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Evaluation of Soil Aggregate Sieving: The Impact of Field Moisture Content on Size Distribution and Stability

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Abstract: Soil aggregation, a critical component of soil structure, is significantly influenced by soil moisture content, which can vary substantially across different field conditions. The objective of this study was to evaluate the impact of soil relative water content (SRWC) on the performance and sensitivity of soil aggregate size distribution (DOSA) assessments. We conducted a comprehensive analysis across a range of SRWC levels and observed a consistently high recovery rate of sieving (exceeding 99.22%), indicating a robust methodology. The relative standard deviation (RSD) of DOSA was minimal, highlighting the high precision of sieving outcomes, particularly up to an SRWC of 40%. Cluster analysis, based on soil properties, identified six distinct soil groups, each demonstrating a significant correlation between the characteristic values of DOSA and SRWC, with determination coefficients (R^2) above 0.717. This finding underscores the sensitivity of aggregate distribution to variations in moisture levels. However, the fitting curves varied among clusters at the same site, with the exception of clusters 5 and 6 at the Jinliuhuan Agricultural Sci-Tech Park (JLH), reflecting the intricate nature of soil–moisture interactions. Our results emphasize the necessity of sieving soil aggregates under controlled field moisture conditions to ensure reliable DOSA measurements. This research provides valuable insights into the dynamics of soil aggregation and its response to different moisture regimes, offering practical implications for enhancing sustainable agricultural practices. This study provides a comprehensive analysis of the impact of soil relative water content (SRWC) on soil aggregate size distribution (DOSA), revealing the high recovery rate and precision of sieving under various moisture conditions. The significant correlation between DOSA and SRWC, along with the varied responses across soil clusters, highlights the complex interplay between soil moisture and aggregate stability. These findings are crucial for optimizing soil aggregate assessments and sustainable agricultural practices.

Keywords: sensitivity; soil relative water content; soil aggregate size distribution; sustainable agriculture

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1. Introduction

Soil structure, defined by the distribution of soil aggregate sizes, is a cornerstone of soil health and functionality in sustainable agriculture [1,2]. This structure is integral to

a myriad of ecological processes, including water infiltration, nutrient cycling, and root growth [3]. The genesis of soil aggregates is orchestrated by the intricate interplay of biotic, abiotic, and environmental factors, with varying bonding mechanisms taking precedence at different stages of aggregation [4,5].

Soil aggregation, as the basic unit of soil structure, plays a crucial role in soil ecological functions. Although it is widely acknowledged that soil moisture influences aggregate distribution, there exists a significant gap in our understanding of the stability of aggregates derived from sieving under varying moisture conditions of the same soil. This lack of evaluation poses a significant challenge to the reliability of research results based on aggregates under any given moisture condition [6]. Current research has primarily focused on the effects of soil moisture on aggregate size distribution under specific conditions, but few studies have systematically evaluated the performance and sensitivity of soil aggregate sieving across a range of soil relative water contents (SRWC). This study aims to fill this gap by examining the impact of SRWC on soil aggregate size distribution (DOSA) and its implications for soil stability.

Historically, the assessment of soil aggregate size distribution has been undertaken employing either wet or dry sieving methodologies, each imbued with distinct advantages and challenges [7]. The dry sieving method offers an indirect measure of aggregate size distribution, subject to forces such as abrasion and impact among soil aggregates [8]. In contrast, the wet sieving method, dominated by the slaking process, is influenced by the rapid compression and release of air within aggregates upon wetting [9]. The choice between these methods is crucial for standardizing disruptive forces and ensuring comparability with field phenomena [10,11].

Achieving acceptable stability in aggregate distribution within a certain range of soil moisture raises a critical question, does the variability in soil properties influence the acceptability of this stability? Comparing the distribution of aggregates across different soil properties within a moisture range where stability is acceptable would provide valuable insights into how these properties interact with moisture levels to influence soil structure and function, thereby enhancing our understanding of sustainable agricultural practices. Conversely, if such stability is not acceptable, the comparability of research on the ecological functions of aggregates under different soil properties at a specific moisture level would be highly uncertain [10].

Soil moisture content, which fluctuates due to irrigation and rainfall [12], serves as a modifier of soil properties, encompassing consistency, cohesion, structure, and porosity. It is particularly influential in the distribution of soil aggregate sizes, which is highly dependent on soil moisture levels [6], especially in soils prone to swelling and shrinking [13]. The aggregate size distribution, as an index of soil structure in the field, is therefore intricately linked to the prevailing soil moisture conditions [13].

To better simulate whether the sieving of soil aggregates under different moisture conditions results in a stable distribution of aggregates, this study selected soils with different properties, subjected them to pre-treatment processes, and then conducted stability studies on aggregates under varying moisture and soil properties. The aim was to provide data support for soil ecological function studies based on aggregates [14].

This study addresses a critical gap in the literature by examining the impact of soil relative water content (SRWC) on the sieving process and the subsequent size distribution of soil aggregates. We aim to understand how SRWC affects the recovery rate of soil aggregates and their size distribution, which are essential for assessing the impact of different soil properties and water content interactions. Our research objectives are twofold: (1) to elucidate the influence of SRWC on soil aggregate sieving, focusing on recovery rate and size distribution as impact indices; and (2) to evaluate the sensitivity of the soil

aggregate size distribution to the interplay between soil properties and water content, as reflected by the relative standard deviation and characteristic indices of the distribution. The significance of this study lies in systematically evaluating the universal significance of aggregate distribution stability under different moisture and soil properties, providing data support for research based on "soil aggregates" [5].

By conducting this study, we aim to establish a recommended sieving method for soil aggregates that will provide technical support for a better understanding of soil aggregation and its implications for sustainable agricultural practices.

2. Materials and Methods

2.1. Experimental Site

This study was conducted across three distinct agricultural facilities, strategically located within the Dongdadi Sci-Tech Park at Beijing University of Agriculture (DDD), the Jinliuhuan Agricultural Sci-Tech Park (JLH), and the Crop Variety Test and Display Base (ZZZ) in Changping District, Beijing. These sites were chosen for their contrasting soil properties. DDD has loamy soil with lower organic matter content and a slightly warmer climate, JLH has sandy loam soil with moderate organic matter content and a temperate climate, and ZZZ has sandy loam soil with higher organic matter content and a similar climate to JLH. These contrasting conditions allowed us to assess the impact of soil relative water content (SRWC) on soil aggregate size distribution (DOSA) across a range of soil properties. For a detailed understanding of the experimental locales and the intricate details of the soil characteristics, refer to Table 1.

Table 1. Soil properties at three sites.

Site	Longitude	Latitude	Soil Layers (cm)	Inside/Outside the Greenhouse	Texture (Sand/Silt/Clay)	pH (2.5:1)	SOM (%)	BD (g/cm^3)	FC (%)
DDD	116°19′17″ E	40°06′00″ N	0–15	Inside	Loam	7.39 ± 0.02 bc	1.85 ± 0.05 h	1.4 ± 0.03 de	28.77 ± 0.49 cd
				Outside	(35:49:16)	7.52 ± 0.01 a	1.49 ± 0.06 j	1.57 ± 0.02 b	28.23 ± 0.15 de
			15–30	Inside	Loam	7.35 ± 0.03 c	1.59 ± 0.05 i	1.44 ± 0.01 cd	26.33 ± 0.21 f
				Outside	(34:49:17)	7.44 ± 0.02 b	1.18 ± 0.03 k	1.6 ± 0.01 ab	25.97 ± 0.12 fg
JLH	116°17′39″ E	40°12′32″ N	0–15	Inside	Sandy Loam	6.82 ± 0.05 ef	4.32 ± 0.01 d	1.39 ± 0.02 e	29.00 ± 0.36 c
				Outside	(66:25:09)	6.95 ± 0.04 d	2.75 ± 0.01 f	1.62 ± 0.01 a	27.67 ± 0.29 e
			15–30	Inside	Sandy Loam	6.84 ± 0.02 e	2.22 ± 0.06 g	1.48 ± 0.02 c	25.63 ± 0.15 g
				Outside	(68:22:10)	6.95 ± 0.09 d	1.89 ± 0.04 h	1.60 ± 0.02 ab	26.03 ± 0.29 fg
ZZZ	116°09′43″ E	40°12′42″ N	0–15	Inside	Loam	6.76 ± 0.02 fgh	6.78 ± 0.03 a	1.14 ± 0.02 g	32.5 ± 0.17 a
				Outside	(52:35:13)	6.71 ± 0.02 h	5.3 ± 0.1 b	1.47 ± 0.05 c	30.03 ± 0.23 b
			15–30	Inside	Sandy Loam	6.78 ± 0.03 efg	4.86 ± 0.06 c	1.32 ± 0.02 f	27.77 ± 0.71 e
				Outside	(53:35:12)	6.73 ± 0.03 gh	4.11 ± 0.08 e	1.42 ± 0.02 de	28.57 ± 0.29 cd

Note: the Dongdadi Sci-Tech Park at Beijing University of Agriculture (DDD), the Jinliuhuan Agricultural Sci-Tech Park (JLH), and the Crop Variety Test and Display Base (ZZZ) in Changping District, Beijing; pH (2.5:1): Measured at a soil-to-water ratio of 2.5:1, SOM (%): soil organic matter content (%), BD (g/cm^3): soil bulk density (g/cm^3), FC (%): soil field capacity (%), The texture is determined using the USDA soil texture triangle. Different letters in the same column indicate significant differences at $p < 0.05$ levels, and data in the table are mean ± SD.

The experimental activities were carried out in 2021, during which soil samples were collected and analyzed to evaluate the effects of different soil moisture conditions on aggregate size distribution. A meticulous crop rotation cycle was implemented at all sites, with cucumbers, a fruiting vegetable, cultivated during the summer, and lettuce, a leafy green, grown during the spring and autumn seasons. Manure application, derived from chickens, cows, and sheep, was uniformly administered at an approximate rate of 22.5 mg/ha in the spring, ensuring a consistent baseline for nutrient input across the experimental sites. Supplemental fertilizers were applied as necessary to support crop growth, reflecting standard agricultural practices. The research also featured a comparative analysis of irrigation methods, with border irrigation utilized at DDD and drip irrigation employed at the remaining two sites, introducing variability in soil moisture conditions.

2.2. Soil Sampling

Soil samples were collected from each experimental site to assess the impact of soil relative water content (SRWC) on soil aggregate size distribution. At each site, a randomized 1 × 1 m square plot was selected, and soil was sampled from two depth intervals: the upper layer from 0 to 15 cm and the sub-layer from 15 to 30 cm. This stratified sampling approach ensured that the soil's vertical structure was adequately represented in our analysis. To ensure statistical rigor and to account for spatial variability, triplicate samples were collected from each stratum, resulting in a total of 36 samples (3 sites × 2 locations: inside and outside × 2 soil layers × 3 replicates).

The soil extraction was performed with precision, utilizing a shovel in a manner that minimized disruption to the soil's natural architecture. This careful extraction technique preserved the structural integrity of the soil and maintained the lowest possible ratio of wall surface area to volume, as per the established methods [15]. Post collection, each soil sample was meticulously placed into a rigid plastic container for secure transport to the laboratory, ensuring that the samples remained undisturbed during transit.

In the laboratory, the soil blocks were carefully disaggregated along their natural cleavage planes into constituent aggregates. These aggregates were then sieved through a 1 cm mesh to achieve a uniform particle size, facilitating subsequent analysis. The samples were air-dried and subsequently stored in a controlled environment, all in preparation for detailed analysis, following the procedural guidelines outlined by Verhulst et al. [15].

2.3. Pretreatment for Sieving

To accurately assess the impact of soil relative water content (SRWC) on the sieving process, a systematic pretreatment protocol was established for the soil samples. A total of 12 soil samples were prepared, with 200 g of soil from each sample placed into a plastic container according to the bulk density (BD) values listed in Table 1.

Each soil sample was subjected to the following six distinct soil moisture conditions: air-dried; 10% SRWC; 20% SRWC; 40% SRWC; 60% SRWC; and 80% SRWC. These levels were chosen to cover a broad range of soil moisture conditions commonly encountered in agricultural and natural settings. The selection of these specific levels was based on previous studies that have identified critical moisture thresholds for soil aggregation and stability [6,10]. The air-dried condition represents the baseline, while the 10% and 20% SRWC levels simulate relatively dry conditions, the 40% and 60% SRWC levels represent moderate moisture conditions, and the 80% SRWC level represents the optimal soil moisture condition for crop growth.

Based on the field capacity (FC) values for each soil listed in Table 1, the moisture content of each soil sample was adjusted to the designated SRWC levels by weight. This was achieved by evenly moistening the soil surface using a spray pot, ensuring uniform water application. After moistening, the containers were sealed with plastic film, which had small holes punched in it to ensure air circulation between the inside and outside of the container. The samples were then incubated at a temperature of 25 °C for 7 days to allow the soil to equilibrate and remain in a natural state. This step was crucial for achieving a stable moisture condition in the soil, mimicking field conditions and ensuring that the sieving process would reflect real-world scenarios. Each moisture treatment was replicated three times for each soil sample, resulting in a total of 216 samples (12 soil samples × 6 moisture treatments × 3 replicates), to ensure experimental rigor and statistical reliability.

2.4. Aggregate Sieving

The soil aggregate size distribution was determined using a Lab Tester NV300 from Navector Electrical & Mechanical Technology Co., Ltd., Shanghai, China, which provided

a standardized and efficient method for sieving. A nested series of sieves with varying mesh sizes was employed to separate the soil into distinct aggregate fractions. This method allowed for a detailed analysis of the soil aggregate size distribution across different moisture conditions.

The sieving process involved agitating the soil at a frequency of 90 cycles per minute for a duration of 3 min. This agitation frequency and duration were selected based on previous studies that demonstrated their effectiveness in separating soil aggregates without causing excessive breakdown, thus preserving the integrity of the aggregates. The soil was separated into seven aggregate size fractions: 10–7, 7–5, 5–3, 3–2, 2–0.5, 0.5–0.25, and <0.25 mm.

Following the sieving process, each fraction was subjected to drying at a controlled temperature of 40 °C for a period of 24 h to remove any remaining moisture content. This drying step was crucial for obtaining accurate mass measurements of the aggregates, as moisture can significantly affect the mass determination.

The dried aggregates were then weighed to ascertain their mass. To account for the presence of sand and to provide an accurate assessment of the soil aggregate mass, the sand content was utilized to adjust the mass measurements for each aggregate size fraction. For example, if the total soil sample mass is A grams, and the gravel content is x grams, the mass of a certain particle size fraction is a gram. The adjusted percentage of this particle size fraction is calculated as follows:

$$\text{a\%} = \frac{a \times \left(\frac{A-x}{A}\right)}{A-x} \times 100$$

This adjustment was essential to ensure that the mass of the soil aggregates was not confounded by the presence of non-soil particles, such as sand.

2.5. Calculations

(1) Performance of soil aggregate sieving: accuracy and precision.

The performance of the soil aggregate sieving process is a critical parameter, reflecting the consistency and reliability of the method in assessing soil aggregate size distribution under varying moisture conditions. This section details the metrics used to evaluate the accuracy and precision of the sieving process, which are fundamental to ensuring the robustness of our findings.

Accuracy in sieving is determined by the recovery rate, which quantifies the proportion of soil aggregates recovered post-sieving relative to the initial amount. The recovery rate is calculated using the following formula:

$$\text{Recovery Rate : RR (\%)} = \frac{Mass\ of\ aggregates\ after\ sieving}{Initial\ mass\ of\ soil\ sample} \times 100\% \quad (1)$$

This metric is essential for validating the completeness of the sieving process, ensuring that the majority of the soil aggregates are accounted for, and that minimal loss occurs during the procedure.

Precision is assessed by the relative standard deviation (RSD) of the distribution of soil aggregate sizes (DOSA), which measures the variability in sieving outcomes across replicates. The RSD is calculated as follows:

$$RSD\ (\%) = \frac{\text{Standard Deviation of DOSA}}{Mean\ DOSA} \times 100\% \quad (2)$$

A low RSD indicates high precision, suggesting that the sieving process yields consistent results across replicates, which is vital for comparative analyses and the generalization of findings.

To ensure that our sieving methodology is both accurate and precise, we conducted multiple replicates for each soil sample under various moisture conditions. This approach allowed us to assess the variability in sieving outcomes and to identify any trends or anomalies that may be attributed to changes in soil moisture content. By maintaining rigorous standards for accuracy and precision, we enhanced the credibility of our research and its applicability to real-world soil aggregate assessments.

(2) Sensitivity of the distribution of soil aggregate size

To evaluate the responsiveness of soil aggregate size distribution to various soil and field management practices, we employed several indices that are sensitive to changes in soil relative water content (SRWC). These indices are crucial for understanding how soil management and moisture conditions influence soil structure and function.

The percentage of soil aggregates larger than 0.25 mm, denoted as $R_{0.25}$, is a key index that reflects the proportion of macro-aggregates in the soil. This index is determined by the following equation:

$$R_{0.25} = \frac{M(r > 0.25)}{Mtotal} \times 100\% \quad (3)$$

where M (r > 0.25) is the mass of soil aggregates larger than 0.25 mm and M_{total} is the total mass of soil aggregates.

The mean weight diameter (MWD), expressed in millimeters, is calculated using the formula [16]:

$$MWD = \sum (Mi \times di) \quad (4)$$

where Mi is the mass of soil aggregates in size category i and d_i is the midpoint of the size range for category i.

The geometric mean diameter (GMD), also in millimeters, is derived from [17]:

$$GMD = \left(\prod_{i=1}^{n} (d_i)^{M_I} \right)^{\frac{1}{\sum M_i}} \quad (5)$$

where n is the number of size categories and di and Mi are as defined above.

The fractal dimension (D) is calculated to understand the self-similarity of the soil aggregates, using the relationship [18]

$$D = \frac{\log(M_{total}) - \log(M(r < r_{max}))}{\log(r_{max}) - \log(r_{min})} \quad (6)$$

where M ($r < r_{max}$) is the cumulative mass of soil aggregates smaller than the largest size r_{max} and r_{min} is the smallest size considered.

These indices provide a comprehensive assessment of the sensitivity of soil aggregate size distribution to changes in soil moisture and management practices. By analyzing how these indices vary with different SRWC levels, we can infer the stability and resilience of soil aggregates under varying field conditions. This sensitivity analysis is essential for developing management strategies that maintain soil structure and function under fluctuating environmental conditions.

2.6. Statistical Analysis

In order to rigorously analyze the data obtained from the soil aggregate sieving and to draw meaningful conclusions, we employed a comprehensive statistical approach. This section details the methods used to process the data and the statistical tests applied to

evaluate the significance of the findings. Before conducting ANOVA, ANCOVA, and regression analysis, we checked the assumptions of normality and homogeneity of variance using appropriate statistical tests (Shapiro–Wilk test for normality and Levene's test for homogeneity of variance). All assumptions were met, ensuring the validity of our statistical analyses.

The soil samples were categorized based on their geographical location, depth within the soil profile, and their position relative to the greenhouse. Each sample was assigned a unique three-digit code, facilitating the organization and analysis of the data. This systematic coding allowed for a clear distinction between samples and enabled a more nuanced understanding of the effects of different environmental conditions on soil aggregate size distribution.

To classify the soils and to identify patterns in the data, we utilized the vegan package in R for conducting analysis of similarities (ANOSIM). This non-parametric method is particularly suited for ecological data and helped to determine the degree of similarity or dissimilarity between different soil samples based on their properties.

The statistical processing was carried out using SPSS software, version 19 (SPSS Inc., Chicago, IL, USA). We employed regression curves to model the relationship between the soil aggregate size distribution indices and soil relative water content (SRWC) for each identified soil cluster. These curves allowed us to visualize and quantify the trends in the data, providing insights into how soil aggregate size distribution responds to changes in moisture content.

In this study, SRWC was selected as the covariate, assuming a linear relationship between the covariate (SRWC) and the dependent variable (DOSA). Based on the analysis of covariance (ANCOVA) as outlined by Armstrong and Hilton [19], a cluster analysis was performed on the 12 soils under investigation. ANCOVA is a powerful tool that allowed us to control for certain variables while examining the effects of others, such as the influence of soil properties on aggregate size distribution.

Additionally, we employed analysis of variance (ANOVA) to determine significant differences in the distribution of soil aggregate sizes (DOSA) among the samples at a significance level of $p < 0.05$. ANOVA is a standard statistical test used to compare means across multiple groups, providing a robust framework for assessing the statistical significance of our findings.

By employing these statistical methods, we ensured that our analysis was both thorough and objective, allowing us to draw reliable conclusions about the impact of soil relative water content on soil aggregate size distribution and stability.

3. Results

3.1. Recovery Rate of Soil Aggregate Sieving Across Varying Soil Water Contents

The recovery rate of soil aggregate sieving serves as a critical metric for evaluating the effectiveness and reliability of our sieving methodology across a range of soil water contents. This section presents the findings on how soil water content influences the recovery rate, providing insights into the consistency of the sieving process under different moisture conditions.

Our results, as depicted in Figure 1, demonstrate that the recovery rate of soil aggregate sieving remained remarkably high (99.22%) across all levels of soil water content. A slight decline in recovery rate was observed with an increase in soil relative water content (SRWC), with the highest recovery rate reaching 99.99% in air-dried soil and the lowest at 99.22% in soil with an SRWC of 80%. Despite these variations, the differences were not statistically significant, indicating that our sieving methodology was robust and reliable under varying soil moisture conditions.

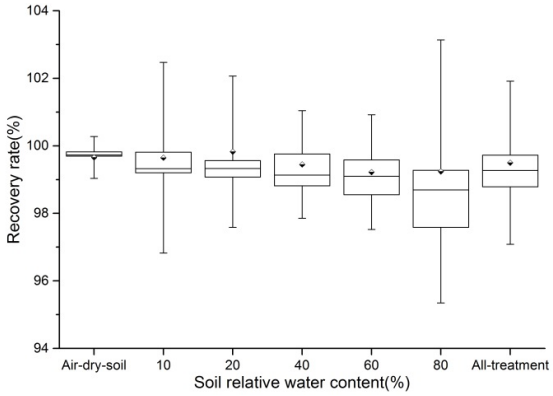


Figure 1. Recovery rate of sieved soil aggregates under different soil relative water contents. Note: the black lines and rhombus, lower and upper edges, and lower and upper bars in or outside the boxes represent median and mean values, 25th and 75th, negative and positive standard deviation of all data, respectively.

The overall average recovery rate of 99.50% achieved across all treatments suggests a high level of accuracy in the sieving process. This consistency in recovery rate is essential for ensuring that the soil aggregate size distribution assessments are representative of the true soil conditions, regardless of the soil's moisture state.

The non-significant variation in recovery rates across different moisture levels indicates that the sieving process is not compromised by changes in soil water content. This finding is particularly important for field studies, where soil moisture can fluctuate significantly, and it underscores the need for a reliable sieving method that can produce consistent results under diverse field conditions.

3.2. Distribution and Stability of Soil Aggregate Sizes Under Diverse Soil Water Contents

The influence of soil water content on the size distribution and stability of soil aggregates is a pivotal aspect of understanding soil structure and its response to environmental conditions. This section delves into the variations in soil aggregate size distribution under different soil water contents, highlighting the implications for soil stability.

Our data, as presented in Table 2, reveal a significant impact of soil moisture on the distribution of soil aggregate sizes. Specifically, we observed an increase in the distribution of soil aggregates larger than 3 mm with rising soil relative water content (SRWC), while a contrasting trend was noted for smaller aggregates (<3 mm). This observation suggests that soil moisture plays a crucial role in the aggregation process, influencing the formation and stability of soil aggregates.

Table 2. Distribution of soil aggregate size in different sizes (%).

SRWC	Size (mm)/Distribution of Soil Aggregates (%)						
	>7	5~7	3~5	2~3	0.5~2	0.25~0.5	<0.25
Air-dry-soil	22.93 ± 15.86 bc	9.41 ± 3.67 c	11.00 ± 2.74 d	6.93 ± 1.42 b	22.06 ± 6.98 b	10.04 ± 5.15 b	17.64 ± 9.07 a
10%	16.89 ± 12.79 c	10.24 ± 3.79 c	12.53 ± 2.91 cd	8.12 ± 2.53 a	24.7 ± 6.26 b	11.96 ± 5.84 a	15.55 ± 7.42 b
20%	19.03 ± 12.09 bc	11.44 ± 3.35 c	13.65 ± 2.61 bc	8.47 ± 1.56 a	25.4 ± 6.58 b	13.70 ± 6.69 a	8.32 ± 3.73 c
40%	23.77 ± 12.40 b	14.29 ± 3.68 b	15.32 ± 3.13 b	9.20 ± 1.57 a	29.94 ± 13.47 a	6.65 ± 3.19 c	0.82 ± 0.90 d
60%	41.16 ± 17.99 a	15.55 ± 2.83 b	15.95 ± 4.30 b	8.90 ± 3.54 a	17.64 ± 14 c	0.76 ± 1.02 d	0.04 ± 0.04 d
80%	44.40 ± 22.94 a	24.05 ± 11.80 a	23.41 ± 14.07 a	4.01 ± 4.04 c	3.61 ± 7.54 d	0.52 ± 3.74 d	0.01 ± 0.01 d

Note: Different letters in the same column indicate significant differences at $p < 0.05$ levels, and data in the table are mean ± SD.

Table 3 presents the RSD of DOSA for different aggregate size classes under varying moisture conditions. The impact of soil moisture on the RSD of DOSA differed among aggregate size categories. For the 10–7 mm aggregate size class, soil moisture levels of up to 60% SRWC did not significantly affect the RSD; however, the RSD under the 80%

SRWC condition was markedly higher than under other moisture conditions. In the case of aggregates $\leq$ 0.5 mm, the RSD of DOSA showed no significant deviation from that of soils with an SRWC of up to 40%, indicating a certain resilience in aggregate stability within this moisture range.

Table 3. RSD for the distribution of soil aggregate sizes.

Treatment	RSD for the Distribution of Soil Aggregate Sizes (%)						
	10~7	5~7	3~5	2~3	0.5~2	0.25~0.5	<0.25
Air-dry-soil	23 ± 16 a	19 ± 11 ab	17 ± 6 b	16 ± 10 b	17 ± 15 b	19 ± 12 b	17 ± 6 c
10%	27 ± 19 a	14 ± 8 b	14 ± 6 b	16 ± 13 b	10 ± 10 b	16 ± 10 b	14 ± 9 c
20%	20 ± 10 a	12 ± 8 b	10 ± 8 b	13 ± 11 b	12 ± 9 b	15 ± 11 b	15 ± 11 c
40%	29 ± 18 a	15 ± 6 b	13 ± 10 b	16 ± 6 b	18 ± 11 b	24 ± 16 b	32 ± 2 bc
60%	25 ± 22 a	12 ± 8 b	18 ± 13 b	22 ± 9 b	29 ± 17 b	58 ± 22 a	58 ± 31 a
80%	26 ± 22 a	26 ± 15 a	32 ± 23 a	79 ± 57 a	95 ± 58 a	70 ± 70 a	46 ± 43 ab

Note: Different letters in the same column indicate significant differences at $p < 0.05$ levels.

The relative standard deviation (RSD) of the distribution of soil aggregate sizes (DOSA) across various SRWC levels, as depicted in Figure 2, fluctuated between 18% and 54% for SRWC levels not exceeding 80%. Notably, the RSD values for soils with air-dried conditions, 10% SRWC, 20% SRWC, and 40% SRWC were not significantly different from each other. However, the RSD for soils at 60% and 80% SRWC stood out as being significantly higher compared to other moisture conditions, with the 80% SRWC treatment showing the most pronounced increase.

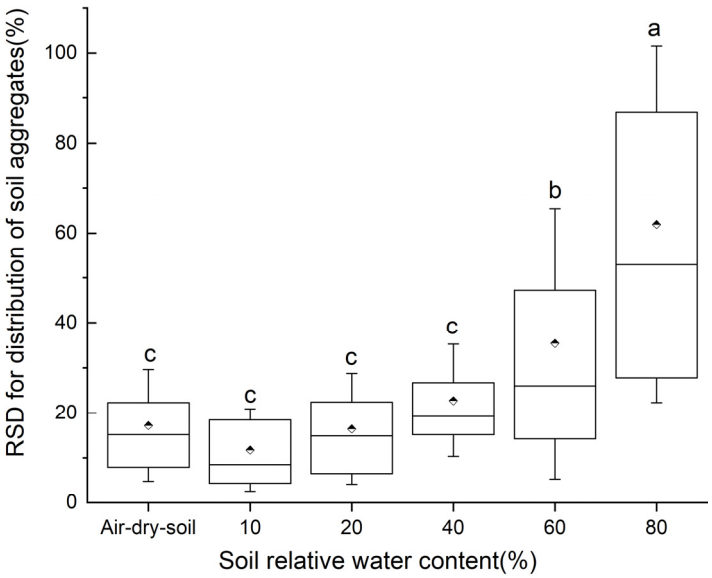


Figure 2. RSD for distribution of soil aggregate size under different soil relative water contents. Note: the black lines and rhombus, lower and upper edges, and lower and upper bars in or outside the boxes represent median and mean values, 25th and 75th, negative and positive standard deviation of all data, respectively. Note: Different letters indicate significant differences at $p < 0.05$ levels.

These findings underscore the complex relationship between soil moisture and aggregate stability. The changes in RSD with varying SRWC suggest that soil aggregates exhibit different sensitivities to moisture levels, which has implications for soil management practices aimed at maintaining soil structure and function.

3.3. Characteristic Values of Soil Aggregate Size Distribution Under Various Soil Water Contents

The characteristic values of soil aggregate size distribution are pivotal for understanding the structural attributes of soil and its response to varying soil water contents. This

section examines the influence of soil relative water content (SRWC) on key indices of soil aggregate size distribution, including $R_{0.25}$, mean weight diameter (MWD), geometric mean diameter (GMD), and fractal dimension (D).

The soil samples were grouped into four distinct clusters based on a comprehensive analysis of their properties, including texture, pH, soil organic matter (SOM), and bulk density (BD) with ANOSIM. The categorization was as follows: Cluster 1 comprised soils as Symbol 112 and 122 from both the 0–15 cm and 15–30 cm layers inside the greenhouse at DDD, respectively; Cluster 2 consisted of soils as Symbol 111 and 121 from the 0–15 cm and 15–30 cm layers but outside the greenhouse at DDD, respectively; Cluster 3 included soils such as Symbol 211, 212, 221, and 222 from the 0–15 cm and 15–30 cm layers outside and the 15–30 cm layer inside the greenhouse at JLH; Cluster 4 encompassed soils such as Symbol 311, 312, 321, and 322 from the 0–15 cm layer inside the greenhouse at JLH; Cluster 5 incorporated soils from the 0–15 cm and 15–30 cm layers outside and the 15–30 cm layer inside the greenhouse; finally, Cluster 6 was comprised of soils from the 0–15 cm layer inside the greenhouse at JLH (refer to Figure 3 for a visual representation of these clusters based on soil properties).

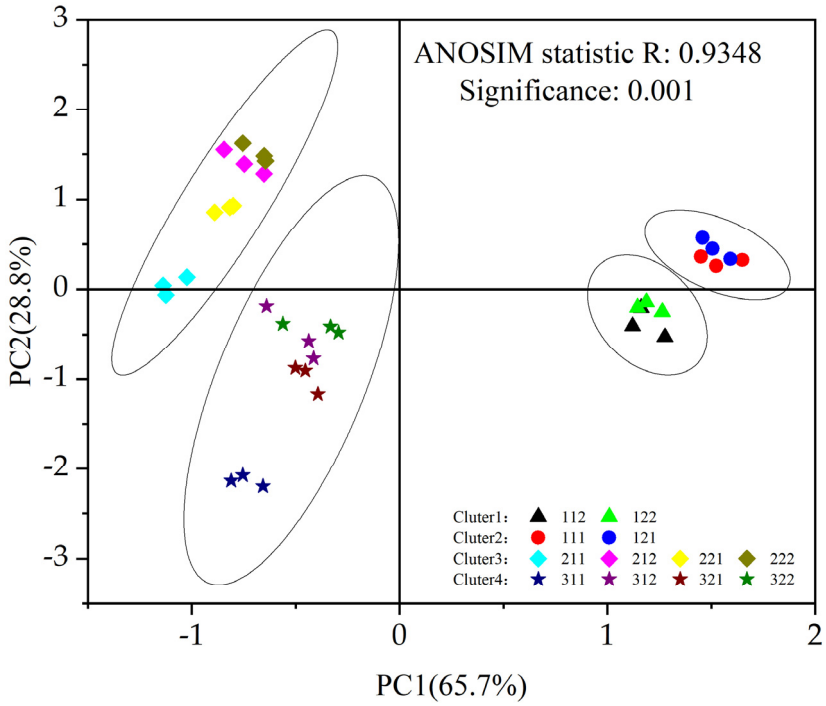


Figure 3. PCA of soils based on soil properties (soil text (percentage of sand, silk and clay), pH, SOM, BD). Note: 12 colors means 12 soils, the three digits represent the following in order: The first digit indicates the soil sampling experimental site, with 1 for DDD, 2 for JLH, and 3 for ZZZ. The second digit indicates whether the sampling point is inside or outside the greenhouse, with 1 for inside and 2 for outside. The third digit represents the soil layer for sampling, with 1 for the 0–15 cm layer and 2 for the 15–30 cm layer. Shape means different clusters, ellipse was plotted at 95% confidence.

Post clustering, the influence of soil relative water content (SRWC) on the characteristics of the distribution (R0.25%, MWD, GWD, and D) of soil aggregate sizes (DOSA) was examined (as shown in Figure 4). The DOSA characteristics varied significantly between clusters at the same site, with the exception of the percentage of soil aggregates larger than 0.25 mm (R0.25) for Clusters 5 and 6 at JLH, where the difference was not statistically significant (p = 0.068; see Table 4 for details). Despite these variations, a consistent trend was observed in the response of DOSA characteristics to changes in soil moisture. Specifically, R0.25 exhibited an exponential increase with rising SRWC, with the determination

coefficient (R^2) exceeding 0.794. Both the mean weight diameter (MWD) and geometric mean diameter (GMD) followed a linear increase with SRWC, maintaining an R^2 value of no less than 0.717. Conversely, the fractal dimension (D) decreased exponentially as soil moisture increased, with an R^2 value greater than 0.778, indicating a complex relationship between soil moisture and the structural attributes of soil aggregates.

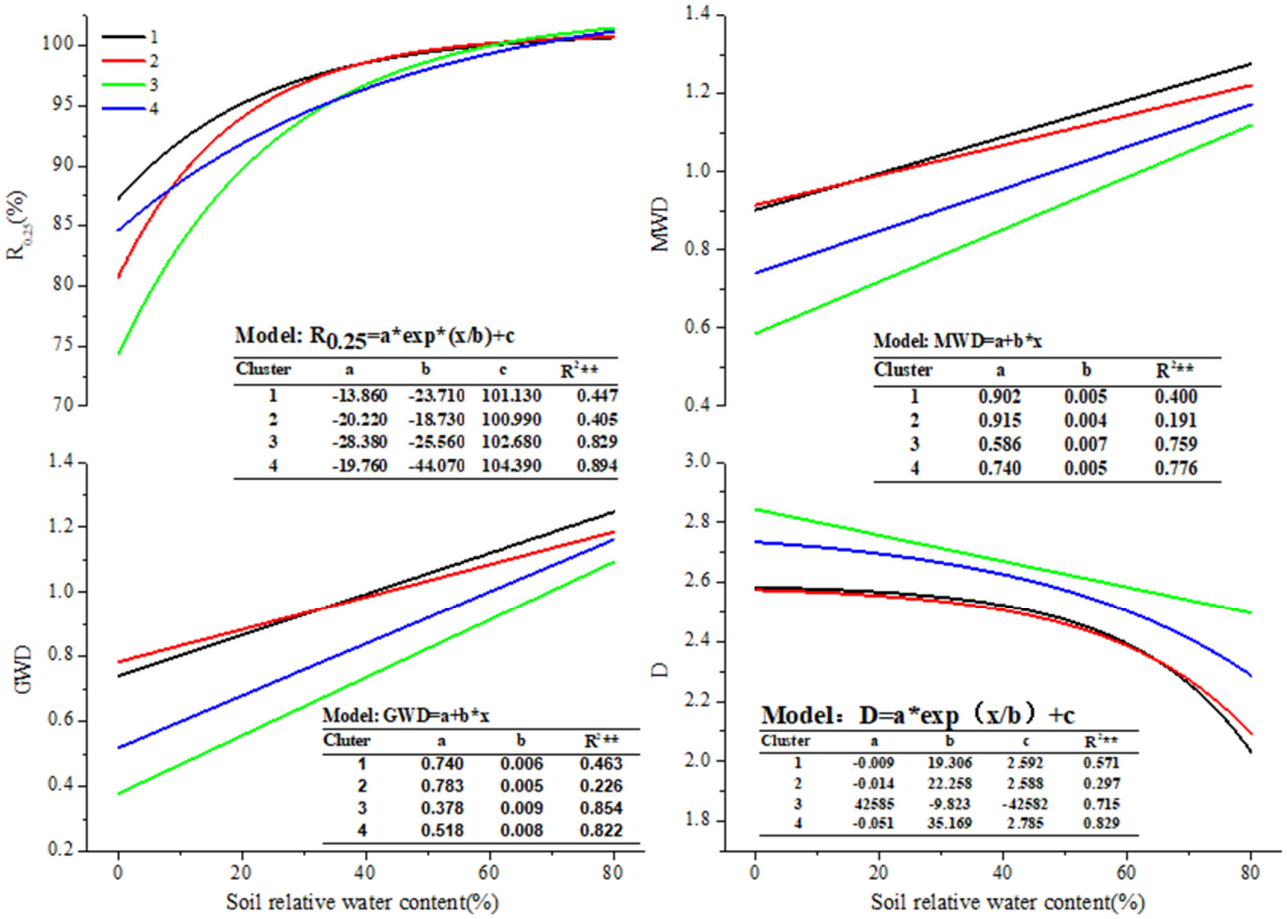


Figure 4. Fitting curve of characteristic value ($R_{0.25}$, mean weight diameter/MWD, geometric mean diameter/GMD, and fractal dimension/D) of soil aggregates under different soil relative water contents. Note: soils used in the research were classified based on their soil properties (Table 1), and they are categorized into 4 clusters; ** means that fitting curve is significant at $p < 0.001$.

Table 4. Comparison of fitting curve of characteristic value of soil aggregates under different soil relative water contents between two clusters in same site.

Cluster	$R_{0.25}$			MWD			GWD			D		
	MS	F	*p*	MS	F	*p*	MS	F	*p*	MS	F	*p*
1 2	9.643	1.678×10^2	0.000	4.282	5.115×10^{11}	0.000	7.381	8.836×10^{11}	0.000	0.463	2.751×10^4	0.000
3 4	0.722	8.255	0.004	0.916	1.098×10^{11}	0.000	0.931	1.115×10^{11}	0.000	0.002	5.253×10^2	0.000
5 6	0.036	3.335	0.068	0.209	2.506×10^{11}	0.000	0.001	5.996×10^7	0.000	0.004	3.836×10^2	0.000

Note: MS, F and *p* are mean square, value of F-test and value of significance when analysis of covariance.

4. Discussion

4.1. Influence of Soil Water Content on Soil Aggregation Dynamics

Soil moisture content is a critical factor that significantly modulates the dynamics of soil aggregation [10], influencing key ecological processes such as water infiltration,

nutrient cycling, and root growth [3]. This section discusses the mechanisms by which soil water content affects soil aggregation and the stability of soil aggregates.

Our findings, as detailed in Table 2, indicate that the distribution of soil aggregate sizes (DOSA) exhibits a complex response to changes in soil moisture. We observed an increase in DOSA for aggregates larger than 3 mm with rising soil moisture levels, while a contrasting trend was noted for smaller aggregates (<3 mm). This observation diverges from classic studies [20], which reported higher percentages of both macro-aggregates and micro-aggregates when soil samples were sieved under air-dried conditions as opposed to field moisture conditions. The discrepancy arises from the directionality of moisture change; our study involved a transition from air-dried to increasingly humid states, in contrast to previous investigations, which have examined the effects of transitioning from field moisture to air-dried conditions [20]. These contrasting moisture dynamics yield divergent outcomes in soil aggregation patterns.

Recent studies have also highlighted the role of soil moisture in influencing the stability and formation of soil aggregates. For instance, research by Rabbi et al. [21] demonstrated that the soil moisture content significantly affects the formation of macro-aggregates through the enhancement of microbial activity and organic matter decomposition. Similarly, a study by Mao et al. [22] showed that soil moisture content can alter the physicochemical properties of soil aggregates, thereby affecting their stability and distribution.

The adhesive properties of completely dry and dispersed soil particles are negligible under normal pressure conditions. However, the introduction of water introduces surface tension within the thin film of water surrounding the soil grains, promoting adhesion among adjacent particles [14]. Optimal adhesion is achieved when the water film is uniformly distributed, facilitating the formation of meniscuses at soil particle contact points [23]. This phenomenon was evident in our study's findings, as indicated in Table 2. Consequently, the characteristic values of DOSA, including $R_{0.25}$, MWD, and GMD, escalated with an increase in soil relative water content (SRWC), while the fractal dimension (D) diminished, underscoring the aggregation process's sensitivity to soil water content.

Conversely, as soil moisture levels decreased, a phenomenon widely reported in the literature was observed, namely, the flocculation of basic ions such as silica and carbonates on the aggregate surfaces. This occurrence is recognized as a key mechanism contributing to the aggregation process in air-dried soils, supported by numerous studies that have demonstrated similar findings [24]. Despite the apparent stability conferred by this cementation, it is transient and can be readily disrupted by mechanical forces, as evidenced during the sieving process of air-dried soils in previous studies [25]. These findings collectively highlight the nuanced and dynamic nature of soil aggregation, which is intricately linked to the prevailing soil moisture conditions and the inherent properties of the soil matrix [20].

In addition, the influence of soil moisture on soil aggregation is not only limited to the physical properties of soil but also extends to the biological and chemical processes within the soil matrix. For example, soil moisture can affect the activity of soil microorganisms, which play a crucial role in the decomposition of organic matter and the formation of stable aggregates [21]. Moreover, the interaction between soil moisture and soil texture can also influence the distribution and stability of soil aggregates, as demonstrated by Mao et al. [22]. These studies further emphasize the importance of considering soil moisture content in the assessment and management of soil aggregation.

The influence of soil water content on soil aggregation dynamics is multifaceted, with implications for soil structure, fertility, and ecological function. Our study provides insights into how soil moisture content can alter the aggregation process, affecting the stability and distribution of soil aggregates, which is crucial for informing agricultural practices and soil management strategies.

4.2. Performance and Sensitivity of Soil Aggregate Sieving Under Varied Soil Water Contents

The performance and sensitivity of soil aggregate sieving are essential parameters for assessing the reliability and responsiveness of our methodology to changes in soil water content. This section evaluates the consistency and variability of the sieving process under different moisture conditions, which are critical for the validity of our research findings.

Performance, quantified through the recovery rate and relative standard deviation (RSD) [26], is a key indicator of the sieving process's accuracy and precision. The recovery rate, an accuracy measure, and the RSD, a precision indicator, were employed to evaluate the sieving process's performance under varied soil moisture conditions. Our results, with an average recovery rate of 99.50% across all treatments, exceeded the threshold of 99.22%, suggesting high accuracy in the sieving process under varied soil moisture conditions (Figure 1). Notably, the recovery rates were indifferent to the soil moisture levels, reinforcing the robustness of our sieving methodology.

However, the precision, as reflected by the RSD, was sensitive to the soil relative water content (SRWC). While the RSD remained consistent up to an SRWC of 40%, it increased significantly at higher moisture levels, particularly at 60% and 80% SRWC (Figure 2). This increase in RSD was primarily attributed to the altered distribution of larger and finer aggregates (Tables 2 and 3). The diminished precision at elevated SRWC underscores the importance of standardizing sieving conditions to ensure reliable DOSA measurements.

The sensitivity of the sieving process to soil water content is further evidenced by the changes in the distribution of soil aggregate sizes (DOSA) with varying moisture levels. The initial increase in DOSA for the 3–0.25 mm aggregate range, followed by a decline, and the significant decrease in DOSA for aggregates smaller than 0.25 mm, highlight the complex response of soil aggregates to changes in moisture conditions. These observations are crucial for understanding how soil management practices, such as irrigation and drainage, can impact soil structure and function [6,10,12].

Recent studies have also shown that the interaction between soil moisture and soil texture can significantly influence the distribution and stability of soil aggregates. For example, Yang et al. [27] demonstrated that soil moisture content can alter the physicochemical properties of soil aggregates, thereby affecting their stability and distribution. Similarly, a study by Yang et al. [28] found that the combination of soil moisture and soil texture can influence the formation and stability of soil aggregates, highlighting the need to consider these factors in soil management practices.

Our findings advocate for conducting soil aggregate sieving under controlled moisture conditions to maintain the precision and accuracy of DOSA. Furthermore, the analysis of multiple replicates is essential for achieving a representative DOSA, allowing for meaningful comparisons across different soil management practices. This approach is vital for advancing our understanding of soil aggregation dynamics and optimizing agricultural practices that are attuned to the dynamic soil moisture milieu [29].

4.3. Effect of Soil Properties on the Distribution of Soil Aggregate Size

The distribution of soil aggregate sizes is intricately linked to the soil's properties, which are shaped by agricultural practices and soil texture [2,5,10]. This section explores the impact of soil properties on the distribution of soil aggregate sizes and how these properties interact with soil moisture to influence soil structure.

The diversity in agricultural practices, such as tillage, cropping systems, irrigation schedules, and fertilization methods, results in a gradient of soil properties [5,6,30], particularly distinguishing the conditions inside and outside the greenhouse (Table 1). To dissect the complex interplay between soil moisture and soil properties on the distribution of soil aggregate sizes (DOSA), we classified 12 soils into six distinct clusters based on their

soil properties (as depicted in Figure 3). Each cluster encompassed soils from the same experimental site, either within or outside the greenhouse, highlighting the uniformity in treatment conditions (Table 1). The strong correlation between DOSA and soil water content within these clusters, with R^2 values surpassing 0.717, validates the clustering approach. Furthermore, the analysis of covariance revealed significant discrepancies in the fitting curves between clusters at the same site, with the DDD site exhibiting the most pronounced differences, potentially attributable to variations in soil texture (Table 1 and Figure 3) [19]. The role of soil hydrophobicity in aggregation processes has been well-documented in the literature [31]. While our study did not include direct measurements of soil hydrophobicity, the observed effects on aggregate stability are in line with these reports, indicating that hydrophobic interactions could be a contributing factor. This suggests that future research could benefit from incorporating direct assessments of hydrophobicity to further elucidate its influence on soil aggregation. Chenu et al. [32] documented that the carbon content can lower the surface tension of water, significantly affecting clayey and sandy soils. In this study, the sand content and organic carbon levels varied significantly between the DDD site and others, which could account for the variations in DOSA (Table 1). These findings collectively indicate that the distribution of soil aggregate sizes is highly responsive to both the soil's properties and its relative water content [6], echoing the foundational work by Chepil [33].

Recent studies have further emphasized the importance of soil properties in influencing the distribution and stability of soil aggregates. For example, Yang et al. [27] demonstrated that soil moisture content can alter the physicochemical properties of soil aggregates, thereby affecting their stability and distribution. Similarly, a study by Yang et al. [28] found that the combination of soil moisture and soil texture can influence the formation and stability of soil aggregates, highlighting the need to consider these factors in soil management practices.

Moreover, the interaction between soil moisture and soil texture can also influence the distribution and stability of soil aggregates. For instance, soil moisture can affect the activity of soil microorganisms, which play a crucial role in the decomposition of organic matter and the formation of stable aggregates [21]. Additionally, the physicochemical properties of soil aggregates can be altered by soil moisture, which in turn affects their stability and distribution [22]. These findings underscore the importance of considering soil moisture and soil texture in the assessment and management of soil aggregation.

The distribution of soil aggregate sizes is not only influenced by soil moisture content but also significantly modulated by soil properties such as texture, organic matter, and pH. Understanding these interactions is crucial for developing soil management strategies that optimize the soil structure and function under varying environmental conditions. The complex response of soil aggregate sizes to soil properties underscores the need for tailored agricultural practices that consider the specific characteristics of different soil types.

5. Conclusions

The present study provides a comprehensive analysis of the impact of soil relative water content (SRWC) on the sieving process and the subsequent size distribution of soil aggregates. Our findings offer valuable insights into the dynamics of soil aggregation and the response to different moisture regimes, which are crucial for enhancing sustainable agricultural practices.

Our results demonstrated that the sieving process achieved a remarkably high recovery rate, exceeding 99.22%, under field-moist conditions, with negligible variation between air-dried and 80% SRWC treatments. However, a discernible increase in the relative standard deviation (RSD) of the distribution of soil aggregate sizes (DOSA) was noted

when the SRWC was elevated beyond 40%. This observation underscores the imperative of deriving a representative DOSA through a series of replicate sieving operations under field-moisture conditions.

The intrinsic soil properties, modulated by agricultural stewardship and textural composition, were found to significantly dictate the DOSA's responsiveness to moisture fluctuations. Notably, the data from clustered soil samples revealed a robust correlation (with R^2 values surpassing 0.717), indicating a coherent pattern in the aggregate size distribution relative to soil moisture. The fitting curves diverged markedly between clusters at identical sites, highlighting the nuanced interplay between soil moisture and aggregate stability.

In conclusion, soil aggregation, a critical determinant of soil fertility and structure, is profoundly influenced by variable soil moisture content, especially within agricultural settings. This study was meticulously designed to appraise the efficacy of soil aggregate sieving under targeted moisture conditions. The outcomes advocate for the precision of aggregate sieving under controlled field moisture conditions, given the high fidelity and sensitivity of the process to moisture levels. This approach is pivotal for enhancing the reliability of soil aggregate assessments and, by extension, for informing sustainable agricultural practices that are attuned to the dynamic soil moisture milieu.

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