Journal of Agricultural Sciences (Belgrade) https://doi.org/10.2298/JAS2401057A
Vol. 69, No. 1, 2024 UDC: 631.4:631.863
Pages 57-76 Original scientific paper

EFFECTS OF THE APPLICATION OF ANAEROBICALLY DIGESTED SEWAGE SLUDGE ON THE CONSISTENCY LIMITS AND COMPACTION CHARACTERISTICS OF DIFFERENTLY TEXTURED SOILS

Ekrem Lutfi Aksakal[1*], Armagan Cambaztepe[1], Ilker Angin[2] and Serdar Sari[3]

[1]Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Atatürk University, 25240, Erzurum, Türkiye
[2]Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Atatürk University, 25240, Erzurum, Türkiye
[3]Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Igdir University, 76000, Igdir, Türkiye

Abstract: Notwithstanding their beneficial characteristics, the agricultural utilization of organic wastes may have an adverse effect on soil properties if used improperly. To evaluate proper use, a laboratory study was conducted to investigate the effects of different sewage sludge application doses (0, 2, 4, and 8% weight/weight) on the consistency limits and the compaction characteristics of three differently textured soils. The application of sewage sludge significantly improved the consistency limits and reduced the compactibility. The efficacy depended on the amount applied. The rates of increase in liquid limit (LL) values at 8% sewage sludge were 58.7% for sandy loam, 43.4% for loam, and 16.2% for clay soil. As the application dose increased, the optimum moisture content (OMC) values increased and the maximum dry bulk density (MBD) values decreased. The highest application dose decreased the MBD by 9.5% in sandy loam, by 6.5% in loam, and by 13.7% in clay-textured soils. The rates of increase in OMC values were 73.4%, 53.8%, and 27.1%, for sandy loam, loam, and clay, respectively. The results presented in this study clearly indicated that the application of sewage sludge made the soils more resistant to mechanical forces, since the increase in the proportion of OMC over LL and PL implied that the soil was easier to till at higher moisture contents without any deformation, which also resulted in a higher workable range.

Key words: Atterberg limits, compactibility, sewage sludge, soil degradation, soil friability.

*Corresponding author: e-mail: elaksakal@atauni.edu.tr

Introduction

Soil, one of nature's most complex and diverse ecosystems, is one of the most neglected, essential, and precious non-renewable natural resources. According to estimates, 36–75 billion tonnes of fertile soil is lost every year due to poor farming practices and degradation (Gobinath et al., 2021). To maintain soil sustainability and recover it to its former condition, simple, proper, and economic steps should be taken into account. The application of wastes (e.g., crop residues, biosolids, composts, etc.) to the soil is generally the most economical way of increasing organic matter content, thus maintaining its sustainability. The utilization of organic wastes as an organic matter not only provides an opportunity to recycle beneficial plant nutrients and increase crop productivity through the improvement of the physical (Lindsay and Logan, 1998; Asghari et al., 2009), chemical (Angin et al., 2012, 2017), and biological (Tejada et al., 2006; Adewole and Ilesanmi, 2012) properties of soils, but also decreases the environmental concerns regarding the disposal of these materials.

Sewage sludge is an inevitable waste byproduct of wastewater processes, which is a concentrated suspension of semi-solid materials, usually rich in mineral nutrients and organic matter. The utilization of sewage sludge as a source of organic matter is known to improve the soil properties such as water retention capacity, water availability, aggregate stability (Tsadilas et al., 2005), bulk density (Cogger et al., 2013), porosity (Tsadilas et al., 2005), hydraulic conductivity (Aggelides and Londra, 2000), compactibility (Stone and Ekwue, 1993), penetration resistance (Kumar et al., 1985), and crusting (Pagliai et al., 1983). In addition to the positive effects, the agricultural utilization of sewage sludge not only provides a cost-effective method of sludge disposal but is also essential to decreasing the environmental issues associated with the disposal of this material in landfills and the high volumes generated (Smith, 1995; Angin et al., 2012). The amount of sludge produced during wastewater treatment ranges from 35 to 85 g of dry solids per day for the equivalent of one person (Foladori et al., 2010). Notwithstanding its beneficial characteristics, sewage sludge may have an adverse effect on soil properties if used improperly. Therefore, greater attention is being paid to the management and proper use of sewage sludge for agricultural purposes.

Soil structure is a key indicator of soil quality because it influences processes critical to soil productivity, environmental and water quality, and agricultural resilience (Bronick and Lal, 2005). The risks of undesirable degradation effects such as erosion, flooding, and compaction can be reduced by the improvement of soil structure (Connolly, 1998; Six et al., 2004). Among these effects, compaction is perhaps the most encountered problem in agricultural areas due to conventional and intensive agricultural practices. The Proctor test has been employed to characterize the compaction resistance of agricultural soils and to evaluate the compaction status of soils (Wagner et al., 1994; Ekwue and Stone, 1995, Zhang et al., 1997; Hakansson and Lipiec, 2000). Parameters for comparing the compactibility of soils are the maximum dry bulk density (MBD) according to the Proctor test and the optimum moisture content (OMC), at which the maximum dry bulk density is reached. The maximum dry bulk density may be used as a reference value for evaluating the compaction status of soils (Hakansson and Lipiez, 2000). The corresponding water content indicates the moisture status for maximum compaction at a defined energy impact. The agronomic importance of these parameters is elucidated by Wagner et al. (1994). Wagner et al. (1992) have also found that the best soil fragmentation during tillage is obtained at the Proctor optimum moisture content. The sensitivity of the soil to compaction and the maximum dry soil bulk density in the case of maximum compaction are closely related to the consistency limits. Therefore, the consistency limits (Atterberg) are accepted as an important indicator of the mechanical behavior of the soil (Dexter and Bird, 2001; Hemmat et al., 2010; Sari et al., 2017). Consistency limits could be used to determine the ideal and practicable water content range for tillage operations with the least amount of effort and risk of structural degradation and deformation (Dexter and Bird, 2001). Therefore, studies aimed at improving the mechanical properties of agricultural soils should be given special attention. Several studies have found a significant and positive relationship between the optimum soil water content for tillage and the liquid and plastic liquid limits (Terzaghi et al., 1988; Mueller et al., 1990; Dexter and Bird, 2001; Mueller et al., 2003; Barzegar et al., 2004). However, there is little information about the effects of sewage sludge application on soil compaction, especially on the consistency limits.

To evaluate the effects of sewage sludge on sustainable soil management properly, it is important and necessary to determine the influences of sewage sludge on the consistency limits (Atterberg) and the parameters of the Proctor compaction test. Therefore, this study was carried out to investigate the influences of sewage sludge application on the consistency limits and compaction characteristics of three differently textured soils.

Material and Methods

A pot experiment with four sewage sludge application rates and three replicates was carried out under laboratory conditions with a relative humidity of 60±5% and an average temperature of 25±2ºC. The soil samples used in the experiment were under similar tillage and crop management practices and were collected from the 0-20-cm depth of widely distributed great soil groups (sandy loam [Ustorthent], loam [Fluvaquent] and clay [Haplustert]) (Soil Survey Staff, 2014) in Erzurum, Türkiye. The collected soils were air-dried under laboratory conditions, crumbled by hand, sieved through an 8-mm sieve, and homogenized by mixing thoroughly after sieving. Anaerobically stabilized sewage sludge obtained from the Ankara Metropolitan Municipality Treatment Plant, passed through a 2-mm sieve, was applied to the soils within the doses of 0, 2, 4, and 8% weight/weight basis (w/w) (dry matter). The prepared samples were thoroughly mixed (including the control) and placed into 36 plastic pots (0.25 m wide and 0.40 m long) to a depth of 0.15 m. The amount of soil in each pot was 17000 g for sandy loam, 16000 g for loam, and 14000 g for clay. To achieve microbial activity and organic matter mineralization, the experimental soils were incubated for 120 days at near field capacity moisture content.

The main descriptive properties of the soils and sewage sludge used in the study are presented in Table 1. A WDXRF spectrometer (Rigaku ZSX-100e) was used to determine the concentrations of O, Ca, Si, Mg, K, Al, P, S, Fe, Na, Mn, and Sr in sewage sludge and soils. The Bouyoucos hydrometer method was used to determine the particle size distribution (Gee and Or, 2002). The bulk density was determined using soil sampling rings (volume of 100 cm^3) (Grossman and Reinsch, 2002). Particle density was determined by the pycnometer method (Flint and Flint, 2002). The pH and electrical conductivity (EC) measurements of soils and sewage sludge were carried out in 1:2.5 (soil:water) and saturation extracts, respectively (Rhoades, 1996; Thomas, 1996). While the soil organic matter content was determined by using the Smith-Weldon method, the organic matter content of the sewage sludge was determined using the loss-on-ignition method described by Nelson and Sommers (Nelson and Sommers, 1996). A Schreiber calcimeter was used to determine the lime content of the soils and sewage sludge (Loeppert and Suarez, 1996). The cation exchange capacity (CEC) of the soils was determined with a flame photometer using 1-M neutral ammonium acetate (Sumner and Miller, 1996). The aggregate stability values of the soils were determined using the standard Yoder wet sieving method (Nimmo and Perkins, 2002).

The liquid limit (LL) values of the soils were determined by the standard drop-cone penetrometer (McBride, 2002). The plastic limit (PL) values of the soils were determined using the rod formation method (McBride, 2002). The "ASTM D427-04" standard method was used to determine the shrinkage limit (SL) of the soils (ASTM, 1992). The plasticity index (PI) was calculated by subtracting the PL from the LL. The difference in moisture content between SL and PL values was determined as the friability index (FI). The standard Proctor compaction test (ASTM, 2000) was used to determine the compaction test curves, optimum moisture content and maximum dry bulk density values of the soils.

The SPSS Statistical Package v.20.0 was used to conduct the statistical analysis (IBM, 2011). The data were subjected to a one-way ANOVA, followed by a comparison of the relevant means using the Tukey's multiple comparison test at the significance level of $p<0.05$. Furthermore, correlation and regression analyses were carried out to assess the influences of sewage sludge application on the investigated parameters.

Table 1. Initial characteristics of the soils and sewage sludge used in the study.

Properties	Soil I	Soil II	Soil III	Sewage sludge (SS)		
Clay (%)	16.6±1.2	25.9±1.1	64.2±0.1	-	Particle size distribution (%) (dry sieving)	
Silt (%)	24.5±0.2	40.7±2.5	19.1±0.1	-	2000–1000 μ	24.8
Sand (%)	58.9±1.2	33.4±1.4	16.7±0.1	-	1000–500 μ	32.4
Textural class	Sandy loam	Loam	Clay	-	500–250 μ	21.9
Great soil group	Ustorthent	Fluvaquent	Haplustert	-	250–100 μ	9.8
CEC (cmol kg^{-1})	22.5±1.3	40.7±1.3	47.0±1.5	-	100–53 μ	7.7
$CaCO_3$ (%)	0.5±0.02	0.5±0.03	0.9±0.04	1.2±0.03	<53 μ	3.4
Organic matter (%)	1.9±0.07	1.2±0.09	1.1±0.03	45.5±1.02	(wet sieving)	
pH	6.6±0.08$^{\Psi}$	7.8±0.02$^{\Psi}$	7.3±0.04$^{\Psi}$	7.2±0.11$^{\Omega}$	2000–1000 μ	3.8
EC (mS cm^{-1})	0.5±0.1$^{\Psi}$	0.9±0.1$^{\Psi}$	1.1±0.1$^{\Psi}$	14.1±0.2$^{\Omega}$	1000–500 μ	16.3
Bulk density (g cm^{-3})	1.32±0.02	1.21±0.02	1.07±0.03	0.67±0.02	500–250 μ	18.7
Particle density (g cm^{-3})	2.66±0.02	2.63±0.02	2.67±0.02	1.93±0.03	250–100 μ	10.1
X-ray fluorescence spectrometer analysis (concentration, %) O	47.29	46.96	47.71	47.62	100–53 μ	15.0
Ca	3.85	4.88	2.10	13.18	<53 μ	36.1
Si	31.67	30.25	32.51	9.44		
Mg	1.44	1.51	1.77	1.25		
K	2.09	1.75	1.93	0.96		
Al	8.43	8.32	8.90	3.54		
P	0.17	0.16	0.05	2.27		
S	0.04	0.05	0.07	2.21		
Fe	1.82	2.42	2.18	1.81		
Na	1.75	1.42	0.48	0.23		
Mn	0.04	0.06	0.05	0.04		
Sr	0.01	0.01	0.01	0.02		

$^{\Psi}$ Determined in the 1:2.5 (soil: water) extract. $^{\Omega}$ Determined in the saturation extract.

Results and Discussion

Effects of sewage sludge on soil consistency limits

The application of sewage sludge had significant effects on the consistency limits of the soils studied (Table 2). The highest values were obtained from clay soil, which had the highest clay content. While the investigated parameters showed significant positive correlations with clay content, they showed a negative correlation with sand and silt. The amount of organic matter, sand, and clay, which affect the characteristics of the diffused double layer of the soil, has significant effects on the consistency limits (Canbolat and Öztaş, 1997; Canbolat et al., 1999; Hemmat et al., 2010). Clay, which reflects a high specific surface, has been reported to be the most important fraction of soil affecting consistency limits (De Jong et al., 1990; Stanchi et al., 2015). Keller and Dexter (2012) stated that soils containing negligible amount of organic matter, should have at least 10% of clay in the texture to exhibit plastic properties.

Table 2. Effects of sewage sludge on the organic matter content, aggregate stability, and consistency limits of soils.

Parameters	Application dose (w/w)	Soil I (sandy loam)	Soil II (loam)	Soil III (clay)
OM (%)	0%	1.9±0.4c*	1.2±0.1c	1.1±0.1c
	2%	3.4±0.3b	3.9±0.1b	2.0±0.2bc
	4%	3.6±0.1b	4.3±0.3ab	2.3±0.3b
	8%	4.4±0.3a	4.7±0.4a	3.3±0.4a
	Mean	3.3±0.9B	3.5±0.8A	2.2±0.7C
	p	.000	.000	.000
	R^2	.841	.825	.822
AS (%)	0%	32.7±0.8c	31.4±1.9b	31.4±2.1c
	2%	40.9±3.9b	33.1±2.0b	35.9±3.3bc
	4%	46.5±2.6b	39.1±0.4a	42.2±4.0ab
	8%	59.5±5.4a	41.6±2.0a	46.3±4.3a
	Mean	44.9±10.7A	36.3±4.6C	39.0±6.7B
	p	.000	.000	.004
	R^2	.880	.841	.773
LL (%)	0%	27.0±0.5d	34.7±0.7d	70.3±1.7d
	2%	32.8±0.9c	41.8±1.2c	74.7±1.9c
	4%	36.8±1.1b	46.2±1.6b	78.5±1.1b
	8%	42.9±1.5a	49.7±1.5a	81.7±1.7a
	Mean	34.9±6.1C	43.1±6.0B	76.3±4.6A
	p	.000	.000	.000
	R^2	.975	.893	.938
PL (%)	0%	20.6±1.7d	23.0±1.4d	44.2±1.9c
	2%	24.0±0.5c	29.1±0.8c	47.9±2.4b
	4%	28.7±0.7b	33.8±2.6b	51.9±0.4a
	8%	32.4±0.8a	38.8±1.1a	53.3±1.5a
	Mean	26.4±4.8C	31.2±6.3B	49.3±4.0A
	p	.000	.000	.001
	R^2	.960	.951	.655
PI (%)	0%	6.4±1.3c	11.7±1.2ns	26.2±0.6ns
	2%	8.9±0.7bc	12.7±1.0	26.9±1.9
	4%	8.1±0.7ab	12.4±1.0	26.6±0.8
	8%	10.5±0.8a	10.9±2.1	28.4±1.7
	Mean	8.5±1.7C	12.0±1.4B	27.0±1.5A
	p	.004	.464	.271
	R^2	.798	.347	.861
SL (%)	0%	7.1±1.3d	9.9±0.3d	16.8±0.8b
	2%	8.9±0.6c	13.5±1.0c	19.5±2.3a
	4%	11.8±0.6b	16.8±1.2b	21.7±0.8a
	8%	13.8±0.7a	20.5±1.0a	22.2±1.1a
	Mean	10.4±2.8C	15.1±4.2B	20.0±2.5A
	p	.000	.000	.005
	R^2	.917	.959	.700
FI (%)	0%	13.5±1.3c	13.1±1.1c	27.4±1.0c
	2%	15.0±0.2c	15.6±0.2b	28.4±0.9ab
	4%	16.9±1.2b	17.0±1.4ab	30.2±0.8ab
	8%	18.6±0.1a	18.3±0.4a	31.0±2.1a
	Mean	16.0±2.1B	16.0±2.2B	29.3±1.9A
	p	.001	.001	.031
	R^2	.864	.834	.603

OM: organic matter; AS: aggregate stability; LL: liquid limit; PL: plastic limit; PI: plasticity index; SL: shrinkage limit; FI: friability index. w/w: weight/weight *The letters in each column (capital letters) show the differences between the soils, whereas the letters in the columns (small letters) show the differences between the application doses (mean±std). ns: not significant.

The efficacy of the sewage sludge on the consistency limits depended on the amount of sewage sludge applied (Table 2). Sewage sludge played a significant role in increasing the LL, depending on the application dose. Among the application doses tested, the highest LL values were observed in the 8% treatment. When compared with the controls, the LL values of sandy loam, loam, and clay soil increased by 58.7%, 43.4%, and 16.2%, respectively. Similarly, the highest PL values were determined at an 8% sewage sludge application dose. As compared with the control, the rates of increase in PL values at the 8% sewage sludge application were found to be 57.0% for sandy loam, 68.9% for loam, and 20.6% for clay soil. The increase in LL and PL values could be related to an increase in the adsorption surface and water-holding capacity due to the addition of organic material. This statement is consistent with the findings of Rixon et al. (1991), Lindsay and Logan (1998), Bhushan and Sharma (2002). The organic matter content of sandy loam soil was 1.9% in the control and increased to 3.4%, 3.6%, and 4.4% after the application of 2, 4, and 8% sewage sludge, respectively. The organic matter content of loam soil increased from 1.2% to 3.9%, 4.3%, and 4.7% and that of clay soil from 1.1% to 2.0%, 2.3%, and 3.3% after 2, 4, and 8% sewage sludge application, respectively. The addition of sewage sludge to the soil not only augmented the aggregate stability of the soil, but also the absorptive capacity of the soil to absorb water, which therefore increased the consistency limits.

The effects of sewage sludge application on PL and LL values were more pronounced in soils with lower clay content and higher sand content. While the highest rates of increase in PL and LL values were determined in sandy loam soil, the lowest rates were determined in clay soil. The correlation coefficients between sewage sludge (SS) and LL were found to be 0.985^{**} for sandy loam, 0.969^{**} for loam, and 0.951^{**} for clay. The correlation coefficients between SS and PL were determined as 0.981^{**} for sandy loam, 0.974^{**} for loam, and 0.915^{**} for clay (Table 3). The organic matter content of soil, which is a great factor in increasing the specific surface area and consequently water retention, influences LL and PL of coarse-textured soils much more than other textured soils (Smith et al., 1985; Hemmat et al., 2010). The increase in LL and PL values of soils allows soils to be easily cultivated in wider and higher ranges of soil water contents (Lindsay and Logan, 1998). Although aggregate stability plays a major role in the soil swelling behavior, there is limited information on the relationship between AS and consistency limits. Significant positive correlations were observed between AS, –LL and –PL parameters. The correlation coefficients between AS–LL and AS–PL were 0.986^{**} and 0.954^{**} for sandy loam, 0.928^{**} and 0.911^{**} for loam, and 0.879^{**} and 0.835^{**} for clay, respectively (Table 3). The relationships between sewage sludge application –LL, –PL and –PI were presented in Table 2 and Figure 1. In general, irregular changes in PI values were obtained upon the application of sewage sludge to soils. The results showed that an increase in the LL value might not result in an increase in the PI value due to the simultaneous increase in the PL value. Regression analyses showed that the sewage sludge application had a high and positive linear relationship with LL (R^2=0.975), PL (R^2=0.960) and PI (R^2=0.798) for sandy loam soil. The same relationships were observed for loam and clay soils (Table 2, Figure 1).

Table 3. The Pearson's correlation coefficients between the parameters.

		SS	OM	AS	LL	PL	PI	SL	FI	OMC
Soil I (sandy loam)	OM	.925**	-							
	AS	.964**	.897**	-						
	LL	.985**	.922**	.986**	-					
	PL	.981**	.919**	.954**	.980**	-				
	PI	.783**	.731**	.862**	.838**	.714**	-			
	SL	.962**	.912**	.931**	.958**	.976**	.701*	-		
	FI	.936**	.863**	.915**	.939**	.959**	.680*	.875**	-	
	OMC	.967**	.925**	.937**	.960**	.970**	.725**	.929**	.952**	-
	MBD	-.966**	-.877**	-.920**	-.944**	-.964**	-.683*	-.952**	-.910**	-.955**
Soil II (loam)	OM	.917**	-							
	AS	.929**	.845**	-						
	LL	.969**	.947**	.928**	-					
	PL	.974**	.892**	.911**	.975**	-				
	PI	-.229	.042	-.123	-.104	-.322	-			
	SL	.981**	.895**	.919**	.970**	.993**	-.312	-		
	FI	.922**	.851**	.859**	.946**	.974**	-.329	.940**	-	
	OMC	.937**	.799**	.933**	.929**	.946**	-.278	.945**	.911**	-
	MBD	-.934**	-.887**	-.943**	-.944**	-.928**	.133	-.933**	-.881**	-.941**
Soil III (clay)	OM	.915**	-							
	AS	.853**	.763**	-						
	LL	.951**	.837**	.879**	-					
	PL	.915**	.748**	.835**	.953**	-				
	PI	.521	.612*	.510	.571	.297	-			
	SL	.853**	.711**	.758**	.849**	.932**	.151	-		
	FI	.799**	.635*	.756**	.886**	.873**	.428	.638*	-	
	OMC	.904**	.752**	.860**	.894**	.865**	.475	.834**	.719**	-
	MBD	-.953**	-.952**	-.838**	-.919**	-.843**	-.617*	-.737**	-.801**	-.781**
General correlation	OM	.678**	-							
	AS	.783**	.633**	-						
	LL	.377*	.367*	.336*	-					
	PL	.419*	.241	.238	.981**	-				
	PI	.370*	.315*	.204	.966**	.898**	-			
	SL	.412*	.281	.278	.877**	.937**	.745**	-		
	FI	.268	.429**	.196	.977**	.963**	.938**	.808**	-	
	OMC	.503**	.342*	.330*	.950**	.976**	.859**	.938**	.922**	-
	MBD	-.428**	-.459**	-.431**	-.974**	-.959**	-.936**	-.897**	-.924**	-.945**

SS: sewage sludge; OM (%): organic matter; AS (%): aggregate stability; LL (%): liquid limit; PL (%): plastic limit; PI (%): plasticity index; SL (%): shrinkage limit; FI (%): friability index; OMC (%): optimum moisture content; MBD (%): maximum dry bulk density. **The correlation is significant at the 0.01 level. *The correlation is significant at the 0.05 level.

Among the sewage sludge application doses tested, the highest PI values were obtained at 8% (10.5%) for sandy loam, 2% (12.7%) for loam, and 8% (28.4%) for clay soils. Stanchi et al. (2009) found a significant positive correlation between soil organic matter content and LL and PL, but no significant relationship between organic matter and PI. On the other hand, Ball et al. (1996), Blanco-Canqui et al. (2006), and Zentar et al. (2009) obtained a significant positive correlation between soil organic matter content and PI. As a result of a study conducted on 44 soil samples, McBride and Bober (1989) have stated that an increase in the soil organic matter content leads to a decrease in PI values. In this study, a significant positive correlation (0.315^{*}) was found between the soil organic matter content and the PI. When the correlation coefficients between organic matter content and PI were examined for each soil, correlation coefficients were found to be 0.731^{**} for sandy loam, 0.042 for loam, and 0.612^{*} for clay soil (Table 3). The reason for the inconsistencies could lie in the different inherent soil properties originating from the parent material, clay type, clay mineralogy, and clay content (De Jong et al., 1990; Hemmat et al., 2010). Lal and Shukla (2004) have reported that an increase in the organic matter content of mineral soil generally leads to an increase in both LL and PL values. Therefore, an increase in organic matter content is expected to have coherent effects on PI.

The application of sewage sludge significantly increased both the shrinkage limit (SL) and the friability index (FI) of soils studied (Table 2). The highest SL and FI values were obtained with the highest dose of sewage sludge application (8%). When compared with the controls, the SL values of sandy loam, loam, and clay soil increased by 94.2%, 106.7%, and 32.3%, respectively, at a dose of 8% sewage sludge application. The shrinkage limit of the soils increased with the increase in the sewage sludge application dose.

As compared with the control, the SL values of sandy loam increased by 25.4%, 66.0%, and 94.2% at 2, 4, and 8% sewage sludge applications, respectively. Similar increases were observed in the loam and clay soils. The highest SL values were obtained in clayey soil, which has the highest clay content. Our result suggested that an increase in clay content increased the magnitude of shrinkage due to the micropore volume, pore volume of clay-matrix organized in clay aggregates, and the interaggregate pore volume (Boivin et al., 2004). The increase in SL values with the application of sewage sludge may be attributed to an increase in soil organic matter, which increases the moisture content due to its high-water absorption capacity. The strong correlation between the SL and the soil organic matter content supports this argument. The correlation coefficients between OM and SL were found to be 0.912^{**} for sandy loam, 0.895^{**} for loam, and 0.711^{**} for clay soil (Table 3). An increase in FI may extend optimal tillage and the cultivation period, as the soil structure is only minimally disturbed (Munkholm, 2011; Obour et al., 2017; Seleiman et al., 2019). As observed for SL and PL values, the highest increase in FI values was found at an 8% sewage sludge application dose (Table 2). In general, a higher sewage sludge application dose increased the FI value.

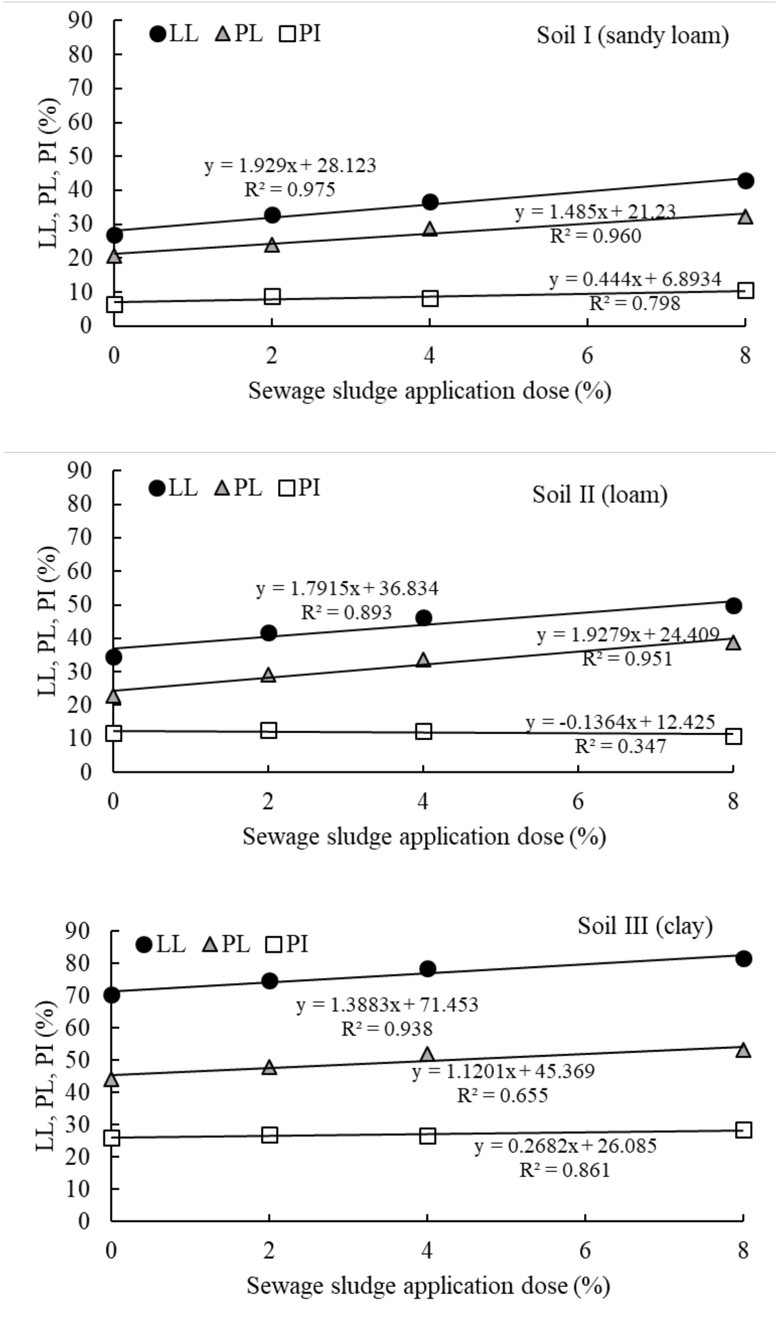

Figure 1. The relationship between the sewage sludge application dose and LL, PL, and PI.

These results showed that the application of sewage sludge made the soil friable at a higher water content compared to the control, making the soil more tillable and cultivable at a higher water content. The correlation coefficients between the soil OM content and the FI were 0.863^{**} for sandy loam, 0.851^{**} for loam, and 0.635^{*} for clay soil (Table 3). Similar results were reported by Macks et al. (1996), Watts and Dexter (1998), Munkholm (2011).

Effects of sewage sludge on Proctor compaction test parameters

As the sewage sludge application dose increased, the optimum moisture content (OMC) values increased and the maximum dry bulk density (MBD) values decreased (Table 4, Figures 2 and 3). A higher amount of sewage sludge generally resulted in a higher OMC and a lower MBD. For all soils studied, the highest OMC and the lowest MBD values were obtained at the highest sewage sludge application doses. While the regression analysis between the sewage sludge application dose and OMC had a high and positive relationship (R^2=0.949), the regression analysis between the sewage sludge application dose and MBD generally had a high and negative relationship (R^2=0.981) (Table 4). The lowest OMC and the highest MBD values were obtained in sandy loam soil, which has the highest sand content and the lowest clay content. The results obtained show that the OMC values increased and the MBD values decreased with the associated decrease in sand content and the increase in clay content. Similar results regarding the effects of soil texture on OMC and MBD were reported by Smith et al. (1997), Nhantumbo and Cambule (2006), Sari et al. (2017). While the mean OMC value of the non-amended (control) soils was 21.0%, the OMC values at 2, 4 and 8% sewage sludge application doses were found to be 24.9%, 28.0%, and 30.6%, respectively. These values were 1.68, 1.64, 1.58, and 1.52 g cm^{-3} for the MBD of the control, 2, 4, and 8% application doses, respectively (Table 4). The lossiest compaction state was achieved with the application of 8% sewage sludge. These findings clearly show that the sewage sludge application made the soil more resistant to compaction and extended the range of workability in the field without deforming it. Extending the workability range makes soil more easily tilled without any mechanical compactions or deformations. The sewage sludge application showed a significant positive correlation with the OMC and a significant negative correlation with the MBD. The correlation coefficients between SS and OMC were found to be 0.967^{**} for sandy loam, 0.937^{**} for loam, and 0.904^{**} for clay soil. Moreover, the coefficients between SS and MBD were determined to be -0.966^{**}, -0.934^{**}, and -0.953^{**} for sandy loam, loam, and clay, respectively. On average for all soils, the correlation coefficient between SS–OMC was significant (0.503^{**}) compared to a significant correlation coefficient of -0.428^{**} between SS–MBD (Table 3). General correlation coefficients between SS–OMC and –MBD were determined to be 0.503^{**} and -0.428^{**}, respectively (Table 3). Many studies have shown that improving the structural stability of soil significantly decreases the compactness of the soil (Baumgartl and Horn, 1991; Ball et al., 1996; Buck et al., 2000; Batey, 2009; Sari et al., 2017). Agricultural management practices that provide organic matter to the soil are known to increase structural stability and AS. The organic matter addition to soil, which is known to increase the cohesive forces between mineral particles and organic components, improves structural stability and AS (Chenu et al., 2000; Yazdanpanah et al., 2016). Organic matter decreases the impact of compaction force on the soil through its elastic properties and by increasing the amount of stable aggregates (Soane, 1990; Nawaz et al., 2013; Holthusen et al., 2020). A significant positive effect was found between sewage sludge application and AS in the present study. The AS of the sandy loam soil was 32.7% in the control and increased to 40.9%, 46.5%, and 59.5% after 2, 4, and 8% sewage sludge applications, respectively. The AS of the loam soil increased from 31.4% to 33.1%, 39.1%, and 41.6%, and that of the clay soil from 31.4% to 35.9%, 42.2%, and 46.3% after 2, 4, and 8% sewage sludge applications, respectively. It is apparent that the increase in AS significantly increased OMC and significantly decreased MBD, as revealed by the significant correlations between the variables. The correlation coefficients between AS and OMC were 0.937^{**} for sandy loam, 0.933^{**} for loam, and 0.860^{**} for clay soil. The coefficients between AS and MBD were -0.920^{**}, -0.943^{**}, and -0.838^{**} for sandy loam, loam, and clay, respectively.

Table 4. Effects of sewage sludge on the Proctor compaction test parameters of soils.

Parameters	Application dose (w/w)	Soil I (sandy loam)	Soil II (loam)	Soil III (clay)
OMC (%)	0%	14.6±1.2d	18.9±2.0c	29.6±2.2c
	2%	18.5±0.9c	22.0±1.8c	34.2±1.0b
	4%	22.6±1.7b	25.4±1.8b	36.1±0.6ab
	8%	25.3±1.0a	29.0±1.3a	37.6±0.6a
	Mean	20.2±4.4C	23.8±4.2B	34.4±3.4A
	p	.000	.000	.000
	R^2	.928	.977	.818
MBD (g cm^{-3})	0%	1.89±0.03a	1.70±0.03a	1.46±0.03a
	2%	1.84±0.01b	1.66±0.01ab	1.41±0.02a
	4%	1.75±0.02c	1.63±0.01b	1.35±0.03b
	8%	1.71±0.02d	1.59±0.02c	1.26±0.02c
	Mean	1.80±0.08A	1.64±0.05B	1.37±0.08C
	p	.000	.001	.000
	R^2	.906	.988	.997

OMC: optimum moisture content; MBD: maximum dry bulk density; w/w: weight/weight. *The letters in each column (capital letters) show differences between the soils, whereas the letters in the columns (small letters) show the differences between the application doses.

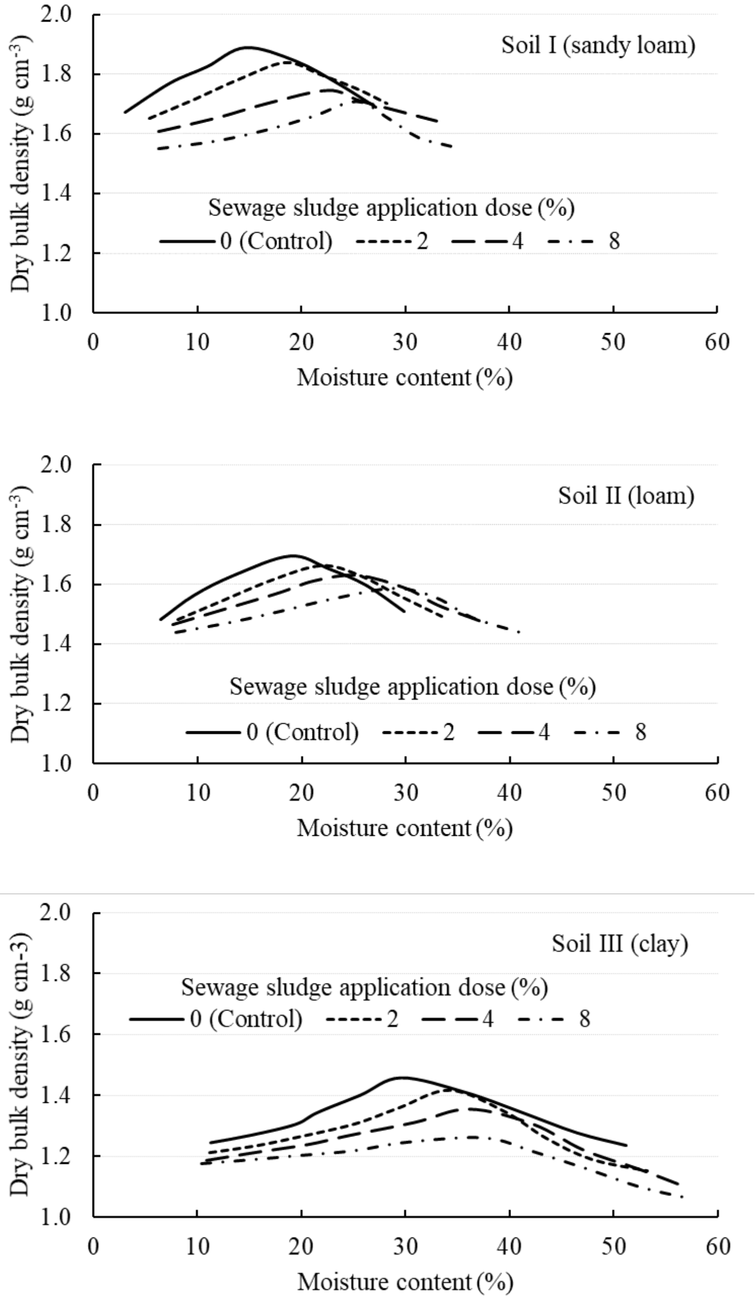

Figure 2. Proctor compaction test curves of soils studied.

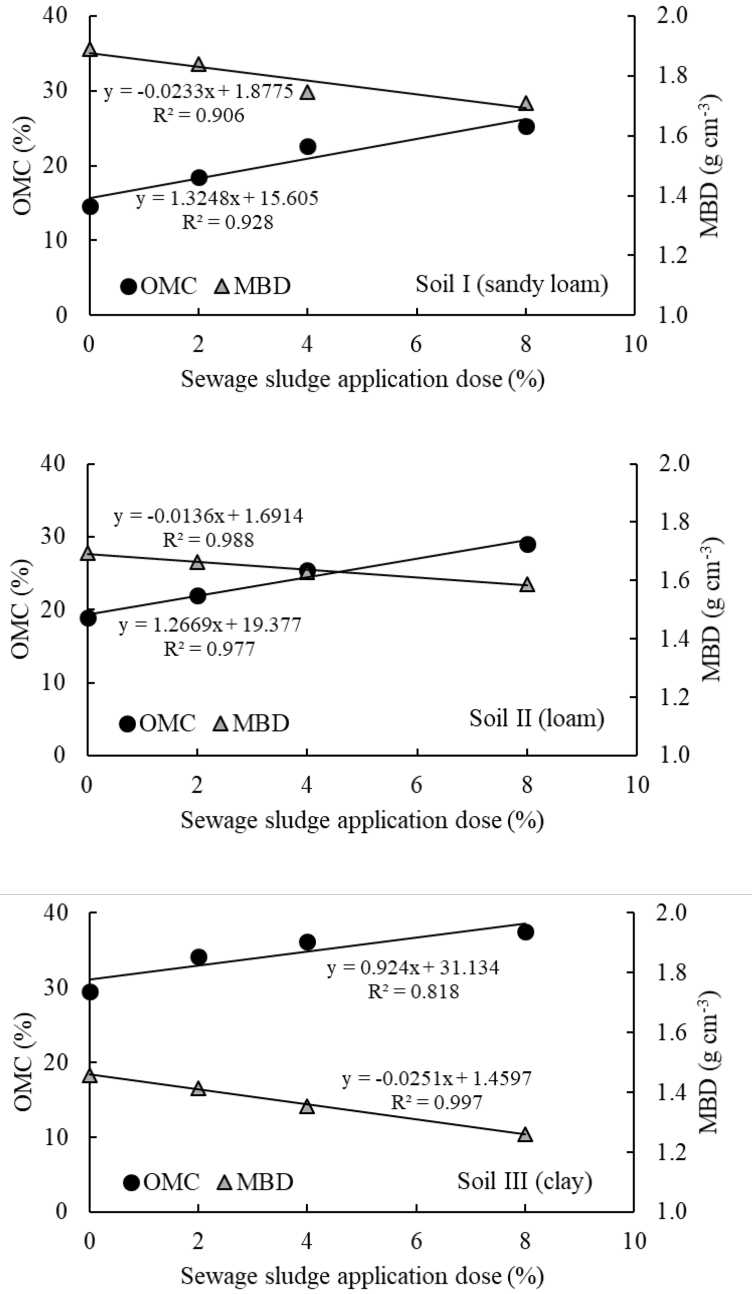

Figure 3. The relationship between the sewage sludge application dose and OMC and MBD.

Soil LL and PL values were evaluated as useful indicators of soil physical and mechanical properties, such as compressibility and strength, providing strategic indicators for management actions. The application of sewage sludge increased the water content at LL and PL of OMC where the maximum soil compaction occurred. Increasing the sewage sludge application dose increased the OMC of the control of the sandy loam soil, for which the initial LL and PL values were 54.0% and 70.7%, respectively. These values were reached at 56.3%, 61.4%, 59.0% for LL, and 77.1%, 78.7%, 78.1% for PL in response to 2, 4, and 8% sewage sludge application doses, respectively. Similar increases were observed in loam and clay soils. A significant and positive correlation between OMC–LL and –PL was found in several studies (Mueller et al., 2003; Aksakal et al., 2013; Sari et al., 2017). Overall, the correlation coefficients between OMC and LL, OMC and PL were found to be 0.950^{**} and 0.976^{**}, respectively.

Conclusion

The application of sewage sludge was found to improve the consistency limits and Proctor compaction parameters of soils. The response was not only dependent on the amount of sewage sludge applied, but also on the initial soil properties, mainly the soil texture. The application of sewage sludge at a dose of 2% of the soil was sufficient to significantly improve the soil mechanical properties, due to the development and stabilization of soil aggregates. The results obtained from this research have shown that soils increase their ability to withstand mechanical forces or withstand greater mechanical forces when properly mixed with sewage sludge. The increase in the optimum moisture contents of the liquid limit, plastic limit, and friability index indicated that soils amended with sewage sludge became more friable than the control soils at a relatively higher moisture content. Increasing the moisture content extends the range of workability in the field and allows the soil to be workable without degradation (aggregate breakdown and compaction) at higher moisture content. The application of sewage sludge has shown that it is possible to improve both soil tillage and workability simultaneously. The quality assessment of sewage sludge intended for agricultural use requires careful consideration of parameters such as nutrient content, organic matter, and potential contaminants. This evaluation is crucial to ensure that the sewage sludge, when utilized as soil amendment agent, has positive effects on soil properties and complies with environmental standards. The electrical conductivity of the sewage sludge used in this study was high, therefore, it requires careful and controlled use in terms of soil salinity when applied in high doses.

References

Adewole, M.B., & Ilesanmi, A.O. (2012). Effects of different soil amendments on the growth and yield of okra in a tropical rainforest of southwestern Nigeria. *Journal of Agricultural Sciences, 57* (3), 143-153.

Aggelides, S.M., & Londra, P.A. (2000). Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil. *Bioresource Technology, 71* (3), 253-259.

Aksakal, E.L., Angin, I., & Oztas, T. (2013). Effects of diatomite on soil consistency limits and soil compactibility. *Catena*, *101*, 157-163.

Angin, I., Aslantas, R., Kose, M., Karakurt, H., & Ozkan, G. (2012). Changes in chemical properties of soil and sour cherry as a result of sewage sludge application. *Horticulture Science (Prague), 39* (2), 61-66.

Angin, I., Aslantas, R., Gunes, A., Kose, M., & Ozkan, G. (2017). Effects of sewage sludge amendement on some soil properties, growth, yield and nutrient content of raspberry (*Rubus ideas L.*). *Erwerbs-Obstbau, 29,* 93-99.

Asghari, S., Neyshabouri, M.R., Abbasi, F., Aliasgharzad, N., & Oustan, S. (2009). The effects of four organic soil conditioners on aggregate stability, pore size distribution, and respiration activity in a sandy loam soil. *Turkish Journal of Agriculture and Forestry, 33* (1), 47-55.

ASTM (1992). *Annual book of ASTM standards.* Philadelphia: ASTM Intl.

ASTM (2000). *Test method for laboratory compaction characteristics of soil using standard effort.* Philadelphia: ASTM Intl.

Ball, B.C., Cheshire, M.V., Robertson, E.A.G., & Hunter, E.A. (1996). Carbohydrate composition in relation to structural stability, compactibility and plasticity of two soils in a long-term experiment. *Soil and Tillage Research, 39,* 143-160.

Barzegar. A.R., Hashemi, A.M., Herbert, S.J., & Asoodar, M.A. (2004). Interactive effects of tillage system and soil water content on aggregate size distribution for seedbed preparation in fluvisols in Southwest Iran. *Soil and Tillage Research, 78* (1), 45-52.

Batey, T. (2009). Soil compaction and soil management-a review. *Soil Use and Management, 25* (4), 335-345.

Baumgartl, T., & Horn, R. (1991). Effect of aggregate stability on soil compaction. *Soil and Tillage Research, 19* (2-3), 203-213.

Bhushan, L., & Sharma, P.K. (2002). Long-term effects of lantana (*Lantana spp. l.*) residue additions on soil physical properties under rice wheat cropping. I. soil consistency, surface cracking and clod formation. *Soil and Tillage Research, 65* (2), 157-167.

Blanco-Canqui, H., Lal, R., Post, W.M., Izaurralde, R.C., & Shipitalo, M.J. (2006). Organic carbon influences on soil particle density and rheological properties. *Soil Science Society of America Journal, 70* (4), 1407-1414.

Boivin, P., Garnier, P., & Tessier, D. (2004). Relationship between clay content, clay type, and shrinkage properties of soils samples. *Soil Science Society of America Journal, 68* (4), 1145-1153.

Bronick, C.J., & Lal, R. (2005). Soil structure and management: a review. *Geoderma, 124* (1-2), 3-22.

Buck, C., Langmaack, M., & Schrader, S. (2000). Influence of mulch and soil compaction on earthworm cast properties. *Applied Soil Ecology, 14* (3), 223-229.

Canbolat, M.Y., & Öztaş, T. (1997). Factors affecting consistency limits of soil and evaluation of consistency limits for agricultural purposes. *Atatürk University Journal of Agricultural Faculty, 28* (1), 120-129. (in Turkish with an abstract in English).

Canbolat, M.Y., Barik, K., & Özgül, M. (1999). Consistency limits and shrink-swell characteristics of three soil profiles formed from different parent materials around Erzurum. *Atatürk University Journal of Agricultural Faculty, 30* (2), 121-129. (in Turkish with an abstract in English).

Chenu, C., Le Bissonnais, Y., & Arrouays, D. (2000). Organic matter influence on clay wettability and soil aggregate stability. *Soil Science Society of America Journal, 64* (4), 1479-1486.

Cogger, C.G., Bary, A.I., Kennedy, A.C., & Fortuna, A. (2013). Long-term crop and soil response to biosolids applications in dryland wheat. *Journal of Environmental Quality, 42* (6), 1872-1880.

Connolly, R.D. (1998). Modelling effects of soil structure on the water balance of soil-crop systems: a review. *Soil and Tillage Research, 48* (1-2), 1-19.

De Jong, E., Acton, D.F., & Stonehouse, H.B. (1990). Estimating the atterberg limits of southern saskatchewan soils from texture and carbon contents. *Canadian Journal of Soil Science, 70* (4), 543-554.

Dexter, A.R., & Bird, N.R.A. (2001). Methods for predicting the optimum and the range of soil water contents for tillage based on the water retention curve. *Soil and Tillage Research, 57* (4), 203-212.

Ekwue, E.I., & Stone, R.J. (1995). Organic matter effects on the strength properties of compacted agricultural soils. *Transactions of the ASAE, 38,* 357-365.

Flint, A.L., & Flint, L.E. (2002). Particle density. In: J.H. Dane & G.C. Topp (Eds.) *Methods of soil analysis, Part 4 physical methods, SSSA book series 5.* (pp. 229-240). Madison, Wisconsin: SSSA Inc.

Foladori, P., Andreottola, G., & Ziglio, G. (2010). Sludge composition and production in full-plants. In P. Foladori (Ed.) *Sludge reduction technologies in wastewater treatment plants.* (pp. 6-19). London: IWA Publishing.

Gee, G.W., & Or, D. (2002). Particle-size Analysis. In J.H. Dane & G.C. Topp (Eds.), *Methods of soil analysis, Part 4 physical methods, SSSA book series 5*. (pp. 255-293). Madison, Wisconsin: SSSA Inc.

Gobinath, R., Ganapathy, G.P., Gayathiri, E., Salunkhe, A.A., & Pourghasemi, H.R. (2021). Ecoengineering practices for soil degradation protection of vulnerable hill slopes. In H.R. Pourghasemi (Ed.), *Computers in earth and environmental sciences: artificial intelligence and advanced technologies in hazards and risk management*. (pp. 255-270). Amsterdam: Elsevier.

Grossman, R.B., & Reinsch, T.G. (2002). Bulk density and linear extensibility. In J. H. Dane & G.C. Topp (Eds.), *Methods of soil analysis, Part 4 physical methods. SSSA book series 5*. (pp. 201-228). Madison, Wisconsin: SSSA Inc.

Hakansson, I., & Lipiec, J. (2000). A review of the usefulness of relative bulk density values in studies of soil structure and compaction. *Soil and Tillage Research, 53* (2), 71-85.

Hemmat, A., Aghilinategh, N., Rezainejad, Y., & Sadeghi, M. (2010). Longterm impacts of municipal solid waste compost, sewage sludge and farmyard manure application on organic carbon, bulk density and consistency limits of a calcareous soil in Central Iran. *Soil and Tillage Research, 108* (1-2), 43-50.

Holthusen, D., Pértile, P., Awe, G.O., & Reichert, J.M. (2020). Soil density and oscillation frequency effects on viscoelasticity and shear resistance of subtropical oxisols with varying clay content. *Soil and Tillage Research, 203,* 104677.

IBM (2011). *IBM Statistics for Windows. Version 20.0.* New York: IBM Corporation.

Keller, T., & Dexter, A.R. (2012). Plastic limits of agricultural soils as functions of soil texture and organic matter content. *Soil Research, 50* (1), 7-17.

Kumar, S., Malik, R.S., & Dahiya, I.S. (1985). Influence of different organic wastes upon water retention, transmission and contact characteristics of a sandy soil. *Australian Journal of Soil Research, 23* (2), 131-136.

Lal, R., & Shukla, M.K. (2004). *Principles of soil physics.* New York: Marcel Dekker Inc.

Lindsay, B.J., & Logan, T.J. (1998). Field response of soil physical properties to sewage sludge. *Journal of Environmental Quality, 27* (3), 534-542.

Loeppert, R.H., & Suarez, D.L. (1996). Carbonate and gypsum. In D.L. Sparks (Ed.), *Methods of soil analysis, Part 3 chemical methods, SSSA book series 5.* (pp. 437-474). Madison, Wisconsin: SSSA Inc.

Macks, S.P., Murphy, B.W., Cresswell, H.P., & Koen, T.B. (1996). Soil friability in relation to management history and suitability for direct drilling. *Australian Journal of Soil Research, 34* (3), 343-360.

McBride, R.A. (2002). Atterberg limits. In J.H. Dane & G.C. Topp (Eds.), *Methods of soil analysis, Part 4 physical methods, SSSA book series 5.* (pp. 389-398). Madison, Wisconsin: SSSA Inc.

McBride, R.A., & Bober, M.L. (1989). A re-examination of alternative test procedures for soil consistency limit determination: I. a compression-based procedure. *Soil Science Society of America Journal, 53* (1), 178-183.

Mueller, L., Tille, P., & Kretschmer, H. (1990). Trafficability and workability of alluvial clay soils in response to drainage status. *Soil and Tillage Research, 16* (3), 273-287.

Mueller, L., Schindler, U., Fausey, N.R., & Lal, R. (2003). Comparison of methods for estimating maximum soil water content for optimum workability. *Soil and Tillage Research, 72* (1), 9-20.

Munkholm, L.J. (2011). Soil friability: a review of the concept, assessment and effects of soil properties and management. *Geoderma, 167-168,* 236-246.

Nawaz, M.F., Bourrié, G., & Trolard, F. (2013). Soil compaction impact and modelling. a review. *Agronomy for Sustainable Development, 33*, 291-309.

Nelson, D.W., & Sommers, L.E. (1996). Total carbon, organic carbon, and organic matter. In D.L. Sparks (Ed.), *Methods of soil analysis, Part 3 chemical methods, SSSA book series 5.* (pp. 961-1010). Madison, Wisconsin: SSSA Inc.

Nhantumbo, A.B.J.C., & Cambule, A.H. (2006). Bulk density by proctor test as a function of texture for agricultural soils in Maputo Province of Mozambique. *Soil and Tillage Research, 87* (2), 231-239.

Nimmo, J.R., & Perkins, K.S. (2002). Aggregate stability and size distribution. In J.H. Dane & G.C. Topp (Eds.), *Methods of soil analysis, Part 4 physical methods, SSSA book series 5.* (pp. 317-328). Madison, Wisconsin: SSSA Inc.

Obour, P.B., Lamandé, M., Edwards, G., Sørensen, C.G., & Munkholm, L.J. (2017). Predicting soil workability and fragmentation in tillage: a review. *Soil Use and Management, 33* (2), 288-298.

Pagliai, M., Bisdom, E.B.A., & Ledin, S. (1983). Changes in surface structure (crusting) after application of sewage sludge and pig slurry to cultivated agricultural soils in Northern Italy. *Geoderma, 30* (1-4), 35-53.

Rhoades, J.D. (1996). Salinity: electrical conductivity and total dissolved solids. In D.L. Sparks (Ed.), *Methods of soil analysis, Part 3 chemical methods, SSSA book series 5.* (pp. 417-435). Madison, Wisconsin: SSSA Inc.

Rixon, A.J., Yao, X., & Zhu, H.X. (1991). Effect of heavy applications of organic residues on the physical properties of paddy soils in China. *Soil and Tillage Research, 20* (1), 101-108.

Sari, S., Aksakal, E.L., & Angin, I. (2017). Influence of vermicompost application on soil consistency limits and soil compactibility. *Turkish Journal of Agriculture and. Forestry, 41* (5), 357-371.

Seleiman, M.F., Kheir, A.M.S., Al-Dhumri, S., Alghamdi, A.G., Omar, E.H., Aboelsoud, H.M., Abdella, K.A., & El Hassan, W.H.A. (2019). Exploring optimal tillage improved soil characteristics and productivity of wheat irrigated with different water qualities. *Agronomy, 9* (5), 233.

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research, 79* (1), 7-31.

Smith, C.W., Hadas, A., Dan, J., & Koyumdjisky, H. (1985). Shrinkage and atterberg limits in relation to other properties of principal soil types in Israel. *Geoderma, 35* (1), 47-65.

Smith, C.W., Johnston, M.A., & Lorentz, S. (1997). Assessing the compaction susceptibility of south african forestry soils I. the effect of soil type, water content and applied pressure on uni-axial compaction. *Soil and Tillage Research, 41* (1-2), 53-73.

Smith, S.R. (1995). *Agricultural recycling of sewage sludge and the environment.* Wallingford: CAB International.

Soane, B.D. (1990). The role of organic matter in soil compactibility: a review of some practical aspects. *Soil and Tillage Research, 16* (1-2), 179-201.
Soil Survey Staff (2014). *Keys to soil taxonomy.* Washington DC: USDA Natural Resources Conservation Service.
Stanchi, S., Oberto, E., Freppaz, M., & Zanlni, E. (2009). Linear regression models for liquid and plastic limit estimation in alpine soils. *Agrochimica, 53* (5), 322-338.
Stanchi, S., D'Amico, M., Zanini, E., & Freppaz, M. (2015). Liquid and plastic limits of mountain soils as a function of the soil and horizon type. *Catena, 135,* 114-121.
Stone, R.J., & Ekwue, E.I. (1993). Maximum bulk density achieved during soil compaction as affected by the incorporation of three organic materials. *Transactions of the ASAE, 36* (6), 1713-1719.
Sumner, M.E., & Miller, W.P. (1996). Cation exchange capacity and exchange coefficients. In D.L. Sparks (Ed.), *Methods of soil analysis, Part 3 chemical methods, SSSA book series 5.* (pp. 1021-1229). Madison, Wisconsin: SSSA Inc.
Tejada, M., Hernandez, M.T., & Garcia, C. (2006). Application of two organic amendments on soil restoration: effects on the soil biological properties. *Journal of Environmental Quality, 35* (4), 1010-1017.
Terzaghi, A., Hoogmoed, W.B., & Miedema, R. (1988). The use of the 'wet workability limit' to predict the land quality 'workability' for some Uruguayan soils. *Netherlands Journal of Agricultural Science, 36* (1), 91-103.
Thomas, G.W. (1996). Soil pH and soil acidity. In D.L. Sparks (Ed.) Methods of soil analysis, Part 3 chemical methods, SSSA book series 5. (pp. 475-490). Madison, Wisconsin: SSSA Inc.
Tsadilas, C.D., Mitsios, I.K., & Golia, E. (2005). Influence of biosolids application on some soil physical properties. *Communications in Soil Science and Plant Analysis, 36* (4-6), 709-716.
Wagner, L.E., Ambe, N.M., & Barnes, P. (1992). Tillage-induced soil aggregate status as influenced by water content. *Transactions of the ASAE, 35* (2), 499-504.
Wagner, L.E., Ambe, N.M., & Ding, D. (1994). Estimating a proctor density curve from intrinsic soil properties. *Transactions of the ASAE, 37,* 1121-1125.
Watts, C.W., & Dexter, A.R. (1998). Soil friability: theory, measurement and the effects of management and organic carbon content. *European Journal of Soil Science, 49* (1), 73-84.
Yazdanpanah, N., Mahmoodabadi, M., & Cerdà, A. (2016). The impact of organic amendments on soil hydrology, structure and microbial respiration in semiarid lands. *Geoderma, 266,* 58-65.
Zentar, R., Abriak, N.E., & Dubois, V. (2009). Effects of salts and organic matter on atterberg limits of dredged marine sediments. *Applied Clay Science, 42* (3-4), 391-397.
Zhang, H., Hartge, K.H., & Ringe, H. (1997). Effectiveness of organic matter incorporation in reducing soil compactability. *Soil Science Society of America Journal, 61,* 239-245.

Received: July 5, 2023
Accepted: January 25, 2024

UTICAJI PRIMENE ANAEROBNO RAZGRAĐENOG KANALIZACIONOG MULJA NA GRANICE KONZISTENCIJE I ZBIJENOST ZEMLJIŠTA RAZLIČITE TEKSTURE

Ekrem Lutfi Aksakal[1*], Armagan Cambaztepe[1], Ilker Angin[2] i Serdar Sari[3]

[1]Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Atatürk University, 25240, Erzurum, Türkiye
[2]Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Atatürk University, 25240, Erzurum, Türkiye
[3]Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Igdir University, 76000, Igdir, Türkiye

R e z i m e

Bez obzira na njihove korisne karakteristike korišćenje organskog otpada u poljoprivredi može imati negativan uticaj na svojstva zemljišta ukoliko se nepravilno koristi. Radi procene pravilne upotrebe kanalizacionog mulja sprovedena je laboratorijska studija kako bi se istražili efekti primene različitih doza (0, 2, 4 i 8% mas.) na granice konzistencije i zbijenost tri zemljišta različite teksture. Primena kanalizacionog mulja značajno je poboljšala granice konzistencije i smanjila zbijenost. Efikasnost je zavisila od količine primenjenog materijala. Stepeni povećanja vrednosti gornje granice plastičnosti (engl. *liquid limit* – LL) pri primeni 8% kanalizacionog mulja bile su 58,7% za peskovitu ilovaču, 43,4% za ilovaču, i 16,2% za glinovito zamljište. Kako se doza primene povećavala, vrednosti optimalnog sadržaja vlage (engl. *optimum moisture content* – OMC) su se povećavale, a vrednosti maksimalne suve gustine zemljišta (engl. *maximum dry bulk density* – MBD) su se smanjivale. Najviša doza mulja je smanjila MBD za 9,5% kod peskovite ilovače, za 6,5% kod ilovače, i za 13,7% kod glinovitog zemljišta. Stepeni povećanja vrednosti optimalnog sadržaja vlage bili su 73,4, 53,8, odnosno 27,1% za peskovitu ilovaču, ilovaču i glinu. Rezultati prikazani u ovoj studiji jasno su pokazali da je primena kanalizacionog mulja učinila zemljište otpornijim na delovanje mehaničke sile, s obzirom na to da je povećanje optimalnog sadržaja vlage u odnosu na LL i PL ukazalo na lakšu obradu zemljišta pri većim sadržajima vlage bez negativnih deformacija, što je dovelo i do povećanja intervala vlage pri kojem se zemljište može obrađivati.

Ključne reči: Aterbergove granice, zbijenost, kanalizacioni mulj, degradacija zemljišta, drobljivost zemljišta.

Primljeno: 5. jula 2023.
Odobreno: 25. januara 2024.

[*]Autor za kontakt: e-mail: elaksakal@atauni.edu.tr