Original Research

Effect of Organic Amendment and Mineral Fertilizer on Soil Aggregate Stability and Maize Yield on the Loess Plateau of China

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Abstract

Organic amendment has proven to improve soil quality and crop production, in addition to reduce resource waste. However, the effect of organic amendment on soil water-stable aggregates and soil organic carbon is unclear. A two-year field experiment with four organic amendment treatments, biochar, organic fertilizer, microbial agents and polyacrylamide (PAM), was conducted to investigate the effect of different soil organic amendments on Loess Plateau. The results revealed that organic amendments significantly influenced the mean weight diameter (MWD) and geometric mean diameter (GMD) of water-stable aggregates, particularly in the case of PAM treatment. The MWD and GMD values increased significantly by 33.7% and 29.8% in the PAM treatment. The proportion of macro-aggregates (2-0.25 mm) showed a remarkable 52.9% increase compared to the control (CK) treatment in the PAM-treated soil. Biochar-amended treatments increased soil organic carbon (SOC) in all aggregate fractions compared to CK treatment. Soil organic amendments also decreased soil bulk density and increased total nitrogen (TN) and available phosphorus (AP). Compared to CK treatment, the maize yields in the organic fertilizer and biochar treated soil increased by 19.8 and 30.3%, respectively. These findings suggest that biochar and PAM amendments are particularly suitable for loessal soil in arid and semi-arid regions

Keywords: organic amendment, soil aggregate, aggregate stability, organic carbon, maize yield

Introduction

As the most serious area of soil and water loss in China, Loess Plateau is one of the key areas for ecological conservation and high-quality development in the Yellow River Basin [1-3]. The loessial soils, widely distribute in the Loess Plateau, had many attribute barriers and derivative barriers such as bad structure, weakly alkaline, highly erodible and low organic matter [4, 5], which all result in low ability of water and fertilizer preservation [6]. As a rainfed agricultural

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and major grain producing area, the main ecological environment problems in the Loess Plateau are serious soil erosion and fragility environment because of little and unevenly distributed rain, vast hilly gully area and irrational land use [7]. It has been widely acknowledged that soil erosion leads to the physical degradation of soils and loss of plant nutrients. Thus, there are great limitation on harmonious development of the region ecological environment and agricultural production [8].

Aggregates are main component of soil structure, which is a group of particle formed by various forces, hence affecting pore continuity and nutrient supply capacity [9]. Aggregate stability and distribution are the key factors affecting the stability of soil structure, which is an important indicator to evaluate soil quality [10]. Also, Aggregate is an important storage place for soil organic carbon (SOC), which can provide cemented material for the formation of aggregates [11]. The distribution of organic carbon affects the ability of aggregates to fix and store organic carbon, also affects the stability of aggregates [12]. The application of organic matters is effective at promoting soil aggregates formation and changes the revolution and distribution of organic carbon in soil aggregates [13]. Thus, maintaining high stability of soil aggregates is crucial to protection of soil organic matter, reduction of run-off and erosion and improvement of soil productivity. Over the years, aggregate stability increases or decreases due to climatic conditions and human activities (land consolidation or use patterns).

Soil organic ameliorant is found as a sustainable substance to improve soil structure and organic carbon, increasing soil fertility, quality and crop yield, while decrease the use of chemical fertilizer and pesticide [14, 15]. There are various studies investigating the effects of organic material applications on soil aggregate stability and organic carbon content [16-18]. Generally, organic amendment improved soil aggregate stability and SOC content compared to inorganic fertilization. This is due to the aggregate-core and binding agents provide by the abundant organic matter input and microbial activities [19]. For instance, biochar, a new-style and environmental-friendly amendment, has a positive effect on improving soil physical properties and fertility [20-22]. Dai et al. (2019) reported that organic amendment such as biochar application in the wheat-maize system improved aggregate stability and increased C concentrations in all aggregate fractions in sandy soil [19]. As has been demonstrated, biochar amendment had positive effects on mean weight diameter (MWD) of water-stable aggregates and SOC content within aggregates [23]. Therefore, biochar could be a soil conditioner to enhance formation and stability of aggregates and increase soil organic carbon content. Moreover, biochar application significantly increased soil microbial abundance and activity and enzyme activities [24]. Polyacrylamide (PAM) of low molecular weight added to sandy loam soil obviously improved soil aggregate stability and organic carbon [14].

In addition, Organic fertilizer, such as vermicompost, also had significant and positive effects on aggregate stability and increased soil organic carbon content in aggregate scale of clay loam textured soil [17]. Furthermore, organic fertilizer significantly improved soil mechanical stability and >0.25 mm water-stable aggregates while decreased fractal dimension of water-stable aggregates with improvement of soil organic carbon [25]. Whether single microbial agents and compound microbial agent all improved water-stable aggregate of Pisha sandstone soil, while reduced soil pH and increased soil organic carbon content and available nutrients [26]. There is abundant evidence in the soil science literature to suggest that organic amendment can enhance water-stable aggregates in loess soil, red soil and clay loam soil in China [27, 28]. Overall, the formation and stability of aggregates mainly depends on the type of organic material input and the soil texture [13]. Thus, soil organic amendments are the essential methods to improve soil structure and land productivity for ensure high yield, stable yield and sustainable development on the Loess Plateau.

The object of this study is to research the effect of organic amendments under equal nitrogen application rate on aggregate stability, organic carbon content and maize yield, and relationships between organic carbon and aggregate stability in a silty loam soil of new created land in loess plateau. The experiment was designed to test the hypothesis that organic amendments combined with chemical fertilizer would enhance the structural, productive capacity and sustainable use of soil.

Material and Methods

Study Site

The field experiments were conducted during May 2018 to October 2019 at the Chuandi Test Farm (N 36°51′06″, E 109°18′46″) of the experimental base of Institute of Soil and Water Conservation Northwest A&F University in Yan 'an City, Shaanxi Province. The region is a typical hilly and gully area with a semi-arid continental monsoon climate on the Loess Plateau. The average altitude is about 1371.9 m, and the average sunshine duration is 2395.6 h. The annual mean precipitation is 505.3 mm, of which 80% occurs between May and September with large interannual variability. The temperature varies widely from day to night and the average temperature over the years is 8.8ºC. There are 157 days without frost all year. Maize and soybean are the main food crops in the test area. The soil type up to the 20 cm depth at the experimental site is a silty loam based on the international classification criterion of the USDA. Soil texture is silty loam. The maize of Shandan 650 was grown throughout the experiment. The soil properties are shown in Table 1.

Field Experimentation

Six treatment were set as CK (control, no amendments, no fertilizer), NP (N, P fertilizers), BNP (biochar with N, P fertilizers), ONP (organic fertilizer with N, P fertilizers), MNP (microbial agents with N, P fertilizers) and PNP (PAM with N, P fertilizers) to conduct field experiment (Table 2). Each trial plot was 12 m^2 (4 m × 3 m). All the field plots were laid out in a randomized complete block design with three replications. The individual plots were separated by protection rows that were 0.5 m in width. Except CK, all treatments received a total fertilizer of 240 kg hm^{-2} N and 174 kg hm^{-2} P$_2$O$_5$ with NP fertilizer and amendments application together. Chemical fertilizers were urea (46% N) and calcium superphosphate (16% P$_2$O$_5$). The additives were spread evenly over the surface of loess soil, completely mixed into the soil at the depth of 20 cm by shovel to keep a uniformly mixture of additive and soil. To ensure consistency, the CK plots were treated in the same way but without application of additive and fertilizer. The PAM and microbial agents were produced as soil improvers by Dongying Huaye New Material Co., Ltd. The organic fertilizer was chicken manure compost. Biochar was generated from apple tree branches subjected to 550~600ºC under anaerobic conditions and ground into a 2 mm sieve, which were provided by Shaanxi Yixin Biotechnology Development Co., Ltd. The properties of biochar are shown in Table 3.

Table 1. Some physicochemical properties of experiment soil.

Properties	Soil
pH (H₂O, 1:2.5)	8.87±0.64
Electrical Conductivity (EC, dS m^{-1})	0.18±0.04
Sand (2-0.05 mm) (%)	11.42±2.36
Silt (0.05-0.002 mm) (%)	70.13±11.25
Clay (<0.002 mm) (%)	18.45±2.78
Texture	Silt loam
Field capacity (%)	21.89±4.25
Wilting point (%)	8.32±1.69
Available water (%)	11.53±2.58
Bulk density (g cm^{-3})	1.25±0.14
CEC (cmol kg^{-1})	7.45±1.58
SOM (g kg^{-1})	3.12±0.27
Total nitrogen (TN, g kg^{-1})	0.41±0.08
Available P (AP, mg kg^{-1})	3.29±0.34
Available K (AK, mg kg^{-1})	67.1±8.26

Note: EC: Electro conductivity; SOC: Soil organic carbon; CEC: Cation exchange capacity; TN: Total nitrogen; AP: Available phosphorus; AK: Available potassium; BD: Bulk density

Table 2. The basic properties of biochar in this experiment.

Test Material	pH	EC (μS cm^{-1})	OM (g kg^{-1})	CEC (cmol kg^{-1})	TN (g kg^{-1})	AP (g kg^{-1})	AK (g kg^{-1})
Biochar	8.98±3.34	269.4±21.26	414.7±32.57	15.8±1.63	2.1±0.36	19.38±3.31	40.21±5.27

	Elements (%)			
	C	H	N	O
Biochar	78.8±2.21	2.82±0.23	1.28±0.16	16.26±1.78

Notes: EC: Electro conductivity; SOC: Soil organic carbon; TN: Total nitrogen; AP: Available phosphorus; AK: Available potassium; BD: Bulk density

Table 3. Some physicochemical properties of experiment soil.

Treatment	Crop	Biochar (t hm⁻²)	Polyacrylamide (kg hm⁻²)	Organic fertilizer (t hm⁻²)	microbial agents (kg hm⁻²)	Fertilizer	
						P_2O_5 (kg hm⁻²)	$CO(NH_2)_2$ (kg hm⁻²)
CK	Maize						
NP	Maize					64	128
MNP	Maize				50	64	128
ONP	Maize			7.5		64	128
PNP	Maize		15			64	128
BNP	Maize	20				64	128

Note: CK-No amendment and fertilizer; NP-N, P fertilizers; BNP-biochar with N, P fertilizers; ONP-organic fertilizer with N, P fertilizers; MNP-microbial agents with N, P fertilizers and PNP- PAM with N, P fertilizers.

Soil samples were collected during maize mature stage in 2018-2019. Five samples (0-20cm) were collected and mixed together to form one representative composite sample. Three replicate soil samples were collected at each treatment. All visible residues were removed. The soil samples were collected within "S" type and using a hand auger with a 6.7 cm diameter. Soil samples were taken back to the laboratory, air-dried, ground and passed through 0.15 mm, 1 mm and 2 mm diameter mesh screens for soil physical and chemical properties and water stable aggregates analyses. Minimize perturbation of soil samples during collection and transportation to avoid destruction of soil aggregates.

Measurement Index and Method

The soil bulk density (BD) was determined according to the cutting ring method. Soil pH was measured using a pHS-3E meter with a ratio of 1:2.5 (*w/v*). The soil EC was measured by electromagnetic induction using a DDS-307A meter. The SOC was measured by $K_2Cr_2O_7$ oxidation method after digestion with concentrated sulfuric acid. The TN was determined by semi-micro Kjeldahl instrument. The AP was determined by molybdenum-antimonic resistance colorimetry method using a UV-2300 spectrophotometer. The AK was measured by a flame photometer. The elemental composition of biochar was measured by element analyzer.

The water-stable aggregates were fractionated according to Ke et al. (2016) and Bach and Hofmockel (2014) [29, 30]. A few grams (3-4 g) of air-dried treated soil were placed on the nest with three sieves of 5, 2, 1, 0.25 and 0.053 mm mesh size. The samples were pre-soaked in deionized water for 10 min. After 10-min saturation time, the wet-sieving apparatus were oscillating vertically in water for 20 min at 3 cm stroke length and 40 cycles per minute. After wet-sieving, the soil material retained on each sieve and the unstable aggregates (<0.053 mm) were transferred into separate aluminium containers, dried at 60°C for 12 h.

The obtained size fractions were dried and weighed, then stored for measurement of aggregate-associated C using the same method as that for SOC.

Mean weight diameter (MWD, mm) was used to estimate the stability of aggregates [31], and was calculated as follows using following equation [32].

$$MWD = \sum_{i=1}^{n} \left(\bar{X_i} \cdot w_i \right) \qquad (1)$$

Where: i is the aggregate size class, X_i is the mean diameter of each aggregate fraction, and w_i represented the proportion of the corresponding aggregate fraction weight to the total sample weight, n is the number of aggregate fractions.

Geometric mean diameter (GMD):

$$GMD = \exp\left[\frac{\sum_{i=1}^{n} w_i \log x_i}{\sum_{i=1}^{n} w_i}\right] \qquad (2)$$

Where: w_i (g) is the weight of aggregates in a size class with an average diameter, and x_i (mm) is the same as above.

The percentage of aggregate destruction was calculated as:

$$PAD\ (\%) = (Md–Mw) \times 100/Md \qquad (3)$$

Where: M_d is the content of aggregate > 0.25 mm, M_w is the content of water-stable aggregates > 0.25 mm.

After harvest, maize plants were cut, removed and placed into clean bags. The crop material was then dried in an oven at 90°C for 30 minutes. The aboveground biomass of the maize was subsequently measured once the material had dried to a constant weight at 60°C. We measured the dry weight of the corn seeds per hundred in each plot and then converted into a measure of unit area yield (t hm⁻²).

Statistical Analysis

Statistical analyses were performed using the SPSS 20.0 statistical software package. Significant differences
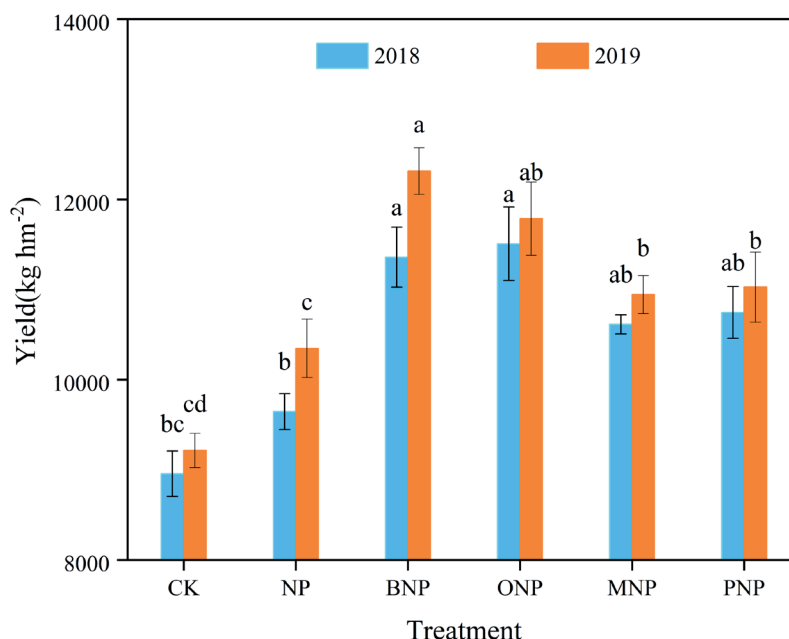
Fig. 1. Maize yields in 2018 and 2019 under different soil organic amendments (n = 3; means and standard deviation).
CK-No amendment and fertilizer; NP-N, P fertilizers; BNP-biochar with N, P fertilizers; ONP-organic fertilizer with N, P fertilizers; MNP-microbial agents with N, P fertilizers and PNP- PAM with N, P fertilizers; Different letters indicate significant difference among treatments at 0.05 level.

between the treatments on soil aggregate stability and crop yields were calculated by one-way analysis of variance (ANOVA) in combination with Duncan's test using SPSS 20.0. Values presented in the tables are mean±standard errors (SE). Origin 2019b was used for plotting.

Results and Discussion

Soil Physicochemical Properties and Maize Yield

Our study showed that the addition of combined organic amendments and mineral fertiliser altered soil properties compared to the CK treatment (Table 4).

The soil bulk density was lowest in the BNP treatment and was reduced by 4.87% compared to CK, but not significant. The soil TN, SOC, AP, and AK contents in the BNP treatment were 3.15-, 3.5-, 5.34- and 0.38-fold (p<0.05) greater than those of CK (Table 4). Soil pH decreased 0.2-1.2 units for different organic amendments, except for the CK treatment. The soil pH was lower in BNP and ONP treatments. However, there was no obvious difference among all treatments (p>0.05).

The yield of maize was higher in all organic amendment treatment than that of the CK treatment (Fig. 1). The lowest yield was from plots with no NP treatment, while the higher yield was occurred in ONP and BNP treatments in 2018 and 2019. The average yields for the

Table 4. Effect of organic amendments on soil physical and chemical properties.

Treatment	Bulk density (g·cm⁻³)	pH	EC (ds·m⁻¹)	SOC (g·kg⁻¹)	TN (g·kg⁻¹)	AP (mg·kg⁻¹)	AK (mg·kg⁻¹)
CK	1.23±0.12a	8.85±1.12a	148.25±21.45b	2.23±0.32de	0.24±0.11d	3.38±0.58cd	103.41±19.56c
NP	1.22±0.09a	8.86±2.24a	135.41±32.16bc	2.94±0.47d	0.39±0.06cd	5.98±0.74c	102.78±23.65c
BNP	1.17±0.21b	8.83±0.98ab	109.72±19.74c	9.25±0.18a	1.08±0.24a	21.43±1.25a	142.31±31.12a
ONP	1.18±0.15b	8.81±1.28b	201.34±35.67a	7.87±1.10b	0.94±0.16ab	19.74±2.23a	128.46±15.47ab
MNP	1.19±0.31ab	8.82±3.02ab	111.69±22.48c	4.89±0.65c	0.85±0.31b	16.583.12±ab	120.24±28.79b
PNP	1.20±0.07ab	8.80±1.57b	113.97±16.75c	4.36±1.23cd	0.57±0.09c	11.26±1.78bc	118.62±12.15b

Note: CK-No amendment and fertilizer; NP-N, P fertilizers; BNP-biochar with N, P fertilizers; ONP-organic fertilizer with N, P fertilizers; MNP-microbial agents with N, P fertilizers and PNP- PAM with N, P fertilizers; Different letters indicate significant difference among treatments at 0.05 level.

ONP and BNP treatments were 11.65 and 11.84 t hm^{-2}, respectively. These yields for the two experimental years were increased by 19.81%-30.28% compared to CK treatment. Simultaneously, biochar combined with N, P fertilizer increased the maize yield more than organic fertilizer combined with N, P fertilizer after two years.

Organic amendments have previously been shown to improved soil structure and crop yield and raised fertilizer use efficiency, specifically when combined with mineral fertilizer enhanced soil properties. The increased in soil SOC, TN, AP, and AK contents were attributed to organic fertilizer and biochar directly providing organics and nutrients as dissolvable fractions [33]. Researchers illustrated that a combination of biochar with fertilizer stimulated the uptake of N, P, and K by roots, thus resulting in the growth and grain yield of rape [34], in contrast to a single amended of organic fertilizer or chemical fertilizer. Moreover, Hu et al. (2021) reported a reduced dispersal of colloidal material after biochar addition, which resembled to the effect of natural organic matter on colloid detachment [35]. Therefore, it was inferred that biochar additions might have potential to maintain or improve soil nutrients content and help to maintain soil productivity as well. Fan et al. (2023) reported that the application of organic fertilizers can improve tomato yield and quality and soil properties, which can explained by the increasing metabolic activity of microorganisms, activating soil nutrients and promoting the absorption of nutrients by crops [36]. Furthermore, the soil C/N turned to be proper after adding organic amendments, which would supply carbon source for microbial growth and promote microbial activity and metabolism to increase nitrogen immobilization and reduce nutrient loss [37].

Aggregate Distribution and Stability

The effects of organic amendments combined with chemical fertilizer on soil water-stable aggregates distribution and stability under equal nitrogen application rate are shown in Table 5. These result showed that treatment with organic amendments improved the aggregates stability when compared to the CK treatment. The water-stable aggregates of the treated loessal soil were main at >0.25 mm size, which accounting for more than 42% of the total aggregate mass. The proportion of water-stable aggregates declined with the decrease of the aggregate diameter. Application of PAM, organic fertilizer and biochar increased the content of > 0.25 mm soil water-aggregates by 52.97%, 45.32% and 47.08%, respectively. There was a similar effect of organic amendments on stability of >2 mm and >0.25 mm size water-stable aggregates, while the increase is slightly less than that of the >0.25 mm aggregate. Meanwhile, there was significant effect of organic amendments on the stability of 0.25-2 mm aggregates (p<0.05). The highest positive effect of 0.25-2 mm aggregates was achieved with PNP treated soil. While, the size of 0.053-0.25 mm aggregates decreased by 10.30% and <0.053 mm size declined by 47.82% in PAM treated soil when compared to CK treatment.

The application of organic amendments significantly affected soil aggregate MWD and GMD under wet sieving at P<0.05. The variation of GWD under the application of organic amendments was consistent with that of MWD. The orders of effectiveness of the organic amendments applications on the MWD and GWD were as follows: PNP>BNP>ONP>MNP>NP>CK. The application of organic amendments also had significant effect on PAD at P<0.05. The minimum PAD of the treated soil was achieved with PNP, which decreased the value of PAD by 38.45% compared to the CK treatment.

In our study, we found that the application of organic amendments significantly increased the content of soil macro-aggregates. Similarly to our conclusion, Hu et al. (2021) reported that application of biochar was more effective in increasing soil macro-aggregates and stabilized soil aggregates [35]. A similar conclusion has been drawn that organic amendment played an important role in improving soil chemical properties,

Table 5 Distribution of water-stable aggregate fractions and aggregate stability under different organic amendments.

Treatment	Distribution of water-stable aggregate fractions/%					Aggregate stability		PAD/%
	>2 mm	2~0.25 mm	0.25~0.053 mm	<0.053 mm	>0.25 mm	MWD	GWD	
CK	12.91c	18.44b	43.21a	25.43a	31.36c	0.59	0.24	15.04
NP	13.16c	19.36b	43.42a	24.06ab	32.525c	0.62	0.25	13.98
BNP	21.54a	24.58a	38.41b	15.47cd	46.12ab	0.77	0.30	9.90
ONP	20.31ab	25.26a	38.09b	16.34c	45.57ab	0.75	0.29	9.51
MNP	19.02b	23.14ab	38.52b	19.32b	42.16b	0.71	0.28	10.55
PNP	21.05a	26.92a	38.76b	13.27d	47.97a	0.79	0.32	9.26

Note: CK-No amendment and fertilizer; NP-N, P fertilizers; BNP-biochar with N, P fertilizers; ONP-organic fertilizer with N, P fertilizers; MNP-microbial agents with N, P fertilizers and PNP- PAM with N, P fertilizers; Different letters indicate significant difference among treatments at 0.05 level.

macro-aggregate formation and aggregates stability [25, 38]. Moreover, Albalasmeh et al. (2021) reported that adding PAM at the concentration 1000 mg L^{-1} of low molecular weight, aggregate stability and saturated hydraulic conductivity increased 3-fold compared to the control treatment [14]. The MWD of soil aggregates also increased by 31.08%~46.12% compared to the CK treatment, which is in line with the outcomes of other studies, such as Dai et al. (2019) [19]. Generally, combined application of organic amendments and mineral fertilizer lead to a higher increase in aggregate stability than individual applications. This result is attributed to the presence of chitin and other polysaccharide polymers in organic amendments, which readily form hydrogen bonds with oxygen atoms on the crystal plane of clay minerals, thereby improving soil agglomeration [39]. Additionally, foreign carbon serves as a cementing agent directly or indirectly, contributing to the formation of soil aggregates and enhancing soil aggregate stability through physical protection.

Organic carbon also plays a pivotal role in aggregate stability, showing a significant positive correlation with the average weight diameter of aggregates (Fig. 2). The introduction of organic amendments increases the content of soil organic cementing substances and stimulates the production of microbial metabolites, such as polysaccharides, which further promote soil agglomeration [40]. Numerous studies have demonstrated that soil organic matter acts as a cementing substance that enhances soil structure and promotes aggregate formation, resulting in improved soil water holding capacity and reduced soil erosion by binding micro-aggregates and soil particles into macro-aggregates [41, 42]. The input of organic materials provides additional cementing materials for aggregate formation by supplying energy for microbial activities and expediting the humification of organic matter. Furthermore, organic amendments encourage the growth of crop roots and fungal hyphae development, which further accelerate the aggregation of soil silt and clay

particles and the transformation of micro-aggregates into macro-aggregates [43]. Soil pH also emerges as a crucial factor influencing the particle size composition of aggregates. The decrease in soil pH caused by organic amendments can increase the solubility of calcium phosphate, resulting in the release of Ca^{2+} that enhances the flocculation effect of soil colloids [44].

Soil Organic Carbon after Organic Amendments

The highest content of organic carbon was achieved in the 2-0.25 mm macro-aggregate, followed by the 0.25-0.053 mm micro-aggregate, and the content of SOC in the silt and clay particles (<0.053 mm) was lowest (Table 6). The application of organic amendments increased the SOC content of the three aggregate size groups, and the levels of effectiveness of the applications on the SOC content of aggregates with a size of >0.25 mm were as follows: BNP>ON>MNP>PNP>NP>CK. The SOC of BNP treatment in macro-aggregates, micro-aggregates and silt and clay fractions was 5.79-, 1.03-, and 0.53-fold greater (p<0.05) than those of CK.

Our results indicate a significant increase in the content of organic carbon in soil macro-aggregates treated with organic amendments. The organic carbon was mainly distributed in these macro-aggregates. A similar conclusion was drawn by Yilmaz and Sönmez (2017), who reported the highest content of soil organic carbon in 2-1 mm size aggregates after applying organic/bio-fertilizer, indicating improved soil aggregate stability [17]. This suggests that the increased carbon input tends to immobilize in macro-aggregates, protecting it from decomposition due to physical protection [45]. However, adding organic fertilizer, biochar and straw as soil ameliorant had a higher content of organic carbon of clay particle than that of macro-aggregates and micro-aggregates according to Dai et al. (2019) [19]. This result was due to the mineral surface saturation and the chemical binding capability between silt and clay particles and organic molecule [39].

Table 6 Effect of organic amendments on soil organic (SOC) content in macro- (2-0.25mm), micro- (0.25-0.053 mm) aggregate and power clay (<0.053mm) aggregate of clay loam textured loessal soil (%).

Treatment	Aggregate size (mm)		
	>0.25 mm	0.25-0.053 mm	<0.053 mm
CK	1.05c	0.65bc	0.53b
NP	1.4c	0.78b	0.67ab
BNP	7.13a	1.32a	0.81a
ONP	5.89ab	1.21a	0.77a
MNP	3.14b	1.03ab	0.72a
PNP	2.89bc	0.85b	0.64ab

Note: CK-No amendment and fertilizer; NP-N, P fertilizers; BNP-biochar with N, P fertilizers; ONP-organic fertilizer with N, P fertilizers; MNP-microbial agents with N, P fertilizers and PNP- PAM with N, P fertilizers; Different letters indicate significant difference among treatments at 0.05 level.

Moreover, Kaiser and Guggenberger (2000) reported that most organic matter remained stable in the soil from binding tightly to clay particles by adsorption [46]. With a larger specific surface area, clay particles was the main adsorbent of soil organic matter and the main active component involved in soil particle aggregation [47].

Correlation Analysis between Soil Organic Carbon Content and Aggregate Stability

The relationship between the soil organic carbon (SOC) content and stability of aggregates is shown in Fig. 2a). The correlation analyses showed that there was a significant ($P<0.05$), positive correlation ($r^2 = 0.76$) between the SOC content and stability of aggregates, and a significant ($P<0.05$), negative correlation ($r^2 = 0.93$) between the pH and stability of aggregates. Results also showed that maize yield was positively correlated with the content and stability of aggregates.

Structural equation model (SEM) revealed that soil physiochemical properties had direct and indirect effects on soil aggregate distribution and stability after application of soil organic amendments (Fig. 2b). Soil pH, SOC and TN can explained 86% distribution
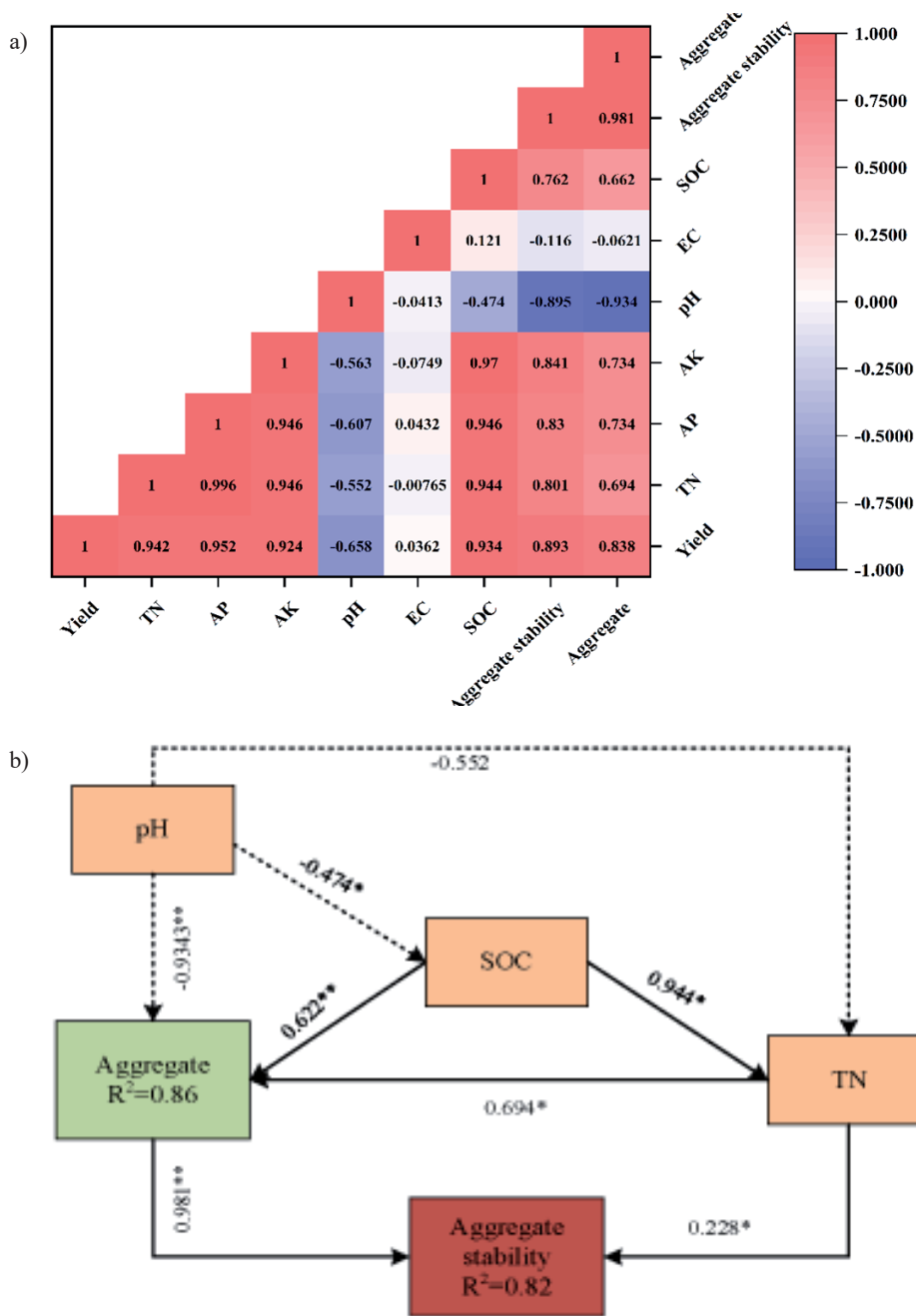

Fig. 2. Correlation between soil properties, aggregate and yield and structural equation model (SEM).
EC: Electro conductivity; SOC: Soil organic carbon; TN: Total nitrogen; AP: Available phosphorus; AK: Available potassium.

of macro- and micro-aggregate, SOC and TN had a positive effect (p<0.01 and p<0.05) while pH had a negative effect on aggregate (p<0.01). In addition, soil macro- and micro-aggregate explained 82% of aggregate stability. These results showed that the combination of organic amendments and mineral fertilizer improving soil aggregate stability and nutrients content and thus the higher yields of maize, especially in relatively poor soils.

Our study indicated that the application of mineral fertilizer alone had no significant effect on SOC content in soil aggregates, whereas combining organic amendments and fertilizer significantly increased SOC content in aggregates of all particle sizes. This increase was linked to the introduction of foreign carbon, which improved soil properties, enhanced microbial activity, and facilitated carbon sequestration. Additionally, the distribution of organic carbon in different particle sizes of aggregates was influenced by the application of organic amendments. Notably, the organic amendment had the highest contribution rate to organic carbon in the 0.25-2 mm size aggregates. Similar to our result, Cao et al. (2020) reported that organic fertilizer increased the organic carbon content of micro-aggregates due to the improve of soil structure, pH and nutrient distribution [48]. Finally, the application of fertilizer and soil amendments significantly increased the organic carbon content of aggregates of all particle sizes.

Overall, soil aggregates stability had a significantly positive effect on soil quality, land productivity and environment, which was an important factor to soil water transport, plant growth and microbial activities. In addition, as a benign straw returning method, the application of biochar to field also an efficient pathway to promote the utilization of agricultural and forestry solid waste resources. Furthermore, biochar has important significance for carbon sequestration and emission reduction of farmland soil ecosystem.

Conclusions

The 2-year field experiment shown that the organic amendments used in this experiment had significant and positive effects on soil macro-aggregates content and stability, while the PAM and biochar treatments had a higher effect on improving soil aggregates stability. The distribution of SOC was significantly correlated with the aggregate size, and the highest content of SOC were achieved in macro-aggregates, followed by micro-aggregates, and that of silt clay was lowest. The soil organic carbon content was highest when biochar combined with fertilizer in each grain size of aggregates. The results confirmed the potential of the co-application of biochar and chemical fertilizer to achieve increases in soil SOC, TN, AP, and AK contents in loessal soil. These results confirmed that the improved yield and soil quality of loessal soil were attributed to the enhanced soil aggregate stability and increased soil nutrients,

especially promoted the availability of N and P. The co-application of biochar and chemical fertilizer can reduce soil bulk density and EC, improve the content of soil organic carbon on loess plateau. However, these promising findings of biochar on farmland ecosystem, particularly in loessal soil in loess plateau, need to be confirmed by long-term field experiments.

Acknowledgments

Conflict of Interest

The authors declare no conflict of interest.

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