Effects of Long-term Different Fertilization Regimes on Soil Aggregate Formation Characteristics in Greenhouse and Cropland Soils in North China (Postprint)

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Abstract

Soil aggregation status is one of the important physical properties of soil, and aggregate quantity is an important indicator for measuring and evaluating soil fertility. Application of organic fertilizer is an important measure to increase soil organic carbon (SOC) content, promote soil aggregate formation, and improve soil structure. This study, using greenhouse soil and farmland soil from the Quzhou long-term located experiment station in North China as research objects and employing the wet sieving method, conducted a comparative study on the effects of three fertilization methods—chemical fertilizer (NP), organic fertilizer plus small amount of chemical fertilizer (NPM), and organic fertilizer only (OM)—on the content, distribution, and stability of soil water-stable aggregates under two land use types (greenhouse and farmland), to reveal the influence of fertilization measures on characteristics of soil water-stable aggregates under different land use patterns. The results showed that in both greenhouse soil and farmland soil, the OM treatment significantly reduced soil bulk density and increased soil organic matter content compared with NP and NPM treatments ($P<0.05$), with the most pronounced effect in the 0~10 cm soil layer. Specifically, in the 0~10 cm soil layer of greenhouse soil, the soil bulk density under organic fertilizer only treatment (OM1) was 1.17 g·cm 3, representing decreases of 12.0% and 8.6% compared with chemical fertilizer (NP1) and organic fertilizer plus small amount of chemical fertilizer (NPM1) treatments, respectively; the soil organic matter content of OM1 was 54.81 g·kg 1, representing increases of 104.8% and 35.7% compared with NP1 and NPM1, respectively. In the 0~10 cm soil layer of farmland soil, the soil bulk density under organic fertilizer only treatment (OM2) was 1.19 g·cm 3, representing decreases of 8.5% and 7.0% compared with chemical fertilizer (NP2) and organic fertilizer plus small amount of chemical fertilizer (NPM2) treatments, respectively; the soil organic matter content of OM2 was 22.67 g・kg 1, representing increases of 23.1% and 15.0% compared with NP2 and NPM2, respectively. In both greenhouse soil and farmland soil, the mean weight diameter (MWD) and geometric mean diameter (GMD) of soil aggregates in the 0~10 cm, 10~20 cm, and 20~40 cm layers all followed the order of OM>NPM>NP. The fractal dimension (D) value of water-stable aggregates was lowest under OM treatment and highest under NP treatment. The OM treatment significantly reduced the D value of water-stable aggregates within the 0~20 cm soil layer, with the most obvious effect in the surface 0~10 cm layer, and soil structure was significantly improved. Compared with farmland soil, greenhouse soil exhibited the most significant changes in stability indicators and the greatest improvement in aggregate structure. There was an extremely significant positive correlation between soil organic matter content and the content of >0.25 mm water-stable aggregates ($P<0.001$), indicating that the higher the soil organic matter content, the higher the content of >0.25 mm water-stable aggregates, the stronger the water stability of soil aggregates, and the more stable the soil structure. Therefore, organic fertilization can significantly increase the content of macro-aggregates and their water stability while replenishing the soil organic carbon pool and available nutrient content, and is an effective measure to improve the structural stability of farmland soil, especially greenhouse soil, in the North China Plain and achieve sustainable soil development.

Full Text

Preamble

Effect of Long-Term Fertilization on Soil Aggregate Formation in Greenhouse and Farmland Conditions in the North China Plain

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Abstract: The status of soil aggregates is an important soil physical property and the amount of soil aggregates is a critical index for measuring and evaluating soil fertility. Organic fertilizer application is an essential measure for improving soil organic carbon (SOC) content, promoting soil aggregate formation and improving soil structure. A long-term experiment was conducted in greenhouse soil and in farmland soil under three fertilizer treatments in Quzhou County in the North China Plain in order to investigate the effects of different modes of fertilization on the content, distribution and stability of soil water-stable aggregates using the wet-sieving method under different land use types. Results indicated that continuous organic matter application (OM) significantly decreased soil bulk density and significantly increased soil organic matter content, compared with chemical fertilizer application (NP) and mixed organic manure with chemical fertilizer treatment (NPM) in both greenhouse and farmland soils ($P < 0.05$). This effect was most pronounced in the 0–10 cm soil layer. The bulk density of the 0–10 cm soil layer under greenhouse conditions with organic fertilizer application treatment was 1.17 g · cm ^{3}, which decreased respectively by 12.0% and 8.6% compared with those under chemical fertilizer and mixed organic manure with chemical fertilizer treatments. The content of organic matter in the 0–10 cm soil layer of greenhouse with organic fertilizer application treatment was 54.81 g · kg ^{1}, which increased respectively by 104.8% and 35.7% compared with those under chemical fertilizer and mixed organic manure with chemical fertilizer treatments. Also the bulk density of soil in the 0–10 cm layer of farmland with organic fertilizer application was 1.19 g · cm ^{3}, which decreased respectively by 8.5% and 7.0% compared with those under chemical fertilizer and mixed organic manure with chemical fertilizer treatments. The contents of farmland organic matter in the 0–10 cm soil layer with organic fertilizer application was 22.67 g · kg ^{1}, which increased respectively by 23.1% and 15.0% compared with those under chemical fertilizer and mixed organic manure with chemical fertilizer treatments. The mean weight diameter (MWD) and geometric mean diameter (GMD) of water-stable aggregates of both greenhouse and farmland soils changed in the following order: OM > NPM > NP. Fractal dimension (D) of water-stable aggregates under OM treatment was lowest while that under NP treatment was highest. Treatments with OM significantly decreased D value in the 0–20 cm soil layer, which effect was most obvious for the 0–10 cm soil layer where soil structure improvement was also very obvious. Compared with farmland soil, changes of soil stability indexes and the effects of aggregate structure were more obvious for greenhouse soil. The most significant correlation was between soil organic matter content and the content of >0.25 mm soil aggregates, which indicated that the more soil organic matter, the greater stability the soil structure. In conclusion, the application of organic matter not only increased the content of soil organic matter and available nutrients, but also promoted the formation of macro-aggregates and improved aggregate stability. It was an effective measure to improve the stability of farmland soil, which also was good for sustaining soil development, especially for soils under greenhouse conditions in the North China Plain.

Keywords: Organic fertilizer; Soil aggregate; Soil organic matter; Fractal dimension; Greenhouse soil; Farmland soil

Introduction

Soil aggregates are the fundamental units of soil structure and essential components of soil [1-2]. They ensure and coordinate the balance of water, nutrients, air, and heat in soil, influence the types and activities of soil enzymes, and maintain and improve soil structure and porosity [3-4]. Soil aggregates are widely considered the "reservoir" of soil nutrients, and an increase in their quantity signifies enhanced soil nutrient supply and storage capacity [5]. The formation, characteristics, and functional roles of soil aggregates are highly complex, influenced by both inherent soil composition and anthropogenic activities. Scholars worldwide have used water stability of soil aggregates as a key indicator for evaluating soil physical properties and erosion resistance [6-9], recognizing that soil structural characteristics directly affect soil fertility and crop growth. Consequently, improving aggregate stability and enhancing both the quantity and quality of aggregates have remained important research directions in agricultural production.

Long-term fertilization practices directly influence soil nutrient content and dynamics while significantly affecting aggregate stability [10-12]. However, because different aggregate size fractions contain varying types and amounts of binding agents, the quantity and stability of nutrients bound within each fraction differ [13-14]. Soil aggregates represent high-quality structural bodies formed under the combined effects of multiple factors, and under relatively consistent conditions of soil texture, cropping systems, and environmental conditions, long-term fertilization regimes become the key factor influencing soil physicochemical properties [15-16].

In recent years, soil quality degradation caused by greenhouse vegetable cultivation has attracted considerable attention from soil scientists, with research focusing primarily on soil acidification, secondary salinization, nutrient changes, and compaction [17-18]. Compared with farmland, greenhouse cultivation features semi-enclosed environments, heavy fertilization, absence of natural rainfall, frequent tillage, and highly intensive utilization, which inevitably exert substantial impacts on soil aggregate characteristics [19]. Sun et al. [20] investigated the effects of different cultivation years on aggregate quantity and stability in greenhouse and open-field soils, concluding that greenhouse soils contained more water-stable macroaggregates than open-field soils and exhibited stronger aggregate stability. However, comparative studies examining the effects of different fertilization methods on aggregate formation characteristics in greenhouse versus farmland soils remain scarce, making it difficult to distinguish the specific impacts of long-term fertilization practices on aggregate size, quantity, and stability under these two land use types. Therefore, comparative studies on the effects of different fertilization treatments on soil aggregate characteristics under greenhouse and farmland conditions are theoretically significant for understanding changes in soil fertility characteristics. This research selected soils from a long-term fertilization experiment station in Quzhou County, North China Plain, under different fertilization regimes and land use types (greenhouse and farmland). Through quantitative analysis of bulk density, organic matter content, and aggregate stability indicators, this study aimed to reveal the effects of fertilization measures on soil water-stable aggregate characteristics under different land use patterns.

1.1 Study Site Overview

The main experimental site was established at the Quzhou Long-term Fertilization Experiment Station of China Agricultural University (36°52 N, 115°01 E). The region features a warm temperate semi-humid continental monsoon climate with an average annual temperature of 13.1 °C, average frost-free period of 210 days, and average annual precipitation of 604 mm. According to the Chinese Soil Taxonomy System, the soil is classified as salinized fluvo-aquic cinnamon soil, which is representative of the North China Plain. Basic physicochemical properties of the soils are presented in Table 1 .

1.2 Experimental Design

Experiments were conducted in both greenhouse vegetable fields and conventional farmland, with three treatments in each: chemical fertilizer only (NP), organic manure with small amount of chemical fertilizer (NPM, with organic manure accounting for 80%), and organic manure only (OM). The long-term fertilization experiment in greenhouse soil began in 2002. The solar greenhouses had an arched design, each measuring 52 m in length (east-west) and 7 m in width (north-south). The three treatments were implemented in three separate greenhouses. The cropping system consisted of tomato (*Lycopersicon esculentum* Mill.)-cucumber (*Cucumis sativus* L.) rotation with two harvests per year, and tillage was performed by plowing. The long-term fertilization experiment in farmland soil began in 1993. Each farmland plot measured 10.3 m in length (north-south) and 3 m in width, with 30 cm ridges between plots as isolation zones and 1 m protective border rows around the perimeter. The cropping system was winter wheat (*Triticum aestivum* L.)-summer corn (*Zea mays* L.) rotation, with plowing as the tillage method. The chemical fertilizer used was compound fertilizer containing 15% N, 10% P, and 20% K. Organic fertilizer was dry chicken manure containing 339.83 g · kg ^{1} organic matter, 23.2 g · kg ^{1} total N, 9.3 g · kg ^{1} P (as P O), and 15.8 g · kg ^{1} K (as K O).

Fertilization methods and amounts converted to single-element fertilizer quantities for different treatments are shown in Table 2 , with total seasonal fertilizer application rates being equal across treatments. Organic materials were applied directly to the soil surface. For greenhouse soil, fertilization was divided into three applications per crop season: one basal application and two topdressings. Basal fertilizers were applied in March and September each year before planting tomatoes and cucumbers, while topdressings were applied during flowering and fruiting stages. For the OM treatment, basal organic fertilizer was applied at 12,500 kg · hm ^{2}, with the first and second topdressings each receiving 750 kg · hm ^{2} of organic fertilizer. For the NPM treatment, basal organic fertilizer was applied at 10,000 kg · hm ^{2}, with each topdressing receiving 600 kg · hm ^{2} of organic fertilizer plus 125 kg · hm ^{2} of chemical fertilizer. For the NP treatment, no organic fertilizer was applied; basal chemical fertilizer was 250 kg · hm ^{2}, with each topdressing receiving 125 kg · hm ^{2}.

For farmland soil, fertilization was divided into two applications per crop season: one basal and one topdressing. Basal fertilizers were applied in June and September each year before planting summer corn and winter wheat, while topdressings were applied during the jointing stage. For the OM treatment, basal organic fertilizer was 12,500 kg · hm ^{2} with a topdressing of 2,500 kg · hm ^{2} of chicken manure. For the NPM treatment, basal organic fertilizer was 10,000 kg · hm ^{2} with a topdressing of 2,000 kg · hm ^{2} of chicken manure plus 300 kg · hm ^{2} of chemical fertilizer. For the NP treatment, no organic fertilizer was applied; basal chemical fertilizer was 300 kg · hm ^{2} with a topdressing of 300 kg · hm ^{2}.

In late September 2011, after greenhouse tomato and farmland corn harvests, soil samples were collected from each plot using an S-shaped sampling method at three depths: 0–10 cm, 10–20 cm, and 20–40 cm. Both mixed soil samples and undisturbed soil cores were collected, with three replicates per plot. During collection and transport, soil disturbance was minimized to avoid aggregate disruption.

1.3.2 Measurement Methods

Soil bulk density was measured using the core method, and soil organic matter was determined by the potassium dichromate external heating method [21]. Soil aggregate distribution and stability were analyzed using the wet-sieving method [22]. Fifty grams of air-dried soil were placed in a 1 L cylinder, and deionized water was slowly added along the cylinder edge until saturation. The saturated soil sample was then transferred to a nested sieve set (with mesh sizes of 2 mm, 1 mm, 0.5 mm, 0.25 mm, and 0.05 mm) in a water bucket. The sample was shaken for 5 minutes at 30 oscillations per minute using a shaker. Soil retained on each sieve was transferred to aluminum boxes, oven-dried, and weighed as Wwit. Then 10 mL of 10 mol · L ^{1} sodium hexametaphosphate solution was added, and the sample was stirred with a glass rod to disperse, followed by shaking on the corresponding sieve. Sand particles retained on the sieve were oven-dried and weighed as Wwis. The weight of aggregates in each size fraction (Wwi) was calculated using equation (1).

1.3.3 Data Processing

The proportion of aggregates in size fraction i (wi) was calculated as wi × 100%. Common indicators used to describe fractal characteristics of soil aggregates include mean weight diameter (MWD), geometric mean diameter (GMD) [23], and fractal dimension (D) [24]. Using aggregate data from each size fraction, the content of aggregates >0.25 mm (R0.25), MWD, and GMD were calculated using the following formulas:

[Formulas would be inserted here as in original]

The fractal dimension D was calculated using the formula derived by Yang et al. [25]. Taking logarithms of both sides of equation (6) yields equation (7), which can be used for data fitting to conveniently obtain D. In this study, all data fitting yielded R^2 values greater than 0.95.

Data were processed using Microsoft Excel 2016, figures were prepared using SigmaPlot 10.0, and statistical analyses including one-way ANOVA and regression analysis were performed using SPSS 22.0. Multiple comparisons were conducted using the least significant difference (LSD) method.

2.1 Effects of Different Fertilization Measures on Soil Bulk Density and Organic Matter Content

In both greenhouse and farmland soils, OM1 and OM2 treatments significantly reduced soil bulk density compared with other treatments (Table 3). In the greenhouse soil, OM1 reduced bulk density in the 0–10 cm layer by 12.0% and 8.6% compared with NP1 and NPM1, respectively; in the 10–20 cm layer by 9.8% and 3.0%; and in the 20–40 cm layer by 7.1% and 2.7%. In the farmland soil, OM2 reduced bulk density in the 0–10 cm layer by 8.5% and 7.0% compared with NP2 and NPM2; in the 10–20 cm layer by 2.6% and 2.0%; and in the 20–40 cm layer by 5.8% and 4.6%. These results demonstrate that long-term organic fertilizer application reduced soil compaction in both greenhouse and farmland soils, with surface bulk density being lower than subsurface layers.

Further analysis of variance for soil bulk density among different soil types (Table 3) showed that organic fertilizer treatments produced significant differences in the 0–20 cm layer for both greenhouse and farmland soils, with the magnitude of reduction being greater in greenhouse soil than in farmland soil, particularly in the 0–20 cm tillage layer.

In both soil types, OM1 and OM2 treatments significantly increased soil organic matter content compared with other treatments (Table 3). In greenhouse soil, OM1 increased organic matter content in the 0–10 cm layer by 104.8% and 35.7% compared with NP1 and NPM1; in the 10–20 cm layer by 83.2% and 68.4%; and in the 20–40 cm layer by 64.3% and 53.2%. In farmland soil, OM2 increased organic matter content in the 0–10 cm layer by 23.1% and 15.0% compared with NP2 and NPM2; in the 10–20 cm layer by 26.8% and 24.4%; and in the 20–40 cm layer by 18.9% and 6.6%. These results indicate that long-term organic fertilizer application increased soil organic matter content in both greenhouse and farmland soils, with higher organic matter content in surface layers than in deeper layers. In the 20–40 cm layer, the three fertilization treatments showed minimal differences in farmland soil organic matter content, primarily because less organic fertilizer was applied to farmland and application was concentrated in the tillage layer (0–20 cm), resulting in minimal organic matter reaching the 20–40 cm depth.

Analysis revealed that organic fertilizer application was more effective at increasing soil organic matter in greenhouse soil than in farmland soil, with overall organic matter content being higher in greenhouse soil across all treatments. This may be attributed to the semi-enclosed, highly intensive cultivation in greenhouses, which results in substantial accumulation of vegetable residues, root exudates, and root debris in the soil, leading to enrichment of organic materials.

2.2 Effects of Different Fertilization Measures on Soil Water-Stable Aggregate Content

According to the hierarchical aggregation theory, micro-aggregates (<0.25 mm) combine to form macro-aggregates (>0.25 mm), which can break down into smaller aggregates. These processes are interdependent and dynamic. Aggregates >0.25 mm (R0.25) are generally considered the optimal soil structural units, and their quantity is positively correlated with soil fertility. Therefore, this study used the proportion of >0.25 mm aggregates to indicate changes in aggregate quantity and reflect the degree of influence of different fertilization measures on soil fertility and stability (Table 4).

Aggregates obtained through wet-sieving are water-stable aggregates, which contribute more importantly to maintaining soil structural stability than non-water-stable aggregates. Table 4 shows that in greenhouse soil, R0.25 under OM1 was significantly higher than under NP1 and NPM1 in the 0–10 cm and 20–40 cm layers; in the 10–20 cm layer, R0.25 under both OM1 and NPM1 was significantly higher than under NP1. In farmland soil, R0.25 followed the order OM2 > NPM2 > NP2 across all layers, with organic fertilizer application showing a more pronounced effect on increasing macro-aggregates in greenhouse soil than in farmland soil.

2.3 Effects of Different Fertilization Measures on Distribution of Different Sized Soil Aggregates

The distribution of water-stable aggregates reflects soil structural stability and erosion resistance. Figure 1 [Figure 1: see original paper] shows that in greenhouse soil, the proportion of >0.25 mm aggregates gradually decreased with soil depth, while the proportion of <0.05 mm micro-aggregates increased. Across the three soil depths, micro-aggregates <0.05 mm constituted the dominant fraction. The content of >0.25 mm aggregates was highest under OM1, intermediate under NPM1, and lowest under NP1.

Similar trends were observed in farmland soil, where the proportion of >0.25 mm aggregates decreased with depth while <0.05 mm micro-aggregates increased. Micro-aggregates <0.05 mm were the dominant fraction across all depths and fertilization treatments. However, the proportion of <0.05 mm micro-aggregates was higher in farmland soil than in greenhouse soil, while the proportion of >0.25 mm aggregates was lower.

2.4 Effects of Different Fertilization Measures on Soil Aggregate Size Distribution

Different aggregate size fractions play distinct roles in nutrient retention and supply, pore composition, hydraulic properties, and biological activity. Therefore, beyond total aggregate content, the size distribution of aggregates is more closely related to soil quality. MWD and GMD are commonly used indicators reflecting aggregate size distribution. Higher MWD and GMD values indicate greater mean aggregate diameter and stronger stability. As shown in Table 5 , MWD and GMD values for soil aggregates in both greenhouse and farmland soils at 0-10 cm, 10-20 cm, and 20-40 cm depths followed the orders OM1 > NPM1 > NP1 and OM2 > NPM2 > NP2, respectively. These results demonstrate that organic fertilizer application enhanced the stability of water-stable aggregates in both soil types, with the improvement being more pronounced in greenhouse soil than in farmland soil.

2.5 Effects of Different Fertilization Measures on Fractal Characteristics of Soil Aggregates

Data fitting using equation (7) yielded R^2 values greater than 0.95 for all treatments. Figure 2 [Figure 2: see original paper] illustrates the distribution of fractal dimension (D) for soil aggregates across the 0–40 cm profile. In greenhouse soil (Figure 2a), OM1 produced the lowest D value in the surface 0-10 cm layer (2.84), which increased with depth. Conversely, NP1 produced the highest D value in the surface layer. Below 10 cm depth, D values under NP1 and NPM1 stabilized, with both treatments showing similar values (approximately 2.95) in the 20-40 cm layer. Across the three fertilization treatments, D values in layers below 10 cm ranged from 2.89 to 2.99, showing less variation than in the surface layer. In the 0-10 cm and 10-20 cm layers, D values followed the order OM1 < NPM1 < NP1, indicating that organic fertilizer application enhanced the stability of water-stable aggregates in the 0–20 cm layer. In the 20-40 cm layer, the order was NP1 NPM1 < OM1, with relatively small variations. These results suggest that the effects of different fertilization methods on aggregate characteristics occurred primarily in the surface 0–20 cm layer, especially in the 0-10 cm layer, where organic fertilizer application significantly reduced the fractal dimension of water-stable aggregates.

In farmland soil (Figure 2b), D values were similar among the three fertilization treatments in the 0–10 cm layer. In the 10-20 cm layer, D values ranged from 2.96 to 2.98, while in the 20-40 cm layer, values again became consistent across treatments. The fractal dimension of water-stable aggregates increased from surface to subsurface layers, indicating decreasing aggregate stability with depth. Overall, organic fertilizer application was more effective at reducing D values in greenhouse soil than in farmland soil.

2.6 Relationship Between Soil Organic Matter Content and R0.25

Figure 3 [Figure 3: see original paper] shows a highly significant positive correlation between soil organic matter content and the content of >0.25 mm water-stable aggregates (R0.25) (greenhouse soil: $R^2 = 0.7144$, $P < 0.0001$; farmland soil: $R^2 = 0.7564$, $P < 0.0001$). This indicates that higher soil organic matter content leads to greater content of >0.25 mm water-stable aggregates, stronger aggregate water stability, and more stable soil structure. The results also demonstrate that organic fertilizer application, alone or in combination with small amounts of chemical fertilizer, can significantly increase macro-aggregate content and water stability while replenishing soil organic carbon pools and available nutrients. This represents an effective approach for improving the physicochemical properties and fertility of both greenhouse and farmland soils in the North China Plain, ensuring healthy and stable crop production.

Soil bulk density and total porosity are important indicators for evaluating soil physical properties, directly affecting water and nutrient supply, aeration, and crop growth [26-27]. Application of chemical fertilizers alone may deteriorate soil physical properties through selective crop absorption of differently charged ions, differential soil adsorption, and effects of impurity ions, though it may also improve properties by increasing organic matter return [28-29]. The net effect depends on the combined intensity of these opposing processes in specific experimental contexts. This study demonstrated that long-term organic fertilizer application significantly reduced soil bulk density and increased porosity in both greenhouse and farmland soils, likely because organic fertilizers provide better nutrient efficiency and directly supply large amounts of active organic matter that promotes crop growth, thus exerting more pronounced effects on reducing bulk density and increasing porosity than chemical fertilizers alone [30-31].

Water-stable aggregates in both greenhouse and farmland soils were dominated by the <0.05 mm fraction, though the content varied among fertilization treatments. Previous studies have shown that organic fertilizer application can increase macro-aggregate content and enhance aggregate stability [32], consistent with our findings. Organic fertilizer treatments significantly increased macro-aggregate content and stability in both soil types, primarily due to organic residue inputs that increased dissolved organic carbon content and microbial activity, thereby cementing smaller aggregates into larger ones and increasing the degree of aggregation [33-34]. Organic fertilizer application also partially offset the disruptive effects of tillage on soil aggregates. Di et al. [35] and Zhao et al. [36] reported that both organic manure alone and organic manure combined with chemical fertilizer significantly increased MWD and GMD values compared with control and inorganic fertilizer treatments. However, in this long-term experiment, organic manure alone showed more pronounced improvements in bulk density, aggregate stability, and organic matter content than the combined treatment, likely because equal nutrient inputs resulted in larger amounts of organic manure being applied in the OM treatment, producing more obvious increases in soil organic matter. As the primary binding agent for soil aggregates, organic matter decomposition produces various organic substances such as polysaccharides, proteins, and lignin, while increased microbial activity forms humic substances. These important organic cementing agents positively influence the formation and stabilization of macro-aggregates, increasing their quantity and stability and markedly improving soil structure [37-38], consistent with findings by Xing et al. [39]. Some studies have also shown that long-term chemical fertilizer application can increase macro-aggregate content [40]. In this study, the high organic matter content in greenhouse soil compared with farmland soil in the 0–20 cm layer resulted from substantial application of cattle and chicken manure to meet the high requirements for soil looseness by vegetable crops, combined with the accumulation of vegetable residues, root exudates, and root debris from intensive cultivation. Increased organic matter content not only enhances soil fertility but also provides binding agents for aggregate formation through decomposition into polysaccharides and humus. Therefore, emphasizing organic fertilizer application in greenhouse cultivation is not only fundamental for producing green organic vegetables but also essential for maintaining good soil structure.

Based on this long-term fertilization experiment, fertilization practices significantly affected bulk density, organic matter content, and aggregate characteristics in both greenhouse and farmland soils. Organic fertilizer application significantly reduced bulk density and increased organic matter content, thereby improving soil physical condition. These effects were more pronounced in the 0–20 cm layer than in the 20–40 cm layer and were stronger in greenhouse soil than in farmland soil. Organic fertilizer application significantly increased the content of >0.25 mm aggregates, MWD, and GMD values while decreasing fractal dimension (D), indicating that organic fertilization promotes aggregate formation, increases particle diameter, and reduces fractal dimension. However, different fertilization methods had minimal effects on D values in the 20–40 cm layer, where values were generally consistent across treatments. The significant positive correlation between soil organic matter content and the proportion of >0.25 mm water-stable aggregates indicates that higher organic matter content leads to greater macro-aggregate content and stronger aggregate stability. Therefore, organic fertilizer application represents an effective approach for improving soil physicochemical properties and fertility in both greenhouse and farmland soils of the North China Plain by replenishing soil organic carbon pools and available nutrients while significantly increasing macro-aggregate content and water stability.

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