IMPROVEMENT OF THE HYDRAULIC PROPERTIES OF SALINE-SODIC SOIL EXPOSED TO FREEZING-THAWING USING SEWAGE SLUDGE AND WETTING-DRYING PROCESS WITH WASTEWATER

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Abstract: Soil improvement practices are needed to protect weakly aggregated saline-sodic soils in cold regions from the negative effects of freezing-thawing events. Amelioration of these soils by adding sewage sludge and applying wetting–drying process with wastewater can be a practical application due to aggregation to be increased with increase in organic matter. Therefore, a laboratory experiment has been conducted to determine the effects on soil properties with three stabilized sewage sludge doses (0, 50, 100 Mg ha^{-1}), two freeze-thaw cycles (5 and 10 times), two wetting-drying intervals (4 and 8 days) and two water types (freshwater and recycled wastewater). The negative effects of freezing-thawing on organic matter and aggregate stability were determined. However, while sewage sludge increased organic matter, aggregate stability, salinity, exchangeable K and Ca+Mg contents, cation exchange capacity (CEC), it was instrumental in inducing a lower pH, exchangeable Na, $CaCO_3$ and exchangeable sodium percentage (ESP), and thus improved field capacity and hydraulic conductivity. Wetting-drying with 8-day intervals and wastewater improved organic matter also. Therefore, it could be concluded that the improvement of hydraulic properties can be attributed to achieving better aggregate stability with increased organic matter in soil from sewage sludge. Long intervals of wetting-drying and recycled wastewater can promote good results as well. However, improving the findings with the proposed treatments in the outer field conditions of the regions exposed to freezing-thawing events will provide more practical use.

Keywords: Aggregate stability, Freeze-thaw, Hydraulic conductivity, Saline-sodic soil, Solid and liquid wastes

1. INTRODUCTION

Soil degradation from salinity and sodicity in agricultural lands is one of the most widespread problems which threatens sustainable agricultural production in the arid and semiarid regions of the world (Angin et al., 2011). The soil salinity is a severe environmental and ecological issue (Demir, 2022). High salinity prevents plant water uptake by increasing osmotic potential while high Na content in the cation exchange complex causes the loss of soil structure with clay swelling and dispersion (Angin et al., 2011; Alcívar et al., 2018).

Soil organic matter is an active soil component which provides supporting contributions to saline–sodic soil amelioration due to improved aggregation, increased water conductivity, water retention and cation exchange capacity and decreases the exchangeable sodium percentage and the pH (Leogrande & Vitti, 2019; Sahin et al., 2020). Organic matter improves aggregation by directly promoting the binding of soil mineral particles, declining aggregate wettability, and providing the mechanical strength (Masciandaro et al., 2018). Treating salt-affected soils with organic waste materials has become a practical application over the last years (Leogrande & Vitti, 2019). The studies have reported that the addition of sewage sludge with considerable amounts of organic matter used as an organic amendment in saline-sodic soils has resulted in improved aggregate stability, hydraulic conductivity and exchangeable sodium percentage values (Sahin et al., 2020; Abdallh & Sahin, 2020). In addition, recycled municipal wastewaters are used to improve soil structural and fertility properties with its high contents of suspended and dissolved organic matter and many beneficial elements for plants such as macro and micronutrients (Abd-Elwahed, 2018; Kun et al., 2018; Cakmakci & Sahin, 2021). Abdallh & Sahin (2020) indicated that recycled wastewaters with low salinity and sodicity can be used in the improvement of saline-sodic soils.

Microbial activity affected by soil moisture is a dynamic environmental factor in the mineralization of organic matter and increases mineralization (Yun et al., 2019). Wetting–drying process with longer intervals preserved organic matter stock and increased aggregate stability in clay soil and saline-sodic soil (Sahin et al., 2020; Badaou & Sahin, 2022). However, there are different findings in previous studies about wetting–drying cycles increasing or decreasing structural stability (Parlak et al., 2014).

Saline-sodic soils in regions with mid or high altitudes are exposed to consecutive freezing-thawing events frequently, especially in late winter-early spring and freezing-thawing creates considerable positive or negative influences on soil structure (Sahin et al., 2008, 2020). Hanay et al. (2003), determined that the effects of freezing-thawing in soils with high salinity and sodicity levels on wet aggregate stability was negative, while Sahin & Anapali, (2007) found non-significant effects. Adding sewage sludge to saline sodic soils improved aggregate stability and the permeability coefficient due to increased soil organic matter content under freezing-thawing conditions (Sahin et al., 2008). In parallel, Sahin et al. (2020) also determined that wet aggregate stability in saline-sodic soil was improved by increasing organic matter content from sewage sludge and Ca from the $CaCO_3$ solution, gypsum and sewage sludge despite the negative effects of freezing-thawing.

The amelioration of saline-sodic soils under freeze-thaw phenomena remains unclear still. Therefore, we hypothesized that municipal wastes may improve the reclamation by improving aggregation, hydraulic conductivity and water retention attributes of salt-affected soils exposed to freezing-thawing and treated with the wetting-drying process.

Consequently, this study aims to: (1) determine the effect of freezing-thawing cycles on saline-sodic soil properties, (2) explore the improve influences of sewage sludge and recycled wastewater and (3) understand the contribution of wetting-drying intervals.

The results of the research are important in terms of their contribution to the sustainability of agricultural production with the improved aggregation required for high hydraulic conductivity from organic matter protected by moisture management in saline-sodic soils exposed to freezing-thawing event, as well as to environmental sustainability through waste disposal. Therefore, the findings may be valuable to researchers and soil and environmental experts.

2. MATERIAL AND METHODS

This study was conducted under laboratory conditions with a mean temperature of 24±2°C and relative humidity less than 35% during the experimental period in Ataturk University, Erzurum, Turkey. The experiment was carried out with three replications using a completely randomized factorial design with three different stabilized sewage sludge doses (D), two freezing-thawing cycles (FT), two water types (fresh and recycled) and two wetting-drying intervals (WD). Sewage sludge doses were selected as 0, 50 and 100 Mg ha^{-1} in the D0 (control), D1, and D2 treatments, respectively while freezing-thawing cycles were repeated 5 times in FT1 and 10 times in FT2 (Ors et al., 2015; Sahin et al., 2008, 2020). After the freezing-thawing process was completed in the soils with added sewage sludge, wetting-drying cycles were applied with intervals of 4 days in WD1 and 8 days in WD2, respectively, using freshwater (FW) and recycled wastewater (RWW).

The saline-sodic soil was collected from a 15 cm surface layer of a land with high salinity and sodicity levels in Iğdır plain in eastern Turkey. The humidity and temperature regimes of the soil sampling region are aridic and thermic. The great soil group is solodized solonetz (Soil Survey Staff, 2014). The loamy (23.6% clay, 34.0% silt, 42.4% sand) textured soil with low organic matter and wet aggregate stability has a high initial pH (10.4), electrical conductivity (EC = 44.2 dS m^{-1}) and exchangeable sodium percentage (ESP = 61.3%).

2.1. Waste Materials and Quality Competencies

The stabilized sewage sludge and recycled municipal wastewater were provided from the biological wastewater treatment plant in Erzurum, Turkey. The determined properties were: pH 7.29, EC 8.77 dS m^{-1}, organic matter 40.7%, $CaCO_3$ 1.78%, exchangeable Na 37.2 cmol kg^{-1}, Ca+Mg 14.1 cmol kg^{-1} and K 8.76 cmol kg^{-1}. The FW (tap water) was of good quality in terms of pH (7.34), EC (0.334 dS m^{-1}) and sodium adsorption ratio (SAR = 0.58). The RWW had a higher EC (0.655 dS m^{-1}) and SAR (2.20) and lower pH

(7.01) compared to the FW. The RWW also had a content of suspended solid matter of 5.7 mg l^{-1}. In addition, considering the heavy metal contents in these wastes determined by Abdallh & Sahin (2020), the contents in stabilized sewage sludge were very low according to the national and international limit values (EC Directive, 1986; Newspaper Official, 2010). The contents in RWW were also appropriate to the FAO irrigation water quality standard values (Ayers & Westcot, 1994).

2.2. Treatment Processes Details

Seventy-two plastic containers (3 sewage sludge doses×2 freezing-thawing cycles×2 water types×2 wetting-drying intervals×3 replicates = 72) measuring 20 cm in length, 15 cm in width and 9 cm in depth were organized in the laboratory. The soil and stabilized sewage sludge were air dried and sieved through a 1 cm mesh. The stabilized sewage sludge was added to the sieved soil at the specified doses and homogeneously mixed, and the containers were packed with these mixtures. Since physical and hydraulic properties in containers are no representative for the natural soil conditions fully, dry repacking procedure to approximate the bulk density of the soil to a value similar to that observed naturally to avoid the formation of preferential flow pathways was applied in the study (Lewis & Sjöstrom, 2010).

Soil containers were fully wetted with capillarity process in pans filled with freshwater for three days and drained with gravity, and then isolated from atmospheric conditions by covering them with stretch film and keeping them incubated for two months. After incubation, the soil containers were treated with different numbers of consecutive freezing-thawing cycles. The freezing process was applied at – 9±1 °C for 12 h in a deep-freezer, while thawing was carried out at laboratory indoor temperature for 12 h (Sahin et al., 2020).

All containers treated with freezing-thawing were weighed to determine initial weights before the wetting-drying process. The FW and RWW containers before each wetting event were weighed again and the decreased amounts of water according to the initial weight were applied to containers manually using freshwater or recycled wastewater. The wetting-drying processes were repeated 10 times in WD1 and 5 times in WD2.

2.3. Water, Soil and Sewage Sludge Analysis

The pH and EC of the waters were measured using a pH-meter and EC-meter, respectively (Tüzüner, 1990). The solid material cumulated on the Whatman filter paper from wastewater was oven-dried and weighed to determine suspended soil matter (Eaton et al., 1995). Ca and Mg contents were determined by the EDTA titration, Na content by the flame photometric method (Eltan, 1998). Sodium adsorption ratio was calculated from the Na, Ca and Mg contents (Kanber & Ünlü, 2010).

Soil pH and EC were measured in saturation extract (1:2.5 soil: water) using a pH-meter and EC-meter, respectively. Organic matter was analyzed by the Smith-Weldon method, and $CaCO_3$ with a Scheibler Calcimeter. The amount of moisture retained at field capacity (FC) was determined with a pressure plate apparatus at a pressure of −0.033 MPa. A wet sieving apparatus described by Yoder was used to determine wet aggregate stability (WAS). Particle size analysis was made by the Bouyoucos Hydrometer method. All analysis above mentioned were made considering the methods in (Page et al., 1982; Klute, 1986). Exchangeable Na and K were measured in a solution extracted with ammonium acetate with a flame photometer and determination of exchangeable Ca+Mg content was made by EDTA titration (Richards, 1954). Cation exchange capacity (CEC) was considered as the sum of the exchangeable cations (Sahin et al., 2020; Cakmakci & Sahin, 2021). The ESP was calculated with a ratio of exchangeable Na content to the CEC (Richards, 1954). Stabilized sewage sludge analysis was also made by the methods used for soil analysis with some revisions when required.

Saturated hydraulic conductivity (HC) was measured through ICW Permeameter in the laboratory under constant water head, and outflow volumes were recorded for 4 h. The HC was calculated by the Darcy approach with the equation below (Klute, 1986).

$$HC = \frac{V \times L}{T \times H \times A}$$

where HC is the saturated hydraulic conductivity (cm h^{-1}), V is the outflow volume (cm^3), L is the height of the soil column (cm), T is the elapsed time (h), H is the height of water ponded above the soil surface (cm), and A is the cross-sectional area of the soil column (cm^2).

2.4. Data Analysis

General Linear Model was used in data analysis in SPSS software. The treatment interactions were found mostly insignificant (Table 1). Significant means were compared with the Duncan's multiple range test at the level of $p<0.05$. The binary relationships of parameters were also evaluated by linear regression analysis.

Table 1. Variance analysis results of the soil properties

		pH		EC		Org. matter		$CaCO_3$		Exc. K		Exc Na	
Source	df	Mean square	P	Mean square	P	Mean square	P	Mean square	P	Mean square	P	Mean square	P
FT	1	0.00281	0.540	0.001	0.981	0.37123	0.000	0.00056	0.847	0.012013	0.020	0.4356	0.282
D	2	3.85795	0.000	30.411	0.000	1.26370	0.000	0.23014	0.000	0.491643	0.000	51.2001	0.000
W	1	0.02531	0.070	2.205	0.145	0.08611	0.000	0.01389	0.336	0.000401	0.661	0.0272	0.787
WD	1	0.03337	0.039	1.334	0.255	0.10200	0.000	0.14222	0.003	0.000401	0.661	0.6806	0.180
FT×D	2	0.00690	0.400	0.071	0.932	0.00675	0.179	0.00014	0.991	0.001779	0.429	0.4985	0.267
FT×W	1	0.00281	0.540	0.201	0.657	0.00117	0.581	0.00222	0.699	0.000401	0.661	0.0089	0.877
FT×WD	1	0.01253	0.199	0.045	0.833	0.00001	0.954	0.00056	0.847	0.000235	0.737	0.5000	0.249
D×W	2	0.01880	0.089	0.140	0.870	0.01175	0.054	0.00264	0.836	0.002110	0.367	0.4151	0.332
D×WD	2	0.04503	0.004	2.557	0.089	0.01442	0.029	0.00597	0.669	0.004976	0.100	0.0010	0.997
W×WD	1	0.01253	0.199	0.681	0.415	0.00587	0.219	0.00056	0.847	0.000501	0.624	0.4672	0.265
FT×D×W	2	0.01243	0.197	0.016	0.985	0.00425	0.333	0.00097	0.936	0.004318	0.135	0.0251	0.934
FT×D×WD	2	0.01313	0.180	0.035	0.966	0.00339	0.415	0.00431	0.748	0.000218	0.900	0.1804	0.615
FT×W×WD	1	0.08473	0.001	0.027	0.870	0.00390	0.315	0.00222	0.699	0.000001	0.979	0.0089	0.877
D×W×WD	2	0.00873	0.316	0.237	0.791	0.00288	0.472	0.00014	0.991	0.001526	0.483	0.0026	0.993
FT×D×W×WD	2	0.01477	0.146	0.057	0.945	0.00186	0.615	0.00014	0.991	0.003251	0.217	0.6526	0.180
Error	48	0.00738		1.005		0.00378		0.01472		0.002064		0.3676	
		Exc Ca + Mg		CEC		ESP		WAS		FC		HC	
Source	df	Mean square	P	Mean square	P	Mean square	P	Mean square	P	Mean square	P	Mean square	P
FT	1	2.347	0.001	5.1735	0.001	2.311	0.132	8.0267	0.000	0.0011045	0.205	0.0000233	0.674
D	2	149.541	0.000	35.1776	0.000	643.257	0.000	12.2381	0.000	0.0051627	0.001	0.0006508	0.011
W	1	0.720	0.058	0.8235	0.149	0.911	0.341	0.3016	0.431	0.0088889	0.001	0.0000361	0.601
WD	1	0.000	1.000	0.7401	0.171	0.661	0.416	0.2544	0.469	0.0002801	0.521	0.0000483	0.546
FT×D	2	0.094	0.614	0.8726	0.113	0.165	0.846	0.0979	0.816	0.0005238	0.463	0.0000477	0.696
FT×W	1	2.722	0.000	2.3835	0.016	5.837	0.019	0.0601	0.725	0.0169280	0.000	0.0000050	0.845
FT×WD	1	0.020	0.747	0.3335	0.355	0.867	0.352	0.0660	0.712	0.0030161	0.039	0.0000000	0.992
D×W	2	0.087	0.637	0.1335	0.707	1.100	0.335	0.0396	0.921	0.0028404	0.020	0.0000143	0.896
D×WD	2	0.045	0.790	0.0476	0.883	0.071	0.930	0.0110	0.977	0.0001636	0.784	0.0002218	0.194
W×WD	1	0.201	0.310	1.2535	0.077	0.003	0.953	0.0128	0.871	0.0001076	0.690	0.0000003	0.959
FT×D×W	2	0.021	0.898	0.0235	0.941	0.207	0.811	0.2008	0.660	0.0005755	0.429	0.0000060	0.955
FT×D×WD	2	0.152	0.457	0.6626	0.188	0.019	0.981	0.0021	0.996	0.0001451	0.806	0.0000268	0.815
FT×W×WD	1	0.045	0.629	0.0168	0.835	0.151	0.697	0.0193	0.842	0.0001742	0.612	0.0000117	0.766
D×W×WD	2	0.029	0.860	0.0335	0.916	0.068	0.934	0.0095	0.980	0.0009632	0.247	0.0000222	0.844
FT×D×W×WD	2	0.102	0.590	1.0101	0.082	0.528	0.588	0.1891	0.676	0.0003510	0.595	0.0000005	0.996
Error	48	0.190		0.3828		0.983		0.4784		0.0006689		0.0001305	

FT: Freezing-thawing cycle, D: Sewage sludge dose, W: Water type, WD: Wetting-drying process, EC: Electrical conductivity, CEC: Cation exchange capacity, ESP: Exchangeable sodium percentage, WAS: Wet aggregate stability, FC: Field capacity, HC: Saturated hydraulic conductivity

3. RESULTS AND DISCUSSION

3.1. Effects of Sewage Sludge Doses

Saline-sodic soil pH and ESP values, and $CaCO_3$ and exchangeable Na contents significantly decreased with an increased dose of stabilized sewage sludge, while organic matter and exchangeable K, Ca+Mg and CEC contents and EC, WAS, HC and FC values increased (Tables 1 and 2, Figures. 1a,b,c).

The highest sewage sludge dose decreased soil pH value by 7.9% compared to the value (9.96) of D0 treatment, while the D1 dose provided a 2.9% lower value (Figure 1a). Organic matter in soil can reduce pH with its increased content (Sahin et al., 2020). Soil organic matter contents in D1 and D2 treatments with low pH were found to be 66.7% and 48.5% higher, respectively, compared to the D0 value (0.66%) (Figure 1b). The increase in organic matter is due to the high organic matter content (40.7%) of sewage sludge. Previous studies conducted by using the same sewage sludge material showed that the applications significantly increased soil organic matter content

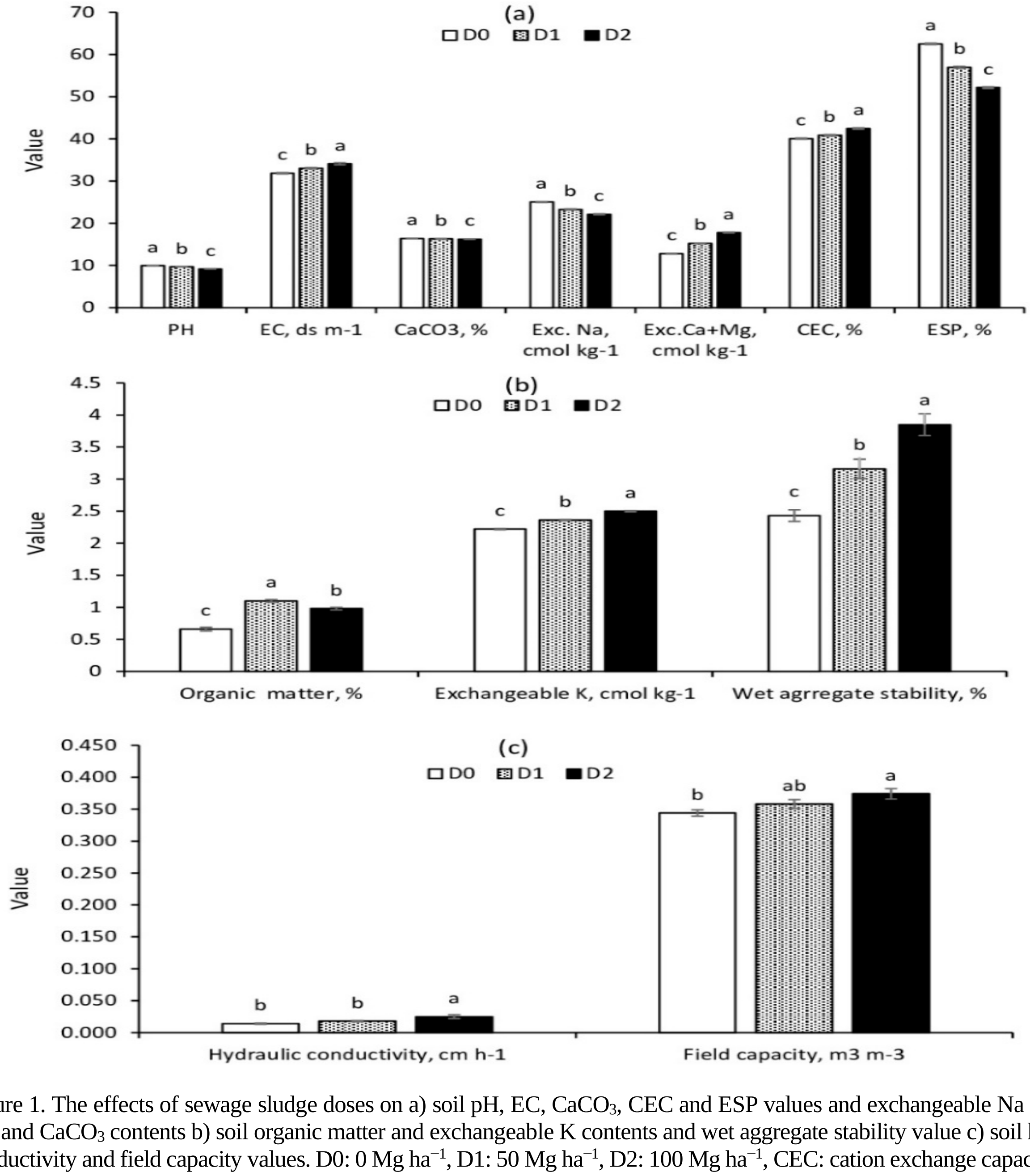

Figure 1. The effects of sewage sludge doses on a) soil pH, EC, $CaCO_3$, CEC and ESP values and exchangeable Na and Ca + Mg and $CaCO_3$ contents b) soil organic matter and exchangeable K contents and wet aggregate stability value c) soil hydraulic conductivity and field capacity values. D0: 0 Mg ha^{-1}, D1: 50 Mg ha^{-1}, D2: 100 Mg ha^{-1}, CEC: cation exchange capacity, ESP: exchangeable sodium percentage. Means marked by the different lowercase letters are significantly different at the level of $p < 0.05$.

and lowered soil pH in saline-sodic soils (Abdallh & Sahin, 2020; Sahin et al., 2020). It could be expected that the low pH (7.29) value of the used sewage sludge could also have had an additional effect on lowering the soil pH.

Binary relationship findings also showed that the pH value decreased linearly ($p<0.01$) with the increase in organic matter content (Fig. 2a). Similar relationships were also found (Karaca et al., 2018; Sahin et al., 2020; Badaou & Sahin, 2022). Singh & Agrawal (2008), Hussein (2009) and Leogrande & Vitti (2019) indicated that the formation of organic/humic acids from the mineralization of organic matter was the main reason for declining soil pH. Similarly, Shan et al., (2021) reported that intermediate products, such as organic acid from the mineralization of organic matter and the low pH of sewage sludge reduce the pH in salt affected soil.

Soil $CaCO_3$ content decreased with increased doses, and D1 and D2 treatments resulted in 0.6% and 1.2% lower values, respectively compared to the D0 treatment value (16.4%) (Figure 1a). It could be said that a decrease in soil pH increased the dissolution of $CaCO_3$ due to a positive linear ($p<0.01$) relationship between the pH and $CaCO_3$ content (Figure 2b). Similarly, Sahin et al., (2020) determined a significant positive linear relationship between the pH and $CaCO_3$ values in saline-sodic soil with added sewage sludge. In agreement with our findings, Mazen et al., (2010) and Leogrande & Vitti (2019) mentioned an increased $CaCO_3$ dissolution as a result of lower pH values. (Fan et al., 2016) reported that the decrease in the pH of saline-sodic soil due to applied sewage sludge can be associated with a decrease in the CO_3+HCO_3 content

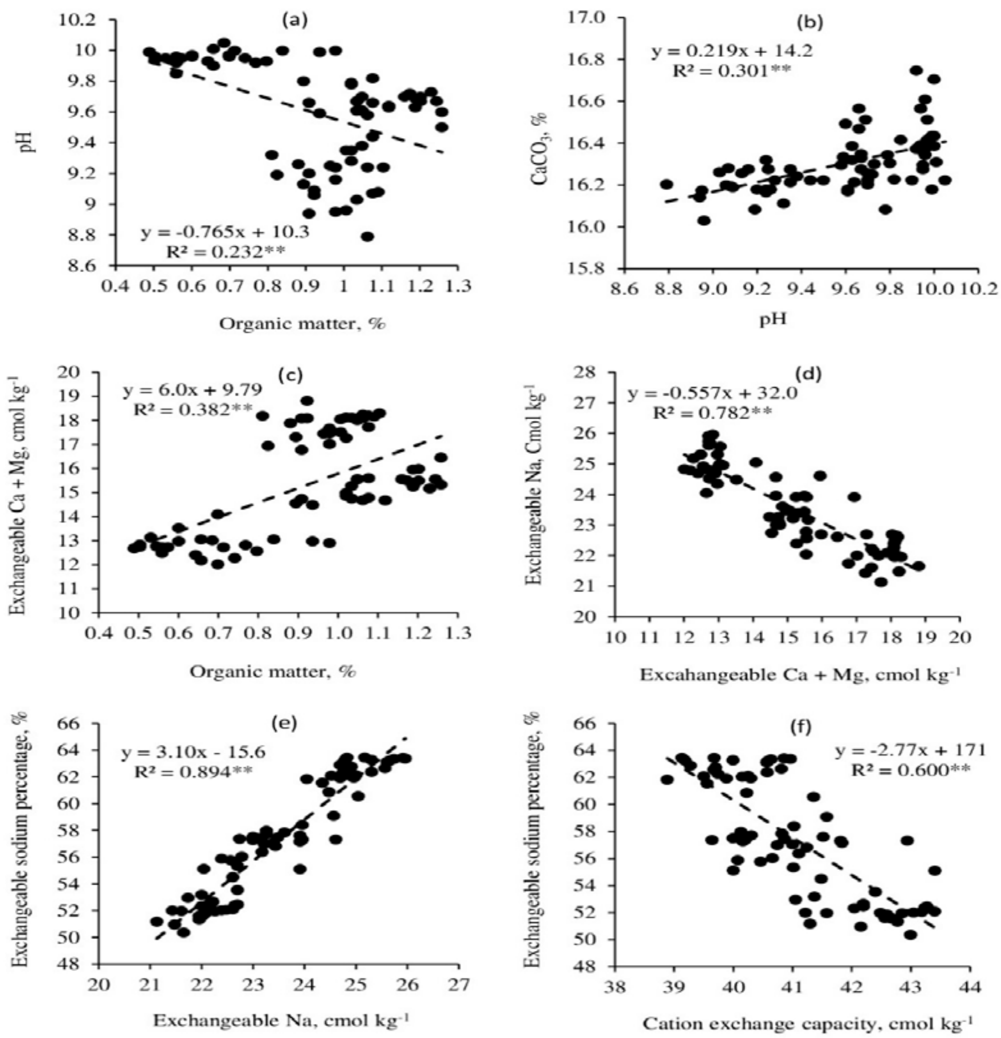

Figure 2. The linear relationship between a) organic matter content and pH b) pH and $CaCO_3$ content c) organic matter and exchangeable Ca + Mg contents d) exchangeable Ca + Mg and Na contents e) exchangeable Na content and exchangeable sodium percentage f) cation exchange capacity and exchangeable sodium percentage. n = 72, ** $p<0.01$

in the soil. Abdel-Fattah (2012) also stated that the addition of organic matter into saline-sodic soils lead to the increase of the solubility of $CaCO_3$ and a decrease in soil pH.

Soil EC values increased with increased sewage sludge doses, the D2 treatment resulted in 7.1% higher EC values compared to the D0 (31.9 dS m^{-1}) (Figure 1a), and this caused by the high EC value (8.77 dS m^{-1}) of sewage sludge. Parallel to our findings, many researchers have reported that increasing the application doses of sewage sludge with high EC values resulted in increased salinity in sandy and calcareous soils (Hussein, 2009), in saline-sodic soils (Ors et al., 2015; Abdallh & Sahin, 2020; Sahin et al., 2020) in sandy clay loam and clay loam soils (Tziachris et al., 2017) and in clay soil (Badaou & Sahin, 2022).

The soil Na content and ESP values in the highest dose were determined to be 11.6% and 16.6% lower than the D0 values, respectively, while the K and Ca+Mg contents 12.6% and 39.1%, were found to be higher (Figures 1a,b). There was a significant positive linear relationship between organic matter and Ca+Mg contents (Figure 2c) because cations such as Ca, Mg and K release with the mineralization of organic matter (Abdel-Fattah, 2012). Increased soil K and Ca+Mg contents could also be directly attributed to the high content of K (8.76 cmol kg^{-1}) and Ca+Mg (14.1 cmol kg^{-1}) in sewage sludge. Similarly, Abdallh & Sahin (2020) indicated that high K contents with higher doses of sewage sludge in saline-sodic soil was due to the high K content of the added sewage sludge. Abdallh & Sahin (2020); Sahin et al. (2020) also determined that the exchangeable Ca+Mg content in saline-sodic soil increased with increased doses of sewage sludge. High Ca concentration in soil solution induces Na–Ca exchange at the cation exchange complex (Qadir et al., 2003). An increase in Ca+Mg content in this study significantly ($p<0.01$) decreased Na content, because the Na content in soil has a linearly negative correlation to the Ca+Mg content (Figure 2d). A similar relationship between Na and Ca+Mg contents was also determined by (Sahin et al., 2020).

High organic matter in D1 and D2 treatments also increased CEC values with increased divalent cations (Ca+Mg) (Table 2, Figure 1a). D2 treatment induced a 5.9% higher CEC value compared to the control (40.1%). Declined Na contents in the cation exchange complex with greater releases of Ca+Mg from the high sewage sludge dose and increased CEC values contributed positively to ESP values (Figure 1a). Considering binary relationships with the Na content and CEC values of the ESP values showed that the decline in ESP was affected more strongly by the decrease in Na content compared to CEC increases (Figures 2e,f). Similarly, Sahin et al. (2020) stated that greater releases of Ca to eliminate Na decreased the ESP values together with negligible changes in CEC values. Many resources have also reported significantly lower ESP values in saline-sodic soils after the application of sewage sludge (Ors et al., 2015); Leogrande & Vitti, 2019; Abdallh & Sahin, 2020).

WAS value increased with dose increases significantly, and the D2 treatment resulted in an increase of 58.4% compared to the control value (2.43%) (Figure 1b). This significant improvement in wet aggregate stability could be associated with directly promoting effect the improvement of soil aggregates by binding soil mineral particles of organic matter (Masciandaro et al., 2018). The significant ($p<0.01$) positive linear relationship between WAS and organic matter content also confirmed this (Figure 3a). Improved aggregate stability values with the addition of organic matter to saline-sodic or sodic soils have been reported in the studies conducted by Gupta et al., (2014), Fan et al., (2016), Abdallh & Sahin (2020) and Sahin et al., (2020). The high Ca+Mg content in D1 and D2 treatments also showed that Ca ions can improve aggregation by forming a cationic bridge between clay particles and soil organic matter as well as the restricting the destruction of clay particles (Gutiérrez et al., 2016; Abdallh & Sahin, 2020).

Sewage sludge application at higher doses improved the water volume retained at field capacity (Figure 1c). The D2 treatment generated an 8.7% higher value compared to the D0 (0.344 m^3 m^{-}3), while the D1 treatment generated an increase of 4.1%. Water retention capacity is directly connected to soil pore size and organic matter induces better pore size (Ors et al., 2015). Similarly, Mujdeci et al., (2017) indicated that probable increases in the pore space between and within aggregates by adding organic matter can improve porosity in favor of available water retention. Therefore, it could be argued that improved WAS values with increased organic matter in this study could be a good indicator of the favorable porosity based on a significant ($p<0.01$) positive linear relationship between FC and WAS (Figure 3b). Badaou & Sahin (2022) concluded that favorable pore sizes created by decreasing macro-porosity in high sewage sludge doses in clay soil could be instrumental in more water retention in the field capacity. Delibacak et al., (2009) has also indicated that field capacity value significantly increased from improved pore size distribution with increased organic matter in the recycled sewage sludge applied to soil.

The HC values increased with increased doses, and the values in D1 and D2 treatments were found to be 78.6% and 28.6% higher than the D0 (0.014 cm h^{-1}) (Figure 1c). Sewage sludge applications ensured an improving effect on the HC from greater structural improvement in the soil considering the significant

Table 2. Soil properties (Mean±Standard error of the mean) after treatments

Sewage sludge	Freezing-thawing	Water type	Wetting-drying		Wetting-drying		Wetting-drying	
			WD1	WD2	WD1	WD2	WD1	WD2
			pH		EC, dS m^{-1}		Organic matter, %	
D0	FT1	FW	9.91±0.03	9.99±0.01	31.3±0.49	32.3±0.35	0.61±0.03	0.75±0.04
		RWW	10.0±0.02	9.98±0.01	31.4±0.54	32.4±0.71	0.68±0.01	0.84±0.12
	FT2	FW	9.97±0.01	9.95±0.01	31.2±0.23	32.2±0.17	0.51±0.01	0.54±0.02
		RWW	9.93±0.01	9.93±0.01	31.5±0.29	32.5±0.29	0.59±0.03	0.77±0.02
D1	FT1	FW	9.68±0.03	9.69±0.03	33.1±0.35	32.9±0.97	1.15±0.02	1.18±0.03
		RWW	9.67±0.02	9.59±0.05	33.1±0.38	33.3±0.21	1.21±0.02	1.24±0.02
	FT2	FW	9.79±0.01	9.73±0.05	32.6±0.37	32.8±0.61	0.98±0.04	1.01±0.05
		RWW	9.59±0.02	9.65±0.02	33.1±0.23	33.4±0.26	1.02±0.04	1.05±0.01
D2	FT1	FW	8.98±0.03	9.39±0.03	34.1±0.59	33.5±0.52	1.01±0.02	1.05±0.02
		RWW	9.10±0.16	9.13±0.06	34.3±1.12	34.2±0.62	1.05±0.01	1.09±0.01
	FT2	FW	9.17±0.12	9.18±0.05	34.3±0.67	33.5±0.74	0.87±0.03	0.93±0.02
		RWW	9.13±0.04	9.25±0.06	34.3±1.05	34.6±0.64	0.88±0.03	0.99±0.01
			$CaCO_3$, %		Exc. K, cmol kg^{-1}		Exc. Na, cmol kg^{-1}	
D0	FT1	FW	16.3±0.06	16.5±0.07	2.22±0.01	2.24±0.03	24.8±0.28	25.2±0.34
		RWW	16.3±0.09	16.5±0.10	2.22±0.01	2.27±0.02	25.2±0.20	24.8±0.25
	FT2	FW	16.3±0.06	16.4±0.07	2.18±0.01	2.20±0.02	25.3±0.36	24.7±0.48
		RWW	16.4±0.03	16.5±0.14	2.19±0.02	2.21±0.01	25.3±0.33	24.9±0.13
D1	FT1	FW	16.3±0.05	16.3±0.09	2.37±0.02	2.37±0.01	23.5±0.76	23.7±0.24
		RWW	16.3±0.04	16.3±0.08	2.36±0.01	2.35±0.04	23.7±0.56	23.1±0.27
	FT2	FW	16.2±0.08	16.3±0.08	2.37±0.02	2.32±0.01	23.3±0.27	23.1±0.15
		RWW	16.3±0.05	16.4±0.12	2.35±0.02	2.39±0.01	23.0±0.20	22.8±0.22
D2	FT1	FW	16.2±0.07	16.2±0.01	2.53±0.02	2.50±0.03	22.1±0.08	22.0±0.46
		RWW	16.2±0.02	16.3±0.04	2.53±0.04	2.51±0.05	22.1±0.32	22.4±0.22
	FT2	FW	16.1±0.02	16.2±0.03	2.52±0.01	2.51±0.01	21.9±0.10	22.0±0.19
		RWW	16.2±0.05	16.3±0.03	2.49±0.05	2.42±0.05	22.8±0.65	21.8±0.19

			Exc. Ca+Mg, cmol kg^{-1}		CEC, %		ESP, %	
D0	FT1	FW	12.6±0.23	12.6±0.30	39.6±0.24	40.1±0.51	62.7±0.57	63.0±0.44
		RWW	13.4±0.35	13.1±0.20	40.8±0.35	40.2±0.20	61.7±0.62	61.7±0.45
	FT2	FW	12.9±0.13	12.7±0.03	40.3±0.37	39.7±0.50	62.6±0.41	62.4±0.43
		RWW	12.6±0.11	12.6±0.16	40.2±0.44	39.7±0.02	63.1±0.13	62.8±0.35
D1	FT1	FW	15.2±0.28	15.0±0.18	41.1±0.57	41.1±0.23	57.2±1.15	57.7±0.41
		RWW	15.8±0.14	15.8±0.35	41.9±0.56	41.2±0.14	56.6±0.63	56.1±0.82
	FT2	FW	14.8±0.13	15.3±0.28	40.4±0.40	40.7±0.23	57.6±0.14	56.7±0.51
		RWW	14.9±0.33	14.9±0.17	40.2±0.14	40.2±0.04	57.1±0.67	56.9±0.49
D2	FT1	FW	17.7±0.21	17.9±0.10	42.3±0.12	42.4±0.58	52. 2±0.33	51.9±0.37
		RWW	18.2±0.04	18.2±0.04	42.8±0.32	43.1±0.19	51.7±0.36	51.9±0.31
	FT2	FW	17.6±0.43	17.9±0.22	42.1±0.51	42.4±0.39	52.2±0.42	51.9±0.09
		RWW	17.7±0.57	17.3±0.18	42.9±0.29	41.5±0.25	53.0±1.39	52.5±0.35
			WAS, %		FC, m^3 m^{-3}		HC, cm h^{-1}	
D0	FT1	FW	2.50±0.13	2.77±0.38	0.337±0.003	0.333±0.019	0.015±0.003	0.016±0.001
		RWW	2.67±0.15	2.82±0.33	0.347±0.07	0.363±0.006	0.012±0.002	0.013±0.001
	FT2	FW	2.12±0.35	2.19±0.12	0.364±0.019	0.344±0.019	0.014±0.003	0.015±0.001
		RWW	2.11±0.06	2.21±0.11	0.342±0.019	0.323±0.010	0.016±0.003	0.015±0.002
D1	FT1	FW	3.21±0.60	3.43±0.25	0.334±0.018	0.335±0.022	0.015±0.002	0.020±0.003
		RWW	3.72±0.20	3.85±0.46	0.390±0.005	0.409±0.018	0.015±0.002	0.019±0.003
	FT2	FW	2.81±0.14	2.76±0.50	0.368±0.007	0.344±0.011	0.015±0.002	0.019±0.003
		RWW	2.64±0.45	2.88±0.28	0.334±0.021	0.346±0.006	0.018±0.002	0.017±0.002
D2	FT1	FW	4.27±0.95	4.14±0.17	0.322±0.017	0.354±0.028	0.035±0.015	0.021±0.002
		RWW	3.98±0.32	4.41±0.30	0.417±0.019	0.407±0.006	0.029±0.016	0.022±0.002
	FT2	FW	3.30±0.67	3.48±0.23	0.378±0.004	0.354±0.004	0.028±0.015	0.021±0.001
		RWW	3.72±0.36	3.53±0.64	0.391±0.021	0.365±0.005	0.023±0.016	0.018±0.003

D0: 0 Mg ha^{-1}, D1: 50 Mg ha^{-1}, D2: 100 Mg ha^{-1}, FT1: 5 freezing-thawing, FT2: 10 freezing-thawing, FW: Freshwater, RWW: Recycled wastewater, WD1: wetting-drying with 4-day intervals, WD2: wetting-drying with 8-day intervals. EC: Electrical conductivity, CEC: Cation exchange capacity, ESP: Exchangeable sodium percentage, WAS: Wet aggregate stability, FC: Field capacity, HC: Saturated hydraulic conductivity

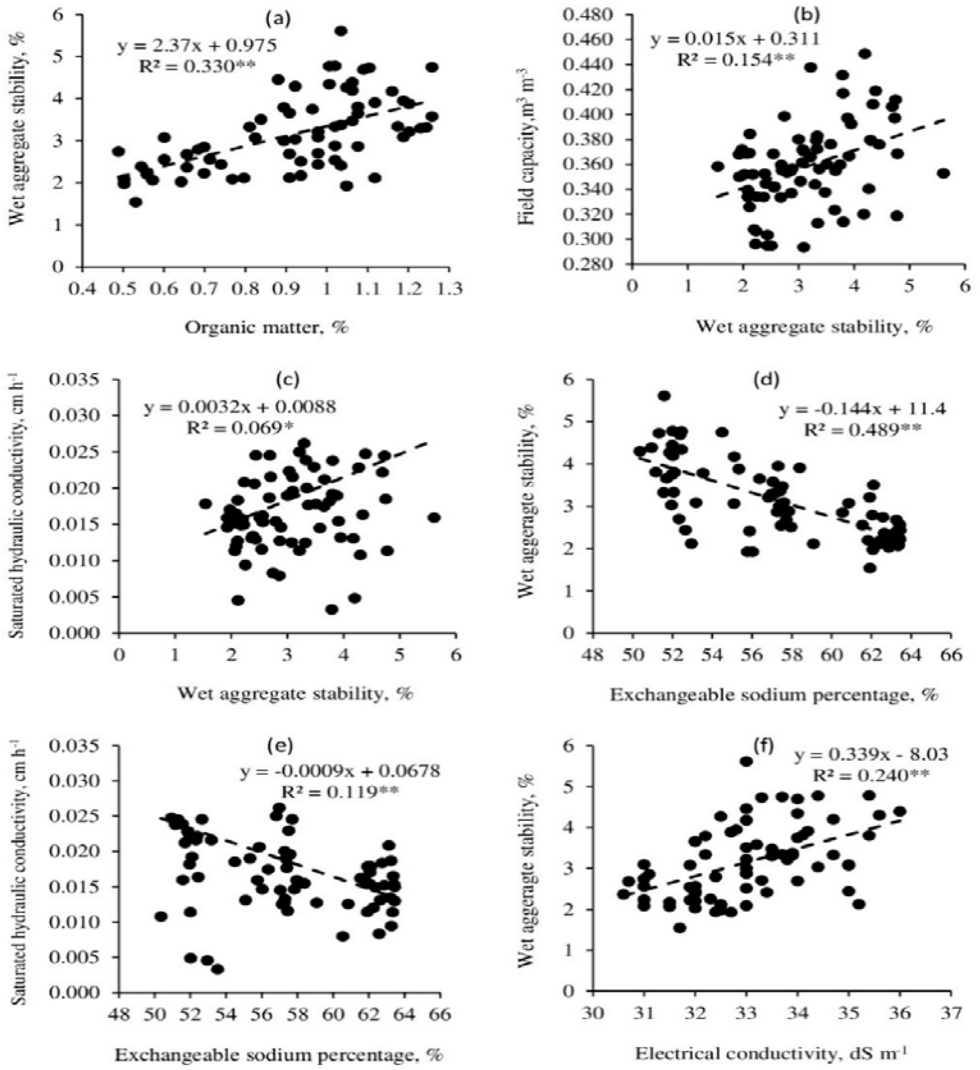

Figure. 3. The linear relationship between a) organic matter content and wet aggregate stability b) wet aggregate stability and field capacity c) wet aggregate stability and saturated hydraulic conductivity d) exchangeable sodium percentage and wet aggregate stability e) exchangeable sodium percentage and saturated hydraulic conductivity f) electrical conductivity and wet aggregate stability. n = 72, * $p<0.05$, ** $p<0.01$

($p<0.05$) linear relationship between WAS and HC (Figure 3c). However, the positive effects on soil structure of reduced soil ESP values with sewage sludge applications could be the main reason considering the strong ($p<0.01$) ESP-WAS negative linear relationship (Figure 3d). This is also supported by the significant ($p<0.01$) negative linear relationship determined between ESP and HC values (Figure 3e).

Moreover, high soil salinity values that provided better WAS values as seen in Figure 3f under the conditions with high ESP might have made an additional contribution to improved HC values with an increase in WAS values. Ors et al., (2015) measured lower hydraulic conductivity values in saline-sodic soils with higher ESP under lower salinity conditions. Sahin et al., (2002) also reported that a high sodicity level in saline-sodic soil reduces hydraulic conductivity due to decreased salinity.

3.2. Effects of Freezing-Thawing Cycles

FT2 treatment significantly decreased organic matter and exchangeable K and Ca+Mg contents, CEC and WAS values compared to FT1 (Table 2, Figure 4 a,b). Soil ecosystems can be affected differently by freezing-thawing cycles due to their possible impacts on soil microbial communities (Kumar et al., 2013) and disturbance of the

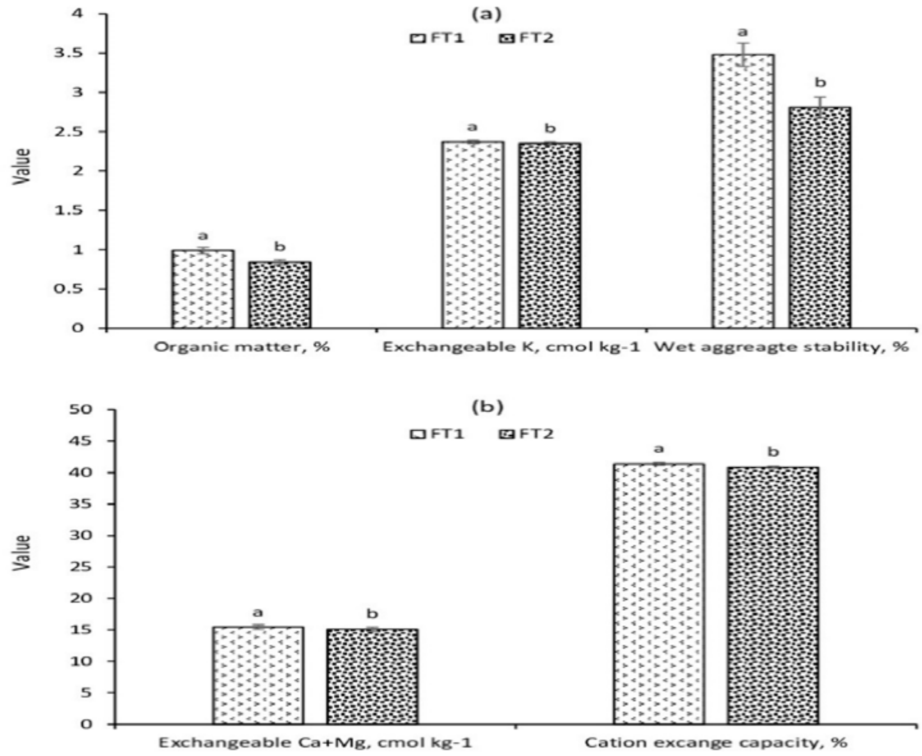

Figure 4. The effects of freezing-thawing cycles on a) soil organic matter, exchangeable K and wet aggregate stability values b) exchangeable Ca + Mg and cation exchange capacity values. FT1: 4 freezing-thawing, FT2: 8 freezing-thawing. Means marked by the different lowercase letters are significantly different at the level of $p < 0.05$

microbial functions of soil (Yanai et al., 2004). Therefore, decreased CEC values in increased freeze-thaw cycles could be associated with negative charges neutralized by changing pH values as a result of soil microbiology changes under freezing condition (Sahin et al., 2020). Moreover, the decline of organic matter content in FT2 could result in reduced WAS values. Phase changes of water in freezing-thawing processes lead to the contraction of organic matter, the breaking of bonds with soil particles, and thus the increased release of organic matter. Moreover, the release of dissolved organic matter at low temperatures, with increases in available carbon sources releases sugars and amino acids with the increasing death of some microbial cells (Zhang et al., 2021). Therefore, it can be argued that the mobilization of organic matter by water transport during the freezing-thawing process under bare soil conditions might be the main possible reason for the decrease in the accumulation of organic matter, and also the decrease in the release of K, Ca+Mg as a result of decreased organic matter.

3.3. Effects of Recycled Wastewater

Recycled wastewater improved organic matter and FC values by 8.0% and 6.6%, respectively, compared to freshwater (Table 2, Figure 5). An increase in soil organic matter indicates that dissolved organic matter from wastewater has accumulated. Increased organic matter is helpful for better pore size formation and therefore micro-pores which are instrumental in more water retention in soil (Badaou & Sahin, 2022). Jnad et al., (2001) also determined that macro-pores decreased as a result of the accumulation of organic matter in pores with wastewater application. It was concluded that the FC could have increased based on the improved pore size. Similarly, Tunc & Sahin, (2015) reported that FC values under wastewater irrigation conditions increased due to the increase in micro-pores.

3.4. Effects of Wetting-Drying Intervals

Wetting-drying intervals significantly affected soil pH value and organic matter and $CaCO_3$ contents (Tables 1 and 2, Figure 6). WD2 treatment increased organic matter, $CaCO_3$ and pH values were 8%, 0.6%, and 0.4% higher, respectively compared to the WD1 values. Soil moisture is one of the important factors in the process of soil organic matter decomposition, thus dry conditions can improve organic matter stock

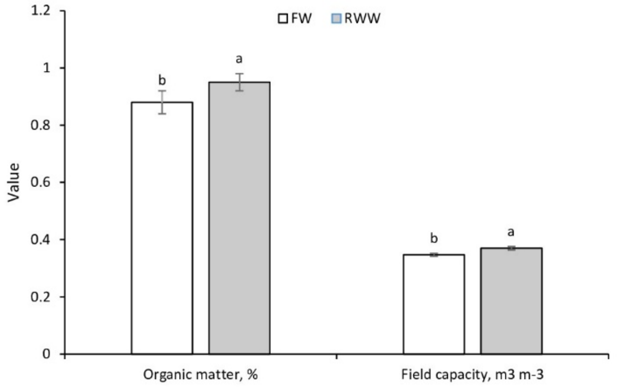

Figure 5. The effects of water types on soil organic matter and field capacity values. FW: Freshwater, RWW: Recycled wastewater. Means marked by the different lowercase letters are significantly different at the level of $p < 0.05$

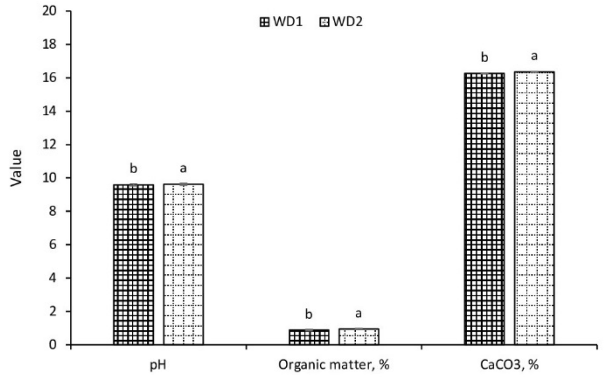

Figure 6. The effects of wetting-drying process on soil pH, organic matter and $CaCO_3$ values. WD1: wetting-drying with 4-day intervals, WD2: wetting-drying with 8-day intervals.

in soil due to less decomposition (Yun et al., 2019). Similarly, Badaou & Sahin (2022) determined a higher soil organic matter content for the longest wetting-drying cycle considering 4, 8 and 12-days intervals in clay soil with sewage sludge. Decreased organic matter mineralization can reduce $CaCO_3$ solubility in WD2 treatment because of less organic acids released from organic matter decomposition (Leogrande & Vitti, 2019). This could also explain the high pH value in the WD2 treatment.

4. CONCLUSIONS

The study findings showed that the organic matter content and wet aggregate stability decreased with increased freezing-thawing cycles in a saline-sodic soil grouped as the solodized solonetz sampled from aridic and thermic region. However, adding stabilized sewage sludge and increasing doses increased organic matter and reduced sodicity, and thus improved wet aggregate stability, saturated hydraulic conductivity and field capacity. The long intervals of the wetting-drying process with recycled wastewater also contributed to the increase in organic matter. Therefore, study findings with an indicative or a suggestive value showed that initial amelioration in saline-sodic soils in freeze-thaw conditions can be promoted by adding stabilized sewage sludge and further amelioration can be achieved with following long wetting-drying intervals and recycled wastewater. In addition, the wastes have the potential to increase soil fertility which can be considered another major benefit to be examined in future studies in nutrient poor saline-sodic soils. However, experiments carried out on undisturbed soils under aridic and thermic conditions would be more improved the findings of this paper.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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