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Interaction force mechanism for the improvement of reclaimed soil aggregate stability in abandoned homestead by different organic-inorganic soil conditioners

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Reasonable application of organic-inorganic soil conditioners can effectively improve the structure and fertility of reclaimed soil in abandoned homestead. Aggregate stability is an important indicator to evaluate soil structure and fertility, and is largely influenced by soil internal forces (van der Waals attractive force, electrostatic repulsive force, hydration repulsive force) and particle surface properties. However, there are few studies on the influence of different soil conditioners on the reclaimed soil internal forces and its relationship with the aggregate stability. Therefore, we selected six different treatments of organic fertilizer (TO), fly ash (TF), maturing agent (TM), maturing agent + organic fertilizer (TMO), fly ash + organic fertilizer (TFO) and control (CK) to conduct a 5-year field experiment to study the effects of reclaimed soil particle interaction forces and surface characteristics on aggregate stability under the treatment of different soil conditioners. The results showed that with the application of soil conditioners, the soil organic matter (SOM), specific surface area (SSA), surface charge (σ_0), cation exchange capacity (CEC), aggregate mean weight diameter (MWD) and Hamaker constant increased gradually, while the pH value decreased slightly. In particular, the MWD under the treatments of TFO and TMO increased by 150.3% and 65.6% respectively compared with that under the CK treatment. With the increasing application of soil conditioners, the electrostatic repulsive force and van der Waals attractive force between reclaimed soil particles increased constantly, but the net resultant force between particles decreased and the net attractive force increased continuously, thus improving the aggregate stability. Therefore, there is a significant negative correlation between the net resultant force among reclaimed soil particles and MWD and CEC. In addition, 10^{-2} mol L^{-1} is the critical concentration that affects the reclaimed soil internal force, and the organic-inorganic treatments of TFO and TMO can improve the net resultant force better. In a word, the particle interaction forces are important factors affecting the reclaimed soil structural stability, and this study provides a scientific reference for the rational selection of soil conditioners and its interaction force mechanism in the reclaimed soil improvement.

KEYWORDS

soil particle interaction forces, organic-inorganic soil conditioners, particle surface charge, soil aggregate stability, soil organic matter, van der Waals attractive force

1 Introduction

Good soil aggregates play an important role in regulating soil properties and maintaining soil fertility and eco-environmental function, which is conducive not only to the efficient use of water and fertilizer and crop growth, but also to the enhancement of soil erosion resistance and carbon sequestration capacity. Its stability is closely related to many soil properties and eco-environment, and it is of utmost importance for the healthy and sustainable soil development and eco-environmental protection (Abiven et al., 2007; Bandyopadhyay and Lal, 2014; Wang et al., 2017; Li et al., 2018). Contrarily, poor soil structure will not only reduce the water and fertilizer use efficiency, affect crop yield, but also aggravate the risk of soil degradation and soil erosion and undermine the healthy and sustainable soil development (Blanco-Canqui and Lal, 2004; Vaezi, et al., 2017; Rabot et al., 2018; Ayoubi et al., 2020). Therefore, the study on improvement of the soil aggregate structural stability and function has always been one of the important topics in the soil management research field.

The number of charges per square centimeter on the soil colloidal particle surface can reach 1,014–1,015, forming a strong electric field of 10^8~10^9 V m^{-1} around the colloid, which can generate an interaction force of 10–1,000 MPa between soil particles. Such a strong electric field and force will have a great impact on the soil structural stability (Li et al., 2013; Hu, et al., 2015; Li and Yang, 2017). The recent research results have shown that the soil internal forces on the microscopic scale include electrostatic repulsive force, hydration repulsive force and van der Waals attractive force, and the intensity of action can be as high as hundreds to thousands of the standard atmosphere pressure, which is the main internal force leading to the soil structural fragmentation and stability, and plays a vital role in the macroscopic process of soil structure stability, water and fertilizer conservation and agricultural non-point source pollution migration (Yu et al., 2020; Hu, et al., 2021). The particle interaction forces are influenced by the soil particle surface electrochemical properties, including surface charge quantity, specific surface area, cation exchange capacity and other indicators. Therefore, measures to change the microscopic particle surface properties will cause variations in the soil internal force and structural stability, which will have significant impacts on many physical, chemical and biological processes on and around the soil particle surface (Hu et al., 2018a; Hu, et al., 2021).

Due to the acceleration of urbanization and industrialization, the Loess Plateau is facing practical problems such as rural hollowing, homestead waste and cultivated land resources reduction, which seriously threatens the quantity and quality of regional cultivated land resources and becomes the main bottleneck to food security and rural revitalization in the Loess Plateau (Huang and Wang, 2010; Liu, et al., 2018; Long and Qu, 2018). Therefore, it is of great strategic significance to further the comprehensive improvement of Hollow Village in Loess Plateau and speed up the land reclamation and fertility improvement of abandoned homestead for improving the cultivated land quality in Loess Plateau, ensuring regional food security and promoting rural revitalization (Liu, et al., 2016; Long, et al., 2019). However, most of the abandoned homestead soil comes from the old wall soil (raw soil) after the demolition of the old houses, with seriously damaged soil physical structure, low nutrient content, and loss of original soil functions and properties, which seriously limits the productivity and utilization of reclaimed soil and affects the crop yield and quality. Thus, it is urgent to improve the reclaimed soil structure, soil fertility and grain production capacity, so as to facilitate the rural revitalization and food security strategy (Liu et al., 2019b; Lei, et al., 2019).

Long-term single application of chemical fertilizer led to the imbalance of soil organic matter and available nutrients, increased soil bulk density and decreased aggregate quantity and structural stability, which hindered the improvement of soil structure and quality (Verchot et al., 2011; Liu et al., 2019a). The combined application of organic and inorganic soil conditioners can not only increase the content of soil organic matter, improve the aggregate quantity and stability and enhance the soil structural properties and the soil fertility, but also reduce the environmental pollution caused by unreasonable use of soil conditioners, which is of great significance for improving soil quality and promoting the healthy development of environment (Fonte, et al., 2009; Liang, et al., 2012). Moghal et al. have showed that calcium salts such as $Ca(OH)_2$, $CaCO_3$, and $CaCl_2$ can regulate the lime leachability and improve soil porosity and structure, among which $Ca(OH)_2$ is an effective stabilizer (Moghal and Sivapullaiah, 2012; Moghal, et al., 2020). Lei et al. has found that soil conditioners such as organic fertilizer, fly ash and maturing agent play an important role in improving the reclaimed soil structure and fertility of abandoned homestead in Loess Plateau, the reasonable application of which can not only enhance the adsorption and agglomeration capacity between soil particles, increase the aggregate quantity and quality and improve the soil structure, but also enhance the soil's water and fertilizer conservation and promote the healthy and sustainable development of abandoned homestead reclaimed soil (Moghal, 2017; Lei, et al., 2019; Liu, et al., 2022). The addition of fly ash can significantly increase the content of clay and silt particles, improve the adsorption and cementation between soil particles, and promote soil physical and chemical properties (Moghal and Sivapullaiah, 2011; Moghal, 2017). Especially, fly ash and chicken manure are commonly-used soil amendments and wastes, and such organic-inorganic combined application can improve soil productivity and save investment costs in land reclamation (Ram and Masto, 2014; Parab, et al., 2015; Liu, et al., 2022). At present, the studies on soil amelioration by different soil conditioners mainly focus on soil fertility, aggregate quantity, pore characteristics and water retention, but the variation in these properties will inevitably lead to changes in the surface properties and interaction forces of reclaimed soil particles, which will in turn affect a series of soil structural changes and hydrological processes such as soil aggregate stability, nutrient adsorption capacity and soil moisture infiltration (Li, et al., 2013; Hu et al., 2018b). However, there is not enough focus on how different soil conditioners affect the reclaimed soil internal forces, with a lack of systematic understanding of the mechanism of the impact of surface properties and interaction force between particles on the improvement of reclaimed soil structural stability and fertility, and the essential relationships between various micro-processes and macro-phenomena of reclaimed soil neglected. Therefore, taking the reclaimed soil of Hollow Village in Loess Plateau treated with different soil conditioners as the research object, and from the perspective of surface properties and interaction forces between soil particle on the micro scale, this paper quantitatively studies the change characteristics of reclaimed soil surface properties, electrostatic repulsive force, van der Waals attractive force and hydration repulsive force under the treatment of different soil conditioners, and explores the microscopic internal force mechanism of macroscopic soil aggregate stability, so as to screen out suitable reclaimed soil conditioners for abandoned homestead and provide scientific basis for the improvement of reclaimed soil structure and quality in Hollow Village.

2 Materials and methods

2.1 Study area

The experimental plot of reclamation soil improvement in Hollow Village is located in Fuping County, Weinan City, Shaanxi Province (34°42′N, 109°12′E) with the background of comprehensive land improvement of abandoned homestead in Hollow Village, mainly aiming at improving the reclaimed soil structure and fertility. The study area belongs to Weibei Loess Plateau, with an average annual temperature of 13.3°C, an average annual precipitation of 513.5 mm and an annual total solar radiation of 135.44 kcal/cm^2, which can meet the basic growth condition for crops. The experimental plot was completed in June 2015, and the reclaimed soil was from backfilling of the old wall soil of abandoned homestead in Hollow Village, with a backfill depth of 30 cm. After removal of the impurities such as rubble and stones in the old wall soil, the reclaimed soil was improved in structure and fertility by applying soil conditioners to enhance the food crops production capacity. The reclaimed soil was mainly developed from loess parent material. At the beginning of the experiment, the surface soil pH value (water-soil mass ratio of 1: 2.5) was 8.5, and the soil texture was silty loam (USDA texture classification), in which clay (<0.002 mm) content was 10.15%, silt (0.05–0.002 mm) content 77.82%, sand (0.05–2 mm) content 12.65%, organic matter content 4.5 g kg^{-1}, soil total nitrogen content 0.16 g kg^{-1}, available phosphorus content 3.1 mg kg^{-1}, rapidly available potassium content 61.4 mg kg^{-1}, soil bulk density 1.40 g cm^{-3}, and the proportion of water-stable aggregates with particle size less than 0.25 mm 93.27%. The overall structure and fertility of reclaimed soil were poor.

2.2 Experiment design

The reclaimed soil remediation experiment began in June 2015. The amount of soil conditioners applied in this study was based on the conditioner properties and published reference research results, in which such amount is commonly used (Lei, et al., 2019; Gao, et al., 2021). The contents of environmental pollution indicators As, Hg, Cu, Pb, Zn and Cd in the fly ash were 13.59, 0.10, 91.6, 22.72, 57.81, and 0.06 mg kg^{-1} respectively (Wang, et al., 2019), all of which met the Environmental Quality Standards for Soils (GB15618-2008, China). This is similar to the heavy metal contents in the fly ash studied by Sivapulliah et al., which indicated that the leachability of heavy metals is primarily influenced by soil liquid-solid ratio, original concentration of heavy metals, pH, and particle cementation (Sivapullaiah and Moghal, 2010). The experiment adopted a random block design with six treatments of soil conditioners, namely, control treatment (CK, without soil conditioners), maturing agent, ferrous sulfate (TM), fly ash (TF), organic fertilizer, chicken manure (TO), maturing agent + organic fertilizer (TMO) and fly ash + organic fertilizer (TFO), with three replicates for each treatment. In order to avoid mutual influence, an 80 cm-wide isolation belt was set between each treatment. The grain crops planting system was a 2-year triple cropping one with a winter wheat-summer maize rotation. The summer maize for the test was sown in early June with 65,000 plants per hectare and harvested in early October. The maize variety was Xianyu 335. Before planting crops, the soil conditioners of different treatments were evenly mixed into reclaimed raw soil, and the soil conditioners were applied for each treatment at one time, with 1,500 kg ha^{-1} compound fertilizer applied. The concentrations of the compound fertilizer were nitrogen, phosphorus and potassium at 15%, 10% and 20% respectively, and the daily management measures such as irrigation, fertilization and pest control were the same for the six treatments. The detailed experiment treatment and soil conditioners application are shown in Table 1.

2.3 Determination of physicochemical properties and surface charge properties of reclaimed soil

After the harvest of summer maize in early October of 2020, the surface physical and chemical samples of reclaimed soil at depth of 0–20 cm and undisturbed soil samples were collected according to the experiment treatments, and three replicates were randomly made for each treatment of soil samples to analyze the effects of different soil conditioners on the reclaimed soil physical and chemical properties and surface electrochemical properties. After the soil samples were naturally air-dried indoors, impurities such as plant residual roots and gravel were removed, and the samples were then ground and sifted through 0.25 mm and 2 mm sieves. The content of soil organic matter was measured by $K_2Cr_2O_7$ heat capacity method (Jenkinson and Kalembasa, 1973), the pH by electrode method (soil and water mass ratio of 1:2.5) (Liu Z et al., 2021), and the mean weight diameter (MWD), an index for soil water-stable aggregate distribution and structural stability, measured and calculated by wet sieving method (Six et al., 2004; Liu et al., 2022).

The soil surface electrochemical properties, such as specific surface area (*SSA*, m^2 g^{-1}), surface charge density (σ_0, C m^{-2}) and cation exchange capacity (CEC, cmol kg^{-1}), were determined and calculated by the conjoint determination method of material surface properties established by Li et al. (2011). The specific steps are as follows. Firstly, six kinds of 0.25 mm 200 g soil samples with

TABLE 1 Experimental treatments of organic-inorganic soil conditioners for the remediation of reclaimed soil in abandoned homestead of Loess Plateau.

Number	Treatments	Organic-inorganic soil conditioners	Application rates
1	CK	Control	0
2	TM	Maturing agent (ferrous sulfate)	0.6 $t{\cdot}ha^{-1}$
3	TF	Fly ash	45 $t{\cdot}ha^{-1}$
4	TO	Organic fertilizer (chicken manure)	30 $t{\cdot}ha^{-1}$
5	TMO	Maturing agent + organic fertilizer	(0.6 + 30) $t{\cdot}ha^{-1}$
6	TFO	Fly ash + organic fertilizer	(45 + 30) $t{\cdot}ha^{-1}$

different treatments were respectively weighed and put into a 1 L beaker, and 0.6 L 0.5 mol L^{-1} hydrochloric acid solution was added, the mixture of which was repeatedly stirred until the calcium carbonate in the soil samples was completely removed. Then, 0.6 L of 0.1 mol L^{-1} HCl solution was added and stirred for 5 h, with the supernatant removed by centrifugation. The above shaking and centrifugation were repeated for 3 times, and the soil samples were dried at 65°C and ground and sifted through a 2 mm sieve to obtain hydrogen-saturated soil samples with different treatments. Third, 5–10 g of hydrogen-saturated sample was weighed and put into a 100 mL centrifuge tube, 40 mL of mixed solution of NaOH and $Ca(OH)_2$ of 0.01 mol L^{-1} was added, the pH of the mixed solution was adjusted to about 7.0 with 1 mol L^{-1} HCl after being shaken for 24 h, and the concentration of Na^+ and Ca^{2+} in the mixed solution was measured with atomic absorption spectrometer, with the measurement of each treated soil sample repeated for three times. Finally, The surface electrochemical properties of reclaimed soil were calculated by following Eqs (1)–(5) with the above experimental measured data (Li et al., 2011; Liu et al., 2021a).

$$\varphi_0 = \frac{2RT}{(2\beta_{Ca} - \beta_{Na})F}\ln\frac{a^0_{Ca}N_{Ca}}{a^0_{Ca}N_{Ca}} \tag{1}$$

$$\sigma_0 = \mathrm{sgn}(\varphi_0)\sqrt{\frac{\varepsilon RT}{2\pi}\left[a^0_{Na}\left(e^{\frac{\beta_{Na}F\varphi_0}{RT}}-1\right)+a^0_{Ca}\left(e^{\frac{2\beta_{Ca}F\varphi_0}{RT}}-1\right)+\left(a^0_{Na}+2a^0_{Ca}\right)\left(e^{\frac{F\varphi_0}{RT}}-1\right)\right]} \tag{2}$$

$$SSA = \frac{N_{Na}k}{ma^0_{N\alpha}}e^{\frac{\beta_{Na}F\varphi_0}{2RT}} = \frac{N_{Ca}k}{ma^0_{Ca}}e^{\frac{2\beta_{Ca}F\varphi_0}{RT}} \times 10^{-2} \tag{3}$$

$$CEC = 10^5\frac{SSA\sigma_0}{F} \tag{4}$$

$$m = 0.5259\ln\left(\frac{c^0_{Na}+c^0_H}{c^0_{Ca}}\right) + 1.992 \tag{5}$$

Where φ_0 (mV) is the surface potential; σ_0 (C m^{-2}) is the surface charge density; *SSA* (m^2 g^{-1}) is the specific surface area; *SCN* (cmolkg^{-1}) is the surface charge number; *R* (J K^{-1} mol^{-1}) is the universal gas constant; *T* (K) is the absolute temperature; *F* (C mol^{-1}) is the Faraday constant; *Z* is cation valence; β_{Na} and β_{Ca} are the corresponding modification factors of *Z* for Na^+ and Ca^{2+}, respectively; ε is the dielectric constant for water (8.9×10^{-9} C^2 J^{-1} dm^{-1}); $\beta_{Na} = 0.0213\ln(I^{0.5}) + 0.7669$, $\beta_{Ca} = -0.0213\ln(I^{0.5}) + 1.2331$; N_i (mol g^{-1}) is the total number of the cation (i = Ca^{2+}, Na^+) adsorbed on the soil particle surface; κ (dm^{-1}) is the Debye–Hückel parameter; *I* (mol L^{-1}) is the ionic strength; κ = $(4\pi F^2\sum ?_?^2 \alpha_?^0/\varepsilon RT)^{1/2}$; and c^0_{Na} (mol L^{-1}), c^0_{ca} (mol L^{-1}) and c^0_H (mol L^{-1}) are equilibrium Na^+, Ca^{2+}, and H^+ concentrations in the bulk solution, respectively.

2.4 Calculation of reclaimed soil particle interaction forces

The reclaimed soil particle interaction forces include electrostatic repulsive force, van der Waals attractive force and hydration repulsive force, and the net resultant force (P_{net}) of soil internal forces is the sum of electrostatic repulsive force pressure (P_E), hydration repulsive force (P_{hyd}) and van der Waals attractive force (P_{vdW}). The reclaimed soil particle interaction force and net resultant force were calculated according to Eqs (6)–(10) based on the calculation results of parameters indicating electrochemical properties such as soil specific surface area and surface charge density (Li et al., 2013; Liu et al., 2021a; Hu et al., 2021).

$$P_E = \frac{2}{101}RTc_0\left\{\cosh\left[\frac{Z_iF\varphi(d/2)}{RT}\right]-1\right\} \tag{6}$$

$$P_{hyd} = 3.33\times10^4 exp^{-5.76\times10^9 d} \tag{7}$$

$$\theta_m = -\rho_w SSA\left(3\sqrt{\frac{A_{eff}}{6\pi\rho_w g\psi}}\right)\times 1000 \tag{8}$$

$$P_{vdW} = -\frac{A_{eff}}{0.6\pi}(10d)^{-3} \tag{9}$$

$$P_{net} = P_E + P_{hyd} + P_{vdW} \tag{10}$$

Where A_{eff} (J) is an effective Hamaker constant which was estimated by analyzing the dry end of the soil water characteristic curves with a dew point potentiometer. θ_m is the gravimetric water content (kg kg^{-1}), ρ_w is the density of water (kg m^{-3}), g is acceleration due to gravity (m s^{-2}), ψ is the matric potential head (m H_2O), Z_i is cation valence, *d* (dm) is the distance between two adjacent particles; φ(d/2) (V) is the potential at the middle of the overlap of the electric double layers of two adjacent particles.

2.5 Statistical analysis

Data statistics and analysis were performed using Microsoft Excel 2010 and SPSS25.0. Figure generation was performed using Origin software. Differences among different treatments were evaluated using one-way analysis of variance (ANOVA), and the least significant range (LSD) method was used for testing the signifcance in soil surface properties of reclaimed soil ($p < 0.05$).

TABLE 2 The surface properties of reclaimed soil under different soil conditioner application.

Treatment	SOM ($g{\cdot}kg^{-1}$)	*SSA* ($m^2{\cdot}g^{-1}$)	σ_0 ($C{\cdot}m^{-2}$)	CEC (cmol kg^{-1})	MWD (mm)	pH
CK	5.94 ± 0.17c	10.22 ± 0.02d	0.83 ± 0.03d	13.90 ± 0.25c	0.32 ± 0.03d	8.66 ± 0.03a
TO	11.36 ± 0.37b	12.90 ± 1.94bc	1.26 ± 0.06b	16.91 ± 0.46b	0.45 ± 0.02c	8.53 ± 0.05b
TF	10.97 ± 0.56b	11.83 ± 0.28bc	1.25 ± 0.03b	15.38 ± 0.26c	0.38 ± 0.02c	8.52 ± 0.05b
TM	6.64 ± 0.05c	11.36 ± 0.31cd	1.14 ± 0.07c	14.34 ± 0.18c	0.32 ± 0.02d	8.38 ± 0.04c
TFO	13.89 ± 0.78a	14.05 ± 0.23a	1.46 ± 0.05a	18.67 ± 0.36a	0.80 ± 0.06a	8.27 ± 0.11cd
TMO	13.08 ± 1.06a	13.25 ± 0.46 ab	1.44 ± 0.03a	17.40 ± 0.23b	0.53 ± 0.05b	8.18 ± 0.07d

SOM: soil organic matter; *SSA*: specific surface area; σ_0: surface charge density; CEC: cation exchange capacity; MWD: mean weight diameter. Different lowercase letters represent significant differences among different soil conditioner treatments in the same index ($p < 0.05$).

3 Results and analysis

3.1 Effects of different organic-inorganic soil conditioners on reclaimed soil properties

After 5 years of application of different soil conditioners, the reclaimed soil properties in abandoned homestead had changed obviously. As can be seen from Table 2, the reclaimed soil was generally weakly alkaline, and a decreasing trend could be seen in the pH value after 5 years of application. With the use of different soil conditioners, the organic matter content of reclaimed soil showed a significant increase ($p < 0.05$), and the organic matter content increased from 5.94 g kg^{-1} to 13.89 g kg^{-1}. The organic-inorganic treatments of TFO and TMO had a better improvement effect on soil organic matter. Similar to the organic matter change, the specific surface area (SSA), surface charge density (σ_0), CEC and MWD also increased continuously. The specific surface area of reclaimed soil under TO, TF, TM, TFO, and TMO treatments increased by 26.2%, 15.8%, 11.2%, 37.5%, and 29.6% respectively compared with that under the CK, and the CEC value by 21.7%, 10.6%, 3.2%, 34.3%, and 25.2% respectively compared with that under the CK, indicating that the soil absorption of ions was on the rise, among which the TFO treatment recorded the largest increase. With the increase of soil organic matter content, the MWD under TFO and TMO treatments increased by 150.3% and 65.6% respectively compared with that under the CK, demonstrating that the reclaimed soil particle aggregation and structural stability were significantly improved.

3.2 Effects of different organic-inorganic soil conditioners on electrostatic repulsive pressure between reclaimed soil particles

The distribution of electrostatic repulsive force between reclaimed soil particles under the treatments of different soil conditioners is shown in Figure 1, according to which, the electrostatic repulsive force between soil particles decreased sharply with the increase of the distance between two particles, and increased continuously with the decrease of the soil electrolyte solution concentration. The electrolyte concentration of 10^{-2} mol L^{-1} was the critical concentration for the drastic change of electrostatic repulsive force between reclaimed soil particles. When the concentration of soil electrolyte decreased from 1 mol L^{-1} to 10^{-2} mol L^{-1}, the electrostatic repulsive force between soil particles increased sharply. When the concentration of soil electrolyte was less than 10^{-2} mol L^{-1}, the electrostatic repulsive force between soil particles changed relatively slowly and gradually tended to be stable. Under a certain concentration of electrolyte solution and distance between particles, the overall trend of electrostatic repulsive force between particles in reclaimed soil treated with different soil conditioners showed the order of TFO > TMO > TO > TF > TM > CK.

In order to further clarify the influence of different soil conditioners on the change of electrostatic repulsive force, we drew the relationship between electrostatic repulsive force and electrolyte concentration at the distance of 1.5 and 2 nm between reclaimed soil particles under different treatments (Figure 2). When the concentration of electrolyte solution was 1 mol L^{-1}, the electrostatic repulsive force at the distance of 2 nm between reclaimed soil particles under TFO, TMO, TFO, TF, TM and CK treatments was 1.59, 1.54, 1.52, 1.51, 1.47, and 1.36 atm, respectively. With the incorporation of soil conditioners, the reclaimed soil electrostatic repulsive force increased slightly. For reclaimed soil samples treated with six different soil conditioners, the decreases of the distance between soil particles and electrolyte solution concentration would lead to the increase of electrostatic repulsive force. Similarly, when the electrolyte concentration decreased from 1 mol L^{-1} to 10^{-2} mol L^{-1}, the electrostatic repulsive force between adjacent particles in reclaimed soil would increase sharply with the decrease of electrolyte concentration, and when the electrolyte concentration decreased from 10^{-2} mol L^{-1} to 10^{-5} mol L^{-1}, the electrostatic repulsive force tended to be stable with the decrease of electrolyte concentration. This finding is similar to the research results of Hu et al., who depicted that the electrostatic repulsive pressure at 2 nm between the Loess soil particles increased with biochar application, which is mainly due to the increase of soil surface charge density and surface electric field after biochar incorporation (Xu et al., 2020; Hu, et al., 2021). Meanwhile, the electrolyte solution concentration of 10^{-2} mol L^{-1} is the key solution concentration that affects electrostatic repulsive pressure, and the electrostatic repulsion between particles increases with the decrease of bulk solution electrolyte concentration, which was also confirmed by previous literature research results (Hu, et al., 2018b; Ding, et al., 2019; Hu, et al., 2021). According to theoretical analysis, it should be that the greater the electrostatic repulsive force between soil particles is, the worse the stability of soil aggregates becomes. However, the

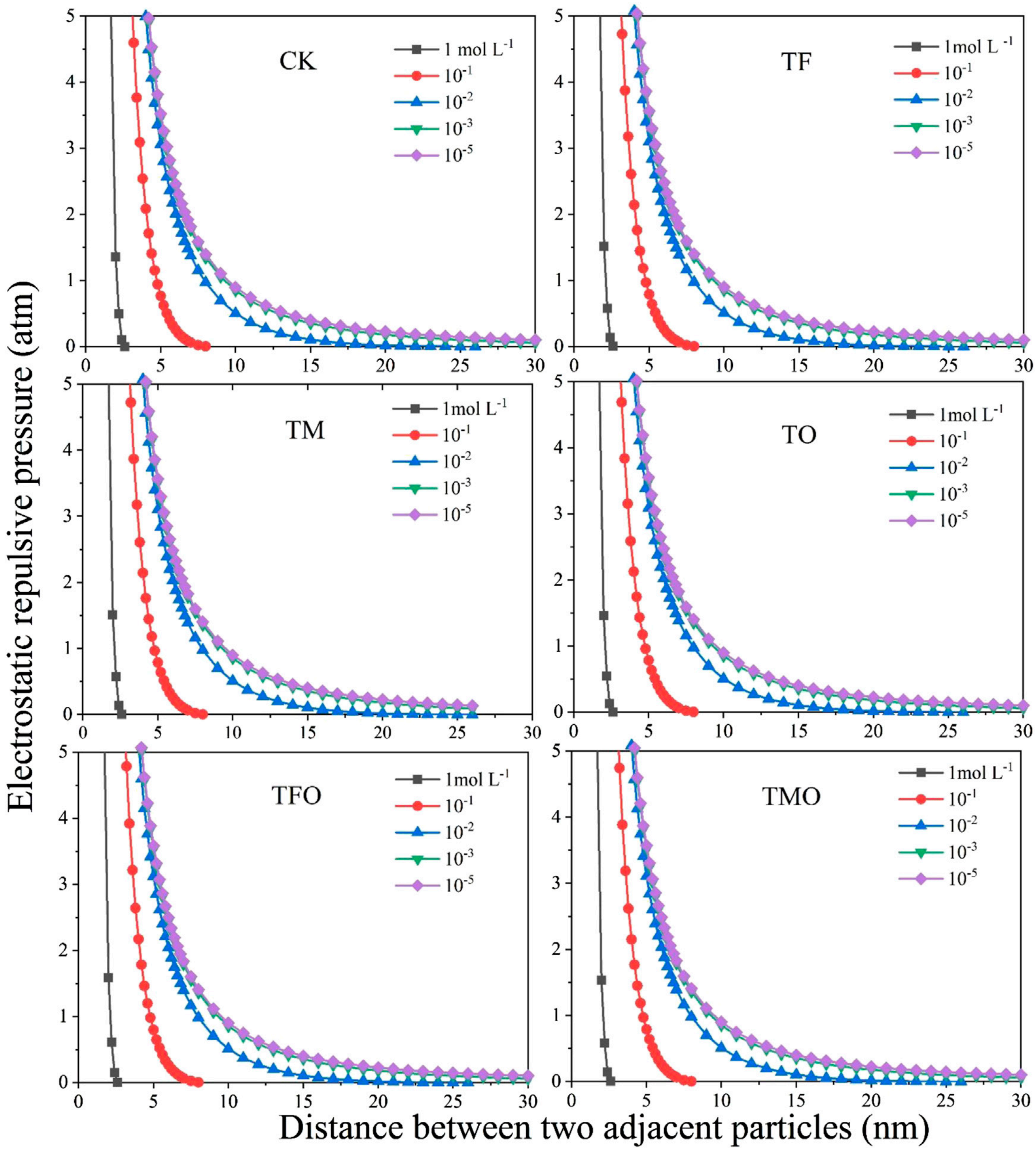

FIGURE 1
Distribution of electrostatic repulsive pressure (P_E) between reclaimed soil under the application of different soil conditioners.

stability of soil aggregates is not determined by electrostatic repulsive force alone, but the resultant force of internal forces. Therefore, we will further discuss the van der Waals attractive force and hydration repulsive force next.

3.3 Effects of different organic-inorganic soil conditioners on van der Waals attractive force and surface hydration repulsive force between reclaimed soil particles

To quantitatively analyze the van der Waals (*vdW*) attractive force among reclaimed soil particles, the fitting curve of the moisture content in the reclaimed soil weight and the matric potential under different treatments (Figure 3) was first obtained according to the method of Tuller et al. (Tuller and Or, 2005), and then the Hamaker constants (A_{eff}) under the treatments of TFO, TMO, TO, TF, TM and CK were calculated to be 9.53×10^{-20}, 5.75×10^{-20}, 4.62×10^{-20}, 3.48×10^{-20}, 3.40×10^{-20} and 2.45×10^{-20} J, respectively. In order to evaluate the influence of organic matter content on the Hamaker constant of soil, by comparison with the organic matter content shown in Table 1, we found that after the incorporation of different soil conditioners, the A_{eff} of reclaimed soil increased significantly while the soil organic matter (SOM) content increased.

After determination of the A_{eff} of reclaimed soil, the van der Waals attractive force and hydration repulsive force of reclaimed soil under

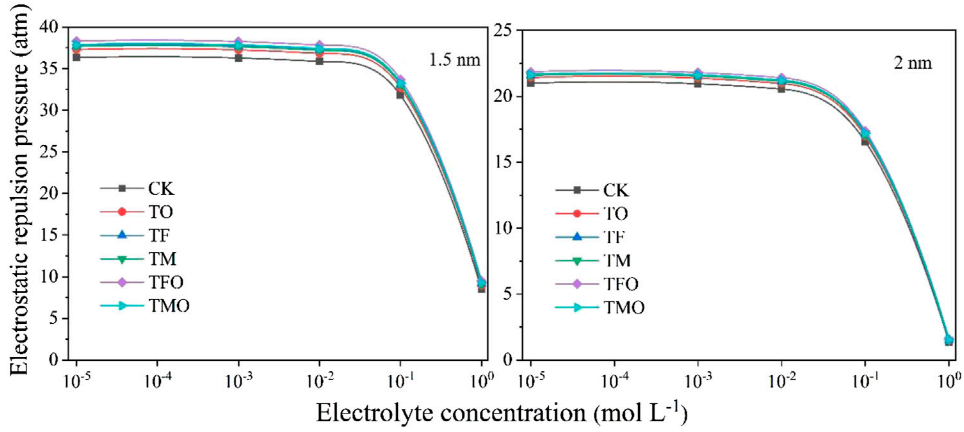

FIGURE 2
Electrostatic repulsive pressure at 2 nm and 1.5 nm between reclaimed soil particles under different soil conditioners.

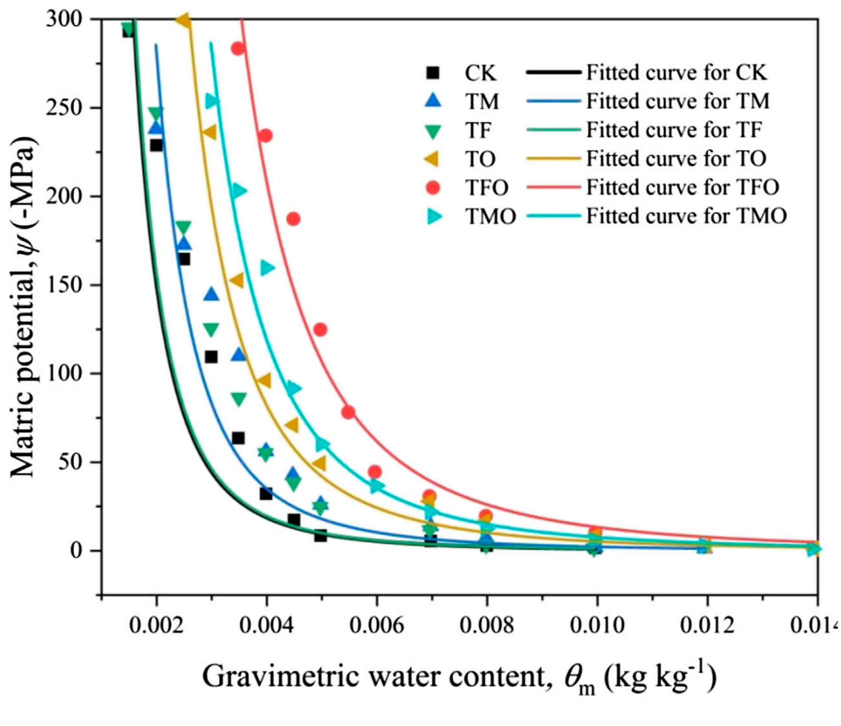

FIGURE 3
Plot of matric potential ψ (-MPa) against gravimetric water content θm (kg^{-1}) of reclaimed soil under the application of different soil conditioners. The dots are measured data and the lines are curves fittedaccording to Eq. 8.

different treatments when the concentration of electrolyte solution were 1 mol L^{-1} (Figure 4) were calculated according to Eqs 8, 9. The positive value in the figure represents a repulsive force between reclaimed soil, and the negative value represents an attractive force. With the application of different soil conditioners, the van der Waals attractive force among the reclaimed soil particles was on the rise, and the organic-inorganic coupling treatments of TFO and TMO had a better effect on increasing the van der Waals attractive force of soil (Figure 4). When the distance between adjacent soil particles was 2 nm, the van der Waals attractive forces of reclaimed soil under the treatments of TFO, TMO, TO, TF, TM, and CK were −6.32, −3.82, −3.07, −2.31, −2.25, and −1.62 atm, respectively, and the absolute values were 290.1%, 135.8%, 89.5%, 42.6%, and 38.9% higher than that under the treatment of CK, respectively. The van der Waals attractive force under the treatment of TFO was the largest, indicating that the soil structure was more stable. With the increase of the distance between soil particles, the hydration repulsive force decreased exponentially, with the hydration repulsive force at 2 nm

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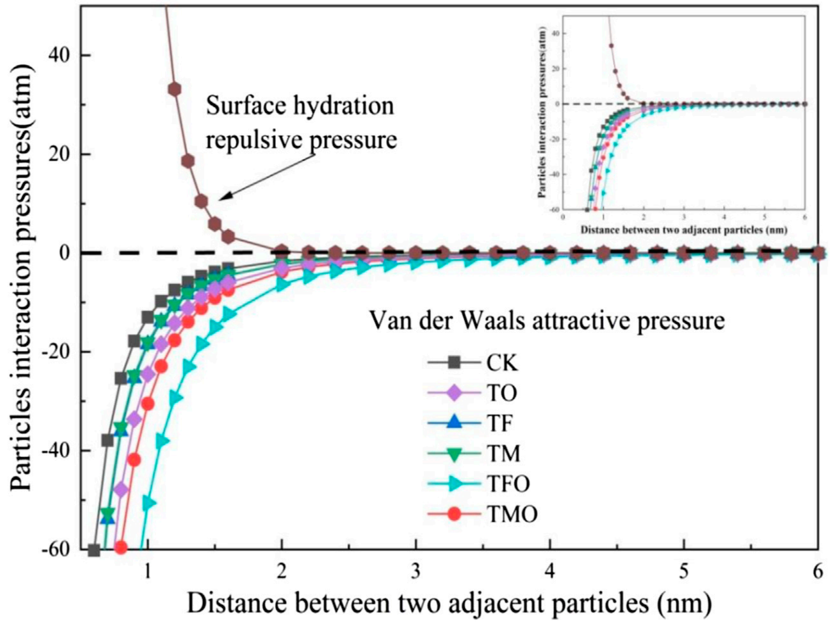

FIGURE 4
Distributions of van der Waals attractive pressure (P_{vdW}) and surface hydration repulsive pressure (P_{hyd}) between reclaimed soil particles under the application of different soil conditioners.

of 0.33 atm. In addition, when the distance between soil particles was or greater than 1.6 nm, van der Waals attractive force was larger than hydration repulsive force at the same distance, and an attractive force showed among soil particles; while the distance between soil particles was smaller than 1.6 nm, the difference between van der Waals attractive force and hydration repulsive force would increase sharply, and a repulsive force showed among soil particles. Therefore, when the dry soil suddenly went wet, the hydration repulsive force could always overcome the van der Waals attractive force within a certain range of soil particles, making the soil swell and break to some extent. By comparison of the van der Waals attractive forces under different treatments of soil conditioners, it was found that the van der Waals attractive forces under the six treatments showed the order as follows: TFO > TMO > TO > TF > TM > CK, indicating that the van der Waals attractive force of reclaimed soil increased with the rise of organic matter content after the application of soil conditioners. In particular, the capacity of organic soil conditioners to enhance the van der Waals attractive force among soil particles was better than that of inorganic soil conditioners, and the organic-inorganic coupling treatment had a better effect on improving the van der Waals attractive force of reclaimed soil.

3.4 Effects of different organic-inorganic soil conditioners on net pressure between reclaimed soil particles

Since the classical DLVO force is hard to explain the result that dry Na^+ saturated aggregates can still break and disperse in different concentrations of NaCl solution when the van der Waals attractive force is significantly greater than the electrostatic repulsive force, it is necessary to consider the influence of hydration repulsive force on the basis of the classical DLVO force between aggregate particles. In order to accurately assess the variation of net resultant force among soil particles, we have drawn the distribution diagram of the sum (net resultant force) of electrostatic repulsive force, van der Waals attractive force and hydration repulsive force among reclaimed soil particles (Figure 5), in which positive value represents repulsive force and negative value represents attractive force. In general, with the application of soil conditioners, the net resultant force between reclaimed soil particles is gradually decreasing, showing an attractive force. The results are consistent with that by Hu, et al. (2021); Yu et al. (2020); Calero et al. (2017), which showed that the incorporation of soil conditioners such as biochar, organic fertilizer and straw could largely enhance the van der Waals attractive force between soil particles, reduce the net pressure and weaken the adverse effect of electrostatic repulsive force on soil aggregates, thus increasing the attractive force between soil particles and improving soil structural stability (Calero, et al., 2017; Yu, et al., 2020; Hu, et al., 2021.). When the concentration of electrolyte solution was 10^0 mol L^{-1}, the net resultant forces between soil particles at the distance of 2 nm under the treatments of TFO, TMO, TO, TF and TM all showed an attractive force except under the CK, which were −4.46, −2.02, −1.22, −0.42, and −0.39 atm, respectively, so the soil structure under this condition was relatively stable, in which the net resultant force under the organic-inorganic treatment of TFO was the smallest, and the net attractive force between soil particles was the largest. When the electrolyte concentration was less than 1 mol L^{-1}, the net resultant force between the reclaimed soil particles was

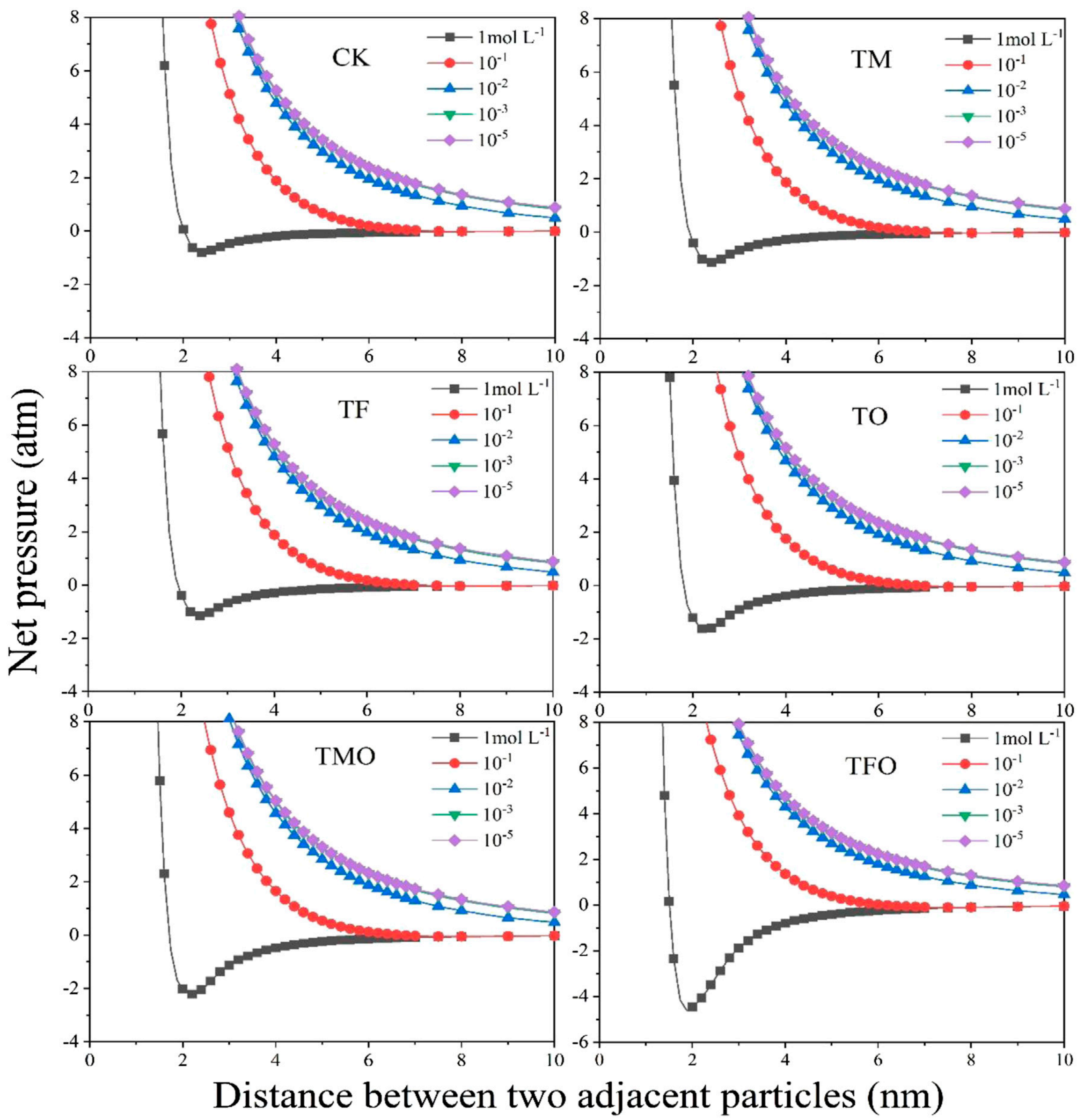

FIGURE 5
Distribution of net pressure (P_{net}) between reclaimed soil particles at various bulk solution electrolyte concentrations.

gradually showing a repulsive force, and the net repulsive force increased with the decrease of the electrolyte concentration. When the electrolyte concentration was or less than 10^{-2} mol L^{-1}, the net resultant force curves of reclaimed soil under different treatments were similar, showing a net repulsive force overall. The above results indicate that the electrolyte concentration of 10^{-2} mol L^{-1} is the key concentration for the variation of net resultant force, at which the structural stability of soil is easy to be destroyed. Liu Z et al. (2021) and Hu et al. (2021) also came to similar conclusions, showing that solution electrolyte concentration was closely related to soil net resultant force. With an increase in solution electrolyte concentration and the incorporation of soil conditioner, the net repulsive resultant force between soil particles decreased, and the electrolyte solution concentration of $\leq 10^{-2}$ mol L^{-1} is the critical concentration where the net resultant force tends to be stable and overlap (Liu, et al., 2021b.; Hu, et al., 2021). In addition, at the same distance, when the electrolyte concentration was or greater than 10^{-2} mol L^{-1}, the net repulsive force between particles increases significantly with the decrease of the electrolyte solution concentration. When the distance between soil particles was less than 1.8 nm, there was a strong net repulsive force at any electrolyte concentration due to the hydration repulsive force, indicating that soil particles would swell to some extent at a very close distance.

TABLE 3 Net pressure at 2 nm between soil particles under the incorporation of different soil conditioners.

Electrolyte concentration (mol L^{-1})	Net pressure between soil particles (atm)					
	CK	TM	TF	TO	TFO	TMO
1	0.06	−0.39	−0.42	−1.22	−4.46	−2.02
10^{-1}	15.27	15.40	15.18	14.40	11.20	13.47
10^{-2}	19.25	19.42	19.20	18.41	15.22	17.48
10^{-3}	19.65	19.83	19.60	18.82	15.63	17.88
10^{-5}	19.69	19.88	19.65	18.87	15.68	17.93

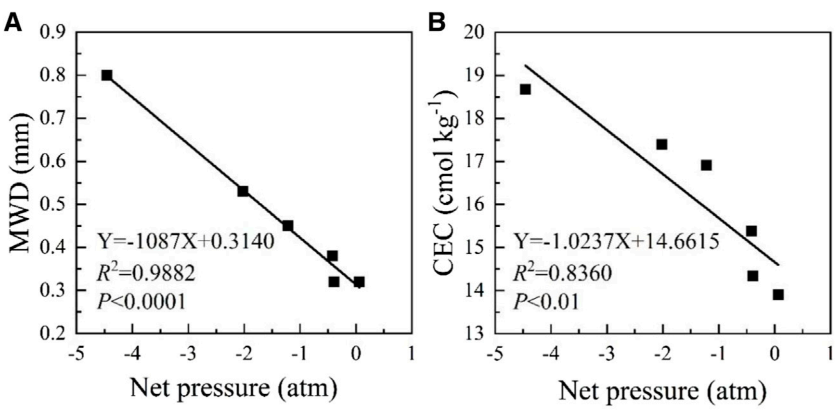

FIGURE 6
Relationship between net pressure and MWD **(A)** and between net pressure and CEC **(B)**. MWD: mean weight diameter; Net pressure: the sum of electrostatic, van der Waals and surface hydration pressures between soil particles; CEC: cation exchange capacity.

In order to further compare and analyze the impact of different soil conditioners on the variation of net resultant force among reclaimed soil particles, we presented the relationship between net resultant force and electrolyte concentration at a distance of 2 nm among reclaimed soil particles under different treatments (Table 3). The overall trend of net resultant force under different treatments was as follows: TFO < TMO < TO < TF < TM < CK, and the negative value represents a net attractive force, which means that the application of soil conditioners enhanced the agglomeration and structural stability of soil particles, among which the organic-inorganic treatments of TFO and TMO had a better effect on improvement of the structural stability of reclaimed soil. With the decrease of electrolyte concentration from 1 mol L^{-1} to 10^{-2} mol L^{-1}, the net resultant forces of reclaimed soil under the six treatments all showed an increasing trend, indicating that the net resultant force gradually exhibited a tendency towards repulsive force, and the structural stability of aggregates would keep decreasing. When the electrolyte concentration was or less than 10^{-2} mol L^{-1}, the net resultant force of reclaimed soil tended to be stable, and the structural stability of aggregates did not vary greatly at large. Furthermore, when the electrolyte concentration was 1 mol L^{-1}, the net resultant forces under the treatments of TFO, TMO, TO, TF, and TM were all negative. Compared with the net resultant force of 0.06 atm under the CK treatment, the application of different soil conditioners significantly enhanced the net resultant force and structural stability of reclaimed soil particles under the same conditions.

3.5 Relationship between reclaimed soil net pressure and MWD and CEC

The net resultant force between soil particles on a micro scale played a crucial role in the formation and stability of soil aggregates, and the structural stability of soil aggregates could also reflect the changes in the properties of soil surface charges and the interaction forces, which significantly influenced the soil fertility and environmental issues (Hu et al., 2021; Liu Z et al., 2021). The results of our study showed that the net resultant force among reclaimed soil particles was significantly negatively correlated with soil MWD and CEC (MWD, R^2 = 0.7611, p < 0.0001; CEC, R^2 = 0.8360, p < 0.01 Figure 6), which revealed that with the application of soil conditioners, especially the application of TFO and TMO, the net resultant force between reclaimed soil particles decreased continuously, and the negative value represented the net attractive force between particles; the MWD value and CEC content of reclaimed soil aggregates increased constantly, and the stability and agglomeration of soil structures were improved continuously.

4 Discussion

4.1 Effects of different organic-inorganic soil conditioners on reclaimed soil physicochemical properties

The application of soil conditioners has significantly ameliorated the basic properties of reclaimed soil in abandoned homestead, and can effectively enhance the structural stability and fertility of soil (Chivenge, et al., 2011; Gao, et al., 2021). Our findings showed that the long-term incorporation of soil conditioners slightly reduced the pH of reclaimed soil, which may be due to the fact that the decomposition of soil conditioners enhances the production of acid substances and the buffering capacity of the pH of reclaimed soil. That is similar to the previous research results of Lentz and Ippolito, (2012) and Choudhary et al. (2011). The returning incorporation of different soil conditioners to the field is an important source of improving soil organic matter. Soil conditioners such as organic fertilizer and fly ash can significantly increase organic matter content in the reclaimed soil of abandoned homestead after application alone or in combination, which is also confirmed in Table 2. The long-term application of soil conditioners furthers the rise of crop biomass and enhances the return of plant residues and roots into the soil. With the increase of organic matter content, the cementing substances help enhance the mutual adsorption and agglomeration among soil particles; Meanwhile, the incorporation of soil conditioners weakens the destructive effect of tillage patterns on soil structure to some extent, ultimately promoting the formation and stability of reclaimed soil aggregates (Singh, et al., 2011; Zhang, et al., 2012; Dong, et al., 2022), and thereby the MWD, an index for structural stability of reclaimed soil, increases significantly.

Among them, the improvement effect of the organic-inorganic treatment of TFO showed the best, followed by the TMO and TO treatment, and that of the inorganic treatment (TM) showed less. The reason is that: due to the difference in the properties and structure of organic fertilizer, maturing agent and fly ash and the discrepancy in the improvement of the physical and chemical properties of reclaimed soil, and the fact that the fly ash itself has high specific surface area and multi-level pores and is rich in clay particles and oxides such as Al_2O_3 and Fe_2O_3, its application to the reclaimed soil can significantly enhance the mutual adsorption, agglomeration and cementation among soil particles; Besides, since the exogenous organic fertilizer itself is rich in organic matter and multiple nutrient elements, the cementing substances such as polysaccharide and humus produced by decomposition can further promote the agglomeration of soil particles and the structural stability of aggregates, as well as physically protect SOM from rapid decomposition (Meng, et al., 2014; Parab, et al., 2015). Therefore, the combined incorporation of organic and inorganic fertilizer (TFO) has the most significant effect on the improvement of organic matter and soil structure, thus it is a good combination to improve the structural stability and fertility of reclaimed soil. The findings in this research are similar to those of Ren et al. (2012). The latter showed that the capacity of organic cement to promote the formation and stability of aggregates is better than that of inorganic cement, and the organic-inorganic coupling treatment is more conducive to the improvement of soil structure and fertility (Ren, et al., 2012; Wei, et al., 2016).

4.2 Effects of different organic-inorganic soil conditioners on reclaimed soil surface charge properties and particle interaction forces

Previous studies showed that the addition of organic and inorganic soil conditioners had a significant influence on the soil surface properties (Gruba and Mulder, 2015; Liu, et al., 2020; Dong, et al., 2022). In the studies on the degraded loess in Northwest China, Liu et al. (2020) found that with the extension of the period of vegetation restoration and the increase of organic matter content, a growth could be seen correspondingly in the surface charge density and specific surface area of the loess (Liu, et al., 2020). And the studies of Dong et al. (2022); El-Naggar et al. (2019) showed that the specific surface area and cation exchange capacity of soil particles could be increased with the use of fly ash and biochar soil conditioners (El-Naggar et al., 2019; Dong et al., 2022). Furthermore, it was manifested in our findings that the application of exogenous soil conditioners such as organic fertilizer and fly ash increased not only the content of organic matter and structural stability of reclaimed soil, but also the specific surface area and surface charge of soil particles, thus improving the capacities of ion adsorption and the agglomeration and cementation of clay particles. Among them, the organic-inorganic treatment (TFO) had a better effect on improving the soil surface electrochemical properties (Table 1).

Particle interaction forces are mainly affected by internal and external factors such as specific surface area (*SSA*), charge density (σ_0), cation exchange capacity (CEC), solution concentration and pH value (Rengasamy, et al., 2016; Yu, et al., 2016). This study found that with the incorporation of soil conditioners, there was a slightly increase in electrostatic repulsive force (ERF) of reclaimed soil, and the electrostatic repulsive force between soil particles increased constantly with the decrease of the distance between particles and the concentration of electrolyte solution (Figures 1, 2). The results were similar to those of previous studies, mainly due to the increase of particle surface charge density and electric field intensity after the application of different soil conditioners (Ding, et al., 2019; Xu, et al., 2020). Meanwhile, according to the theory of electric double layers, the increasing solution electrolyte concentration would compress the electric double layers of soil and decrease the thickness of diffusion layer, and there would be more ions in adsorption layer, thus reducing the electrostatic repulsive force between particles (Liang, et al., 2007). In this study, van der Waals (vdW) attractive force increased gradually with the addition of soil conditioners such as organic fertilizer and fly ash, indicating that the addition of different soil conditioners could to a certain extent enhance the attractive force between soil particles. According to Eq. 9, molecular attractive force was only related to the distance between particles and A_{eff}, and the order of size in the A_{eff} under different treatments showed as follows: TFO > TMO > TO > TF > TM > CK (Figure 3). Therefore, the organic-inorganic treatments of TFO and TMO could significantly improve the van der Waals (vdW) attractive force between reclaimed soil particles (Figure 4), thus increasing the structural stability of reclaimed soil, which was also consistent with the high MWD value of aggregates under TFO and TMO treatments (Table 1).

In our study, when the distance between reclaimed soil particles was less than 1.6 nm, the difference between van der Waals (vdW) attractive force and hydration repulsive force increased sharply, and the hydration repulsion force would be greater than van der Waals force, resulting in net repulsion force between soil particles (Figure 4). This was similar to the research results of Hu et al. (2015)., who found in the study on purple soil when the distance between particles was less than about 1.4 nm, the hydration repulsive force was significantly greater than the van der Waals attractive force, largely influencing the swelling and dispersion of dry soil under aqueous conditions (Hu, et al., 2015). And our results revealed that the order of size in the net resultant force of reclaimed soil particles showed as follows: TFO < TMO < TO < TF < TM < CK (Figure 5), indicating that the addition of soil conditioners reduced the net resultant force between particles and increased the attractive force between soil particles. In particular, the organic-inorganic treatments of TFO and TMO well improved the net resultant force of reclaimed soil structure, and the structural stability of reclaimed soil was greatly bettered. The research results were consistent with those of Yu et al. (2020) and Calero et al. (2017), which showed that the addition of soil conditioners such as organic fertilizer and straw could largely enhance the van der Waals attractive force between soil particles while increasing organic matter, weaken the adverse effect of electrostatic repulsive force on soil aggregates, and thus improve the structural stability and fertility of soil (Calero, et al., 2017; Yu, et al., 2020).

4.3 Responses of reclaimed soil aggregate stability to soil conditioners application

Soil organic matter was a vital soil cementing agent, and 0.1 cmol kg^{-1} negative charge could be increased with an increase of 1 g kg^{-1} organic matter content, and the surface charge density also grew with the increase of organic matter content (Hu et al., 2015). The specific surface area of humus in organic matter was about 800–900 m^2 g^{-1}, nearly 10 times that of inorganic clay minerals. With the growth of organic matter content, the specific surface area of soil particles gradually increased (Zhao et al., 2019). Therefore, in this study, the application of exogenous soil conditioners such as organic fertilizer, fly ash and maturing agent notably increased the content of organic matter in the reclaimed soil of Hollow Village, promoted the formation of organic-inorganic complexes in soil, improved the ion adsorption, cementation and agglomeration, and significantly reduced the net resultant force between particles, thereby showing an attractive force, thus increasing the cation exchange capacity and structural stability of soil particles (Figure 6). Yu et al. (2017). also confirmed the above-mentioned, showing that organic matter content was closely related to soil structural stability and the net resultant force between particles. With the growth of soil organic matter content, the van der Waals (vdW) attractive force between soil particles increased, and electrostatic repulsive force and hydration repulsive force were weakened. The higher the organic matter content was, the smaller the net resultant force between particles was and the greater the stability of soil aggregates became (Xu, et al., 2015; Yu, et al., 2020).

Our results manifested that the electrochemical properties of soil surface and the interaction forces between particles had important effects on the stability of soil aggregates. Since the cementing substances such as humus produced by the decomposition of organic fertilizers had high specific surface area and multi-level pores, fly ash was rich in clay particles and oxides such as Al_2O_3 and Fe_2O_3, and maturing agent ferrous sulfate could adjust soil pH and improve soil structure (Yukselen-Aksoy and Kaya, 2010; Gao, et al., 2021), the organic-inorganic treatments of TFO and TMO significantly enhanced the amount of charge between particles and cation exchange capacity, increased van der Waals attractive force, and generally weakened the influence of repulsive forces between particles, thereby promoting the mutual adsorption and agglomeration among reclaimed soil particles, and improving the structure and fertility of reclaimed soil. This study explored the internal mechanism of the employment of organic matter in improving the stability of reclaimed soil aggregates during the application of soil conditioners, and provided new ideas for further study of the effect of soil conditioners on the stability of soil aggregates and the prevention of soil erosion. The composition of organic matter includes particulate organic matter and mineral-associated organic matter. In the future, we will further explore which component profoundly affects the surface properties and interaction forces of soil particles, which will play an important role in improving soil quality and ecological environment.

5 Conclusion

In this study, SOM, SSA, σ_0, CEC, Hamaker constant and stability of aggregates gradually increased, while pH value slightly decreased after 5-year application of different soil conditioners. With the increase of soil organic matter content, the MWD under TFO and TMO treatments increased by 150.3% and 65.6% respectively compared with CK. The van der Waals attractive force between reclaimed soil particles increased with the soil conditioners application, which increased by 290.1% and 135.8% under TFO and TMO respectively. The net resultant force decreased significantly, showing an overall trend of TFO < TMO < TO < TF < TM < CK. Meanwhile, the net attractive force at 2 nm soil particle distance increased continuously, which were −4.46, −2.02, −1.22, −0.42 and −0.39 atm at 1 mol L^{-1} electrolyte concentration. The structural stability and fertility of soil were significantly improved, and these results were consistent with our experimental data on the stability of aggregates. The electrolyte solution concentration of 10^{-2} mol L^{-1} was the critical concentration for the drastic change of particle interaction forces of reclaimed soil. Overall, the particle interaction forces are important factors affecting the reclaimed soil structural stability and fertility, and the organic-inorganic coupling treatments of TMO and TFO are appropriate measures to improve the soil interaction forces and structural stability. The research results can provide scientific reference for improving reclaimed soil structural stability and fertility, preventing and controlling soil and water erosion in the loess region.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

Conceptualization, ZL and YZ; methodology, YS and NW; software, ZL and XL; writing—original draft preparation, ZL and XL; funding acquisition, YS and YZ. All authors contributed to the article and approved the submitted version.

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Conflict of interest

ZL, YZ, YS, NW, XW, and TM were employed by Shaanxi Provincial Land Engineering Construction Group Co., Ltd and Shaanxi Provincial Land Engineering Construction Group Co.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abiven, S., Menasseri, S., Angers, D. A., and Leterme, P. (2007). Dynamics of aggregate stability and biological binding agents during decomposition of organic materials. *Eur. J. Soil Sci.* 58 (1), 239–247. doi:10.1111/j.1365-2389.2006.00833.x

Ayoubi, S., Mirbagheri, Z., and Mohammad Reza, M. (2020). Soil organic carbon physical fractions and aggregate stability influenced by land use in humid region of northern Iran. *Int. Agrophys.* 34 (3), 343–353. doi:10.31545/intagr/125620

Bandyopadhyay, K. K., and Lal, R. (2014). Effect of land use management on greenhouse gas emissions from water stable aggregates. *Geoderma* 232, 363–372. doi:10.1016/j.geoderma.2014.05.025

Blanco-Canqui, H., and Lal, R. (2004). Mechanisms of carbon sequestration in soil aggregates. *CRC Crit. Rev. Plant Sci.* 23 (6), 481–504. doi:10.1080/07352680490886842

Calero, J., Ontiveros-Ortega, A., Aranda, V., and Plaza, I. (2017). Humic acid adsorption and its role in colloidal-scale aggregation determined with the zeta potential, surface free energy and the extended-DLVO theory. *Eur. J. Soil Sci.* 68 (4), 491–503. doi:10.1111/ejss.12431

Chivenge, P., Vanlauwe, B., Gentile, R., and Six, J. (2011). Organic resource quality influences short-term aggregate dynamics and soil organic carbon and nitrogen accumulation. *Soil Biol. biochem.* 43 (3), 657–666. doi:10.1016/j.soilbio.2010.12.002

Choudhary, O. P., Ghuman, B. S., Singh, B., Thuy, N., and Buresh, R. J. (2011). Effects of long-term use of sodic water irrigation, amendments and crop residues on soil properties and crop yields in rice–wheat cropping system in a calcareous soil. *Field crop. Res.* 121 (3), 363–372. doi:10.1016/j.fcr.2011.01.004

Ding, W. Q., Liu, X. M., Hu, F. N., Zhu, H. L., Luo, Y. X., Li, S., et al. (2019). How the particle interaction forces determine soil water infiltration: Specific ion effects. *J. Hydrol.* 568, 492–500. doi:10.1016/j.jhydrol.2018.11.017

Dong, S. W., Ma, S. H., Chu, M., Wang, X. H., Wang, Y. J., Liu, C. X., et al. (2022). Microstructure changes of saline-alkali soil influenced by fly ash-based soil conditioner. *Chin. J. Process Eng.* 22 (03), 357–365. doi:10.12034/j.issn.1009-606X.220371

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., et al. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma* 337, 536–554. doi:10.1016/j.geoderma.2018.09.034

Fonte, S. J., Yeboah, E., Ofori, P., Quansah, G. W., Vanlauwe, B., and Six, J. (2009). Fertilizer and residue quality effects on organic matter stabilization in soil aggregates. *Soil Sci. Soc. Am. J.* 73 (3), 961–966. doi:10.2136/sssaj2008.0204

Gao, Z. X., Li, X. L., Zhang, J., Jin, L. Q., and Zhou, W. (2021). Effects of different fertilization treatments on soil enzyme activities in coal mining residuals of alpine mining area. *Acta Agrestia Sin.* 29, 1748–1756. doi:10.11733/j.issn.1007-0435.2021.08.018

Gruba, P., and Mulder, J. (2015). Tree species affect cation exchange capacity (CEC) and cation binding properties of organic matter in acid forest soils. *Sci. Total Environ.* 511, 655–662. doi:10.1016/j.scitotenv.2015.01.013

Hu, F. N., Liu, J. F., Xu, C. Y., Du, W., Yang, Z. H., Liu, X. M., et al. (2018a). Soil internal forces contribute more than raindrop impact force to rainfall splash erosion. *Geoderma* 330, 91–98. doi:10.1016/j.geoderma.2018.05.031

Hu, F. N., Liu, J. F., Xu, C. Y., Wang, Z. L., Liu, G., Li, H., et al. (2018b). Soil internal forces initiate aggregate breakdown and splash erosion. *Geoderma* 320, 43–51. doi:10.1016/j.geoderma.2018.01.019

Hu, F. N., Xu, C., Ma, R., Tu, K., Yang, J., Zhao, S., et al. (2021). Biochar application driven change in soil internal forces improves aggregate stability: Based on a two-year field study. *Geoderma* 403, 115276. doi:10.1016/j.geoderma.2021.115276

Hu, F. N., Xu, C. Y., Li, H., Li, S., Yu, Z. H., Li, Y., et al. (2015). Particles interaction forces and their effects on soil aggregates breakdown. *Soil Tillage Res.* 147, 1–9. doi:10.1016/j.still.2014.11.006

Huang, F., and Wang, P. (2010). Vegetation change of ecotone in west of northeast China plain using time-series remote sensing data. *Chin. Geogr. Sci.* 20 (2), 167–175. doi:10.1007/s11769-010-0167-0

Jenkinson, S. J., and Kalembasa, D. S. A. (1973). A comparative study of titrimetric and gravimetric methods for the determination of organic carbon in soil. *J. Sci. Food. Agr.* 24, 1085–1090. doi:10.1002/jsfa.2740240910

Lei, N., Han, J., Mu, X., Sun, Z. H., and Wang, H. Y. (2019). Effects of improved materials on reclamation of soil properties and crop yield in hollow villages in China. *J. Soils Sediments.* 19, 2374–2380. doi:10.1007/s11368-019-02246-1

Lentz, R. D., and Ippolito, J. A. (2012). Biochar and manure affect calcareous soil and corn silage nutrient concentrations and uptake. *J. Environ. Qual.* 41, 775–1043. doi:10.2134/jeq2011.0126er

Li, H., Hou, J., Liu, X. M., Li, R., Zhu, H., and Wu, L. S. (2011). Combined determination of specific surface area and surface charge properties of charged particles from a single experiment. *Soil. Sci. Soc. Am. J.* 75, 2128–2135. doi:10.2136/sssaj2010.0301

Li, H., Yang, G., Zhang, W., Zhao, N., Hai, X., Sun, Q., et al. (2017). Chronic fatigue syndrome treated by the traditional Chinese procedure abdominal tuina: A randomized controlled clinical trial. *Acta Petrol. Sin.* 54 (4), 819–826. doi:10.11766/trxb201703310602

Li, S., Li, H., Xu, C. Y., Huang, X. R., Xie, D. T., and Ni, J. P. (2013). Particle interaction forces induce soil particle transport during rainfall. *Soil. Sci. Soc. Am. J.* 77, 1563–1571. doi:10.2136/sssaj2013.01.0009

Li, S., Li, Y., Huang, X. R., Hu, F. N., Liu, X. M., and Li, H. (2018). Phosphate fertilizer enhancing soil erosion effects and mechanisms in a variably charged soil. *J. Soils Sediments.* 18, 863–873. doi:10.1007/s11368-017-1794-1

Liang, Q., Chen, H. Q., Gong, Y. S., Fan, M. S., Yang, H. F., Lal, R., et al. (2012). Effects of 15 years of manure and inorganic fertilizers on soil organic carbon fractions in a wheat-maize system in the North China Plain. *Nutr. Cycl. Agroecosyst.* 92 (1), 21–33. doi:10.1007/s10705-011-9469-6

Liang, Y., Hilal, N., Langston, P., and Starov, V. (2007). Interaction forces between colloidal particles in liquid: Theory and experiment. *Adv. Colloid Interf. Sci.* 134, 151–166. doi:10.1016/j.cis.2007.04.003

Liu, J. F., Hu, F. N., Xu, C. Y., Wang, Z. L., Ma, R. T., Zhao, S. W., et al. (2021a). Comparison of different methods for assessing effects of soil interparticle forces on aggregate stability. *Geoderma* 38, 114834. doi:10.1016/j.geoderma.2020.114834

Liu, J. F., Wang, Z. L., Hu, F. N., Xu, C. Y., Ma, R. T., and Zhao, S. W. (2020). Soil organic matter and silt contents determine soil particle surface electrochemical properties across a long-term natural restoration grassland. *Catena* 190, 104526. doi:10.1016/j.catena.2020.104526

Liu, J. F., Xu, C. Y., Hu, F. N., Wang, Z. L., Ma, R. T., and Zhao, S. W. (2021b). Effect of soil internal forces on fragment size distributions after aggregate breakdown and their relations to splash erosion. *Eur. J. Soil Sci.* 72 (5), 2088–2101. doi:10.1111/ejss.13094

Liu, Y., Li, J., and Yang, Y. (2018). Strategic adjustment of land use policy under the economic transformation. *Land Use Policy* 74, 5–14. doi:10.1016/j.landusepol.2017.07.005

Liu, Y. S., Long, H. L., Chen, Y. F., Wang, J. Y., Li, Y. R., Li, Y. H., et al. (2016). Progress of research on urbanrural transformation and rural development in China in the past decade and future prospects. *J. Geogr. Sci.* 26, 1117–1132. doi:10.1007/s11442-016-1318-8

Liu, Z., Cao, S. L., Sun, Z. H., Wang, H. Y., Qu, S. D., Lei, N., et al. (2021). Tillage effects on soil properties and crop yield after land reclamation. *Sci. Rep-UK.* 11, 4611. doi:10.1038/s41598-021-84191-z

Liu, Z., Deng, L., Zhou, W., Chen, L., and Zou, G. (2019a). Evaluation of effects of organic materials on soil fertilization of reclaimed homestead. *Soils* 51, 672–681. doi:10.13758/j.cnki.tr.2019.04.007

Liu, Z., Han, J. C., Sun, Z. H., Chen, T. Q., Hou, Y., Dong, Q. G., et al. (2019b). Long-term effects of different planting patterns on greenhouse soil micromorphological features in the North China Plain. *Sci. Rep-UK* 2200, 2200–2210. doi:10.1038/s41598-019-38499-6

Liu, Z., Zhang, Y., Sun, Z. H., Sun, Y. Y., Wang, H. Y., and Zhang, R. Q. (2022). Effects of the application of different improved materials on reclaimed soil structure and maize yield of Hollow Village in Loess Area. *Sci. Rep-UK.* 12, 7431. doi:10.1038/s41598-022-10898-2

Long, H. L., and Qu, Y. (2018). Land use transitions and land management: A mutual feedback perspective. *Land Use Policy* 74, 111–120. doi:10.1016/j.landusepol.2017.03.021

Long, H. L., Zhang, Y. N., and Tu, S. S. (2019). Rural vitalization in China: A perspective of land consolidation. *J. Geogr. Sci.* 29 (4), 517–530. doi:10.1007/s11442-019-1599-9

Meng, Q. F., Sun, Y. T., Zhao, J., Zhou, L. R., Ma, X. F., Zhou, M., et al. (2014). Distribution of carbon and nitrogen in water-stable aggregates and soil stability under long-term manure application in solonetzic soils of the Songnen plain, northeast China. *J. Soils Sediments.* 14 (6), 1041–1049. doi:10.1007/s11368-014-0859-7

Moghal, A. A. B., and Sivapullaiah, P. V. (2011). Effect of pozzolanic reactivity on compressibility characteristics of stabilised low lime fly ashes. *Geotech. Geol. Eng. (Dordr).* 29 (5), 665–673. doi:10.1007/s10706-011-9408-y

Moghal, A. A. B., and Sivapullaiah, P. V. (2012). Role of lime leachability on the geotechnical behavior of fly ashes. *Int. J. Geotech. Eng.* 6 (1), 43–51. doi:10.3328/IJGE.2012.06.01.43-51

Moghal, A. A. B. (2017). State-of-the-Art Review on the role of fly ashes in geotechnical and geoenvironmental applications. *J. Mater. Civ. Eng.* 29 (8), 04017072. doi:10.1061/(ASCE)MT.1943-5533.0001897

Moghal, A. A. B., Vydehi, V., Moghal, M. B., Almatrudi, R., AlMajed, A., and Al-Shamrani, M. A. (2020). Effect of calcium-based derivatives on consolidation, strength, and lime-leachability behavior of expansive soil. *J. Mater. Civ. Eng.* 32 (4), 04020048. doi:10.1061/(ASCE)MT.1943-5533.0003088

Parab, N., Sinha, S., and Mishra, S. (2015). Coal fly ash amendment in acidic field: Effect on soil microbial activity and onion yield. *Appl. Soil Ecol.* 96, 211–216. doi:10.1016/j.apsoil.2015.08.007

Rabot, E., Wiesmeier, M., Schlüter, S., and Vogel, H. J. (2018). Soil structure as an indicator of soil functions: A review. *Geoderma* 314, 122–137. doi:10.1016/j.geoderma.2017.11.009

Ram, L. C., and Masto, R. E. (2014). Fly ash for soil amelioration: A review on the influence of ash blending with inorganic and organic amendments. *Earth-Sci Rev.* 128, 52–74. doi:10.1016/j.earscirev.2013.10.003

Ren, S., Shao, Y., and Yang, J. (2012). Study on effects of fertilizations on homestead reclamation soil. *J. Soil Water Conserv.* 26, 78–81. doi:10.13870/j.cnki.stbcxb.2012.03.017

Rengasamy, P., Tavakkoli, E., and McDonald, G. K. (2016). Exchangeable cations and clay dispersion: Net dispersive charge, a new concept for dispersive soil. *Eur. J. Soil Sci.* 7, 659–665. doi:10.1111/ejss.12369

Singh, J. S., Pandey, V. C., and Singh, D. P. (2011). Coal fly ash and farmyard manure amendments in dry - land paddy agriculture field: Effect on N-dynamics and paddy productivity. *Appl. Soil Ecol.* 47, 133–140. doi:10.1016/j.apsoil.2010.11.011

Sivapullaiah, P. V., and Moghal, A. A. B. (2010). Leachability of trace elements from two stabilized low lime Indian fly ashes. *Environ. Earth Sci.* 61 (8), 1735–1744. doi:10.1007/s12665-010-0487-5

Six, J., Bossuyt, H., Degryze, S., and Denef, K. (2004). A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* 79, 7–31. doi:10.1016/j.still.2004.03.008

Tuller, M., and Or, D. (2005). Water films and scaling of soil characteristic curves at low water contents. *Water Resour. Res.* 41 (9). doi:10.1029/2005wr004142

Vaezi, A. R., Ahmadi, M., and Cerda, A. (2017). Contribution of raindrop impact to the change of soil physical properties and water erosion under semi-arid rainfalls. *Sci. Total Environ.* 583, 382–392. doi:10.1016/j.scitotenv.2017.01.078

Verchot, L., Dutaur, L., Shepherd, K. D., and Alain, A. (2011). Organic matter stabilization in soil aggregates: Understanding the biogeochemical mechanisms that determine the fate of carbon inputs in soils. *Geoderma* 161, 182–193. doi:10.1016/j.geoderma.2010.12.017

Wang, D., Fonte, S. J., Parikh, S. J., Six, J., and Scow, K. M. (2017). Biochar additions can enhance soil structure and the physical stabilization of C in aggregates. *Geoderma* 303, 110–117. doi:10.1016/j.geoderma.2017.05.027

Wang, N., Han, J. C., Wei, Y., Li, G., and Sun, Y. Y. (2019). Potential ecological risk and health risk assessment of heavy metals and metalloid in soil around xunyang mining areas. *Sustainability* 11 (18), 4828. doi:10.3390/su11184828

Wei, W., Yan, Y., Cao, J., Christie, P., Zhang, F., and Fan, M. (2016). Effects of combined application of organic amendments and fertilizers on crop yield and soil organic matter: An integrated analysis of long-term experiments. *Agric. Ecosyst. Environ.* 225, 86–92. doi:10.1016/j.agee.2016.04.004

Xu, C. Y., Yu, Z. H., and Li, H. (2015). The coupling effects of electric field and clay mineralogy on clay aggregate stability. *J. Soils Sediments.* 15, 1159–1168. doi:10.1007/s11368-015-1063-0

Xu, C. Y., Zhou, T. T., Wang, C. L., Liu, H. Y., Zhang, C., Hu, F. N., et al. (2020). Aggregation of polydisperse soil colloidal particles: Dependence of Hamaker constant on particle size. *Geoderma* 359, 113999. doi:10.1016/j.geoderma.2019.113999

Yu, Z. H., Li, H., Liu, X. M., Xu, C. Y., and Xiong, H. L. (2016). Influence of soil electric field on water movement in soil. *Soil Tillage Res.* 155, 263–270. doi:10.1016/j.still.2015.08.020

Yu, Z. H., Zhang, J. B., Zhang, C. Z., Xin, X. L., and Li, H. (2017). The coupling effects of soil organic matter and particle interaction forces on soil aggregate stability. *Soil Tillage Res.* 174, 251–260. doi:10.1016/j.still.2017.08.004

Yu, Z. H., Zheng, Y. Y., Zhang, J. B., Zhang, C. Z., Ma, D. H., Chen, L., et al. (2020). Importance of soil interparticle forces and organic matter for aggregate stability in a temperate soil and a subtropical soil. *Geoderma* 362, 114088. doi:10.1016/j.geoderma.2019.114088

Yukselen-Aksoy, Y., and Kaya, A. (2010). Method dependency of relationships between specific surface area and soil physicochemical properties. *Appl. Clay Sci.* 50 (2), 182–190. doi:10.1016/j.clay.2010.07.020

Zhang, S. X., Li, Q., Zhagn, X. P., Wei, K., Chen, L. J., and Liang, W. J. (2012). Effects of conservation tillage on soil aggregation and aggregate binding agents in black soil of Northeast China. *Soil Tillage Res.* 124, 196–202. doi:10.1016/j.still.2012.06.007

Zhao, Z. J., Chang, E., Lai, P., Dong, Y., Xu, R. K., Fang, D., et al. (2019). Evolution of soil surface charge in a chronosequence of paddy soil derived from Alfisol. *Soil Tillage Res.* 192, 144–150. doi:10.1016/j.still.2019.05.011