizelge 3. Farklı arıtma çamuru dozları ve sulama rejimlerinde 0-30 cm toprak tabakasında tarla kapasitesi, devamlı solma noktası ve kullanılabilir su içeriği değerleri

Parameter	Year	Irrigation treatment	D0	D1	D2	D3	Mean
Field capacity (% of weight)	2021	S1	23.1±0.47	23.5±0.35	23.6±0.32	23.8±0.15	23.5±0.17
		S2	23.4±0.17	23.4±0.26	23.6±0.20	23.8±0.23	23.6±0.11
		S3	23.2±0.35	23.3±0.26	23.7±0.34	23.9±0.09	23.5±0.14
		Mean	23.2±0.18 C	23.4±0.15 AB	23.7±0.15 AB	23.8±0.08 A*	
	2022	S1	23.0±0.09	23.3±0.19	23.6±0.34	23.7±0.21	23.4±0.13
		S2	23.2±0.06	23.3±0.17	23.4±0.22	23.8±0.12	23.4±0.13
		S3	23.1±0.15	23.2±0.09	23.6±0.32	23.7±0.18	23.4±0.12
		Mean	23.1±0.06 C	23.3±0.08 BC	23.6±0.15 AB	23.8±0.09 A*	
	2021-2022	S1	23.0±0.20	23.4±0.26	23.6±0.32	23.8±0.12	23.5±0.13
		S2	23.3±0.09	23.3±0.22	23.5±0.20	23.9±0.18	23.5±0.10
		S3	23.2±0.23	23.3±0.16	23.7±0.29	23.8±0.13	23.5±0.12
		Mean	23.2±0.10 C	23.3±0.11 BC	23.6±0.14 AB	23.8±0.07 A*	
Permanent wilting point (% of weight)	2021	S1	13.2±0.03	13.4±0.20	13.4±0.14	13.5±0.02	13.4±0.06
		S2	13.3±0.20	13.3±0.18	13.4±0.05	13.5±0.26	13.4±0.08
		S3	13.3±0.20	13.3±0.17	13.4±0.28	13.5±0.47	13.4±0.13
		Mean	13.3±0.08	13.3±0.09	13.4±0.09	13.5±0.16	
	2022	S1	13.3±0.03	13.4±0.06	13.2±0.19	13.6±0.09	13.4±0.06
		S2	13.4±0.09	13.4±0.12	13.5±0.07	13.4±0.12	13.4±0.04
		S3	13.4±0.12	13.3±0.09	13.5±0.19	13.5±0.09	13.4±0.06
		Mean	13.4±0.04	13.4±0.05	13.4±0.09	13.5±0.05	
	2021-2022	S1	13.3±0.00	13.4±0.09	13.3±0.16	13.5±0.05	13.4±0.05
		S2	13.3±0.11	13.4±0.13	13.4±0.04	13.5±0.17	13.4±0.06
		S3	13.3±0.16	13.3±0.11	13.5±0.23	13.5±0.24	13.4±0.09
		Mean	13.3±0.06	13.4±0.06	13.4±0.08	13.5±0.09	
Available water content (mm)	2021	S1	37.2±1.99	38.3±2.04	38.1±1.16	38.0±0.50	37.9±0.68
		S2	38.2±1.57	38.1±1.47	38.4±0.95	38.5±2.06	38.3±0.67
		S3	37.6±1.99	38.0±0.62	38.9±2.17	38.3±1.84	38.2±0.77
		Mean	37.7±0.94	38.2±0.75	38.5±0.77	38.3±0.81	
	2022	S1	36.6±0.54	37.5±0.77	38.8±0.65	37.5±0.85	37.6±0.38
		S2	37.4±0.46	37.5±0.65	37.4±0.74	38.4±0.67	37.7±0.30
		S3	36.8±0.85	37.6±0.14	38.0±1.57	37.9±0.40	37.6±0.42
		Mean	36.9±0.34	37.5±0.29	38.1±0.57	37.9±0.36	
	2021-2022	S1	36.9±0.73	37.9±1.40	38.5±0.91	37.8±0.55	37.8±0.44
		S2	37.8±0.82	37.8±1.04	37.9±0.85	38.4±1.32	38.0±0.45
		S3	37.2±1.34	37.8±0.36	38.4±1.75	38.1±1.12	37.9±0.55
		Mean	37.3±0.52	37.9±0.52	38.3±0.63	38.1±0.53	

*$p < 0.05$

Although a statistical change was not observed in the permanent wilting point and available water holding capacity, it was determined that there was a 1.5% improvement in the permanent wilting point and a 2.1% improvement in the available water content compared to D0 at the highest dose with increasing dose in the two-year average. Similarly, Gardner et al. (2010) indicated that although biosolids added to the soil increased gravimetric water retention at field capacity and wilting point, no significant change occurred in gravimetric water retention because of a proportional increase in both field capacity and wilting point values.

Considering the significant increase in field capacity due to organic matter in this study, it was evaluated that the partial increase in the amount of available water was also due to field capacity. Yerli et al. (2024) also stated that there was an increase in field capacity, wilting point and available water content with the increase in the amount of organic matter in the surface soil. Tunc and Sahin (2015) and Dogan Demir and Sahin (2019) stated that increases in the amount of available water have a strong relationship with porosity from soil properties. Considering the views of Ors et al. (2015) that water retention capacity is directly related to pore sizes and that organic material contribute to water retention capacity by improving the pore size distribution, it can be said that the change in pore size distribution may be more important in improving water retention at low tensions, since no significant increases in porosity were detected in this study.

4. Conclusions

This study aim was to examine the effects of four different sewage sludge doses and three irrigation regimes on the soil physical and hydraulic properties. As a result of the study, it was concluded that 90 t/ha dose of stabilized sewage sludge, with non-significant effect of irrigation regimes, can be good practice and contribute to the physical and hydraulic properties of the soil in silage maize cultivation. However, it has been evaluated that the contribution of irrigation at wide intervals to the preservation of organic matter in the soil should also considered, and that this may be important in terms of the effect of doses over 90 t/ha of sewage sludge on soil properties. Therefore, it could be concluded that, further investigation of the long-term effects of sewage sludge with higher doses also on soil physical and hydraulic properties in agricultural areas is necessary to verify the permanence of short-term results. This will be particularly useful in clarifying the effects of increased salinity in soil from sewage sludge on physical and hydraulic soil properties in the long term.

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