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Mechanisms of carbon and nitrogen distribution in soil aggregates in response to soil conditioners

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Soil conditioner has good performance in improving soil environment and solving soil barrier problems. The purpose of this study was to analyze the effects of different types of soil conditioners on the distribution of soil aggregates and the yield of corn, and to find out the suitable soil conditioners for improving the barren soil in the Yellow River irrigation area. The treatments include no soil conditioner (CK), cow dung organic fertilizer soil conditioner with different organic matter contents (Om-20%, Om-30%, Om-40%, Om-45%), humic acid soil conditioner (Hu-20%) and amino acid soil conditioner (Am-25%). The result indicated that different types of soil conditioners promoted the formation of aggregates with particle size > 0.25 mm, improved the stability of aggregates, and increased the content of organic carbon and total nitrogen in macroaggregates. Compared with CK, the contents of organic carbon and total nitrogen of various soil conditioners in macroaggregates increased by 20.08-48.89% and 8.36-42.86%, respectively. The organic carbon content of macroaggregates under Am-25% treatment was significantly increased by 7.15% compared with Hu-20% treatment. The contents of available phosphorus, available potassium, organic carbon and total nitrogen under Am-25% treatment was increased by 6.37-45.86%, 6.29-22.39%, 3.49-12.05% and 2.64-19.74% than that of cow dung organic fertilizer soil conditioner treatments, respectively. Correlation analysis and structural equation model analysis showed that macroaggregates with particle size greater than 0.25 mm were positively correlated with corn hay yield. Aggregate stability and chemical properties accounted for 71% of corn hay yield changes, and organic carbon mainly affected corn hay yield through soil C/N ratio. Therefore, the application of soil conditioner, especially amino acid soil conditioner, to the barren soil in the Yellow River irrigation area can improve the physical and chemical properties of soil, promote the formation of macroaggregates, improve the stability of aggregates, and promote the high and stable yield of corn.

Keywords Soil conditioners, The stability of soil aggregates, Organic carbon, Soil chemical properties, Corn

Soil aggregates, as nutrient reservoirs and microbial habitats, are the most basic structural foundation of soils. Soil aggregate stability is a result of combined effects of complex biological, chemical, and physical processes in soil[1]. Aggregates of different sizes play different roles in the process of soil nutrient retention and supply[2], and their quantity reflects soil's ability to water retention, nutrient supply and storage, and permeability to a certain degree, which have been used to evaluate the quality of soil as an important indicator[3]. In recent years, highly intensive agricultural production and irrational farming activities have led to the destruction of soil structure, reduced stability of soil aggregates, loss of soil nutrients, and reduced crop yields and their stability[4–6]. In addition, ecological problems such as soil and water pollution, reduced soil fertility and lower quality of agricultural products are becoming more and more prominent due to the large amounts of chemical fertilizers applied, which seriously restricts the development of agricultural economy[7]. The negative impacts caused by the irrational use of chemical fertilizers have attracted the attention of the government and researchers, and it is believed that the efficient use of bio-organic fertilizers will be an inevitable trend in the development of fertilizers in China[8]. Therefore, regulating the distribution of soil aggregates through organic conditioners is essential to improve soil structure and crop yield.

With the development of industrial technology, the application of soil conditioners is gradually becoming an effective method of modern soil improvement. Previous studies have shown that soil conditioners have positive

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effects on improving acidified, salinized and heavy metal polluted soils. At the same time, it can further expand and increase soil fertility by increasing the organic matter in the soil[9,10]. In traditional agricultural practices, a single type of fertilizer and improper use are the key factors leading to the destruction of soil structure and degradation of soil quality[11]. Compared with traditional fertilizer application methods, soil conditioner application can aggregate dispersed particles in the soil, promote the formation of water-stable aggregate structure in the tillage soil, and improve the soil structure retention rate[12]. In addition, different types of soil conditioners have different effects on the soil, the addition of organic matter (corn and wheat straw) and humic acid significantly increased content and mass fraction of water-stable aggregates > 0.25 mm in the soil and increased organic carbon stock in soil[13]. Biochar conditioners combined with nitrogen and phosphorus fertilizers could improve proportion and stability of 0.25–2 mm aggregate, and increase the contents of soil matter carbon, total nitrogen, and phosphorus[14]. It is worth noting that research on soil conditioners is developing rapidly at home and abroad, mainly focusing on single types of organic fertilizers or soil conditioners for soil erosion, soil remediation[15–17]. Fewer studies have been conducted on the effects of continuous application of different types of soil conditioners with different organic matter contents on the structural improvement of sandy loam soils, changes in soil aggregate characteristics, and crop yield increases.

Sandy loam soil, as one of the widely distributed soil types along the yellow irrigation area, has more problems, such as poor structure, humus accumulation and insufficient water and fertilizer storage capacity, etc., and the use of conditioners to improve the soil structure is of great significance in solving the problem of high and stable yield along the yellow irrigation area. we hypothesis that application the soil conditioners can improve the physical and chemical properties of sandy loam soils, promote the formation of macroaggregates, and promote the yield of corn. The primary objectives of the present study were: (1) to analyze the effects of different types of soil conditioners on the distribution and stability of soil aggregates in the Yellow River irrigation area; (2) to evaluate the effects of soil conditioner application on the distribution and contribution rate of organic carbon and total nitrogen in soil aggregates; (3) to clarify the difference of soil physicochemical properties and corn yield under different types of soil conditioners.

Results

The effect of different soil conditioners on the distribution and stability of water-stable soil aggregates

Different types of conditioners have significant effects on soil aggregate distribution (Fig. 1). The mesoaggregate (0.053–0.25 mm) was main aggregate component, with an average content of 69.54% (2021) and 69.81% (2022). Compared with CK, except Om-45% treatment, the content of macroaggregates significantly increased by 19.36-26.34%, and the content of microaggregates significantly decreased by 17.25-29.98%. In 2022, the Am-25% and Hu-20% treatments showed significant increase in macroaggregate content of 22.14% and 20.81%, significant decrease in microaggregate content of 10.19% and 11.94%, and significant increase in macroaggregate content of 18.23–19.77% in the Om-20%, Om-30%, and Om-40% treatments, respectively, as compared to Om-45% ($p < 0.05$).

Different types of conditioners have significant effects on soil aggregate MWD and GMD ($p < 0.05$; Fig. 2). In 2021, MWD and GMD were significantly increased by 11.02-15.30% and 11.43-16.41% under different types of conditioners compared to CK ($p < 0.05$). In 2022, MWD and GMD were significantly increased by 15.99-

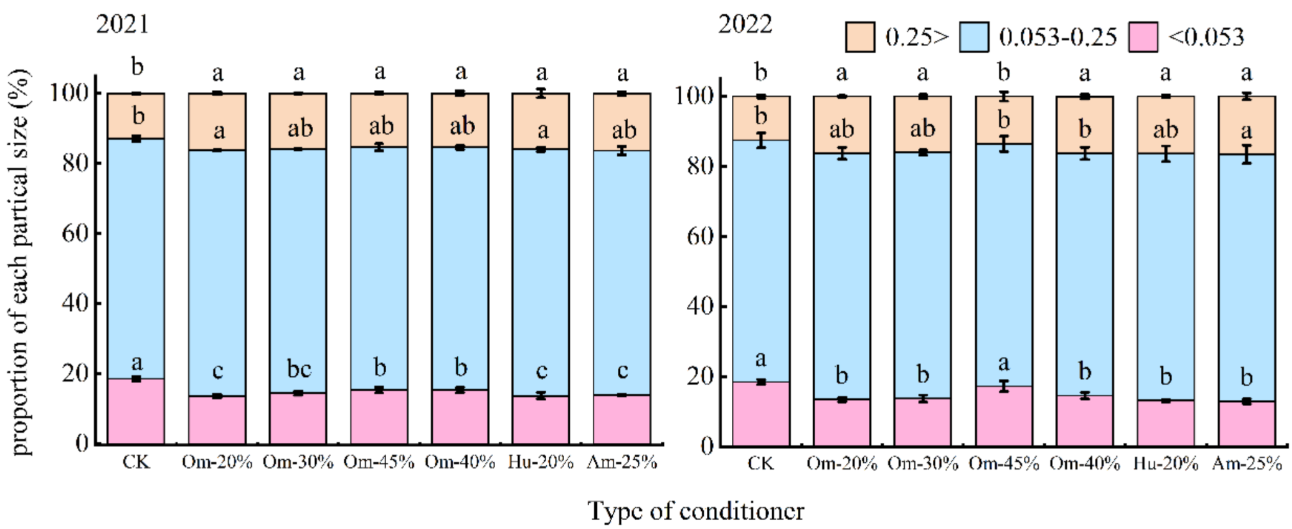

Fig. 1. Particle size distribution characteristics of soil aggregates treated with different conditioners. Treatments and parameters in the legend: CK, no soil conditioner; Om-20%, Om-30%, Om-45%, Om-40%, cow dung organic fertilizer soil conditioner with different organic matter contents; Hu-20%, Humic Acid soil conditioner; Am-25%, Amino acid (liquid) soil conditioner. Different lowercase letters (a, b, c) indicated significant differences ($p < 0.05$, LSD) between control and soil conditioners treatments. The same as below.

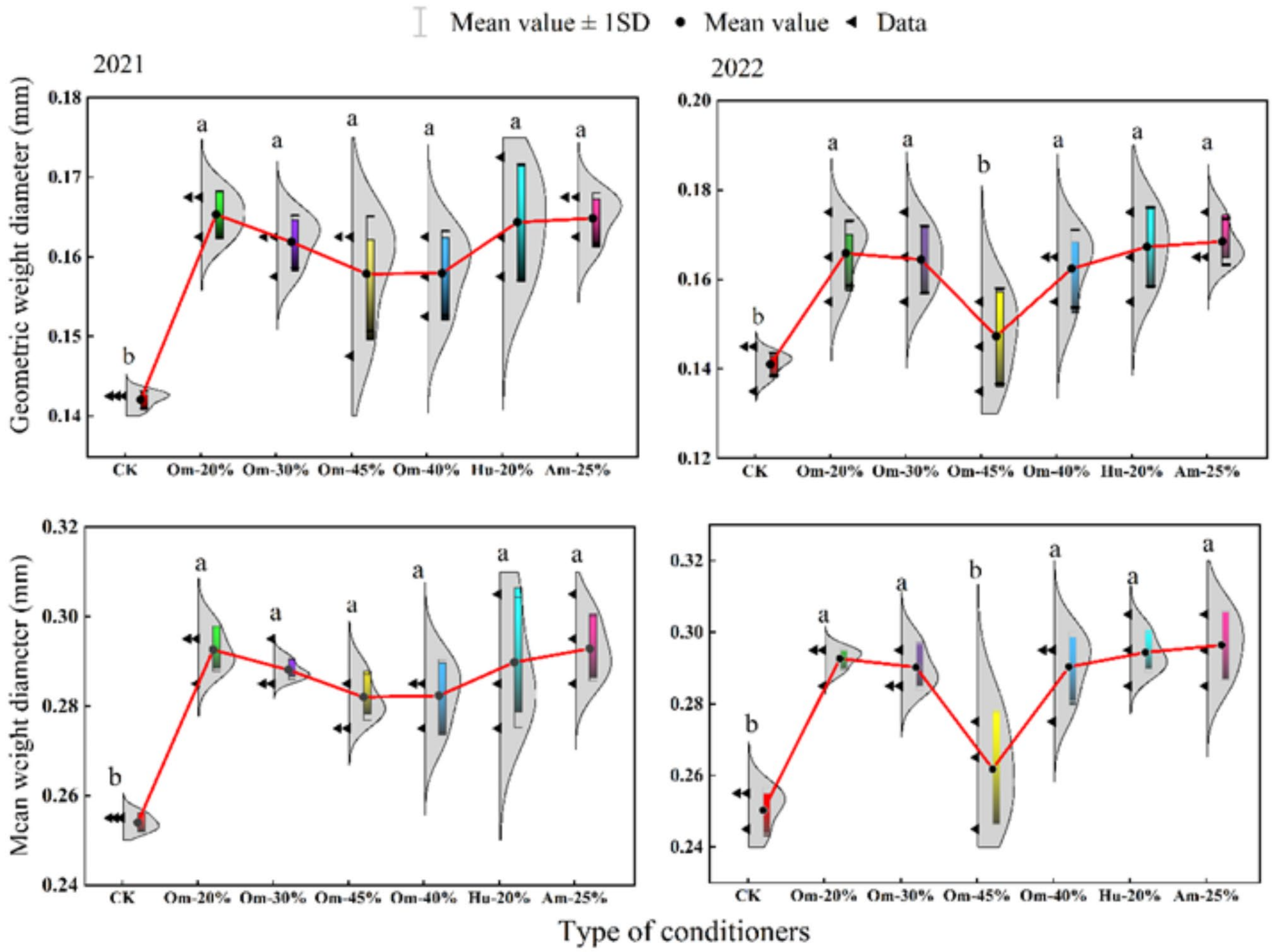

Fig. 2. MWD and GMD values for different types of soil conditioners in 2021 and 2022.

18.47% and 15.18-19.50% under different types of conditioners except Om-45% treatment as compared to CK. In 2021, there was no significant difference between the different types of conditioners ($p < 0.05$). In 2022, GMD and MWD were significantly increased by 14.39% and 13.22% for Am-25%, 13.51% and 12.45% for Hu-20%, 10.25-10.56% and 10.85-11.76% for Om-20%, Om-30%, and Om-40% treatments, respectively, as compared to Om-45% treatment ($p < 0.05$).

Organic carbon and nitrogen content in water-stable soil aggregates

Different types of conditioners had significant effects on the distribution of organic carbon and total nitrogen in soil aggregates ($p < 0.05$; Fig. 3). Comparison of the average content of organic carbon and total nitrogen in aggregates of different particle sizes showed that the content of organic carbon and total nitrogen was 20.07 and 0.83 g/kg in macroaggregates, 16.21 and 0.76 g/kg in mesoaggregates, and 17.65 and 0.77 g/kg in microaggregates. Compared with CK, organic carbon and total nitrogen average contents were significantly increased by 20.08–48.86% and 8.36%-42.86% in macroaggregates and 28.33-59.21% and 8.59-51.85% in microaggregates under different types of conditioner treatments. The organic carbon average content in the macroaggregate significant increased by 15.22% and 15.97% under the Am-25% treatment and by 12.32% and 11.59% under the Hu-20% treatment compared to the Om-45% and Om-40% treatments, respectively. The total nitrogen average content in the macroaggregate significant increased by 8.6% and 7.42% under the Am-25% and Hu-20% treatments, respectively, compared to the Om-45% treatment ($P < 0.05$). Am-25% significantly increased the organic carbon content in microaggregates by 10.90% and 11.29% compared to Om-40% and Om-45%, respectively ($P < 0.05$).

Carbon and nitrogen contribution rate in different soil particle size aggregates

Different types of soil conditioners significantly affected the contribution of organic carbon and total nitrogen in soil aggregates (Table 1; $p < 0.05$). The carbon and nitrogen contributions of soil aggregates of different grain sizes are as follows mesoaggregates are the highest, followed by macroaggregates, and microaggregates are the lowest. In 2021, compared with CK, the contribution of organic carbon in macroaggregates was significantly increased by 11.93-25.29% in all treatments except Hu-20% treatment, and the contribution of total nitrogen in macroaggregates was significantly increased by 12.49–22.96% in all treatments except Om-40% treatment ($p < 0.05$). In 2022, different conditioner treatments significantly increased the organic carbon and total nitrogen

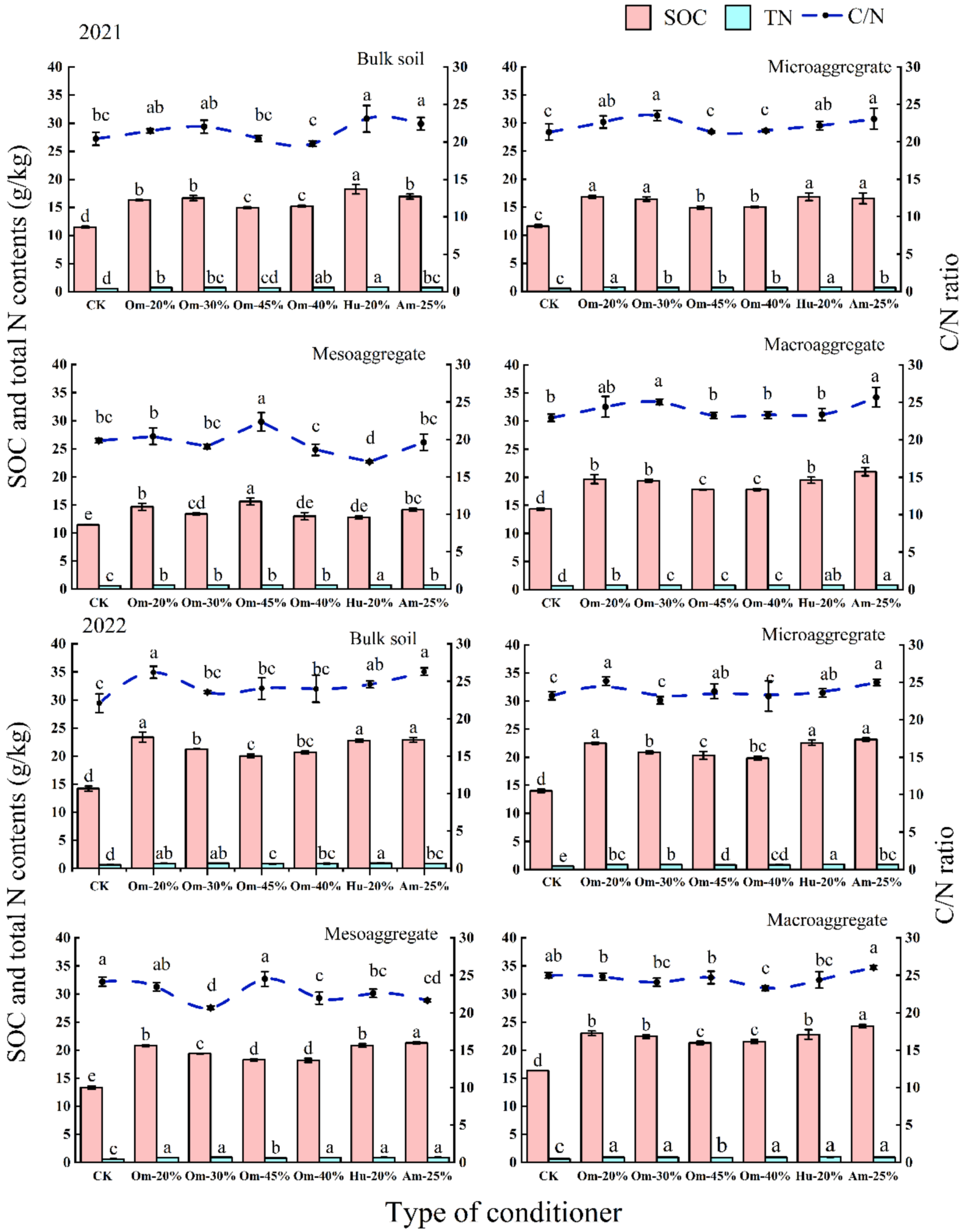

Fig. 3. Carbon, Nitrogen Content, and C/N Ratio in Different Soil Particle-Sized Aggregate.

contributions in macroaggregates by 11.12–22.03% and 15.28–23.66% compared to CK, except for Om-45% treatment. In 2021, comparisons between conditioners revealed that the Am-25% treatment increased the contribution of macroaggregate organic carbon by 10.16% and 11.94% compared to the Om-45% and Om-40% treatments, and increased the contribution of macroaggregate total nitrogen by 15.39% compared to the Om-40% treatment. In 2022, the Hu-20% and Am-25% treatments significantly increased the organic carbon contribution by 13.75% and 21.94% and the total nitrogen contribution by 18.17% and 26.75% in the macroaggregates compared to the Om-45% treatment ($p < 0.05$).

Years	Item	Treatment	Aggregate size(mm)		
			< 0.053 mm	0.053–0.25 mm	> 0.25 mm
2021	Organic C	CK	18.78 ± 0.82 a	68.23 ± 1.29 b	16.09 ± 0.21 d
		Om-20%	14.14 ± 0.77 bc	62.81 ± 2.62 c	19.56 ± 0.78 ab
		Om-30%	14.27 ± 0.54 bc	55.84 ± 0.83 d	18.45 ± 0.17 ab
		Om-45%	15.37 ± 0.73 b	72.26 ± 1.79 a	18.30 ± 0.57 bc
		Om-40%	15.16 ± 1.04 bc	59.02 ± 3.64 d	18.01 ± 0.95 bc
		Hu-20%	12.72 ± 1.35 d	49.21 ± 1.90 e	17.09 ± 2.05 cd
		Am-25%	13.62 ± 0.64 cd	58.18 ± 1.47 d	20.16 ± 0.77 a
	Total N	CK	18.02 ± 0.63 a	70.34 ± 1.77 a	14.33 ± 0.71 d
		Om-20%	13.41 ± 0.42 c	66.12 ± 1.91 b	17.24 ± 0.84 ab
		Om-30%	13.39 ± 0.76 c	64.49 ± 1.89 bc	16.22 ± 0.34 bc
		Om-45%	14.74 ± 0.50 b	66.27 ± 1.55 b	16.12 ± 0.18 bc
		Om-40%	13.94 ± 0.59 bc	62.71 ± 0.35 c	15.27 ± 0.28 cd
		Hu-20%	13.19 ± 0.43 c	66.74 ± 2.22 b	16.79 ± 0.89 ab
		Am-25%	13.25 ± 0.31 c	66.58 ± 1.31 b	17.62 ± 0.97 a
2022	Organic C	CK	18.26 ± 0.83 a	64.86 ± 1.83 a	14.39 ± 0.27 b
		Om-20%	12.92 ± 0.83 b	62.70 ± 4.43 a	15.99 ± 0.24 a
		Om-30%	12.96 ± 0.78 b	64.02 ± 0.86 a	16.89 ± 0.42 a
		Om-45%	16.83 ± 1.76 a	63.12 ± 3.27 a	14.40 ± 1.47 b
		Om-40%	13.75 ± 0.36 b	60.81 ± 0.76 a	16.80 ± 0.86 a
		Hu-20%	13.09 ± 1.17 b	64.46 ± 2.39 a	16.38 ± 0.51 a
		Am-25%	12.32 ± 0.73 b	65.59 ± 1.29 a	17.56 ± 1.12 a
	Total N	CK	17.33 ± 0.61 a	65.19 ± 2.35 b	12.71 ± 0.60 b
		Om-20%	13.43 ± 0.73 b	67.96 ± 2.22 ab	16.88 ± 0.49 a
		Om-30%	13.49 ± 0.91 b	69.69 ± 0.84 a	16.53 ± 0.10 a
		Om-45%	17.02 ± 2.29 a	67.04 ± 1.40 ab	13.98 ± 1.02 b
		Om-40%	14.27 ± 0.47 b	70.58 ± 4.45 a	17.29 ± 1.11 a
		Hu-20%	13.62 ± 1.12 b	67.49 ± 0.42 ab	16.52 ± 0.69 a
		Am-25%	12.95 ± 0.72 b	70.33 ± 1.15 a	17.72 ± 1.09 a

Table 1. Effect of soil conditioners on the contribution of soil organic carbon and total nitrogen (%).

Years	Treatment	Total *N* (mg/kg)	Available *P* (mg/kg)	Available K (mg/kg)	Organic C (g/kg)	pH
2021	CK	0.81 ± 0.02 d	20.43 ± 2.17 c	123.77 ± 6.02 e	14.63 ± 0.79 d	8.92 ± 0.03 a
	Om-20%	0.86 ± 0.01 b	58.90 ± 4.58 ab	145.23 ± 2.53 b	18.50 ± 1.17 b	8.88 ± 0.04 a
	Om-30%	0.85 ± 0.0.1 bc	55.47 ± 7.34 b	143.93 ± 3.82 b	18.42 ± 0.44 b	8.72 ± 0.03 c
	Om-45%	0.83 ± 0.01 cd	49.78 ± 17.37 b	126.13 ± 2.66 d	16.67 ± 0.17 c	8.82 ± 0.03 b
	Om-40%	0.85 ± 0.01 bc	51.89 ± 5.81 b	134.63 ± 2.81 c	16.98 ± 0.15 c	8.78 ± 0.01 b
	Hu-20%	0.87 ± 0.01 ab	63.50 ± 5.68 ab	147.60 ± 2.79 ab	18.69 ± 0.45 b	8.82 ± 0.02 b
	Am-25%	0.89 ± 0.03 a	70.56 ± 3.75 a	154.37 ± 4.49 a	19.96 ± 0.82 a	8.67 ± 0.01 c
2022	CK	0.80 ± 0.02 d	21.51 ± 2.81c	122.77 ± 8.70 d	14.21 ± 0.47 d	8.87 + ± 0.04 a
	Om-20%	0.89 ± 0.02 ab	61.54 ± 13.33 ab	154.33 ± 2.61 b	22.75 ± 0.28 a	8.65 ± 0.01 cd
	Om-30%	0.87 ± 0.01 bc	59.58 ± 10.42 ab	150.93 ± 2.04 b	21.25 ± 0.06 b	8.75 ± 0.07 b
	Om-45%	0.83 ± 0.04 cd	44.88 + ± 7.543 b	145.17 ± 6.55 bc	20.02 ± 0.33 c	8.78 ± 0.03 b
	Om-40%	0.86 ± 0.05 bc	55.66 ± 12.32 ab	137.83 ± 3.80 cd	20.67 ± 0.24 bc	8.73 ± 0.02 bc
	Hu-20%	0.90 ± 0.01 ab	73.79 ± 6.736 a	150.47 ± 6.22 b	22.87 ± 0.44 a	8.63 ± 0.09 d
	Am-25%	0.93 ± 0.02 a	65.46 ± 11.03 a	165.27 ± 2.05 a	23.35 ± 0.90 a	8.57 ± 0.04 d

Table 2. The impact of different soil conditioners on Soil Chemical properties.

Effects of applying different soil conditioners on soil chemical properties

Different types of soil conditioners had significant effects on soil chemical properties ($p < 0.05$; Table 2). In 2021, available phosphorus, available potassium and organic carbon were significantly increased by 143.66-245.37%, 2.04–24.72% and 13.94–36.43% in different types of conditioners as compared to CK. In 2022, available phosphorus and organic carbon in different types of conditioners were significantly increased by 108.65-243.05%

and 40.89–64.32%, respectively, compared to CK. pH was significantly decreased by 1.03–3.5%. The Am-25% treatment significantly increased the mean contents of total nitrogen, quick-acting phosphorus, quick-acting potassium and organic carbon by 9.64, 43.8, 18.12 and 9.64% as compared to Om-45% ($p < 0.05$). In 2021, there was a significant decrease in pH of 0.69-1.83% under Om-30% compared to Om-20%, Om-45% and Om-40%. In 2022, there was a significant decrease in pH of 2.45% under Am-25% compared to Om-45%.

Yield with different soil conditioners applied

Soil conditioner had a significant effect on corn hay yield ($p < 0.05$; Fig. 4). Corn hay yield was significantly increased by 16.38–40.62% under all conditioner treatments except Om-45% treatment as compared to CK. Yield was significantly increased by 11.42-30.63% under Am-25% treatment as compared to Om-20%, Om-30%, Om-45% and Om-40%. There was a significant increase in yield of 17.25% and 12.59% for Om-20% and Om-30% compared to Om-45%.

The interaction between soil aggregates, soil nutrients, and crop yield

Correlation analysis reveals that corn hay yield is positively associated with the soil nutrients, C/N ratio, organic carbon, aggregate stability, and distribution, while negatively correlated with soil pH (Fig. 5). Structural equation modeling (SEM) analysis indicates that aggregate stability and chemical traits account for 71% of the variation in corn hay yield, where organic carbon mainly affects corn hay yield through soil C/N (path coefficient = 0.39) (Fig. 5). Moreover, there exists a highly significant negative correlation between pH and corn hay yield (path coefficient = 0.60). The relationship between organic carbon content in soil aggregates of different particle sizes and corn hay yield is shown in Fig. 6. It can be seen that organic carbon content in aggregates of > 0.25 mm is significantly correlated with corn hay yield. In addition, there was a significant interaction between the soil SOC, pH and aggregate stability. It is indicating that SOC and pH have important effects on aggregate stability (Fig. 5).

Discussion

By analyzing the distribution of soil aggregates, we found that the soil aggregates were mainly composed of mesoaggregates, accounting for 69.67% of the total aggregates. It has been found that after applying organic

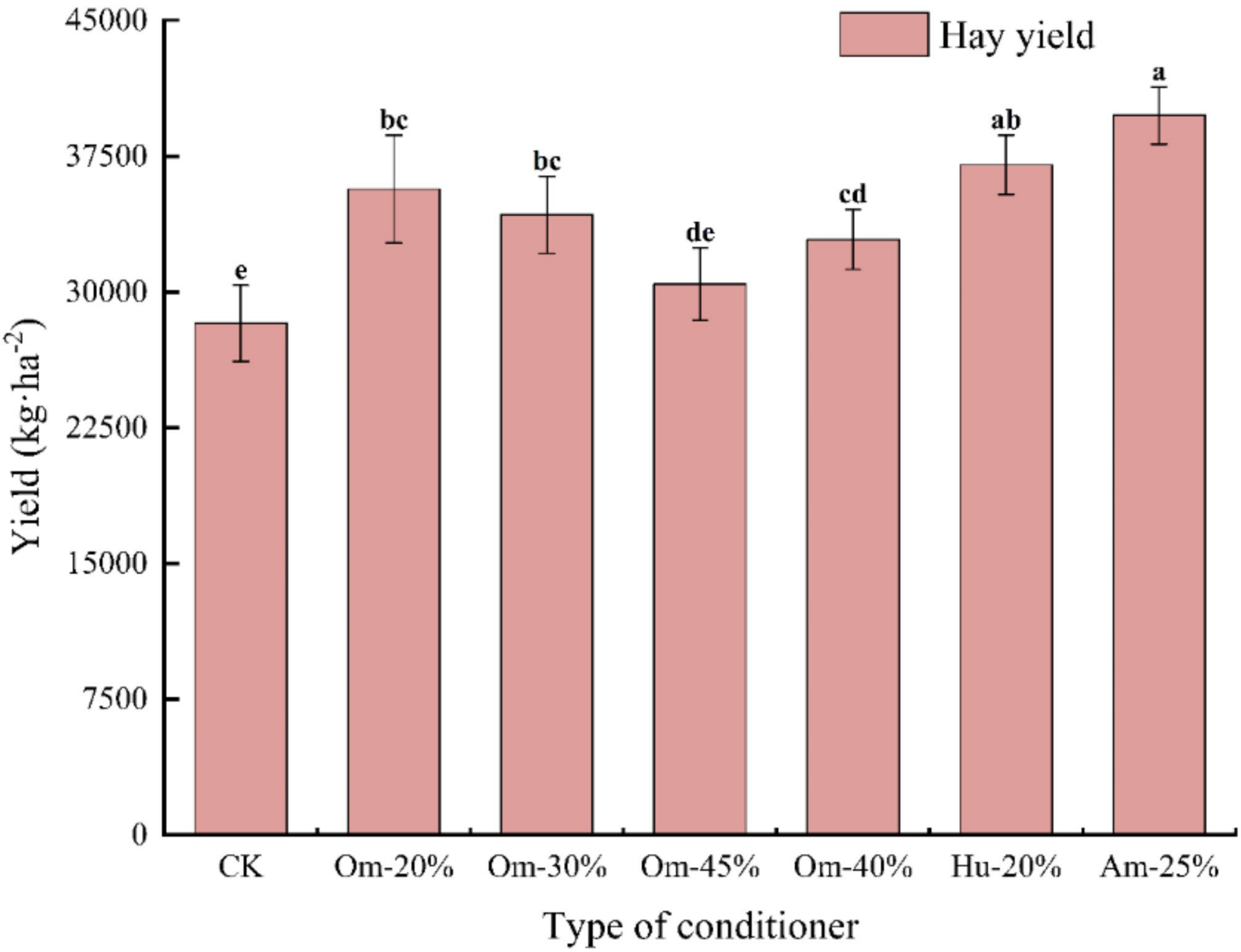

Fig. 4. Different treatments of corn grass and hay yield.

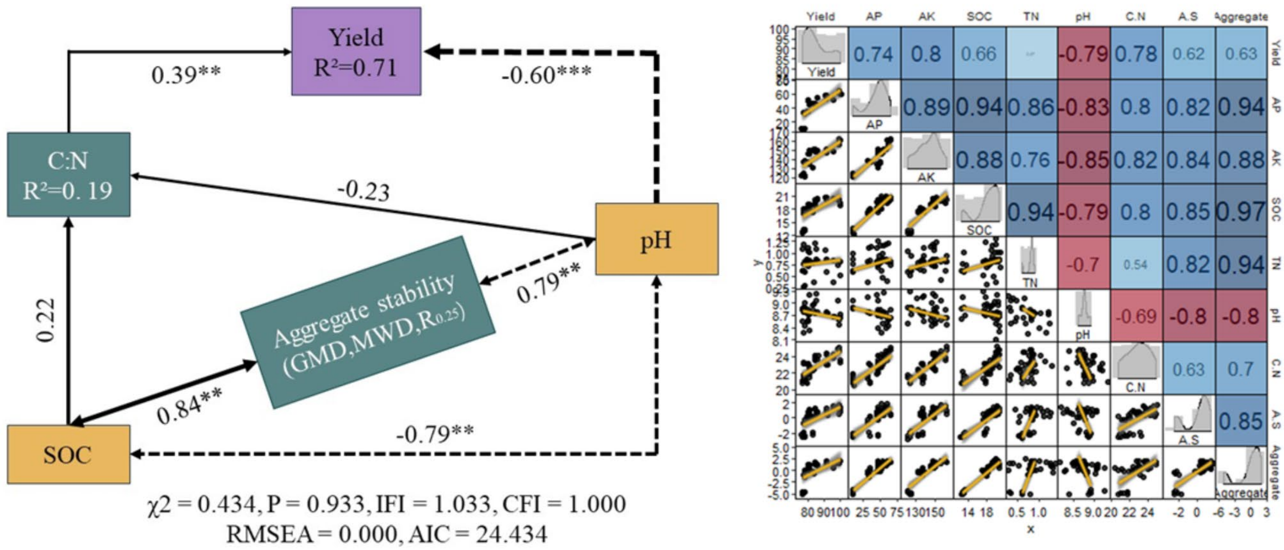

Fig. 5. Structural equation model of Soil chemical properties, aggregate stability, and yield. On the left: the thickness of the lines indicates the size of the influence, and the numbers indicate the path coefficients between different variables. Dashed and solid lines show positive and negative relationships. R^2 was the variance ratio, χ^2, P, IFI, CFI, RMSEA and AIC were the model fitting parameters. The indicators in the diagonals on the right represent aggregate stability (A.S) and the distribution of soil aggregates. Red indicates a negative correlation, while blue indicates a positive correlation. ** -mean $P<0.01$.

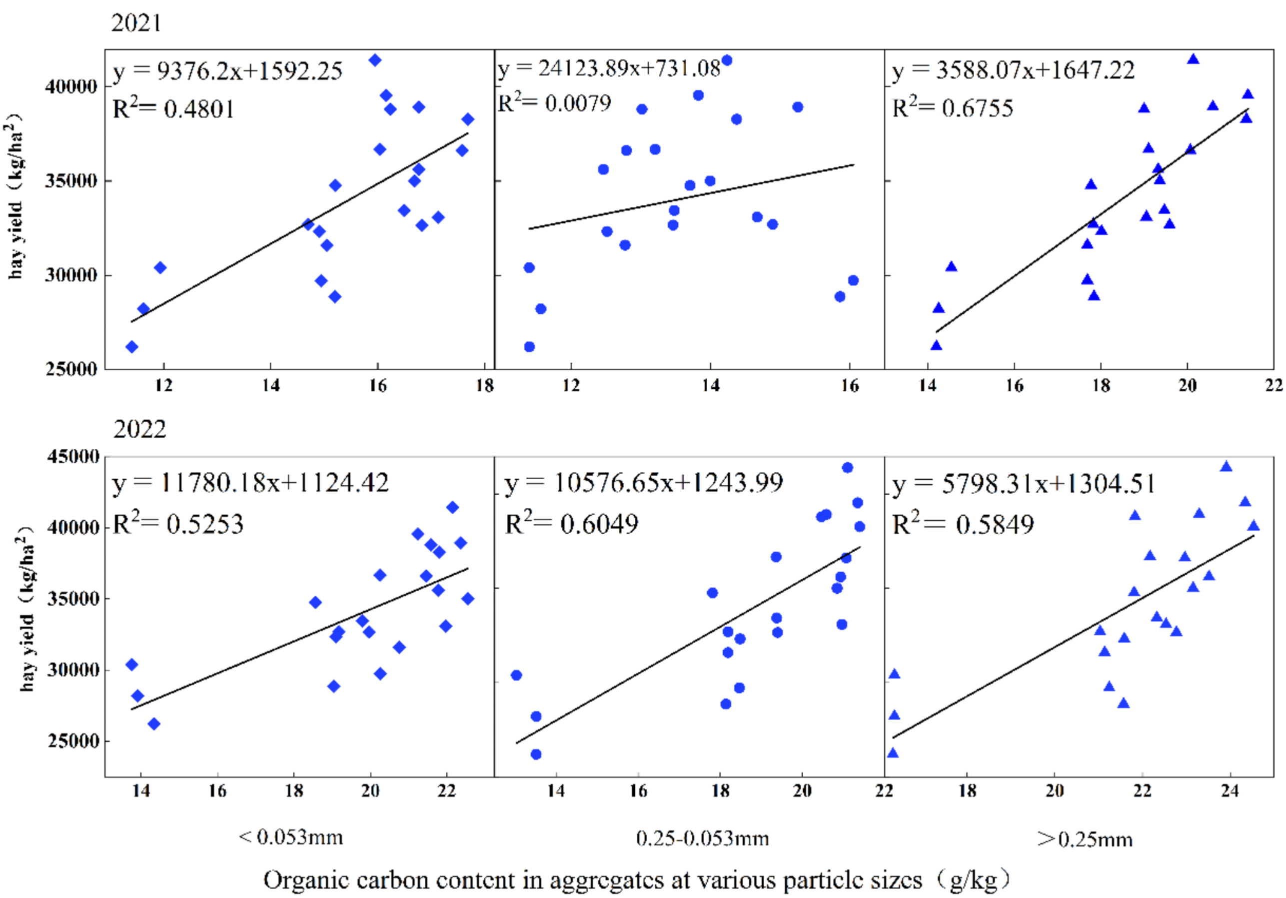

Fig. 6. Relationship between organic carbon content in soil aggregates and 2-year average maize yield.

and inorganic fertilizer conditioners in sandy loam soil, the soil aggregates consist mainly of mesoaggregates[18], while after applying organic fertilizer conditioners in red loam soil, the soil aggregates consist mainly of macroaggregates[19,20]. This may be because the soil has a different texture. In sandy soil, the content of silt clay is quite low, the proportion of sand to gravel is high, and the viscosity between soil particles is poor, which is not conducive to the formation of soil macroaggregates. In the present study, it was observed that application of soil conditioner led to an increase in macroaggregate content and aggregate stability of the soil to varying degrees. This finding is consistent with studies of long-term application of organic fertilizer using straw improvers on sandy soils[12,21]. The main reason is that compounds such as amino acids, humic acids and organic matter in soil conditioners enhance soil microbial activity, accelerate mineralization of organic matter, and promote the formation of macroaggregate[22], moreover, the addition of conditioners activates the elements of nitrogen, phosphorus and potassium in the soil, which in turn promotes the growth of the corn root system, enhances the interaction between the corn root system and soil fungi, and promotes the formation of macroaggregates[23]. Comparison of the different types of conditioners revealed that amino acid and humic acid conditioners increased the formation of soil macroaggregates compared to cow dung conditioners, the main reason for this difference being that lower soil pH enhanced enzyme activity and microbial diversity, which facilitated the decomposition of organic matter and the production of organic acids, which in turn increased the aggregation of microaggregates[24,25].

Application of soil conditioners increased organic carbon and total nitrogen content in macroaggregates. On the one hand, microaggregates aggregated to form macroaggregates, which led to the transfer of organic carbon and total nitrogen from microaggregates, and on the other hand, organic carbon produced by microbial decomposition of roots and mycelium preferentially entered into macroaggregates[26,27]. However, some studies have shown that mesoaggregates more carbon, which may be caused by differences in soil structure[28]. Our study also found that amino acid conditioners were more effective in increasing organic carbon and total nitrogen in macroaggregates. This may be related to the soil pH, which decreases the soil pH and reduces the potential of the soil colloid surface, making the repulsion of the soil colloid surface decrease[29]. Secondly, this study was an alkaline soil, where phosphorus in the soil forms calcium phosphate compounds with exchangeable calcium ions, and the decrease in pH led to the dissolution of calcium phosphate releasing calcium ions, which increased the flocculation of soil colloids[30]. Structural equation modeling also confirmed this. In addition, we found that the content of organic carbon in microaggregates was relatively high compared to mesoaggregates, which on the one hand was still because the soil selected for this experiment contained more sand particles in mesoaggregates, which was unfavorable for organic carbon storage, and on the other hand, it was related to chemical binding ability of microaggregates to organic molecules and the saturation of the mineral surface, and microaggregates have a larger surface area to adsorb more organic carbon[31].

Considering the content of soil aggregates at each grain level in combination with the organic carbon and total nitrogen content of aggregates at different grain levels can better reflect the contribution of aggregates at each grain level to soil organic carbon and total nitrogen, and can comprehensively and objectively reflect the effects of different conditioners on soil organic carbon and total nitrogen[32,33]. The contribution of soil aggregates to organic carbon and total nitrogen was mainly concentrated in the mesoaggregates of 0.053 ~ 0.25 mm. This is inconsistent with the results of previous studies, some studies have shown that the contribution of organic carbon and total nitrogen in soil aggregates with grain size > 0.25 mm is the largest, which may be caused by the difference in soil aggregate content[34,35]. In sandy loam soil, the mesoaggregate content accounted for more than 60% of the aggregates at all particles sizes (Fig. 2). However, comparing the contributions of organic carbon and total nitrogen in soil aggregates of various particle sizes, it was found that the contributions of organic carbon and total nitrogen in macroaggregates was greater, mainly due to the fact that the soil conditioners increased the effective residues and effective carbon in the soil after entering the soil, and the organic carbon produced was decomposed by microorganisms to form an organic and inorganic composite with clay particles, which contributed to the transfer of organic carbon and total nitrogen agglomerates from micro-agglomerates to macroaggregates[16], thus increasing the organic carbon and total nitrogen content in the macroaggregates. Therefore, it can be seen that the increase of contribution rate of organic carbon and total nitrogen in aggregates of different particle sizes is significantly related to the distribution of aggregates.

In this study, it was found that soil conditioner application increased hay yields of maize. Further analysis with SEM showed that soil conditioners affect crop yields mainly by increasing the organic carbon content in the soil, increasing soil aggregate stability, improving soil C/N, and decreasing soil pH. The specific yield increase mechanism may be that conditioners can increase the content and stability of macroaggregates, increase the storage of organic carbon and total nitrogen in macroaggregates, improve soil C/N, and thus provide a favorable nutrient environment for corn growth[36,37]. The C/N ratio controls the degradation of fresh plant residues[38], which is critical in carbon uptake and soil aggregation[20,39]. In addition, a reasonable C/N ratio can promote the growth and activity of microorganisms, adjust the fixation of nitrogen by microorganisms, reduce nutrient loss, and improve nutrient use efficiency[40]. However, the effect of soil conditioners on plant nutrient content is still unclear. In the future, the correlation between plant nutrient changes and yield due to the application of soil conditioners should be further investigated, so as to provide a theoretical basis for the rational utilization of soil conditioners. In conclusion, the application of soil conditioners can be used as an effective way to increase corn yield and improve soil structure in the irrigation areas along the Yellow River, which has a good supportive role in the sustainable development of agriculture as well as high and stable corn yields.

Conclusion

Application of the different types of soil conditioner increased the content of macroaggregates in the soil and improved aggregate stability, in addition, it increased the contribution of organic carbon and total nitrogen in the macroaggregates and improved the soil C/N ratio. In addition, different type of Soil conditioners had significant effects on the soil content of available nutrients, such as soil available phosphorus and available potassium content were increased, and soil pH was reduced, especially the effect of amino acid soil conditioner is the most obvious. These findings suggest that the application of soil conditioners, especially amino acid soil conditioners, can improve the physicochemical properties of barren soils in the Yellow River Irrigation District, promote high and stable corn yields, and advance sustainable agricultural development.

Materials and methods

Experimental site

The experiment was conducted from October 2020 to October 2022 at Tiaoshan Farm (103° 33'e, 36° 43'n) in Jingtai County, Baiyin City, central Gansu Province of China. The annual average temperature was recorded as 9.1℃, with an approximate frost-free period of around 141 days. Annual average precipitation amounted to 185.6 mm, while the average annual evaporation reached a value of approximately 1722.8 mm. Furthermore, the region experienced an annual average of sunshine hours totaling up to approximately 2713 h per year. It falls under a temperate continental arid climate category and is characterized by abundant solar radiation resources throughout the entire county area. The proportion of silt, sand, and clay in soil was 67.4%, 24.4%, and 5.6%, respectively, soil texture is sandy loam. The initial characteristics of the soil at 0–30 cm depth were as follows: pH (1:2.5 soil-water ratio) 8.92, the bulk density 1.45 g cm^{-3}, SOC 8.11 g kg^{-1}, TN 0.48 mg kg^{-1}, AP 14.67 mg kg^{-1}, and AK 147.46 mg kg^{-1}.

Experimental design and management

Experimental design

In this study, a randomized complete block design was employed for a field experiment using the local staple and forage dual-purpose corn variety 'Kenyu 1608' as the test crop. Three different types of soil conditioner were used, including no soil conditioner (CK), cattle manure conditioner with different organic matter concentrations (20% (Om-20%), 30% (Om-30%), 40% (Om-40%), and 45% (Om-45%) organic matter content, respectively), and humic acid conditioner with 20% organic matter content (Hu-20%), Amino acid conditioner (Am-25%) with 25% organic matter content. Each treatment was replicated three times and each plot was 30 m^2 (3 m × 10 m) in size. Protected rows were set up between plots, and irrigation and fertilization were carried out strictly according to the plots to prevent nutrient transfer between plots.

Field management

During the growing seasons from 2020 to 2022, corn was sown on April 17, 2021, and April 19, 2022, respectively, and harvested on September 27, 2021, and September 28, 2022. Corn was sown at a density of 87,000 plants-ha^{-2} with wide row spacing of 80 cm, narrow row spacing of 30 cm, and plant spacing of 23 cm. Irrigation and fertilization are done using integrated drip irrigation with plastic mulch. The total amount of irrigation was 4050 m^3 ha^{-2}, the water applied to the maize crop was 900 m^3 ha^{-2} at the seedling stage, 750 m^3 ha^{-2} at the nodulation stage, 900 m^3 ha^{-2} at the tassel stage, 750 m^3 ha^{-2} at the flowering stage, and 750 m^3 ha^{-2} at the kernel filling stage. A water meter was installed in the pipeline to control the irrigation volume, and a fertilizer valve was installed in the main pipe to apply the fertilizer into the main pipe through the fertilizer valve after dissolving the fertilizer thoroughly in the fertilizer tank, with a drip irrigation main pipe of 63 mm, a sub-pipe of 32 mm, a capillary diameter of 16 mm, a wall thickness of 0.2 mm, a drip irrigation hole spacing of 30 mm, a drop spacing of 110 cm, a drop flow rate of 2.2 L.h^{-1}. Each plot has three drip irrigation strips, with one drip irrigation strip irrigating two rows of corn. Fertilization followed local recommendations for maize cultivation with nitrogen (N) applied at a rate of 180 kg·ha^{-2}, phosphorus (P_2O_5) at a rate of 105 kg·ha^{-2}, and potassium (K_2O) at a rate of 130 kg·ha^{-2}. Phosphorus and potassium fertilizers were applied as base fertilizers during sowing while nitrogen fertilizer was split into two doses: an initial dose of 110 kg·ha^{-2} as the base fertilizer and an additional 70 kg·ha^{-2} during the tasseling stage. The experiment was carried out under field conditions, using drip irrigation to ensure irrigation regularly, and other field management measures were mainly based on local field specific methods to ensure the best growth and development of corn. The application rates of the different types of conditioners are detailed in Table 3. The amino acid soil conditioner is applied to the soil by mixing with water during winter irrigation, and the other conditioners are applied by tilling after the fall harvest each year.

Sample Collection

During the corn harvest period in 2021 and 2022, soil samples were collected from the plow layer (0 ~ 30 cm). These samples underwent debris removal, including gravel and roots, before being transported to the laboratory for air-drying. Subsequently, the air-dried soil samples were sieved through a 2 mm mesh to determine their fundamental physicochemical properties. Throughout the collection and transportation process, utmost care was taken to minimize any disturbance to the soil samples to preserve aggregate integrity.

Measurement of soil parameters

Soil chemical parameters

The organic carbon content was determined using the potassium dichromate-sulfuric acid digestion method, while the total nitrogen content was determined using the semi-micro Kjeldahl distillation method. The available phosphorus content was assessed through sodium bicarbonate extraction and the molybdenum-antimony anti-colorimetry method. Additionally, available potassium content was measured via ammonium acetate extraction and flame photometry[41]. The pH was determined by a pH meter (Sartorius PT10, Germany), and the soil-water ratio is 1: 2.5.

Types of soil conditioners	Cow dung organic fertilizer soil conditioner				Humic Acid soil conditioner	Amino Acid (liquid) soil conditioner
Treatment	Om-20%	Om-30%	Om-45%	Om-40%	Hu-20%	Am-25%
Nutrient composition of soil conditioners	Organic matter ≥ 20% $N + P_2O_5 + K_2O \geq 4\%$ pH 3 ~ 4	Organic matter ≥ 30% $N + P_2O_5 + K_2O \geq 5\%$ pH 4 ~ 6	Organic matter ≥ 45% $N + P_2O_5 + K_2O \geq 5\%$ pH 5 ~ 8.5	Organic matter ≥ 40% $N + P_2O_5 + K_2O \geq 4\%$ pH 5.5 ~ 8.5	Organic matter≥ 20% Humic acid ≥ 25% pH 4 ~ 6	Organic matter ≥ 25% Amino acid ≥ 20% Insoluble matter ≤ 10% pH 3.5 ~ 5
Recommended application rate ($kg \cdot ha^{-2}$)	1800 ~ 4500	3000 ~ 7500	3000 ~ 7500	3000 ~ 7500	3000 ~ 6000	300 ~ 450(Dilute 300 times)
Actual application rate ($kg \cdot ha^{-2}$)	3000	4500	5000	5000	4500	350
Conditioner nutrient concentrations ($kg\ ha^{-2}$)	Organic matter ≥ 600 $N + P_2O_5 + K_2O \geq 120$ (low)	Organic matter ≥ 1350 $N + P_2O_5 + K_2O \geq 225$ (medium)	Organic matter ≥ 2250 $N + P_2O_5 + K_2O \geq 250$ (high)	Organic matter ≥ 2000 $N + P_2O_5 + K_2O \geq 200$ (high)	Organic matter ≥ 900 Humic acid ≥ 1125 (medium)	Organic matter ≥ 875 Amino acid ≥ 700 (medium)

Table 3. Composition and use of soil conditioners for different treatments.

Soil aggregate composition and stability

The analysis was performed using the method described by Elliott[42]. Macroaggregates > 0.25 mm, Mesoaggregates 0.053 ~ 0.25 mm, and microaggregates < 0.053 mm were separated by wet sieving.

Using Mean Weight Diameter (MWD) and Geometric Mean Diameter (GMD) as indicators to evaluate the stability of soil aggregates, the specific calculation formulas were used as follows:

$$MWD = \sum_{i=1}^{n} \bar{X} \times W_i \tag{1}$$

$$GMD = exp\left[\frac{\sum_{i=1}^{n} M_i \times \ln \bar{X}}{\sum_{i=1}^{n} M_i}\right] \tag{2}$$

where X_i was the mean diameter (mm) of the soil aggregate size fractions and W_i was the proportion of each aggregate size with respect to the total sample weight.

Corn yield

At the time of corn harvest, three intact plants were randomly selected from each plot, dried and measured for dry weight, and the average dry weight per plant was calculated and then converted to corn yield per hectare based on the measured values.

Nutrient contribution rate

The rate of nutrient contribution is as follows[43]:

$$\text{Nutrient contribution rate} = \frac{N_i \times W_i}{\sum_{1}^{n}(N_i \times W_i)} \tag{3}$$

where Ni was the organic carbon and total nitrogen content of aggregates of each particle size (g·kg^{-1}), and Wi was the proportion of aggregate mass of each particle size.

Statistical analysis

One-way analysis of variance (ANOVA) was performed with SPSS 22.0 (SPSS statistical package v.24.0, SPSS Inst., Chicago, IL, USA) and structural equation modeling (SEM) analysis using IBM SPSS AMOS 24.0 (SPSS Inc., Chicago, IL, USA). Before the analysis, employ the "vegan" package in R language (University of Auckland, Auckland, New Zealand) to conduct Principal Component Analysis (PCA) for the content of soil macroaggregates, microaggregates, and their carbon-nitrogen content. Choose the results of the first principal component (PC1) as the indicator for soil aggregate distribution. Perform PCA for soil Mean Weight Diameter (MWD), Geometric Mean Diameter (GMD), and aggregates with particle size > 0.25 mm using R language. Select the results of the first principal component (PC1) as the indicator of soil aggregate stability. For visualization, use R language packages "ggplot" and "tidyverse" for plotting, along with "Origin 2021" software.

Data availability

The datasets generated and analysed during the current study are not publicly available due restrictions apply to the availability of these data but are available from the corresponding author on reasonable request.

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Author contributions
X.F., Y.G. and R.W. conceived the experment. X.F., Y.W. and Z.W. wrote the first draft of the manuscript. X.F., B.W. and B.Y. performed data analyses. X.F., Z.C., J.W. and P.L. wrote the final manuscript. All authors reviewed and contributed to the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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