Original Research Article

Enhancing soil resilience in Iranian Haploxeralfs: A study on the impact of two organic matters on aggregate stability and mechanical resistance

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Abstract: In arid regions around the world, erosion is a frequent occurrence due to low annual rainfall weakening plants, which in turn affects the concentration of soil organic matter (SOM). When the soil is exposed, sudden and heavy rainfall can lead to soil degradation, particularly in soil with high sodicity where unstable aggregates are easily ruptured, initiating the first phase of soil erosion. To investigate this phenomenon, soil samples were collected from an erosion-prone area near Maharloo Salt Lake, specifically Chah-angiri (soil 1) and Kamal-abad (soil 2), which are loam and silty clay loam soils with low SOM. To evaluate the effect of organic matter sources on soil stability, cow manure (animal source) and wheat straw (plant source) were applied to both soil samples at four different rates (0.0, 10.0, 20.0, and 40.0 g kg^{-1}) and incubated for four months. The soil's aggregate stability and mechanical resistance were then assessed using two different methods: mechanical resistance, which was measured as the module of rupture and penetration resistance, and aggregate stability, which was evaluated using the conventional and Le Bissonnais methods. The application of organic matter resulted in a linear increase in aggregate stability in both soils, with the increase in Chah-angiri (with lower sodicity) being greater than Kamal-abad (with higher ESP). Both linear and exponential equations showed that organic matter treatment reduced soil mechanical resistance exponentially, with wheat straw proving more effective than cow dung at stabilizing aggregates against slaking and lowering soil mechanical resistance in both soils. Furthermore, the stability of aggregates changed by mechanical breakdown (MWD_{stir}) was found to have the strongest relationship among three Le Bissonnais treatments (MWD_{slow}, MWD_{fast}, and MWD_{stir}) and the aggregate stability test using the usual technique (Kemper and Rosenau). The organic matter rate had a significant effect (P < 0.001) on MWD_{stir}, which increased with rate in a linear relationship (r^2 = 0.957, P = 0.022). Finally, the stability of soil aggregates in water was also investigated.

Keywords: organic matter; soil aggregate stability; mechanical resistance

1. Introduction

Most of the dry and semi-arid regions around the world have SOM, which is a crucial element of soil physicochemical characteristics. The ability of transition metal cations to form stable complexes with organic ligands has made SOM a subject of particular interest in research on heavy metal sorption by soils[1–5]. Pearson[6] introduced the concept of hard and soft acids and bases to explain the strength of metal complexes. In this definition, cations and ligands are Lewis acids and Lewis bases, respectively, and in a complex, metal cation and ligand are acting as electron acceptor and donor. Strong bonding occurs between hard bases and hard acids, whereas weak bonding occurs between hard-soft or soft-hard acids and bases. A poor SOM results in physical phenomena such as dispersion, lumping, degradation, and runoff. Structural fragmentation is the most typical source of poor soil physical properties. Therefore, soil structure stability is a crucial factor in managing soil quality. The stability of aggregates is used as an indicator of soil structure[7–

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10]. An aggregate is a group of primary particles that stick together more strongly than other soil particles in the area[11,12]. Agricultural practices such as tillage, cropping system, and fertilizer type affect aggregate formation[13]. Soil structure affects porosity and infiltration, which, in turn, affects plant water availability and soil erosion potential. Maintaining soil structure is crucial for limiting the environmental impact of agricultural activities. The durability of soil aggregates is influenced by physical and chemical parameters such as texture, Fe, Al oxides, calcium carbonate, and organic matter content. Meanwhile, organic matter plays an essential role in these variables, with several writers emphasizing its expanding influence on aggregation[14–20]. Organic matter is one of the recognized soil supplements, and its effects have been observed in various farmers' fields[21–24].

Various forms of organic matters have been employed to enhance soil structure, such as utilizing organic waste such as poultry manure, and biochar to increase organic matter and infiltration rate[25–28], and using cattle manure to promote soil particle distribution[28–31]. According to Chenu et al.[32], SOM safeguards aggregates against dispersive processes in two ways. Firstly, organic matter enhances aggregate cohesion by binding mineral particles with organic polymers or physically entangling particles with fine roots or fungus. Secondly, organic matter can reduce aggregate wettability, slowing the pace of wetting, and consequently, the extent of slaking. Organic content in both sodic and non-sodic soils can help prevent dispersion and disaggregation[17,32–36]. Organic materials such as green manure, farmyard manure, compost, or food processing wastes, added up to 50 ton/ha^{-1}, have been employed to improve soil structure[37,38]. Additionally, SOM and soil structure are interrelated: SOM creates stable soil aggregates by binding with primary mineral particles, and this stable aggregation protects otherwise mineralizable SOM[14–40]. Agricultural management practices affect SOM[41,42], micro and macroaggregate distributions, and the rate of SOM turnover. Crust and seals are generated by raindrop impacts and/or slaking processes that break down soil aggregates. The dispersed particles are then deposited within the soil pore spaces, clogging them and forming a denser and more continuous structure. Clays can bind particles while strengthening the permanence of the crusty layer since the seals dry to form crusts[43].

The impact of organic additions on soil structure and hydraulic properties varies depending on several parameters, including the amendment's feedstock and manufacturing conditions, application quantity and duration, meteorological circumstances, soil types, and crop types[22,44].

There is no single method that can be used to measure aggregate stability for all soils and conditions. However, if only one test is to be chosen, the Determination of the Retention and Yield (DRY) rainfall simulation method is considered better at representing disaggregation processes when aggregates are exposed to rainfall or overhead irrigation, while the wet sieving method may be more suitable for representing aggregates exposed to floods or furrow irrigation[45].

To determine aggregate stability in this study, the mean weight diameter (MWD) of residual combinations after three treatments and wet sieving in alcohol was used. According to Fox and Le Bissonnais[46], slow wetting (cracking) may occur due to low-intensity, widely distributed precipitation, while stirring during pre-wetting (mechanical breakdown) may result from low-intensity, continuous precipitation. The advantage of this method is that it provides data on combination breakdown mechanisms and can be replicated. However, its main disadvantages are that it is time-consuming and requires the use of alcohol.

The aim of this study was to investigate the effect of adding plant residue (wheat straw) and animal residue (cow manure) on soil aggregate stability and establish a link between soil aggregate stability and soil mechanical resistance. Both residues are commonly used in the field, and the study aimed to evaluate the effect of different organic matter amendments and doses (cow manure and wheat straw) on soil aggregate stability.

2. Materials and methods

2.1. Study area and soil's properties

Two soil samples were collected from the surface horizon (depth 0–20 cm) of Haploxeralfs soils sensitive to erosion in Chah-angiri (soil 1) and Kamal-abad (soil 2), which are located near Maharloo Salt Lake in southeast Fars, Iran. Wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and sugar beet (*Beta vulgaris* L.) are the dominant crops grown in these soils under a crop rotation system. According to the USDA Soil Taxonomy, soil 1 and soil 2 are classified as Calcic Haploxeralfs and Natric Haploxeralfs, respectively. The soil texture was analyzed using the hydrometer method[47], pH was measured in a 1:1 suspension of soil and water[48], organic carbon was determined using the Walkley and Black method[49], and electrical conductivity (EC) was measured in a 1:1 suspension extract of soil and water[50]. The calcium carbonate equivalent (CCE) was calculated using the acid-neutralization method[48], and the available Mn, Fe, Zn, Cu, and Cd were extracted with the 0.005 M DTPA solution[51]. The two soils differ primarily in qualities such as EC, exchangeable sodium percentage (ESP), texture, and other soil factors that may influence the sensitivity of soil to erosion. **Table 1** contains information about these qualities. The native farmers in these locations sometimes burn plant residues after harvesting, leading to a decrease in organic matter content and increased soil sensitivity to erosion due to high ESP and silt content. Stormy rain slakes aggregates and causes seal development, surface runoff, and soil detachment once the ground is bare in the winter.

Table 1. Characteristics of the two soils used in the experiment (depth: 0–20 cm).

Property	**Soil 1 (Chah-angiri)**	**Soil 2 (Kamal-abad)**
Texture	Loam	Silty clay loam
Sand ($g\ kg^{-1}$)	280	105
Silt ($g\ kg^{-1}$)	457	525
Clay ($g\ kg^{-1}$)	263	370
SP (%)[1]	38.0	41.3
pH (H_2O)	8.14	8.17
EC ($dS\ m^{-1}$)[2]	2.70	0.36
$CaCO_3$ (%)	42.5	42.0
CEC ($cmol^+\ kg^{-1}$)[3]	8.04	14.67
Total organic carbon (%)	1.02	0.59
Total N (%)[4]	0.071	0.064
C/N ratio[5]	14.36	9.21
ESP[6]	5.2	13.5
Extractable sodium ($g\ kg^{-1}$)	0.229	0.360
Extractable calcium ($g\ kg^{-1}$)	0.188	0.040
Extractable magnesium ($g\ kg^{-1}$)	0.074	0.024

1: Saturation percent; 2: electrical conductivity; 3: cation exchange capacity; 4: nitrogen; 5: carbon/nitrogen; 6: exchangeable sodium percentage.

2.2. Application of organic matter

Three kilograms of each soil were mixed entirely with two types of organic matter (separately, Table 5) and poured into three-kilogram plastic pots at four different rates of 0.0, 1.0, 2.0, and 4.0 percent. Soil water content was maintained at around field capacity of 18 and 31 percent, w/w for loam and silty clay loam, respectively, by weighing the pots on the first day and comparing their weight with the initial one in the following days[39]. The temperature in the greenhouse was regulated at 30 °C to create an optimal environment for microorganisms to degrade organic matter. This experiment was carried out for four months. After four months of incubation, descriptive methods were used to measure aggregate stability and soil mechanical resistance.

2.3. Study on soil aggregate stability and mechanical resistance

2.3.1. Determination of soil aggregate stability

The mean weight diameter (MWD) index is an approach comparable to Kemper and Rosenau[11] (usual method) for evaluating aggregate structural stability. Four grams of 1–2 mm aggregates were placed on four sieves with mesh openings of 2, 1, 0.50, and 0.25 mm and vapor chambered to maintain consistent water content. In distilled water, the sieves were elevated and lowered via a 1.30 cm vertical distance at 36 cycles per minute for 5 min in a modified Yoder apparatus. The sieves were separated and dried in the oven at 105 °C. The dry weight of aggregates on each sieve was measured, and the MWD_{slow} was calculated.

Le Bissonnais[52] proposed a new method for measuring aggregate stability against various disaggregation factors. Three different disruptive techniques were used to measure the stability of 1–2 mm aggregates. For the fast wetting treatment, 4 g of air-dried 1–2 mm aggregates were placed in a 0.25 mm diameter sieve and submerged gently in a 250 mL beaker filled with 100 mL of deionized water for 10 min. The aggregates were then sieved in 95 percent ethanol using Yoder equipment (MWD_{fast}). In the gradual wetting treatment, 4 g of 1–2 mm aggregates were deposited in 0.25 mm hole diameter sieves and wetted until saturated using a vapor chamber, causing cracking. The sieves were then transferred to a Yoder apparatus and sieved in ethanol. For the mechanical breakdown treatment, 4 g of 1–2 mm aggregates were gently immersed in 50 mL of ethanol for 10 min and stirred after pre-wetting, causing mechanical breakdown. The ethanol was then removed, and the aggregates were transferred to an Erlenmeyer flask filled with 50 mL of deionized water, and the level was adjusted to 200 mL. The Erlenmeyer was corked and agitated end over end 20 times and left for 30 min to allow coarse particles to settle. Excess liquid and suspended material were carefully removed by pipette, and the remaining soil-water mix was moved to a 0.25 mm sieve for disaggregation by sieving in ethanol. The sieves were mechanically moved ten times with a distance of only 1.3 centimeters in ethanol to facilitate disaggregation. The > 0.25 mm fraction was collected with the 0.25 mm sieves, oven-dried, and dry-sieved for 1 min on sieves with hole openings of 2.0, 1.0, 0.5, and 0.25 mm using an average mechanical sieve shaker (MWD_{stir}). The MWD can be calculated by multiplying the mean aperture of sieve meshes (Di) by the remaining aggregate on each sieve (Wi) and dividing by the initial soil weight (W), the MWD can be calculated:

$$\text{MWD} = \sum W_i D_i / W \tag{1}$$

2.3.2. Determination of soil mechanical resistance

In order to measure simulated soil crust resistance, the modulus of rupture (M.R.) was used along with the methodology projected by Reeve[53]. Soil aggregates passing through a 2.00 mm sieve were collected from the experimental treatments and poured into a lightweight aluminum rectangle mold (7 cm × 3.5 cm × 1 cm) that was aligned on a screen covered with filter paper.

The inside surface of the mold was carefully covered with a layer of petroleum gel to prevent the soil from sticking. Aggregates were then soaked with water from below the screen for 31 min until they became weaker, slaked, and cohered to each other, filling the interaggregate pore areas and creating a simulated crust similar to natural conditions. The samples were then transferred to an oven at 50 ℃ and dried thoroughly. The soil briquettes (simulated crust) were carefully removed and the pressure required to break them was measured using the formula:

$$S = 3FL/2bd^2 \tag{2}$$

where S is the modulus of rupture in dyne per square centimeter, F is the breaking force in dyne (the breaking force in grams' weight × 980), L is the distance between the two lower supports, b is the width of the briquettes, and d is the depth or thickness of the briquettes, all expressed in centimeters. The bar is a CGS unit of pressure and is equal to one million dynes per square centimeter. Thus, dyne per square centimeter is converted to milibar. To calculate F, the mass of water needed (in grams) to break the briquettes standing on two supports on a single handle scale was used.

Soil penetration resistance was measured using a pocket penetrometer (ELS29-3729) on the surface soil treatments in the pots. This instrument has a special spring dynamometer with a pressure-indicating scale on the stem of the needle[54]. Penetration is sensitive to soil moisture, so initially, the moisture content of all treatments was adjusted to approximately 1/3 field capacity (6% w/w). Then, the penetration resistance was measured (in kg cm^{-2}) by pushing the probe of the penetrometer into the surface soil treatments in the pots with three replications for each of them.

3. Data analysis

Data analysis was carried out using a completely randomized design (CRD) with two replications. Analysis of variance (ANOVA) was established for each soil on an individual basis as a 24 factorial in a completely randomized design (CRD). Two forms of organic matter amendments (cow dung and wheat straw) were used at four rates of each, and two types of soil were tested with two replications. To compare changes between pairs of treatment means, the *P*-value in Duncan's multiple ranges was utilized. Pearson's correlation coefficients (r) were calculated using SPSS (Statistical Package for the Social Sciences) version 16 to discover the correlations between the measured parameters. Furthermore, simple linear and exponential regressions were constructed to evaluate the slope and r-square to quantify the role of organic matter in controlling aggregates to determine the effects of various rates of organic matter application on the parameters.

4. Results

4.1. Effect of organic matters on soil aggregate stability

4.1.1. Effect of organic matters types and rates on aggregate stability (MWD) in usual method

In soil 1, application of organic matter amendments at rates of 10, 20, and 40 g kg^{-1} increased the mean weight diameter (MWD) by 3.0, 3.50, and 7.50 times, respectively, compared to the control (**Table 2**). A similar relationship was observed in soil 2, where organic fertilizer doses of 10, 20, and 40 g kg^{-1} resulted in 1.2-, 2.6-, and 5.5- fold increases in MWD, respectively, compared to the control. This increase in MWD with increasing organic fertilizer application dose was statistically significant for linear and exponential regression, with a higher R^2 value obtained for the linear regression for both soil 1 and soil 2 (**Table 3**). The type of organic matter amendment applied also influenced aggregate stability in the surface horizon of Calcic Haploxeralfs (soil 1). Statistically significantly higher average MWD values were obtained with the application of wheat straw than with cow manure. In the case of Natric Haploxeralfs (soil 2), the effect of improving aggregate stability of the surface horizon was the same for organic fertilization with wheat straw and cow manure (**Table 2**).

Table 2. Effect of type and dose of OM on MWD (mm) in two soil samples at two usual and Le Bissonnais different treatments.

	Soil 1			**Soil 2**		
Type	**Cow manure**	**Wheat straw**	**Means**	**Cow manure**	**Wheat straw**	**Means**
Rate						
	MWD (usual method)					
0.00	0.235	0.270	0.252c	0.257	0.289	0.273c
10.00	0.443	1.073	0.758b	0.337	0.310	0.324c
20.00	0.519	1.266	0.892b	0.783	0.649	0.716b
40.00	1.002	2.754	1.878a	1.425	1.600	1.513a
Means	0.549b	1.340a		0.700a	0.712a	
	MWD_{slow}					
0.00	0.758	0.748	0.753b	0.530	0.545	0.537c
10.00	0.763	0.787	0.775b	0.842	0.819	0.831b
20.00	0.817	1.025	0.921a	0.931	1.048	0.989a
40.00	0.948	1.127	1.037a	0.977	1.069	1.023a
Means	0.821a	0.922a		0.820b	0.870a	
	MWD_{fast}					
0.00	0.102	0.075	0.089d	0.176	0.182	0.179d
10.00	0.251	0.262	0.256c	0.198	0.360	0.279c
20.00	0.376	0.422	0.399b	0.275	0.646	0.461b
40.00	0.469	0.581	0.525a	0.356	0.807	0.582a
Means	0.299b	0.335a		0.251b	0.499a	
	MWD_{stir}					
0.00	0.178	0.199	0.189c	0.389	0.419	0.404c
10.00	0.182	0.303	0.243c	0.422	0.610	0.516b
20.00	0.411	0.544	0.477b	0.600	0.809	0.705a
40.00	0.398	0.938	0.668a	0.620	0.883	0.751a
Means	0.292b	0.496a		0.508b	0.680a	

Similar letters (down the last column and across the row) indicate means of the main treatment effects are not significantly different at 5% level from each other.

4.1.2. Effect of organic matter type and rate on aggregate stability influenced by slow wetting (MWD_{slow})

There was a significant effect of mean rate application of organic matter on MWD_{slow} in soil 1, with a significant linear relationship ($r^2 = 0.949$, $P = 0.026$) between rate and MWD_{slow} (**Table 3**). However, neither organic matter type nor the interaction with rate was significant in this soil. In soil 2, there was a significant effect of organic matter type ($P = 0.003$), rate ($P < 0.001$), and interaction between type and rate ($P = 0.011$) on MWD_{slow}, but no significant relationship was observed between rates and MWD_{slow}, although there was a 1.5-, 1.8-, and 1.9- fold increase in MWD_{slow} compared to the control treatment.

4.1.3. Effect of organic matters types and rates on aggregate stability influenced by fast wetting (MWD_{fast})

There was a significant effect of mean rate application of organic matter in soil 1 ($P < 0.001$) with a 2.9-, 4.5-, and 5.9-fold increase compared to the control treatment, with a positive linear significant relationship ($r^2 = 0.941$, $P = 0.030$) (**Table 3**). Organic matter type also had a significant effect ($P = 0.003$) on aggregate stability, and the interaction between type and rate showed a significant effect on MWD_{fast} (P = 0.003). In soil 2, there was a significant effect of organic matter rate on MWD_{fast} (P < 0.001), with a significant linear relationship (r^2 = 0.951, P = 0.025). The increase in different rates of organic matter application was 1.6-, 2.6-, and 3.3- fold compared to the control treatment. Organic matter type and the interaction with rate also had a significant effect on MWD_{fast} (P < 0.001).

Table 3. Linear ($Y = mX + b$) and exponential regression analysis ($Y = \alpha e^{\beta.X}$) of measured parameters with organic matter rates (0, 1, 2 and 4%) added to soils.

Y	***X***		**Linear regression**				**Exponential regression**			
			m	*b*	r^2	*P*	*α*	*β*	r^2	*P*
MWD	Organic matter added (%)	Soil 1	0.393	0.257	0.973	0.013	0.337	0.458	0.891	0.056
MWD		Soil 2	0.327	0.133	0.951	0.025	0.251	0.453	0.964	0.018
MWD_{slow}		Soil 1	0.076	0.738	0.949	0.026	0.743	0.085	0.942	0.030
MWD_{slow}		Soil 2	0.112	0.648	0.754	0.132	0.635	0.146	0.706	0.160
MWD_{fast}		Soil 1	0.106	0.130	0.941	0.030	0.128	0.408	0.800	0.106
MWD_{fast}		Soil 2	0.102	0.196	0.951	0.025	0.205	0.289	0.900	0.051
MWD_{stir}		Soil 1	0.126	0.172	0.957	0.022	0.195	0.329	0.925	0.038
MWD_{stir}		Soil 2	0.088	0.440	0.861	0.072	0.440	0.154	0.837	0.085
M.R		Soil 1	−63.6	513.8	0.996	0.002	526.4	−0.17	0.997	0.001
M.R		Soil 2	−32.3	176.7	0.960	0.020	187.7	−0.31	0.995	0.002
P.R		Soil 1	−0.45	3.142	0.935	0.033	3.229	−0.20	0.958	0.021
P.R		Soil 2	−0.14	1.394	0.640	0.200	1.375	−0.12	0.644	0.197

4.1.4. Effect of organic matters types and rates on aggregate stability influenced by mechanical breakdown (MWD_{stir})

The impact of organic matter on aggregate stability, as influenced by mechanical breakdown (MWD_{stir}), is presented in **Table 2** for soil samples 1 and 2. The results indicate a significant effect of O.M rate (P < 0.001) on MWD_{stir}, which can be attributed to a significant (r^2 = 0.957, P = 0.022) linear relationship (**Table 3**) between rate and MWD_{stir}, with the latter increasing with increasing rates. The increases in MWD_{stir} were 1.3, 2.5, and 3.5 compared to the control treatment. Furthermore, the type of organic matter and its interaction with the rate also had significant impacts (P < 0.001) on soil stability in both soils. In soil 2, there was also a significant effect of O.M rate (P < 0.001), although there was no significant relationship (r^2 = 0.861, P = 0.072) between MWD_{stir} and rate, despite increases of 1.3, 1.7, and 1.9 compared to the control treatment. The type of organic matter and its interaction with rate were also significant (P < 0.001) in this soil.

4.2. Effect of organic matters on soil mechanical resistance

4.2.1. Effect of organic matters types and rates on modulus of rupture (M.R)

The effect of organic matter type and rate on modulus of rupture (M.R) is presented in **Table 4** for both soil samples. The data indicate a significant effect of O.M rate (P < 0.001) on M.R, which can be explained by a negative significant (r^2 = 0.997, P = 0.001) exponential relationship (**Table 3**) between rate and M.R, with the latter decreasing with increasing rates. The effect of organic matter type and its interaction with rate were also significant (P < 0.001) in both soils. For soil sample 2, there was also a significant effect of O.M rate (P < 0.001) on M.R, with an exponential significant (r^2 = 0.995, P = 0.002) negative relationship observed between rate and M.R. The type of organic matter and its interaction with rate were also significant ($P < 0.001$).

4.2.2. Effect of organic matters types and rates on penetrometer resistance (P.R)

The effect of organic matter type and rate on P.R is presented in **Tables 4** and **3** for both soil samples. The data indicate a significant effect of O.M rate ($P < 0.001$) on P.R, which can be explained by a significant ($r^2 = 0.958$, $P = 0.021$) exponential relationship (**Table 3**) between rate and P.R, with the latter decreasing with increasing rates. The effect of organic matter type was significant ($P = 0.020$), but the interaction of type with rate was not significant ($P = 0.088$). In soil 2, there was a significant effect of O.M rate ($P < 0.001$) on P.R, but there was neither a significant linear nor exponential relationship observed between rate and P.R. The type of organic matter was not significant ($P > 0.091$), but its interaction with rate was significant ($P = 0.002$).

Table 4. Effect of type and dose of OM on soil mechanical resistance in two soil samples.

	Soil 1			**Soil 2**		
Type	**Cow manure**	**Wheat straw**	**Means**	**Cow manure**	**Wheat straw**	**Means**
Rate						
	Modulus of rupture (milibar)					
0.00	537.1	506.0	521.5a	201.2	177.0	189.1a
10.00	519.1	367.1	443.1b	147.6	116.8	132.2b
20.00	426.6	337.8	382.2c	133.6	77.5	105.5c
40.00	371.4	155.3	263.3d	89.5	17.5	53.5d
Means	463.5a	341.5b		142.9a	97.2b	
	Penetrometer resistance (kg cm^{-2})					
0.00	3.13	3.16	3.15a	1.75	1.38	1.56a
10.00	2.88	2.88	2.88a	1.19	1.15	1.17b
20.00	2.63	1.29	1.96b	0.64	1.18	0.91c
40.00	1.90	0.97	1.43b	1.08	0.85	0.96c
Means	2.63a	2.08b		1.16a	1.14a	

Similar letters (down the last column and across the row) indicate means of the main treatment effects are not significantly (at 5% level) from each other.

5. Discussion

The impact of organic matters types and rates is observed to be significant in most of the treatments. Testing both linear and exponential equations resulted in the expected outcome (**Table 3**), with the linear regression being more significant in terms of organic matter quantity, as noted by several authors[13,15,55–57].

When comparing the application of 4.0% organic matter with the control treatment using the conventional method, there is a 7.5- fold increase in aggregate stability in soil 1, while it is 5.5- fold in soil 2. This trend is also observed in MWD_{fast} (5.9 and 3.3- fold for soil 1 and 2, respectively) and MWD_{stir} (3.5 and 1.9- fold for soil 1 and 2, respectively) in the Le Bissonnais treatments (**Table 2**). These results suggest that applying an equal rate of organic matter to the soil with lower sodicity (soil 1) is more effective in enhancing aggregate stability than to the soil with higher sodicity (soil 2). This could be attributed to the higher exchangeable sodium percentage (ESP), which is a dispersing agent, and lower electrical conductivity (EC), which is a cohesive agent, in soil 2 compared to soil 1 (**Table 1**). Soil organic carbon (SOC) stocks are generally low in salt-affected soil conditions. However, SOC enhances clays' flocculation and promotes bond formation with clay particles and polyvalent cations, leading to better aggregate stability[58,59].

Sodium is a monovalent cation with a high hydration radius that neutralizes free surface charges on colloids and inhibits flocculation and aggregation of soil particles. In neutral to alkaline soils dominated by lattice silicates, clay dispersion is strongly affected by exchangeable sodium and soil water composition[60]. Therefore, in soils with high ESP, variations in organic matter cause differences in clay dispersion[61], and organic matter, in the presence of Na, prevents clay dispersion and is more efficient in stabilizing aggregates[62].

According to Le Bissonnais[52], aggregates subjected to fast wetting undergo sudden immersing slakes due to the pressure of entrapped air, while slow wetting simulates cracking, and aggregates resist more to disruption. Thus, a reduced rate of water entry into aggregates allows air to escape and minimizes slaking[63]. Our study results show that applying 4% of organic matter increases MWD_{fast} (5.9- fold) more than MWD_{slow} (1.4- fold) in soil 1, and the slope (m) in MWD_{fast} function is higher (**Table 3**). Similarly, there is a difference between control and 4% rate of organic matter in MWD_{fast} (3.3- fold comparing with 1.9- fold in MWD_{slow}) in soil 2. These findings suggest that higher amounts of organic matter are needed to stabilize aggregates subjected to fast wetting, simulating sudden and strong rainfall or steep irrigation, than slow wetting, simulating light rainfall and droplet irrigation[46].

In general, SOM increases aggregate stability by lowering wetting and increasing cohesion. SOM may partially impart repellency to soil aggregates, contributing to their stability[64]. Chenu et al.[32] reported that after fast wetting of humic soils in southwest France, most of the initial aggregates remained in millimetric size classes for low organic C contents. However, for soils with high amounts of organic C, the aggregate mean size was larger. They also found that increased water stability of aggregates could be attributed to better resistance to slaking through increased hydrophobicity and cohesion of the aggregates with carbon contents. Resistance of aggregates to mechanical disruption after rewetting with ethanol (MWD_{stir}) is also related to SOM contents. This implies that organic matter increases internal cohesion of aggregates, increasing resistance to slaking and differential swelling of clays[32].

When comparing the effects of two different types of organic matter on collective stability, wheat straw performs better than cow manure (**Table 2**). There are two reasons for this, both of which are related to the unique features of organic matter. Firstly, the amount of organic carbon affects the effectiveness of organic matters on aggregate stability. **Table 5** shows that wheat straw (45.0%) has a higher organic carbon content than cow manure (26.8%). Furthermore, cellulose, a slow-decomposing substance, makes up the majority of organic carbon in wheat straw, whereas easily decomposable substances such as glucose make up the majority of organic carbon in cow manure. As a result, cow manure has the greatest impact during the first few weeks following application, whereas wheat straw has the greatest impact after several months[14]. Secondly, the Na/Ca+Mg ratio in wheat straw is relatively low (0.05) compared to cow manure (1.13), and as sodium is a dispersive cation, it influences the rate of soil particle flocculation (**Table 5**).

Linear and exponential equations were both used to establish a suitable function between mechanical resistance and organic matter content, and **Table 3** shows that the exponential equation revealed a higher significant association (r^2 = 0.997, P = 0.001 in soil 1 and r^2 = 0.995, P = 0.002 in soil 2) between modulus of rupture and organic matter content, with a declining trend in two soils (r^2 = 0.997, P = 0.001 and r^2 = 0.995, P = 0.002 in soil 2). When the two equations were tested using penetrometer resistance, the exponential was more significant in soil 1 (r^2 = 0.958, P = 0.021). According to this claim, clay has a tendency to scatter in low-stable aggregates, which leads to macro and micro pores collapsing and producing high soil strength (a tough and hard clod) when the soil is dry. Increasing the amount of organic matter in the soil makes the aggregates more stable, reducing the amount of clay dispersion and crust development. Studies have shown that the application of green waste is significant for improving physicochemical properties because the surface layer is more receptive to the direct input of fresh organic matter[65–68]. Lado et al.[69] also observed that the low OM-soil developed a thicker, higher density crust than the high OM-soil.

Table 5. Characteristics of selected properties of two organic matter amendments.

Properties	**Cow manure**	**Wheat straw**
pH 1:5 (H_2O)	8.67	5.84
EC 1:5 (dS m^{-1})[1]	7.2	8.3
O.C (%)[2]	26.8	45.0
Total N (%)[3]	1.75	0.32
C/N ratio[4]	15.3	140.6
Sodium (meq lit^{-1})	34.0	8.7
Calcium (meq lit^{-1})	19.0	101.3
Magnesium (meq lit^{-1})	11.0	63.5
Na/Ca+Mg	1.13	0.05

1: Electrical conductivity; 2: organic carbon; 3: nitrogen; 4: carbon/nitrogen.

It is necessary for multivalent cations to form bridges in order to prevent clay dispersion and ionic bonding between organic matter, which has a net negative charge, and negatively charged clay particles[70,71]. According to **Table 5**, wheat straw is more effective at forming aggregates and less effective at dispersing, which reduces the strength of the soil's ability to rupture and penetrate. It also has a lower Na/Ca+Mg ratio than cow manure. Similarly, others have found that in natural soils, the sensitivity of dispersion and mechanical resistance to sodicity were negatively correlated with organic matter content[17,72–74].

Surface sealing has a significant impact on soil detachment, sediment transport, and deposition processes in many erodible soils[75,76]. One way to predict the severity of surface sealing is to use aggregate stability indices because surface sealing results from aggregate breakdown, erosional transport, and depositional processes[77]. Agassi et al.[78] proposed that the process of forming a seal and crust involves two main steps: (i) breaking down the aggregates and dispersing clay at the soil surface, and (ii) rearranging these detached particles into a seal layer by migrating through and clogging the inter-aggregate pores.

In this study, a negative correlation was found between soil mechanical resistance, measured as the modulus of rupture and penetration resistance, and aggregate stability, evaluated using conventional and Le Bissonnais methods. Weak aggregates slake with soil soaking, while stable aggregates remain intact. Unstable aggregates break up and fill the spaces between them, creating a seal. Clays can bind particles together to form crusts, which enhance the endurance of the crusted layer[43]. The durability of the aggregates against slaking determines the hardness of the resulting crust. Slaking occurs when the aggregate is exposed to stresses produced by differential swelling, entrapped air explosion, rapid release of heat during wetting, and the mechanical action of moving water[61,79].

According to Le Bissonnais[52], the amount of trapped air, the pace of wetting, and the shear strength of wet aggregates all affect the effect of trapped air. High stable aggregates do not surrender their inter-aggregate pores, so the formed crust can easily break during weak tracks, even though low stable aggregates have an integrated crust with insufficiently few delicate zones to rupture it. Lado et al.[69] found that high organic matter content in the soil served as a cement to hold the aggregate's particles together against disruptive forces during the wetting process, whereas the low-organic matter concentration in the low-OM soil was too low to prevent the dissolution of the aggregate.

The mechanical breakdown, represented by MWD_{stir}, showed the highest correlation coefficient with mechanical resistance in all three treatments, with a negative correlation coefficient of −0.94** for both soils. In soil 1, the penetrometer resistance showed similar results, and MWD_{stir} had the most correlation with it. The trend was as follows: MWD_{stir} > MWD_{fast} > MWD_{slow} (**Table 6**). Two methods of determining soil mechanical resistance showed a high positive correlation with each other (**Table 6**). As a result, the penetrometer resistance can be substituted for modulus of rupture measurement because it is easier and quicker. Finally, it was found that the usual method of aggregate stability showed the most significant correlation coefficient with mechanical breakdown (MWD_{stir}). This may be due to the same pretreatment of wetting aggregates in these two methods, which test the mechanical cohesion of aggregates independently of slaking by removing air from inside the aggregates.

Table 6. Pearson's correlation coefficients (r) between soil aggregate stability and mechanical resistance.

	Soil	**MWD**	**MWD_{slow}**	**MWD_{fast}**	**MWD_{stir}**	**M.R**	**P.R**
MWD	1	1	0.78^{**}	0.81^{**}	0.93^{**}	-0.96^{**}	-0.81^{**}
	2	1	0.72^{**}	0.67^{*}	0.70^{**}	-0.81^{**}	-0.57^{*}
MWD_{slow}	1		1	0.81^{**}	0.87^{**}	-0.81^{**}	-0.81^{**}
	2		1	0.76^{**}	0.85^{**}	-0.88^{**}	-0.73^{**}
MWD_{fast}	1			1	0.85^{**}	-0.85^{**}	-0.84^{**}
	2			1	0.96^{**}	-0.92^{**}	$-0.44^{n.s}$
MWD_{stir}	1				1	-0.94^{**}	-0.87^{**}
	2				1	-0.94^{**}	-0.58^{*}
M.R	1					1	0.83^{**}
	2					1	0.64^{**}
P.R	1						1
	2						1

$^{n.s}$ $P > 0.05$; $^{*}P < 0.05$; $^{**}P < 0.01$.

6. Conclusion

According to the study's findings, aggregate stability generally increases linearly as the amount of organic matter increases, whereas mechanical resistance reduces exponentially as contact points between soil particles decrease. When soil particles are fused together into aggregate units, the resulting cracks in the soil allow for less forceful root penetration and seedling germination. Additionally, it was discovered that soil with higher sodicity had worse aggregate stability than soil with lower ESP. Wheat straw is more effective than cow manure because it has a higher organic carbon content and a lower Na/Ca+Mg ratio. Therefore, to improve soil aggregate stability, it would be preferable to apply plant waste rather than animal dung. By evaluating the effect of organic matter on aggregate stability, it was determined that higher rates of O.M are likely needed to stabilize aggregates that are subjected to fast wetting. The modulus of rupture (M.R) and penetrometer resistance (P.R) decreased with the addition of organic matter, and wheat straw had a greater percentage of decreasing effect. Low stable aggregates have an integrated crust with not enough tender zones to rupture, whereas high stable aggregates don't sacrifice their inter-aggregate pores, so the resulting crust ruptures easily during weak tracks. This relationship fits an exponential curve. All methods of aggregate stability negatively correlated with M.R and P.R, which may indicate that soils that are more stable against external mechanical forces are not as stable against slaking due to wetting.

7. Highlights

1) Aggregate stability increases linearly with organic matter content and decreases exponentially as contact points decrease.

2) Fused soil particles create cracks that hinder root penetration and seedling germination.

3) Higher sodicity results in worse aggregate stability than lower ESP.

4) Wheat straw is more effective than cow manure for improving soil aggregate stability.

5) Higher rates of organic matter are needed to stabilize aggregates subjected to fast wetting.

6) Wheat straw has a greater percentage of decreasing effect on modulus of rupture and penetrometer resistance.

7) Low stable aggregates have an integrated crust, whereas high stable aggregates don't sacrifice inter-aggregate pores.

8) All methods of aggregate stability negatively correlate with modulus of rupture and penetrometer resistance, indicating that more stable soils are not as stable against slaking due to wetting.

Author contributions

Conceptualization, FR and SA; methodology, EM; software, EM; validation, FR, EM and SA; formal analysis, EM; investigation, FR, and EM; resources, EM; data curation, FR, and SA; writing—original draft preparation, EM; writing—review and editing, FR; visualization, FR; supervision, FR; project administration, FR, SA; funding acquisition, FR, SA. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

Abbreviations

MWD_{slow}, mean weight diameter of slow wetting;

MWD_{fast}, mean weight diameter of fast wetting;

MWD_{stir}, mean weight diameter of stirring after pre-wetting;

M.R, modulus or rupture;

P.R, penetrometer resistance.

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