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Impact of Aggregate-Associated Carbon on Soil Mechanical Properties: Stability and Compaction Indices in Pomegranate Orchards of Different Ages

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Abstract: The relationships between soil aggregates, aggregate-associated carbon (C), and soil compaction indices in pomegranate orchards of varying ages (0–30 years) in Assiut, Egypt, were investigated. Soil bulk density (Bd) and organic carbon (OC) content increased with orchard age in both the surface (0.00–0.20 m) and subsurface (0.20–0.40 m) layers 0.20–0.40 m). The percentage of macroaggregates ($R_{0.25}$) and their OC content in the aggregate fraction > 0.250 mm increased as the pomegranate orchard ages increased in the surface layer (0.00–0.20 m). Older pomegranate orchards show improved soil structure, indicated by higher mean weight diameter (MWD) and geometric mean diameter (GMD), alongside reduced fractal dimension (D) and erodibility (K). As orchard ages increased, maximum bulk density (B_{Max}) decreased due to an increase in OC, while the degree of compactness (DC) increased, reaching a maximum at both soil layers for the 30 Y orchards. Soil organic carbon and aggregate-associated C significantly influenced B_{Max}, which led to reducing the soil compaction risk. Multivariate analyses identified the >2 mm aggregate fraction as the most critical factor influencing the DC, soil compaction, and K indices in pomegranate orchards. The OC content in the >2 mm aggregates negatively correlated with B_{Max}, DC, and K but was positively associated with MWD and GMD. Moreover, DC and Bd decreased with higher proportions of >2 mm aggregates, whereas DC increased with a higher fraction of 2–0.250 mm aggregation. These findings highlight the role of aggregate size fractions and their associated C in enhancing soil structure stability, mitigating compaction, and reducing erosion risks in pomegranate orchards.

Keywords: pomegranate orchards; fractal dimension; soil aggregates; degree of compactness; bulk density; erodibility; associated carbon

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1. Introduction

Soil compaction is a worldwide challenge, threatening soil structure, lowering production, and posing risks to sustainable agriculture. According to Abdel Kawy and Ali, 2012 [1], and El Nahry et al., 2015 [2], soil compaction is a significant issue in arid and semi-arid regions, such as Egypt. Soil compaction is caused primarily by heavy machinery use, overgrazing, intensive tillage, and low organic matter (OM) levels, which damage soil structure and impair resilience [3]. This leads to the compression of soil layers and changes the pore structure of the soil, which negatively impacts several soil processes; these include water infiltration and retention, root penetration and growth, nutrient cycling, gas exchange (aeration), and microbial activity. Such degradation of the soil's physical characteristics can lead to reduced crop yields, increased erosion risks, and diminished overall soil health. It also greatly affects the efficiency of nutrients and water usage, as well as increasing the risk of runoff and soil erosion [4]. Soil compaction is a common hazard in orchards caused by agricultural operations; one factor related to this is that the majority of orchard practices are implemented while the soil has moisture exceeding the plasticity limit, which intensifies the degree of compaction [5]. Therefore, soil compaction levels may vary depending on the climatic conditions and moisture management practices in specific regions. In arid and semi-arid regions, where orchards are often irrigated, soil moisture levels can reach or exceed the plasticity limit at certain times, especially following irrigation [6]. In these cases, soil compaction risks are indeed elevated during operations. In contrast, in humid regions with naturally higher soil moisture, compaction risk may be even more consistent due to prolonged wet conditions [7]. This means that one of the major factors relevant to soil compaction is climate change, as extreme weather increases soil susceptibility. Addressing compaction requires improved soil management strategies, such as minimizing tillage, adding organic amendments, and using precision farming to enhance soil resilience and maintain long-term agricultural productivity [4].

According to previous studies, orchard production changed as plantation age increased due to unfavorable physical conditions, primarily associated with soil compaction, which decreased the soil quality and increased the agricultural soil maintenance expenses [8]. The characteristics of soil are impacted by conventional orchard soil management. Orchard soil may physically degrade due to anthropogenic activities or natural conditions [9,10]. Irrigation methods [11,12], field traffic, limited crop diversity [13,14], intensive farming practices, and low organic matter concentration [15] can all significantly contribute to soil compaction. According to some research, applying extensive chemical fertilizers and less crop diversification may alter ion distribution in the rhizosphere area, worsening soil structure and function and contributing to soil compaction [16,17]. For instance, intensive use of nitrogen fertilizers can lead to localized changes in the soil pH within the rhizosphere, making it more acidic or alkaline depending on the type of fertilizer and soil properties. While these pH changes are typically confined to the rhizosphere and unlikely to affect the entire soil profile, they can still influence nutrient availability and microbial activity in the root zone. Over time, such changes may disrupt the natural aggregation of soil particles, particularly in the rhizosphere, and exacerbate compaction in intensively managed soils. This impacts the mechanism of soil aggregate formation and causes the clay to migrate downward, resulting in subsurface soil compaction. Soil compaction and erosion resistance were mostly related to the formation of soil aggregates of various fraction sizes [18,19]. Additionally, macroaggregates (>0.25 mm), soil compaction, and soil erodibility were significantly but rather adversely correlated [20]. Soil compaction was mostly influenced by poor soil aggregation stability due to low contents of SOM [21] and mud migration downwards [22,23]. One of the most crucial indicators that might reveal important details about the degree and process of soil compaction and erosion is the stability of soil aggregates.

According to Six et al., 2000 [24], the aggregate hierarchical model provides a valuable framework for understanding how SOM influences soil structure at different scales, and in this model, soil aggregates form in a hierarchical manner, beginning with microaggregates (smaller than 0.25 mm) as foundational units that combine to form larger macroaggregates (>0.25 mm). SOM plays a key role in stabilizing both levels: within the microaggregates, organic matter binds fine particles like clay and silt, creating stable units that resist breakdown. As these microaggregates cluster to form macroaggregates, SOM (particularly fresh organic inputs) acts as a "glue," promoting stability and water resistance. This hierarchical aggregation process results in a pore network that improves soil aeration, water infiltration, and root growth. By enhancing the formation and stability of both micro- and macroaggregates, SOM ultimately improves soil structure, decreases compaction, and supports long-term soil health and productivity. In contrast, stable aggregates can efficiently preserve microbially decomposed organic materials [25]. Soil aggregates and associated C can be used as effective indicators of alterations to soil properties caused by various farming strategies. Nonetheless, OC content varies significantly between soil aggregate fractions [6]. Thus, modifications to orchard management strategies, such as reduced tillage, organic amendments, and residue incorporation, can significantly redistribute organic carbon (OC) among soil pools, altering the soil's physical composition. For example, reducing tillage preserves macroaggregates, allowing OC to accumulate in stable forms, which enhances soil structure, water retention, and erosion resistance. Conversely, intensive practices like excessive plowing disrupt aggregates, exposing OC to decomposition and increasing carbon loss. These changes have critical implications for orchard management: practices that promote OC accumulation in stable pools, such as cover cropping, mulching, and precision irrigation, not only improve soil health but also contribute to carbon sequestration and climate resilience [26]. Soil aggregate-associated carbon (C) may be a good indicator of changes in soil structure resulting from various management practices and their effects on soil compaction. Previous research revealed that the soil physicochemical characteristics in pomegranate orchards varied as plantation ages increased [27–30].

Bulk density is often considered as an ineffective indicator of soil compaction due to its sensitivity to factors such as soil texture and organic matter content [2]. Variations in these properties make it challenging to use Bd alone to assess soil mechanical quality consistently [31]. As an example, Farag et al. [12] found that high irrigation levels increased soil bulk density in pomegranate orchards by causing a drop in SOM, resulting in restructured soil particles and changed soil pores. To address these limitations, researchers prefer using the DC and the B_{max} as more reliable indicators [32]. The DC is calculated by dividing the field Bd by the B_{max}, the latter being derived through the Proctor compaction test [33]. This approach has been widely adopted in various studies, including Cavalcanti et al. 2019 [14] and Toledo et al. 2021 [3], as it provides a more consistent measure of compaction across different soil types. By using DC and B_{max}, researchers can better account for the variations in soil properties, offering a more standardized and effective method for assessing soil compaction [27].

Pomegranates are one of Egypt's vital orchard products, contributing significantly to the national economy's agricultural industry [34]. The greatest pomegranate-producing area in Egypt is Assiut Governorate [35]. Pomegranate farming has steadily taken center stage in rural Assiut economies [36]. Taking into consideration the advancement of intensive orchard management in privately owned orchards, extensive agriculture produces an increased number of productive trees and a rise in production, yet extensive plowing, low vegetation cover, and anthropogenic activities promote soil deterioration. Furthermore, a significant amount of crop residue is produced annually in deciduous tree orchards [37]. The composition of soil aggregates as well as variations in associated OC concentrations and their impact on soil compactions and soil erosion under long-term management strategies should be investigated for sustainable development of the orchard ecosystem. Nevertheless, a comprehensive assessment of the relationship between OC, especially aggregate-associated C, and soil compaction, specifically in pomegranate orchards of varied ages, represents one of the novel contributions of the current study.

While previous studies have investigated the relationship between OC and soil structure stability, there has been limited research specifically focused on understanding how the OC within different soil aggregate size fractions contributes to soil compaction indices and erosion resistance, particularly in pomegranate orchards. Additionally, the effect of orchard age on soil compaction and aggregation stability as suitable indicators for monitoring soil compaction in arid regions such as Assiut, Egypt, has not been thoroughly studied; this gap is particularly relevant for improving soil management in long-term orchard cultivation, as well as for mitigating compaction and erosion risks. Thus, this study investigates the relationships between soil compaction, aggregation stability, and associated carbon across pomegranate orchards of varying ages, addressing a significant gap in the literature, and hypothesizes that as orchards age, the danger of soil compaction and erosion will rise, with an increase in OC and C associated with aggregates, given that the traffic-caused stresses and agriculture practices are expected to be greater. While previous research has examined soil compaction or aggregation individually in orchards, this work provides novel insights by directly comparing these indicators across different orchard ages (using bulk density, organic carbon content, aggregate size distribution, mean weight diameter, geometric mean diameter, fractal dimension, and erodibility) in Assiut, Egypt. Therefore, the goals of the current study were to assess the following: (i) soil compaction and variables related to soil structure characteristics (aggregate stability, soil porosity) in four different-aged pomegranate orchards in Assiut Governorate, Egypt; (ii) the relation between soil compaction indices, the associated C content, and the stability of soil aggregates.

2. Materials and Methods

2.1. Study Sites and Orchard Management:

Samples were gathered from four privately-owned pomegranate orchards (mature Manfalouty pomegranate trees) at Sahel-Selim (26°57′00″ to 27°12′00″ N, 31°15′00″ to 31°30′00″ E), Assiut Governorate, Egypt (Figure 1), for varying orchard ages of three years (3 Y), ten years (10 Y), twenty years (20 Y), and thirty years (30 Y). The pomegranate planting intensity is 625 trees per hectare (ha) (4.0 m between trees and between lines). The research region belongs to the subtropical desert climate zone with an average annual temperature of 25.89 °C and less than 0.35 mm of precipitation. All pomegranate orchards included in the study were located on similar geomorphological units and had shared the same soil parent material and fertilization applications. Organic manure, particularly farmyard manure (animal wastes) containing 0.5% nitrogen (N), 0.2% phosphorus (P), and 0.5–0.3% potassium (K), was applied annually in December at a rate of 1000 kg ha^{-1} (1.6 kg $tree^{-1}$) along with 1.0 kg $tree^{-1}$ of calcium superphosphate (15.5% P_2O_2) as a crucial fertilizer. Additionally, 2.0 kg $tree^{-1}$ of ammonium sulfate (20.6% N; 1250 kg ha^{-1}) and 350 g $tree^{-1}$ of potassium sulfate (48% K_2O) were applied in two doses in March and late May as mineral sources. The application of well-decomposed farmyard manure is a widely recognized practice for improving soil organic carbon (SOC) levels and enhancing soil structure. Humic substances, which are a major component of well-decomposed manure, play a pivotal role in soil aggregation. These substances act as binding agents, promoting the formation of stable macroaggregates through their ability to bridge soil particles and enhance microbial activity. Humic acids, in particular, contribute to the stabilization of soil aggregates by forming strong bonds with clay minerals and organic polymers, thereby improving soil porosity, water retention, and resistance to erosion. Conventional farming procedures, such as flood irrigation (20–25 m^3 $tree^{-1}$ $year^{-1}$) and insect control, were applied to each orchard. Each orchard follows standard management practices, including annual pruning to maintain tree health and productivity. Pest control is applied as needed based on observed pest pressures, primarily during flowering and fruiting seasons. Regarding land use history, prior to pomegranate cultivation, the land across these sites was primarily used for low-intensity agriculture, including alfalfa and traditional cereal crops, for approximately 20–30 years, which may have influenced the initial soil conditions. Since orchard establishment, management practices have focused on maintaining optimal soil conditions for pomegranate growth, including consistent irrigation, organic amendments, and soil testing to guide fertilization. Mechanical tillage was used for the first five years, after which conventional tillage was implemented due to the challenges of using machinery due to the high tree density (average depth 20 cm). The physical and chemical characteristics of the soil are displayed in Table 1.

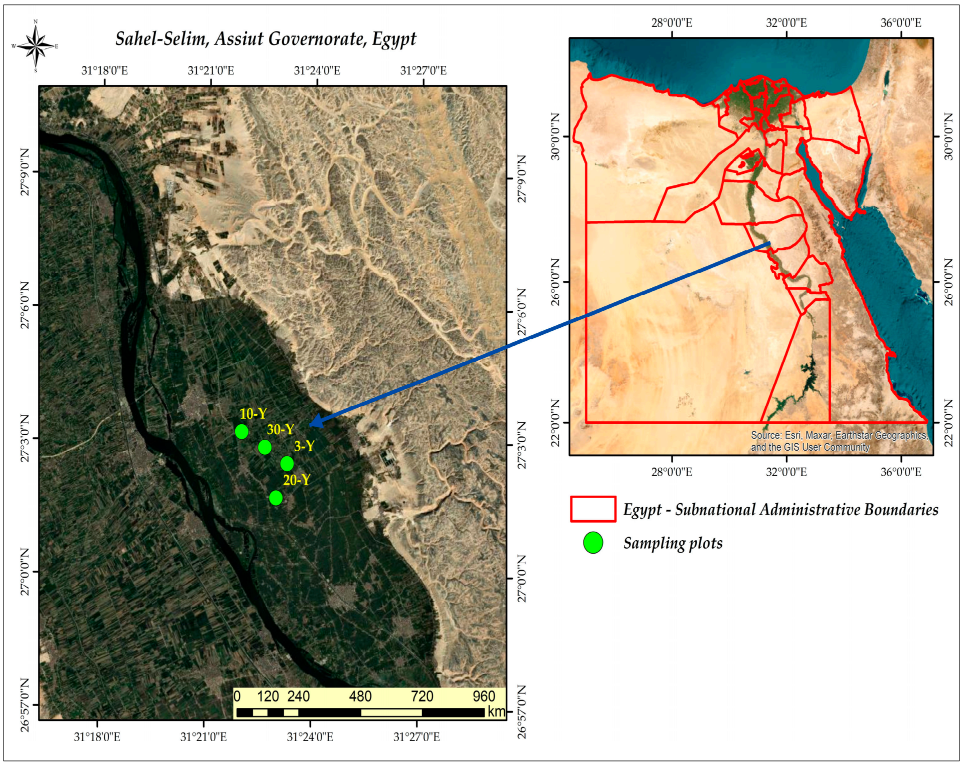

Figure 1. Location of sampling sites for pomegranate orchards.

Table 1. Soil particle size distribution and chemical characteristics during various ages of the pomegranate plantation.

Soil Properties		3 Y	10 Y	20 Y	30 Y	3 Y	10 Y	20 Y	30 Y
		0.00–0.20 m				0.20–0.40 m			
Silt	%	57.62 ± 0.21 a	55.01 ± 0.27 b	56.92 ± 0.56 a	57.00 ± 0.52 a	55.55 ± 0.37 a	54.51 ± 0.62 a	54.72 ± 0.54 a	55.48 ± 0.32 a
Clay	%	37.68 ± 0.56 a	39.13 ± 0.36 a	38.43 ± 0.40 a	38.83 ± 0.65 a	38.77 ± 0.64 a	39.86 ± 0.55 a	40.47 ± 0.32 a	39.67 ± 0.60 a
Sand	%	4.70 ± 0.56 a	5.86 ± 0.49 a	4.65 ± 0.53 a	4.20 ± 0.50 a	5.69 ± 0.67 a	5.63 ± 0.55 a	4.81 ± 0.57 a	4.85 ± 0.62 a
EC	mS cm^{-1}	251	227	270	271	280	265	303	321
pH		8.25	8.40	8.61	8.59	8.30	8.34	8.50	8.33
$CaCO_3$	%	2.65	1.52	2.47	2.53	2.78	1.31	3.48	1.46

Y represents the years of the pomegranate plantation. Different lowercase letters in the same column indicate significant differences at $p < 0.05$ according to Duncan's multiple range tests. ± represent standard errors (N = 4).

2.2. Soil Sampling

To represent the two soil layers (0.00–0.20 and 0.20–0.40 m), a total of 32 disturbed soil samples (8 per orchard) and 64 undisturbed soil samples (16 per orchard) were collected from each orchard in November 2022. For collecting disturbed soil samples (7–10 kg) and soil cores, four randomly selected 15 × 15 m plots were constructed at every orchard, and the main physicochemical characteristics of the soil samples were taken from pomegranate orchards of various ages. Soil samples were brought to the lab and air-dried to achieve constant weight. They were then carefully broken into aggregate sizes of less than 8 mm at the natural break by gently crushing them along their natural planes of weakness using a rubber mallet or a wooden roller; this method ensures that the soil aggregates are not artificially disrupted or destroyed, preserving their natural structure. This approach is consistent with standard protocols for soil aggregate analysis, which emphasize minimizing mechanical disruption to avoid altering the soil's physical properties. Undisturbed soil samples collected in cylinders (0.5 m height, 0.5 m diameter) were used to assess bulk density and soil porosity. The disturbed soil samples were utilized to measure soil particle distribution (clay, silt, and sand), aggregate stability, OC, B_{max} by the Proctor test, and particle density (Pd).

2.3. Sample Analysis

The distribution of soil particle size was measured using the pipette method while the soil reaction (pH) and the electrical conductivity (EC) of the soil samples were measured with a pH meter and a conductivity meter, respectively, using a soil-to-water ratio of 1:2.5 as described by Page (1982) [38]. Calcium carbonate ($CaCO_3$) was determined using the titration method [39], and the OC content was determined using the acid dichromate wet oxidation method [40].

To determine the Bd of the soil, undisturbed soil samples were oven-dried at 105 °C until they reached a consistent weight. The soil particle density (g cm^{-3}) was estimated using the pycnometer method [41]. The soil total porosity (%) was calculated using Equation (1).

$$TP = \left(1 - \frac{Bd}{PD}\right) \times 100 \tag{1}$$

The standard Proctor test for compaction properties was performed according to the current Egyptian Code of Practice or relevant ASTM D698 (2007) [33,35,42]. The soil was wet and weighed several times to calculate its B_{Max}. The DC was determined by applying the relation between Bd (from the field) and B_{Max}, as represented in the following Equation (2).

$$DC = \frac{Bd}{B_{Max}} \times 100 \tag{2}$$

Based on the wet sieve method described by Elliott, 1986 [42], soil samples that were sieved via an 8 mm sieve were subsequently divided into four distinct aggregate size fractions: <0.063 mm, 0.063–0.250 mm, 0.250–2 mm, and >2 mm. Amounts of eighty grams of each sample were put on the top of a 2 mm sieve and gently immersed in deionized water for 5 min at room temperature. The aggregates were separated by manually moving the sieve in a 3 cm vertical distance 50 times in 2 min. The residue of each soil sample on the 2 mm sieve was collected. The passing soil suspension was transferred to the next finer sieve, and the sieving operation was repeated. Each fraction was then dried at 60 °C in an oven, weighed, and the proportion of each water-stable aggregate component to the total dry weight of the sample was calculated. The percentage of the aggregate with a diameter greater than 0.25 mm to total dry weight is expressed as $R_{0.25}$, as shown in Equation (3). The soil aggregate stability index was established by calculating MWD, GMD, K, and D in a specific order to systematically evaluate soil aggregate stability. MWD was calculated first as it directly measures the size of aggregates, reflecting soil stability and resistance to breakdown. GMD was then calculated to understand the overall distribution of aggregate sizes and the uniformity of the soil structure. Next, the K was calculated to quantify the soil's susceptibility to erosion, which is influenced by the stability and cohesiveness of the aggregates. Finally, D was calculated to evaluate the complexity of the aggregate structure and its resistance to compaction and fragmentation. This sequential approach ensures a comprehensive understanding of soil structure, stability, and erosion risk [6,43–45], by starting with basic structural properties (MWD, GMD), then assessing susceptibility to erosion (K), and then evaluating structural integrity at a micro level (D), as represented in the following Equations (4)–(7).

$$R_{0.25} = \frac{m_{i>0.25}}{m_t} \tag{3}$$

$$MWD = \sum_{i=1}^{n} (\overline{x_i} w_i) \tag{4}$$

$$GMD = Exp\left(\sum_{i=1}^{n} w_i In\overline{x}_i / \sum_{i=1}^{n} w_i\right) \tag{5}$$

$$K = 7.594\left\{0.0034 + 0.0405exp\left[-\frac{1}{2}\left(\frac{lg^{GMD} + 1.659}{0.7101}\right)^2\right]\right\} \tag{6}$$

$$D = 3 - lg\left[\frac{m_{i<xi}}{m_i}\right] / lg\left[\frac{\overline{x}_i}{x_{max}}\right] \tag{7}$$

where w_i is the percentage of i-sized aggregates (%), $m_i > 0.25$ is the dry mass of particles retained on the >0.25 mm sieve (g), $m_i < xi$ is the dry mass of particles smaller than the i-sized particles (g), and m_t is the initial dry mass of the entire sample (g). The mean diameter of each aggregate fraction is represented by x_i, while x_{max} is the average diameter of the aggregate with the largest particle size (mm).

2.4. Statistical Analysis

SPSS 21.0 (SPSS Inc., Chicago, IL, USA) was used to perform statistical analyses. In orchards of different ages, the analysis of variance (ANOVA) was used to examine the aggregate stability indices, aggregate-associated C concentrations, and soil compaction attributes. The relationship between the important parameters was assessed using multivariate statistical analyses in the form of principal component analysis (PCA). Using set Verimax rotation with Kaiser Normalization, principal component analysis was performed on a matrix of 17 parameters. Also, Pearson's bivariate test was used to analyze the relationship between the key variables. "In the present study, the aggregation stability indices such as MWD, GMD, and the K-factor were included in the PCA and Pearson correlation analyses due to their significance in understanding soil structural dynamics and erosion susceptibility. However, we recognize that these indices are derived from the same dataset used to calculate soil aggregate size distribution, potentially leading to interdependence and redundancy in the statistical analyses. While these indices provide valuable insights into soil physical properties, their inclusion may influence the weighting of principal components and correlation outcomes. The potential interdependence of these indices was considered in the interpretation of results. The graphical presentation was generated with Origin, 2018 (Northampton, MA, USA, Origin Lab).

3. Results

3.1. Soil Mechanical and Physical Properties

All orchards, regardless of age, exhibited a silty clay loam to silty clay texture in both soil layers, with silt contents ranging from 57.62 to 54.51%, clay contents ranging from 40.47 to 36.68%, and sand contents ranging from 5.86 to 4.20% (Table 1). The total clay content increases with depth throughout all orchard ages, although the silt content decreases. In all orchard ages, there was no significant variation in particle density between the two soil layers, with particle density in the 0.0–0.20 m layer ranging from 2.27 Mg m^{-3} in the 30-year-old orchard (30 Y) to 2.35 Mg m^{-3} in the 3-year-old orchard (3 Y); and from 2.30 Mg m^{-3} (3 Y) to 2.39 Mg m^{-3} (30 Y) in the layer of 0.20–0.40 m (Table 2).

Table 2. Changes in particle density (Pd), bulk density (Bd), total porosity (TP), maximum density (B_{Max}), and degree of compactness (DC), as affected by plantation age of pomegranate orchards.

Soil Properties		3 Y	10 Y	20 Y	30 Y	3 Y	10 Y	20 Y	30 Y
		0.00–0.20 m				0.20–0.40 m			
Pd	Mg m^{-3}	2.35 ± 0.05 a	2.36 ± 0.02 a	2.28 ± 0.02 a	2.27 ± 0.03 a	2.30 ± 0.01 a	2.34 ± 0.02 a	2.37 ± 0.04 a	2.39 ± 0.01 a
Bd		0.93 ± 0.01 d	1.01 ± 0.03 c	1.04 ± 0.0 b	1.26 ± 0.01 a	1.15 ± 0.01 d	1.38 ± 0.01 a	1.28 ± 0.02 b	1.21 ± 0.01 c
TP	%	60.59 ± 0.02 a	57.18 ± 0.02 b	54.47 ± 0.02 c	44.77 ± 0.02 d	49.76 ± 0.02 a	41.29 ± 0.02 c	45.93 ± 0.02 b	49.36 ± 0.02 a
BMax	Mg m$_{3}$	1.85 ± 0.02 a	1.65 ± 0.03 c	1.68 ± 0.01 bc	1.70 ± 0.02 b	1.80 ± 0.01 ab	1.81 ± 0.02 a	1.76 ± 0.03 b	1.67 ± 0.01 c
DC	%	49.87 ± 0.75 c	61.15 ± 0.68 b	61.54 ± 0.36 b	73.72 ± 0.69 a	64.20 ± 0.57 c	76.33 ± 0.93 a	72.56 ± 0.78 b	72.72 ± 0.55 b

Y represents the years of the pomegranate plantation. Different lowercase letters in the same column indicate significant differences at $p < 0.05$ according to Duncan's multiple range tests. ± represent standard errors (N = 8).

3.2. Indicators of Soil Compaction

The Bd of the 0.0–0.20 m layer varies significantly by orchard age, with the 3-year-old orchard having the lowest value (0.93 Mg m^{-3}) and the 30-year-old orchard having the highest value (1.26 Mg m^{-3}) (Table 2). Pomegranate orchards that were 10, 20, and 30 years old had an average increase in soil Bd of 8.6, 11.29, and 34.95%, respectively, compared to those that were 3 years old. Although a similar behavior was found in the 0.20–0.40 m layer, the 10-year-old orchard had the highest value of Bd (1.38 Mg m^{-3}). The total porosity (TP) differs significantly between pomegranate orchard ages in the two soil layers (Table 2). Regardless of the pomegranate orchard ages, Bd increased with soil depth, while TP decreased. B_{Max} was higher in the 3-year-old orchard (3 Y) compared to orchards aged 10, 20, and 30 years, observed in both soil layers (Table 2). At the surface layer, B_{Max} was generally 11, 9, and 8% lower in the 10 Y, 20 Y, and 30 Y compared to the 3 Y, respectively. In the 0.00–0.20 m layer, there were significant differences in B_{Max} between 3 Y and the other older soils from pomegranate orchards. There were insignificant differences between 3 Y, 10 Y, and 20 Y for the deeper layer (0.20–0.40 m), while 3 Y and 30 Y varied significantly (Table 2).

On the other hand, the DC values for depths of 0.00–0.20 and 0.20–0.40 m in the pomegranate orchards varied significantly (Table 2), but they went up from 3 Y to 30 Y as the pomegranate orchards grew older. Except for 30 Y, the DC was generally higher in the subsurface layer than in the surface layer. In the 10 Y, 20 Y, and 30 Y, the DC was, on average, 23, and 48% higher than in the 3 Y at the surface layer, and it was, on average, 19, and 13% higher in the subsurface layer.

3.3. Soil Aggregate Size Distribution and Stability

In the surface layer (0.00–0.20 m), the 10 Y and 30 Y orchards had significantly larger aggregates with a size > 2 mm than the 3 Y orchards. In both soil layers, the older orchards had a much greater impact on the aggregate with a size of 2–0.25 mm than the 3 Y orchard (Table 3). In comparison to the 3 Y orchard, the pomegranate orchards' ages resulted in significant variations in the aggregate sizes of 0.250–0.063, and <0.063 mm in both soil layers. In the soil layers for all orchards, tiny macroaggregates (2–0.250 mm) dominate, followed by microaggregates (0.250–0.063 mm). The percentage of macroaggregates ($R_{0.25}$) varied significantly depending on the pomegranate orchard ages in both soil layers. The surface soil layer (0.00–0.20 m) revealed that $R_{0.25}$ was highest under the 30 Y and 20 Y orchards (74.84–68.50%), followed by the 10 Y orchard (66.41%), and lowest under the 3 Y orchard (60.20%). The same trend in proportion to $R_{0.25}$ was identified in the subsurface layer, which extends from 0.20 to 0.40 m.

Table 3. The structure indices and stability of soil aggregates as affected by the plantation age of pomegranate orchards.

Composition of Aggregates (%)	3 Y	10 Y	20 Y	30 Y	3 Y	10 Y	20 Y	30 Y
	0.00–0.20 m				0.20–0.40 m			
Composition of aggregates (%)								
>2 mm	4.93 ± 0.40 c	7.77 ± 0.28 a	4.32 ± 0.34 c	6.24 ± 0.81 b	1.71 ± 0.16 b	1.58 ± 0.47 b	1.89 ± 0.30 b	3.43 ± 0.54 a
2–0.250 mm	58.39 ± 1.23 c	57.89 ± 0.65 c	63.17 ± 1.00 b	67.52 ± 1.16 a	51.07 ± 1.3 c	57.80 ± 1.38 b	64.44 ± 0.69 a	65.99 ± 0.25 a
0.250–0.063 mm	23.23 ± 0.95 a	20.17 ± 0.40 b	20.85 ± 0.38 b	16.77 ± 0.55 c	28.65 ± 1.25 a	24.44 ± 0.41 b	21.71 ± 0.43 c	18.90 ± 0.37 d
<0.063 mm	12.08 ± 0.26 a	13.05 ± 0.25 a	10.18 ± 0.33 b	8.01 ± 0.44 c	18.13 ± 0.30 a	13.72 ± 0.21 b	10.91 ± 0.39 c	10.69 ± 0.26 c
R0.25	64.20 ± 0.54 c	66.41 b ± 0.18 c	68.50 ± 0.30 b	74.84 ± 0.75 a	53.01 ± 0.78 d	60.87 ± 0.46 c	67.03 ± 0.41 b	70.11 ± 0.31 a
Aggregation stability index								
MWD (mm)	0.95 ± 0.01 b	1.09 ± 0.01 a	0.98 ± 0.01 b	1.11 ± 0.01 a	0.72 ± 0.01 c	0.79 ± 0.01 b	0.84 ± 0.01 b	0.95 ± 0.02 a
GMD (mm)	0.74 ± 0.001 c	0.76 ± 0.001 bc	0.77 ± 0.001 b	0.84 ± 0.01 a	0.63 ± 0.003 d	0.69 ± 0.002 c	0.74 ± 0.004 b	0.77 ± 0.004 a
D	2.30 ± 0.01 b	2.33 ± 0.01 a	2.26 ± 0.01 c	2.26 ± 0.01 c	2.23 ± 0.01 a	2.19 ± 0.03 a	2.19 ± 0.003 a	2.24 ± 0.01 a
K	0.056 ± 0.00 a	0.055 ± 0.00 b	0.055 ± 0.00 b	0.052 ± 0.00 c	0.063 ± 0.00 a	0.059 ± 0.00 b	0.056 ± 0.00 c	0.055 ± 0.00 d

Different lowercase letters in the same column indicate significant differences at $p < 0.05$ according to Duncan's multiple range tests. ± represent standard errors (N = 8).

The MWD and GMD of the soil in the pomegranate orchards exhibited a varied increase with the advancement of orchard age at both soil layers (Table 3). The subsurface layer has reduced MWD and GMD indices compared to the surface layer. The surface layer's MWD values were highest in the 30 Y, 10 Y, 20 Y, and 3 Y pomegranate orchards, respectively, although there was no significant difference between the 3 Y and 20 Y (Table 3). Additionally, the smallest values for D at both soil layers were found in the 20 Y and 30 Y orchards at the surface layer with a significant variance, and in 10 Y and 20 Y orchards at the subsurface layer without significant variation. On the other hand, soil K factor in pomegranate orchards reduced significantly with the increase in orchard age at both soil layers (Table 3). The 0.00–0.20 m soil layer has a lower K value than the 0.20–0.40 m soil layer, indicating that the surface soil is more resistant to soil erosion than the subsurface soil.

3.4. Organic Carbon in Bulk Soil (SOC) and Different Aggregate Fractions (OC)

The content of SOC in pomegranate orchards progressively increased with the orchard age in both the surface and subsurface soil layers (Table 4). Specifically, the SOC content in the 30-year-old orchards was 13.88% higher than that of the 3-year-old orchards. The 30 Y and 20 Y had the highest OC contents in the aggregate fractions > 0.063 mm; additionally, the 3 Y had the highest content of OC in the silt + clay fraction at the surface soil layer. The macroaggregates had the highest OC content in the surface soil layer, ranging from 11.87 to 15.30 g C/kg soil, which was higher than that in the small macroaggregates, microaggregates, and silt + clay fraction. Furthermore, the OC content in the 2–0.250, 0.250–0.063, and >2 mm fractions increased with increasing orchard age. However, the C content in the <0.063 mm fraction initially decreased at the 10 Y and 20 Y orchard ages, before increasing later at the 30 Y. In the subsurface soil layer, the OC content in >2 and 2–0.250 mm fractions decreased (10 Y and 20 Y, respectively) and then increased (30 Y) with orchard age, whereas the OC content in the 0.25–0.063 and >0.063 mm fractions increased with orchard age. In the subsurface soil layer, the OC content in the >2 and 2–0.250 mm fractions decreased (10 Y and 20 Y, respectively) and then increased (30 Y) with orchard age, whereas the OC content in the 0.250–0.063 and >0.063 mm fractions increased with orchard age. The OC content in the <0.063 mm fractions initially declined at the subsurface soil layers compared to the surface soil layer but then increased with orchard age. As a result, at the 10 Y, 20 Y, and 30 Y orchard ages, the OC content in the <0.063 mm fraction increased by 8.6, 13.5, and 16.6%, respectively, at the 0.20–0.40 m soil layer compared to the 0.00–0.20 m soil layer.

Table 4. Impact of pomegranate orchard plantation age on soil aggregate-associated carbon (C) and carbon in bulk soil (OC).

Bulk Soil (OC) + Soil Aggregates (C)	3 Y	10 Y	20 Y	30 Y	3 Y	10 Y	20 Y	30 Y
	0.00–0.20 m				0.20–0.40 m			
	OC (g kg^{-1})							
>2 mm	11.87 ± 0.19 c	12.67 ± 0.10 b	14.84 ± 0.23 a	15.30 ± 0.10 a	11.87 ± 0.20 b	10.80 ± 0.16 b	10.85 ± 0.12 b	11.26 ± 0.31 a
2–0.250 mm	10.65 ± 0.24 c	11.15 ± 0.28 c	13.42 ± 0.30 b	14.83 ± 0.17 a	10.65 ± 0.24 b	10.50 ± 0.17 b	10.19 ± 0.10 b	10.55 ± 0.17 a
0.250–0.063 mm	10.09 ± 0.25 b	10.16 ± 0.33 b	11.15 ± 0.25 a	12.03 ± 0.25 a	10.09 ± 0.27 b	9.48 ± 0.33 b	10.05 ± 0.16 a	10.97 ± 0.11 a
<0.063 mm	11.39 ± 0.29 a	10.33 ± 0.20 b	10.27 ± 0.43 b	11.17 ± 0.29 ab	10.69.39 ± 0.29 c	11.22 ± 0.29 bc	11.66 ± 0.31 b	13.02 ± 0.14 a
Bulk soil	13.76 ± 0.21 c	14.47 ± 0.21 b	15.30 ± 0.28 a	15.67 ± 0.33 a	12.89 ± 0.15 c	13.76 ± 0.25 b	13.83 ± 0.18 b	15.22 ± 0.17 a

Lowercase letters indicate significant differences ($p < 0.05$) between treatments. ± represent standard errors (N = 8).

3.5. Principal Component Analysis (PCA) and Pearson Correlation

The principal component analysis of the surface layer (0.00–0.20 m) revealed three components with eigenvalues greater than one, with group factors relating to soil compaction, aggregate stability, and their associated OC distribution (Table 4). The first factor accounted for 68.202%, the second factor was 18.23%, and the third factor was 8.47%. Factor 1 shows a high load of factors linked to soil compaction, soil structure, and aggregate-associated OC distribution. Bd, DC, GMD, $R_{0.25}$, 2–0.250 mm, >2 mm OC, 2–0.250 mm OC, 0.250–0.063 mm OC fractions, and SOC all showed strong positive loadings, whereas K, D, 0.250–0.063 mm, and <0.063 mm had a negative association. Factor 2 components are mostly connected to aggregate stability. Components with high factor 2 loadings include MWD and aggregates larger than 2 mm. Factor 3 components are primarily related to maximum density and OC concentration in the <0.063 mm fraction.

PCA results from the subsurface layer (0.20–0.40 m) revealed two principal components (PC) (Table 5). PC1 accounted for 71.134% of the overall variation and mostly consisted of soil compaction attributes (B_{Max} and DC), soil aggregate stability, soil structure indices (MWD, GMD, K, and $R_{0.25}$), SOC concentration, and aggregate-associated OC fractions.

Table 5. Principal component analysis of the soil parameters.

Soil Attributes	0.00–0.20 m			0.20–0.40 m	
	1	2	3	1	2
B_{Max}	−0.318	−0.45	**0.792**	**−0.702**	**−0.563**
Bd	**0.923**	0.358	0.014	0.285	**−0.83**
DC	**0.862**	0.439	−0.227	**0.679**	**−0.579**
MWD	0.455	**0.878**	−0.109	**0.95**	0.278
GMD	**0.925**	0.322	0.008	**0.992**	0.007
$R_{0.25}$	**0.955**	0.236	−0.024	**0.992**	−0.007
K	**−0.922**	−0.34	0.021	**−0.994**	0.046
D	**−0.784**	**0.601**	−0.093	0.002	**0.757**
>2 mm	−0.145	**0.973**	−0.111	**0.637**	**0.639**
2–0.250 mm	**0.974**	−0.09	0.045	**0.969**	−0.043
0.250–0.063 mm	**−0.835**	−0.474	0.06	**−0.985**	−0.074
<0.063 mm	**−0.941**	0.129	−0.11	**−0.955**	0.183
>2 mm OC	**0.939**	−0.102	−0.282	**0.758**	**0.568**
2–0.250 mm OC	**0.961**	−0.011	−0.115	**0.665**	0.7
0.250–0.063 mm OC	**0.955**	−0.058	0.043	**0.946**	0.155
<0.063 mm OC	0.11	0.011	**0.939**	**0.885**	0.408
SOC	**0.899**	0.05	−0.242	**0.966**	0.075
Total	**11.594**	**3.098**	**1.44**	**12.093**	**3.106**
% of Variance	**68.202**	**18.225**	**8.473**	**71.134**	**18.271**
Cumulative %	**68.202**	**86.427**	**94.9**	**71.134**	**89.405**

B_{Max}: maximum soil bulk density; Bd: bulk density; DC: degree of compactness; MWD: mean weight diameter; GMD: geometric mean diameter; D: fractal dimension; K: soil erodibility. >2 mm: >2 mm size aggregates; 2–0.250 mm: 2–0.250 mm size aggregates; 0.250–0.053 mm: 0.250–0.063 mm size aggregates; <0.063 mm: <0.063 mm size aggregates; >2 mm OC: >2 mm aggregate-associated OC; 2–0.250 mm OC: 2–0.250 mm aggregate-associated OC; 0.250–0.053 mm OC: 0.250–0.063 mm aggregate-associated OC; <0.063 mm OC: <0.063 mm aggregate-associated OC; SOC: bulk soil organic carbon.

PC2, on the other hand, contributed 18.27% of the total variance, with notable loadings for Bd and D. The results of the PCA analysis show that PC1 is a highly significant factor at both soil layers, accounting for a significant portion of the variance in the indices of soil compaction, aggregate stability, and their associated OC distribution, which is influenced by orchard ages. The 30 Y pomegranate orchard soils trended positively with Bd, DC, GMD, $R_{0.25}$, 2–0.250 mm, >2 mm OC, 2–0.250 mm OC, 0.250–0.063 mm OC fractions, and SOC, and also highly positively with PC1 (Figure 2a). The 3-year-old orchards, on the other hand, trended negatively with PC1 and negatively with microaggregates (0.250–0.063 mm), silt + clay fraction (>0.063 mm), B_{Max}, and K. Clustering (Figure 2b) showed that the 10 Y and 20 Y pomegranate orchards' soils were strongly correlated with soil compaction indices (B_{Max}, Bd, and DC), with DC and Bd having positive values of PC1 and B_{Max} having a negative value of PC1. In contrast, B_{Max}, Bd, and DC had high negative PC2 values. The 3 Y pomegranate orchards' soils tended to have a higher K and lower SOC than the 20 Y and 30 Y; these clusters were explained primarily by the high negative values of PC1.

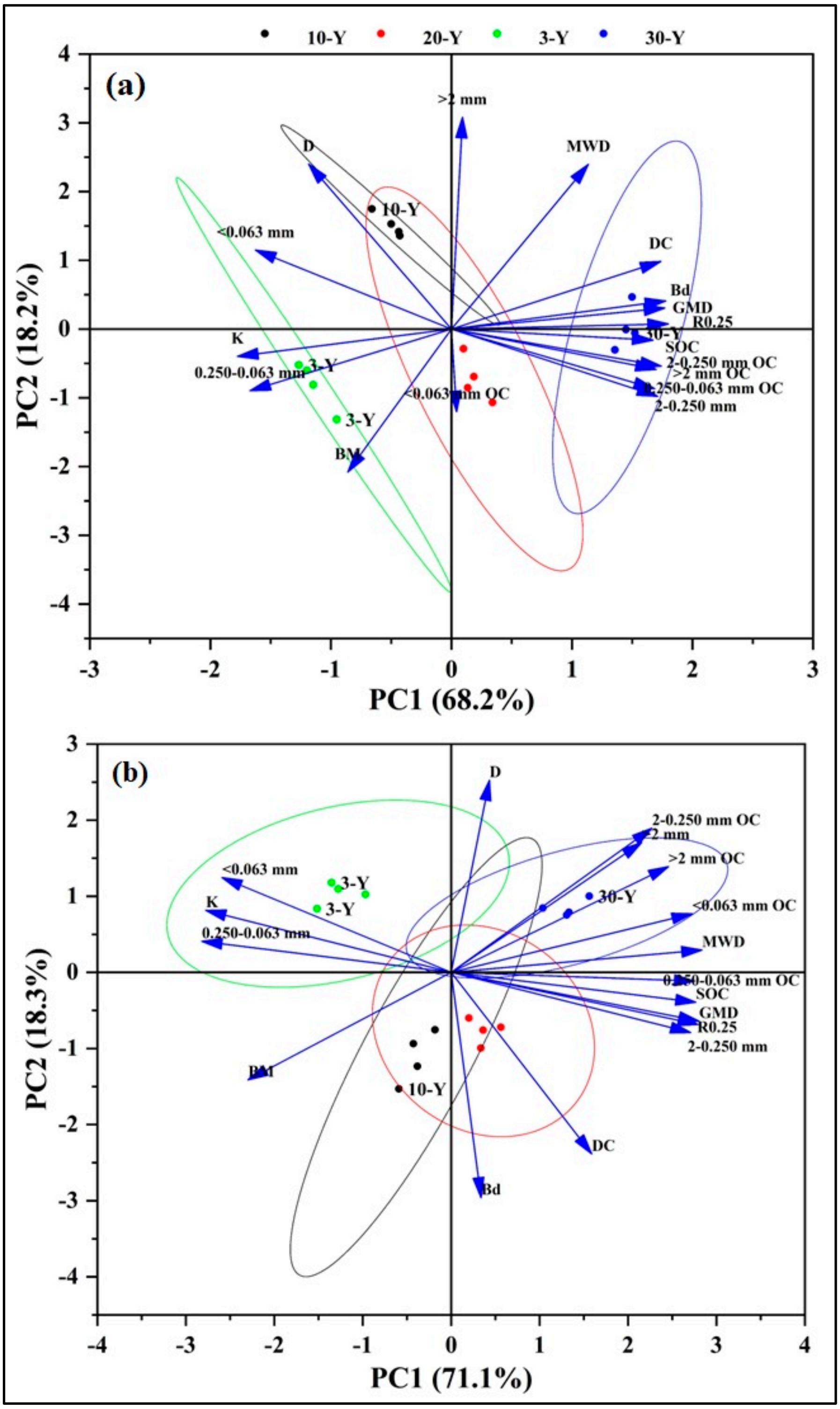

Figure 2. The first two principal coordinates of the dataset are affected by aggregate stability, aggregate-associated OC concentrations, and soil compaction; (**a**) (0.00–0.20 m); (**b**) (0.20–0.40 m).

Regarding Pearson correlation, aggregates > 2 and 2–0.250 mm showed a positive correlation with soil MWD, GMD, and $R_{0.25}$; however, aggregates of 0.250–0.063 and < 0.063 mm showed a negative correlation (Table 6). In contrast, soil erodibility (K) demonstrated a positive correlation with aggregates of 0.250–0.063 and < 0.063 mm and a negative correlation with aggregates of > 2 and 2–0.250 mm. Soil maximum density was linked negatively with aggregates > 2 and 2–0.250 mm, but positively with aggregates 0.250–0.063 and < 0.063 mm. Additionally, the degree of compactness (DC) and soil bulk density (Bd) were negatively related to aggregates > 2 mm and positively linked to aggregates of 2–0.250 mm. These findings suggest that increasing macroaggregates reduces soil compaction and erodibility. Soil MWD, GMD, and $R_{0.25}$ showed significant positive correlations with the aggregate-associated OC concentration and the SOC, while soil K showed a negative correlation. Aggregate-associated OC content and SOC had an important negative correlation with soil B_{Max}. Conversely, the OC content in the microaggregates, silt + clay fractions, and SOC content correlated positively with DC (Table 6). As a result, increased aggregate-associated OC and SOC content decreased the B_{Max} and K while increasing MWD, GMD, and $R_{0.25}$.

Table 6. Pearson correlation coefficients for aggregate size fractions, associated C, and aggregate stability (N = 8).

Soil Properties	BM	Bd	DC	MWD	GMD	$R_{0.25}$	K	D
>2 mm	**−0.481** **	**−0.547** **	**−0.376** *	**0.921** **	**0.641** **	**0.536** **	**−0.644** **	**0.856** **
2–0.250 mm	**−0.492** **	0.225	**0.392** *	**0.559** **	**0.869** **	**0.929** **	**−0.561** **	−0.109
0.250–0.063 mm	**0.646** **	−0.015	−0.235	**−0.842** **	**−0.958** **	**−0.971** **	**0.734** **	−0.27
<0.063 mm	**0.415** *	−0.056	−0.200	**−0.709** **	**−0.936** **	**−0.949** **	**0.617** **	−0.099
>2 mm OC	**−0.608** **	−0.193	0.014	**0.791** **	**0.827** **	**0.784** **	**−0.794** **	**0.353** *
2–0.250 mm OC	**−0.597** **	0.017	0.22	**0.668** **	**0.777** **	**0.758** **	**−0.784** **	0.197
0.250–0.063 mm OC	**−0.465** **	0.238	**0.392** *	**0.578** **	**0.832** **	**0.867** **	**−0.627** **	−0.035
<0.063 mm OC	0.017	**0.353** *	**0.361** *	−0.059	0.163	0.258	−0.223	−0.258
SOC	**−0.620** **	0.179	**0.379** *	**0.620** **	**0.854** **	**0.902** **	**−0.611** **	0.035

* Correlation is significant at $p < 0.05$ level (2-tailed). ** Correlation is significant at $p < 0.01$ level (2-tailed).

4. Discussions

As pomegranate orchards age, soil compaction increases due to repeated agricultural activities, reducing porosity, water infiltration, and root penetration; this may negatively impact soil aggregate stability, carbon sequestration, and overall orchard productivity, depending on management strategy, soil type, cover vegetation, and region conditions.

Particle size distribution is a particularly crucial variable influencing soil geometry, compaction, and structure features. In our results, the silt fraction was superior to clay and sand for all pomegranate orchards' ages in both layers. According to Butzer (1959) [46], silt originates in the Blue River due to the weathering of basalt or other igneous materials from the Ethiopian High Plateau, which is regarded as an important source of water and silt for the Nile. However, the low sand amount can be attributed to wind-blown sand from the Eastern and Western deserts [47]. The current data indicate a slight variance in the soil particle size distribution assessed for all pomegranate orchard ages in both layers, particularly in the clay fraction concentration, one of the major variables influencing soil compaction indicators [32].

In the present research, the continuous application of manure (well-decomposed farmyard manure (FYM) with an average composition of 0.5% nitrogen (N), 0.2% phosphorus (P), and 0.5% potassium (K), was applied at a rate of 1000 kg ha^{-1} (1.6 kg $tree^{-1}$)) in pomegranate orchards, coupled with the supply of tree litter, enhanced the carbon inputs to the SOC pools, and as the orchards aged, this increase in organic matter contributed to higher SOC concentrations, demonstrating a positive relationship between orchard age and

SOC levels; these results align with previous studies by Zhang et al. 2023 [48] and Wang et al. 2022 [49]. This emphasizes the role of organic amendments in improving soil fertility and carbon storage in agricultural ecosystems. The three-year-old orchard (3 Y) had the lowest SOC concentration, which may have been caused by significant soil disturbance during tree planting [24,50]. The observations of this study showed that as the pomegranate orchard grew older, the SOC contents in both soil layers gradually rose, particularly in the aggregate fractions > 0.063 mm; this agrees with our second premise. This was likely caused by an increase in the amount of organic material that was incorporated into the soil. Higher C contributions from increasing organic wastes might promote the creation of soil aggregates [9,11,51] and, as a result, enhance the stability of SOC [29,52], because macroaggregate formation is considered one of the key methods for SOC conservation in the soil [53]. Because the binding agents in microaggregates are more resistant than those in macroaggregates, variations in pomegranate orchard ages have a lower effect on microaggregate fractions and the carbon maintained within them; the outcomes of the research agree with those of previous investigations by Gioacchini et al. 2024 [54]. Our findings demonstrated that the OC contents rose in the aggregate fractions < 0.063 mm of the subsurface soil layer when compared with the surface soil layer as the pomegranate orchard aged. This could be a result of intensive tillage, farming practices, and limited canopy cover during the initial years of tree planting, which can promote C mineralization by inhibiting the development of soil aggregation.

Soil compaction, driven by repeating agricultural activities, reduces porosity and increases bulk density, leading to physical pressure that disrupts soil aggregates, particularly macroaggregates (>0.250 mm), thereby weakening soil structure and stability. Conversely, the breakdown of soil aggregates, especially under conditions of low organic carbon (OC) and fine textured soils with high silt and clay fractions, increases the soil's susceptibility to compaction by reducing its structural integrity and resistance to mechanical stress. In part, soil compaction can be attributed to inadequate soil aggregation capacity, and long-term pomegranate orchards might increase the danger of soil compaction. Macroaggregate content is frequently linked to stable aggregate structures, which support and stabilize developed, permeable soil layers [55]. The results of this study show that soil macroaggregates (>0.250 mm) predominated in all pomegranate orchards (64.20–74.84% and 53.01–70.11% in both soil layers, respectively), indicating that these aggregates are more stable under the present management. The present finding is consistent with the study conducted by Cao et al. 2021 [6], who revealed that macroaggregates accounted for 86.17–91.87% in various citrus orchard ages in Hunan province, China. Pomegranate planting years had significant effects on the soil macroaggregates (>0.250), with the 30 Y showing higher aggregate stability at both soil layers. As the orchard grew older, a steady rise in soil organic carbon led to the formation of large and stable soil aggregates. Additionally, plant polysaccharides and the polymeric compounds secreted by soil microorganisms result in the production of colloids, which promote soil particle aggregation [56]. This indicates that as pomegranate orchards grow older, their soil structure may progressively develop. It also suggests that the Assiut pomegranate orchards' compacted soil has a greater stability of soil aggregates than the non-compacted soil; this finding is consistent with that of Wei et al. 2022 [5]. The clay content of the soil is a crucial factor for the macroaggregate formation. Accordingly, a small proportion of the clay-sized units cause the formation of larger soil aggregates [57]. On the other hand, surface charge and electric attraction play an essential function in the interaction between soil aggregations and organic polymers [58].

An important factor in determining the stability of soil aggregates is their MWD and GMD values. Higher MWD and GMD values indicate that the aggregates are more stable due to an improved capacity for aggregate formation and that the soil is more resilient to erosion and deterioration [48,52]. The ages of the orchard significantly affected the MWD and GMD in the present study; in both soil layers, the 30 Y orchard had higher aggregate stability than the other orchards. Soil D and K are important indices of soil structural geometry and erodibility [46,59]. Increased orchard ages result in more stable soil structures, which causes the soil D and K to decrease as the soil compaction increases, suggesting that good management of orchards improves soil erosion resistance, and the results of this study were in line with earlier studies [25,48,60]. By enhancing the stability of soil aggregates, plants could decrease the soil's resistance to erosion; this is because years of tillage and fertilizer strategies raise the organic carbon contents, which in turn causes an increase in the soil fauna activity and a gradual rise in the cementing substance that binds soil particles together [7,47,58] Physical root impacts and compression of the upper soil layer may be the cause of the poor soil structure and significant soil compaction in a subsurface soil layer. The soil D and K levels would rise with larger silt and clay amounts; in contrast, they decrease with higher sand contents. The examined soils had significant levels of silt and clay, exceeding 90% (Table 1). Nevertheless, in the current study, the K factor provided the opposite result; this was probably caused by flood irrigation with high irrigation levels, low organic carbon contents, and conventional tillage practices, which dispersed the weakly aggregated soils. Dispersal thus causes surface pores to seal and increases the runoff with high concentrations of fine clay particles that are simply moved.

Orchard tree growth requires a bulk density of between 1.00 and 1.65 Mg m^{-3} [5,61]. Consequently, our study showed that both soil layers offered the perfect bulk density (0.93–1.38 Mg m^{-3}) for pomegranate trees. The results revealed that soil Bd and DC increase as pomegranate orchards age and as soil depth increases, whereas the soil porosity and B_{Max} decrease (Table 2). The main factors responsible for the decreased TP and B_{Max} and the increased Bd and DC are farming operations, traffic, conventional tillage, and a lack of vegetative cover caused by excessive herbicide usage [5,7,62]. The higher DC values in this investigation indicated subsurface soil layer compaction, especially if compared with surface soil layer values. This is because conventional tilling practices eventually generate the most severe compaction because a plow pan forms directly beneath the tilling layer. As reported by Liao et al. (2021 and 2023) [18,19], long-term tillage resulted in the formation of a plow pan at depths of 20 to 40 cm, which indicates an increase in soil compaction. According to our findings, the OC in both soil layers increased steadily as the pomegranate orchard aged, which may have contributed to a reduction in B_{Max} [30,57,58]; this is due to organic matter holding more moisture, which decreases the maximum dry density and makes compaction processes more difficult to occur [16,22].

The results of the PCA analysis showed that soil compaction parameters are closely related to soil aggregation and SOC. In the current study, Bd and DC had a highly positive relationship with GMD, $R_{0.25}$, small macroaggregates, SOC, and OC associated with >0.063 mm aggregate fractions. At the same time, they had a negative relationship with K, D, microaggregates, and silt–clay fractions, suggesting that soil aggregation and SOC play an important role in improving soil compaction and erodibility [63]. Furthermore, PCA analysis revealed that at both soil layers, PC1 trended negatively with the 3 Y and 10 Y orchards and with K and B_{Max}, indicating that soils in young pomegranate plantations are more susceptible to compaction and erosion. At the early stages of orchard growth, the soil was disturbed because of tree-planting operations; also, the rate of C decomposition was greater than the rate of C inputs [8,9].

The Pearson correlation analysis demonstrated that B_{Max} and K were negatively influenced by the percentage of aggregate fractions > 0.250 mm, by the OC associated with aggregate fractions > 0.063 mm, and by the SOC. Furthermore, DC showed a negative association with the >2 mm fraction but a significant positive correlation with the proportion of the >2–0.250 mm fraction, the SOC, and the OC content in the aggregate fractions > 0.250 mm. This due to high SOC contents promoting the formation of larger macroaggregates, which enhance soil aggregate stability and improve soil resistance to erosion and compaction [48,63].

Despite the interdependence of MWD, GMD, and the K-factor, their inclusion in the PCA and correlation analysis yielded results that align with established soil structure–function relationships. The strong associations between the aggregate-associated OC content and these indices support the hypothesis that increased macroaggregate formation and stability reduce the soil compaction and erodibility.

Our findings suggest that as orchard age increases, OC accumulation enhances the formation and stability of macroaggregates (>2 mm), which are critical in reducing soil compaction and erodibility. The increased OC in these larger aggregates likely enhances aggregate stability by binding soil particles more effectively, thus lowering Bd and B_{Max}; this stabilization effect is further reinforced by reducing D and K, indicators of improved soil structure stability. Additionally, the increase in the MWD and GMD of soil aggregates with orchard age implies enhanced resistance to breakdown, a key mechanism in maintaining soil integrity under compaction pressures. Therefore, our study posits that OC-associated macroaggregates play a dual role in mitigating soil compaction and enhancing structural stability, thereby reducing erosion risk over time in pomegranate orchards.

5. Conclusions and Recommendations

This study highlights the critical influence of orchard age on soil properties, particularly soil organic carbon (SOC) accumulation and aggregate stability, providing a comprehensive understanding of how soil quality evolves in pomegranate orchards over time. As orchards age, the accumulation of soil organic carbon (SOC) and the formation of stable macroaggregates improve soil structure, reduce compaction, and enhance erosion resistance, thereby supporting sustainable orchard productivity and ecosystem services such as water regulation and soil conservation. These findings highlight the need for management strategies that prioritize organic carbon inputs and promote soil aggregation to ensure the long-term viability of pomegranate orchards and maintain soil health in agricultural ecosystems.

To achieve these benefits, we recommend adopting sustainable soil management practices tailored to pomegranate orchards. First, the continuous application of organic amendments, such as manure, compost, and tree litter, should be prioritized. These materials increase SOC levels and promote the formation of stable macroaggregates through the action of organic polymers and microbial by products, which act as binding agents for soil particles. This practice not only enhances soil structure but also improves water retention and reduces erosion.

Second, reducing soil disturbance through minimized or no-till practices is essential, particularly in the subsurface layer. Conventional tillage often leads to the formation of plow pans and increased compaction, which can be mitigated by adopting reduced tillage methods. This approach helps preserve soil porosity and structure, allowing for better root growth and water infiltration.

Third, integrating cover cropping during fallow periods can protect the soil surface, reduce erosion, and contribute additional organic matter. Cover crops also enhance soil microbial activity and nutrient cycling, further supporting soil health. Additionally, transitioning from flood irrigation to more efficient methods, such as drip or sprinkler systems, can reduce waterlogging and soil dispersion, thereby maintaining soil structure and minimizing erosion risks.

Finally, the use of organic mulches on the soil surface can conserve moisture, regulate soil temperature, and buffer the physical impact of rainfall. Mulching also contributes to the gradual increase in SOC over time, further enhancing soil stability and resilience.

In conclusion, this study underscores the long-term benefits of effective soil management in pomegranate orchards. As orchards age, the accumulation of OC and the formation of stable macroaggregates improve soil structure, reduce compaction, and enhance erosion resistance, thereby supporting sustainable orchard productivity and ecosystem services such as water regulation and soil conservation. These findings highlight the need for management strategies that prioritize organic carbon inputs and promote soil aggregation to ensure the long-term viability of pomegranate orchards and maintain soil health in agricultural ecosystems.

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References

1. Abdel Kawy, W.A.M.; Ali, R.R. Assessment of soil degradation and resilience at northeast Nile Delta, Egypt: The impact on soil productivity. *Egypt. J. Remote Sens. Sp. Sci.* **2012**, *15*, 19–30. [CrossRef]
2. El Nahry, A.H.; Ibraheim, M.M.; El Baroudy, A.A. Assessment of soil degradation in the northern part of Nile Delta, Egypt using remote sensing and GIS techniques. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. ISPRS Arch.* **2015**, *40*, 1461–1467. [CrossRef]
3. Toledo, M.P.S.; Rolim, M.M.; de Lima, R.P.; Cavalcanti, R.Q.; Ortiz, P.F.S.; Cherubin, M.R. Strength, swelling and compressibility of unsaturated sugarcane soils. *Soil. Tillage Res.* **2021**, *212*, 105072. [CrossRef]
4. Naderi-Boldaji, M.; Keller, T. Degree of soil compactness is highly correlated with the soil physical quality index S. *Soil. Tillage Res.* **2016**, *159*, 41–46. [CrossRef]
5. Wei, B.; Li, Z.; Wang, Y. Study on soil compaction and its causative factors at apple orchards in the Weibei Dry Highland of China. *Soil. Use Manag.* **2022**, *38*, 790–801. [CrossRef]
6. Cao, S.; Zhou, Y.; Zhou, Y.; Zhou, X.; Zhou, W. Soil organic carbon and soil aggregate stability associated with aggregate fractions in a chronosequence of citrus orchards plantations. *J. Environ. Manag.* **2021**, *293*, 112847. [CrossRef]
7. Ramos, M.F.; da Silva Almeida, W.R.; do Amaral, R.D.L.; Suzuki, L.E.A.S. Degree of compactness and soil quality of peach orchards with different production ages. *Soil Tillage Res.* **2022**, *219*, 105324. [CrossRef]

8. Andreu-Coll, L.; Cano-Lamadrid, M.; Lipan, L.; López-Lluch, D.; Sendra, E.; Hernández, F. Effects of Organic Farming on the Physicochemical, Functional, and Quality Properties of Pomegranate Fruit: A Review. *Agriculture* **2023**, *13*, 1167. [CrossRef]
9. Cerdà, A.; Novara, A.; Moradi, E. Long-term non-sustainable soil erosion rates and soil compaction in drip-irrigated citrus plantation in Eastern Iberian Peninsula. *Sci. Total Environ.* **2021**, *787*, 147549. [CrossRef]
10. Zheng, J.Y.; Wang, L.; Zhao, J.S.; Niu, Y.H.; Xiao, H.B.; Wang, Z.; Yu, S.X.; Shi, Z.H. Forty-year-old orchards promote carbon storage by changing aggregate-associated enzyme activities and microbial communities. *Catena* **2022**, *213*, 106195. [CrossRef]
11. Chen, R.; Chang, H.; Wang, Z.; Lin, H. Determining organic-inorganic fertilizer application threshold to maximize the yield and quality of drip-irrigated grapes in an extremely arid area of Xinjiang, China. *Agric. Water Manag.* **2023**, *276*, 108070. [CrossRef]
12. Farag, A.; Eltaweel, A.; Abd-Elrahman, S.; Ali, A.; Ahmed, M. Irrigation Regime and Soil Conditioner to Improve Soil Properties and Pomegranate Production in Newly Reclaimed Sandy Soil. *Asian J. Soil. Sci. Plant Nutr.* **2017**, *1*, 1–18. [CrossRef]
13. Abdollahi, L.; Schjønning, P.; Elmholt, S.; Munkholm, L.J. The effects of organic matter application and intensive tillage and traffic on soil structure formation and stability. *Soil Tillage Res.* **2014**, *136*, 28–37. [CrossRef]
14. Cavalcanti, R.Q.; Rolim, M.M.; de Lima, R.P.; Tavares, U.E.; Pedrosa, E.M.R.; Gomes, I.F. Soil physical and mechanical attributes in response to successive harvests under sugarcane cultivation in Northeastern Brazil. *Soil Tillage Res.* **2019**, *189*, 140–147. [CrossRef]
15. Franco, A.L.C.; Cherubin, M.R.; Cerri, C.E.P.; Six, J.; Wall, D.H.; Cerri, C.C. Linking soil engineers, structural stability, and organic matter allocation to unravel soil carbon responses to land-use change. *Soil Biol. Biochem.* **2020**, *150*, 107998. [CrossRef]
16. Pernes-Debuyser, A.; Tessier, D. Soil physical properties affected by long-term fertilization. *Eur. J. Soil. Sci.* **2004**, *55*, 505–512. [CrossRef]
17. Massah, J.; Azadegan, B. Effect of chemical fertilizers on soil compaction and degradation. *Agric. Mech. Asia Afr. Lat. Am.* **2016**, *47*, 44–50.
18. Liao, Y.; Dong, L.; Li, A.; Lv, W.; Wu, J.; Zhang, H.; Bai, R.; Liu, Y.; Li, J.; Shangguan, Z.; et al. Soil physicochemical properties and crusts regulate the soil infiltration capacity after land-use conversions from farmlands in semiarid areas. *J. Hydrol.* **2023**, *626*, 130283. [CrossRef]
19. Liao, Y.; Cao, H.X.; Liu, X.; Li, H.T.; Hu, Q.Y.; Xue, W.K. By increasing infiltration and reducing evaporation, mulching can improve the soil water environment and apple yield of orchards in semiarid areas. *Agric. Water Manag.* **2021**, *253*, 106936. [CrossRef]
20. Cavalcanti, R.Q.; Rolim, M.M.; de Lima, R.P.; Tavares, U.E.; Pedrosa, E.M.R.; Cherubin, M.R. Soil physical changes induced by sugarcane cultivation in the Atlantic Forest biome, northeastern Brazil. *Geoderma* **2020**, *370*, 114353. [CrossRef]
21. Bogunovic, I.; Pereira, P.; Kisic, I.; Sajko, K.; Sraka, M. Tillage management impacts on soil compaction, erosion and crop yield in Stagnosols (Croatia). *Catena* **2018**, *160*, 376–384. [CrossRef]
22. Telak, L.J.; Dugan, I.; Bogunovic, I. Soil management and slope impacts on soil properties, hydrological response, and erosion in hazelnut orchard. *Soil. Syst.* **2021**, *5*, 5. [CrossRef]
23. Zhu, G.; Deng, L.; Shangguan, Z. Effects of soil aggregate stability on soil N following land use changes under erodible environment. *Agric. Ecosyst. Environ.* **2018**, *262*, 18–28. [CrossRef]
24. Six, J.; Paustian, K.; Elliott, E.T. Soil structure and organic matter I. Distribution of aggregate-size classes and aggregate-associated carbon. *Soil Sci. Soc. Am. J.* **2000**, *64*, 681–689. [CrossRef]
25. Rabbi, S.M.F.; Minasny, B.; McBratney, A.B.; Young, I.M. Microbial processing of organic matter drives stability and pore geometry of soil aggregates. *Geoderma* **2020**, *360*, 114033. [CrossRef]
26. Wang, S.; Li, T.; Zheng, Z. Effects of tea plantation age on soil aggregate-associated C- and N-cycling enzyme activities in the hilly areas of Western Sichuan, China. *Catena* **2018**, *171*, 145–153. [CrossRef]
27. Xu, B.; Li, Y.; Liu, Y. Spatial Distribution of Soil Carbon and Nitrogen Content in the Danjiangkou Reservoir Area and Their Responses to Land-Use Types. *Sustainability* **2024**, *16*, 444. [CrossRef]
28. Wang, S.; Yan, X.; Wang, D.; Siddique, I.A.; Chen, J.; Xu, Q.; Zhao, C.; Yang, L.; Miao, Y.; Han, S. Soil microbial community based on plfa profiles in an age sequence of pomegranate plantation in the middle yellow river floodplain. *Diversity* **2021**, *13*, 408. [CrossRef]
29. Li, Z.; Fan, Y.; Zhang, R.; Chen, P.; Jing, X.; Lyu, C.; Zhang, R.; Li, Y.; Liu, Y. Synergistic impacts of Landscape, Soil, and environmental factors on the spatial distribution of soil aggregates stability in the Danjiangkou reservoir area. *Catena* **2024**, *237*, 107840. [CrossRef]
30. Choudhary, R.C.; Bairwa, H.L.; Kumar, U.; Javed, T.; Asad, M.; Lal, K.; Mahawer, L.N.; Sharma, S.K.; Singh, P.; Mohamed, M.H.; et al. Influence of organic manures on soil nutrient content, microbial population, yield and quality parameters of pomegranate (*Punica granatum* L.) cv. Bhagwa. *PLoS ONE* **2022**, *17*, e0266675. [CrossRef]
31. Zhao, Y.; Krzic, M.; Bulmer, C.E.; Schmidt, M.G. Maximum Bulk Density of British Columbia Forest Soils from the Proctor Test: Relationships with Selected Physical and Chemical Properties. *Soil Sci. Soc. Am. J.* **2008**, *72*, 442–452. [CrossRef]
32. Bareta Junior, E.; da Silva, A.A.P.; Sens, T.M.Z.G.; Colecha, K.; Rampim, L.; Pott, C.A. Soil physical properties in variable levels of soil compaction. *Res. Soc. Dev.* **2021**, *10*, e2341028686. [CrossRef]

33. *ASTM D1556-07*; Standard Test Method for Density and Unit Weight of Soil in Place by The Sand-Cone Method. ASTM International: West Conshohocken, PA, USA, 2007.
34. Salama, M.; Mazrou, Y.; Elmorsy, A.; Omar, A.E.-D.; Elbasuiny, R. Using Agro-Chemical Treatments for Controling Fruit Defects and Improving Fruit Quality and Marketability of "Wonderful" Pomegranate. *FRESENIUS Environ. Bull.* **2022**, *31*, 1649–1655.
35. El-zawahry, A.M.I.; Hassan, M.I. Occurrence, Population Density and Biological Control of Root-Knot Nematode, Meloidogyne javanica Infecting Pomegranate Orchards in Assiut Governorate, Egypt. *Assiut J. Agric. Sci.* **2019**, *50*, 90–91. [CrossRef]
36. El-Salhy, A.F.; Abou-Zaid, E.; El-Bolok, T.; Ali, M. Effect of Soil Conditioners on Growth and Fruiting of Manfalouty Pomegranate Trees Grown in New Reclaimed Region. *Assiut J. Agric. Sci.* **2023**, *54*, 93–106. [CrossRef]
37. Andrews, E.M.; Kassama, S.; Smith, E.E.; Brown, P.H.; Khalsa, S.D.S. A review of potassium-rich crop residues used as organic matter amendments in tree crop agroecosystems. *Agriculture* **2021**, *11*, 580. [CrossRef]
38. Page, A.L. *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*; American Society of Agronomy, Soil Science Society of America: Madison, WI, USA, 1982; ISBN 0891180729.
39. Loeppert, R.H.; Suarez, D.L. Carbonate and Gypsum. In *Methods of Soil Analysis: Part 3 Chemical Methods*; Soil Science Society of America: Madison, WI, USA, 1996; Volume 5, pp. 437–474.
40. Walkley, A.; Black, I.A. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [CrossRef]
41. Flint, A.L.; Flint, L.E. *2.2 Particle Density. Methods of Soil Analysis: Part 4 Physical Methods*; Soil Science Society of America: Madison, WI, USA, 2002; Volume 5, pp. 229–240.
42. Elliott, E. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. *Soil. Sci. Soc. Am. J.* **1986**, *50*, 627–633. [CrossRef]
43. Li, Y.; He, X.; Lin, D.; Wei, P.; Zhou, L.; Zeng, L.; Qian, S.; Zhao, L.; Yang, Y.; Zhu, G. Effects of Fractal Dimension and Soil Erodibility on Soil Quality in an Erodible Region: A Case Study from Karst Mountainous Areas. *Forests* **2023**, *14*, 1609. [CrossRef]
44. Hu, W.; Tabley, F.; Beare, M.; Tregurtha, C.; Gillespie, R.; Qiu, W.; Gosden, P. Short-Term Dynamics of Soil Physical Properties as Affected by Compaction and Tillage in a Silt Loam Soil. *Vadose Zo. J.* **2018**, *17*, 1–13. [CrossRef]
45. Dou, Y.; Yang, Y.; An, S.; Zhu, Z. Effects of different vegetation restoration measures on soil aggregate stability and erodibility on the Loess Plateau, China. *Catena* **2020**, *185*, 104294. [CrossRef]
46. Butzer, K.W. Contributions to the Pleistocene geology of the Nile Valley. *Erdkunde* **1959**, *13*, 46–67. [CrossRef]
47. Badawy, W.M.; Ghanim, E.H.; Duliu, O.G.; El Samman, H.; Frontasyeva, M.V. Major and trace element distribution in soil and sediments from the Egyptian central Nile Valley. *J. Afr. Earth Sci.* **2017**, *131*, 53–61. [CrossRef]
48. Zhang, X.; Shen, S.; Xue, S.; Hu, Y.; Wang, X. Long-term tillage and cropping systems affect soil organic carbon components and mineralization in aggregates in semiarid regions. *Soil Tillage Res.* **2023**, *231*, 105742. [CrossRef]
49. Wang, W.; Ingwersen, J.; Yang, G.; Wang, Z.; Alimu, A. Effects of Farmland Conversion to Orchard or Agroforestry on Soil Organic Carbon Fractions in an Arid Desert Oasis Area. *Forests* **2022**, *13*, 181. [CrossRef]
50. Yang, F.; Huang, M.; Li, C.; Wu, X.; Guo, T.; Zhu, M. Changes in soil moisture and organic carbon under deep-rooted trees of different stand ages on the Chinese Loess Plateau. *Agric. Ecosyst. Environ.* **2022**, *328*, 107855. [CrossRef]
51. Xin, X.; Zhang, J.; Zhu, A.; Zhang, C. Effects of long-term (23 years) mineral fertilizer and compost application on physical properties of fluvo-aquic soil in the North China Plain. *Soil Tillage Res.* **2016**, *156*, 166–172. [CrossRef]
52. González-Rosado, M.; Parras-Alcántara, L.; Aguilera-Huertas, J.; Benítez, C.; Lozano-García, B. Effects of land management change on soil aggregates and organic carbon in Mediterranean olive groves. *Catena* **2020**, *195*, 104840. [CrossRef]
53. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176. [CrossRef]
54. Gioacchini, P.; Baldi, E.; Montecchio, D.; Mazzon, M.; Quartieri, M.; Toselli, M.; Marzadori, C. Effect of long-term compost fertilization on the distribution of organic carbon and nitrogen in soil aggregates. *Catena* **2024**, *240*, 107968. [CrossRef]
55. Özbolat, O.; Sánchez-Navarro, V.; Zornoza, R.; Egea-Cortines, M.; Cuartero, J.; Ros, M.; Pascual, J.A.; Boix-Fayos, C.; Almagro, M.; de Vente, J.; et al. Long-term adoption of reduced tillage and green manure improves soil physicochemical properties and increases the abundance of beneficial bacteria in a Mediterranean rainfed almond orchard. *Geoderma* **2023**, *429*, 116218. [CrossRef]
56. Abdelrhman, A.A.; Gao, L.; Li, S.; Lu, J.; Song, X.; Zhang, M.; Zheng, F.; Wu, H.; Wu, X. Long-term application of organic wastes improves soil carbon and structural properties in dryland affected by coal mining activity. *Sustainabilty* **2021**, *13*, 5686. [CrossRef]
57. Schweizer, S.A.; Bucka, F.B.; Graf-Rosenfellner, M.; Kögel-Knabner, I. Soil microaggregate size composition and organic matter distribution as affected by clay content. *Geoderma* **2019**, *355*, 113901. [CrossRef]
58. Zheng, H.; Wang, X.; Wu, J.; Li, W.; Tan, C.; Chen, Y.; Zhang, F.; Duan, J.; Li, Z.; Liu, Y. Long-term impacts of extensive terracing on soil aggregates and associated C–N–P in the Camellia oleifera orchard of southern China. *Catena* **2023**, *233*, 107512. [CrossRef]
59. Liu, M.; Han, G. Assessing soil degradation under land-use change: Insight from soil erosion and soil aggregate stability in a small karst catchment in southwest China. *PeerJ* **2020**, *2020*, e8908. [CrossRef]

60. Martínez-Murillo, J.F.; Remond, R.; Ruiz-Sinoga, J.D. Validation of RUSLE K factor using aggregate stability in contrasted mediterranean eco-geomorphological landscapes (southern Spain). *Environ. Res.* **2020**, *183*, 109160. [CrossRef]
61. Arshad, M.A.; Lowery, B.; Grossman, B. Physical tests for monitoring soil quality. *Methods Assess. Soil. Qual.* **1997**, *49*, 123–141.
62. Topa, D.; Cara, I.G.; Jităreanu, G. Long term impact of different tillage systems on carbon pools and stocks, soil bulk density, aggregation and nutrients: A field meta-analysis. *Catena* **2021**, *199*, 105102. [CrossRef]
63. Usaborisut, P.; Ampanmanee, J. Compaction properties of silty soils in relation to soil texture, moisture content and organic matter. *Am. J. Agric. Biol. Sci.* **2015**, *10*, 178–185. [CrossRef]