agronomy

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Short-Term Effects of Olive-Pomace-Based Conditioners on Soil Aggregation Stability

Ana Caroline Royer [1,2,3,*], Tomás de Figueiredo [1,2], Felícia Fonseca [1,2], Marcos Lado [3] and Zulimar Hernández [1,2]

1 Centro de Investigação de Montanha (CIMO), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal; tomasfig@ipb.pt (T.d.F.); ffonseca@ipb.pt (F.F.)
2 Laboratório Associado para a Sustentabilidade e Tecnologia em Regiões de Montanha (SusTEC), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal
3 Centro Interdisciplinar de Química e Bioloxía (CICA), Universidade da Coruña, Elviña, 15071 A Coruña, Spain; marcos.lado@udc.es
* Correspondence: ana.royer@ipb.pt

Abstract: Mediterranean agriculture asks for sustainable strategies to prevent actual soil organic matter decline rates. Composting agri-food by-products for application in farmland, besides contributing to a circular economy at regional or local scales, may improve soil resistance to physical degradation. Aggregate stability (AS) is a crucial property for building up such resistance. Olive pomace is an abundant by-product of the olive oil industry that may be valorized through composting. This study aimed to assess the influence on AS of olive-pomace-based composts (OPC) applied to a sandy loam Leptosol and a clay loam Fluvisol. To assess the effects of compost characteristics on AS, three OPCs resulting from different olive pomace proportions in the composting raw material (44, 31, and 25% by volume) were applied to aggregate samples in three doses (10, 20, and 40 t.ha^{-1}, plus control) with fine and coarse grain sizes. Controlled laboratory conditions subjected samples to daily wetting-drying cycles during a 30-day experiment. AS was measured by wet sieving. OPC application significantly increased AS in the Leptosol amended with fine (+15% vs. control) and coarse (+19%) grain-size compost. In well-aggregated Fluvisol, amendment induced a significant increase in AS only in the compost coarse grain size (+12%). The application dose significantly affected AS, with 10 t.ha^{-1} being the best-performing dose. OPC applications in weakly aggregated soils are seemingly an encouraging soil management practice for improving soil resistance to physical degradation and reducing soil organic matter decline rates in Mediterranean farmland.

Keywords: organic soil conditioners; two-phase olive oil industry; two-phase derived olive pomace; composting; olive-pomace-based compost

Citation: Royer, A.C.; de Figueiredo, T.; Fonseca, F.; Lado, M.; Hernández, Z. Short-Term Effects of Olive-Pomace-Based Conditioners on Soil Aggregation Stability. *Agronomy* **2024**, *14*, 5. https://doi.org/10.3390/agronomy14010005

Academic Editors: Carmo Horta and María Cruz García González

Received: 10 November 2023
Revised: 14 December 2023
Accepted: 15 December 2023
Published: 19 December 2023

1. Introduction

Soil organic matter loss is directly associated with soil degradation, besides representing a loss of soil carbon storage capacity. Soil degradation is a global problem, especially affecting arid and semi-arid ecosystems [1], where it represents an increasing susceptibility to desertification. According to the Food and Agriculture Organization [1], 1/3 of the world's soils are degraded. Soil aggregation status is a crucial property for defining soil health and its resistance to degradation processes, soil erosion being a major one since most degradation phenomena begin with an aggregate breakdown [2,3].

According to [4], soil aggregation results from particle rearrangement, flocculation, and cementation in a complex interaction between aggregator agents. Soil texture, clay mineralogy, and organic matter content in the soil are intimately correlated with stable aggregates [3,5,6]. Clay dispersion and flocculation phenomena influence aggregate dynamics [7], as do inorganic binding agents such as oxides and calcium [8]. The extraradical hyphal growth of Arbuscular Mycorrhizal Fungi (AMF) often correlates with aggregate stability [9]. Drying and wetting processes and the duration of mechanical energy applied to the aggregates are also related to aggregate formation and breakdown [8,10–12]. Soil type and management practices influence the formation of stable aggregates [6,13,14].

Organic amendments improve soil aggregation by several mechanisms [6,8,15]. They provide an extra carbon source for promoting microbial decomposition of the added organic material. The quality of the organic matter featured in the conditioner, as appraised by the C/N ratio, is important in determining the organic compounds' transformation rates and pathways driven by microbial activity [6,16]. The microbial load in the conditioner also plays a vital role by stimulating soil microbial activity, favoring the bind establishments between the conditioner incorporated and the soil [9]. Moreover, organic amendments influence aggregate stability by reducing aggregate breakdown by increasing soil hydrophobicity [16,17].

Once in the soil, the organic amendments can be (re)distributed in different sizes of particles of the soil, according to a hierarchical order explained by [8]. This pattern has already been reported for some composts [18,19]. In the short term, exogenous organic matter (OM) tends to be stored in the macroaggregates (>250 μm). In the long run, organic substances, condensed and progressively bound to soil mineral fractions, generate microaggregates [18–20]. Also, the size of the aggregates can be associated with the soil OM stabilization degree [8,21]. Microaggregates (20–250 μm) protect soil organic carbon physically from its degradation by occlusion and disconnection, making soil OM mineralization harder for decomposer microorganisms [8,22–24]. Therefore, physical occlusion of SOM within microaggregates and chemical stabilization is associated with stabilized C pools [25]. So, stable aggregates in the soil protect SOM against decomposition and lixiviation processes, while stable organic compounds bound to mineral particles are crucial for aggregate stability.

Increases in soil aggregation due to compost application have been reported for a wide range of experimental conditions. These included an incubation time from 3 weeks to 336 days [26–29], turnover [30,31], a field application rate from 0 to 300 t.ha^{-1} [29,32,33], and a frequency from a single to annual repeated applications [32,34,35]. Different compost maturity levels were also tested for their effect on soil aggregate stability; high-maturity composts performed better than the less mature ones [16]. The influence of compost incorporation or surface application was tested by [36], which demonstrated that the decomposition dynamics and C and N location in the soil depth vary according to the location of crop residues. Ref. [26] added hay litter milled at two size classes (0.63–2 mm and <63 μm) and as bacterial necromass, leading to differences in the microbial community formatted after the amendment. However, as stressed by [6], some research questions regarding compost application mode remain unclarified till now. Effects of other compost characteristics on aggregate formation dynamics and stability, such as grain size, were apparently not yet explored.

The olive oil production chain generates a considerable quantity of by-products every harvest. In 2022, Portugal produced almost 775,000 t of olives, resulting in 1,377,529 hl of olive oil, 97% obtained using a two-phase extraction system, which generates olive pomace as a by-product [37]. Due to its generated volume and physical-chemical characteristics, olive pomace management has recently become a growing problem for olive oil mills. Two-phase olive pomace has a high organic matter and polyphenol content that generates phytotoxicity, making direct disposal in the soil unsuitable [38,39]. Composting can be an alternative to valorizing the two-phase olive pomace since it is an aerobic degradation process performed by microorganisms with other residues with almost zero associated costs [40,41].

In northeast Portugal, where a large part of the territory endures desertification susceptibility, soils are, for the most, weakly aggregated, poor in organic matter, and highly susceptible to erosion due to both the regional sloping relief and their high erodibility [42–44]. Organic conditioner amendment may improve their physical resistance against degradation processes through improvements in soil structure status and stability, which are expected to reduce soil erodibility and increase soil water retention, besides adding to soil carbon and nutrient pools. Northeast Portugal is the second largest olive oil-producing region (8%) in the country, with an agricultural area of 81,745 ha [37]. The quantity and availability of olive pomace in the region is an opening to its valorization through composting. As composts also act as soil conditioners, OPC amendment may improve soil resistance to physical degradation.

Composts obtained from olive mill waste mixtures contain high carbon content levels in their humic form (~13%), which is more beneficial for soils [40,45,46]. Research carried out with soil amendments derived from olive mill pomace has already reported several results for soil chemical properties [35,47,48] and plants and crop productivity [45,49,50]. However, physical properties, namely soil aggregation, are rarely studied on soils amended with olive pomace-based compost [51,52].

This study aimed at assessing the influence on soil aggregate stability of olive-pomace-based conditioners (OPC), applied as soil conditioners to aggregate samples of two contrasting soils: a sandy loam to loam, weakly aggregated soil, a clay loam, and well-aggregated soil. In order to investigate the specific effects of compost's physical-chemical characteristics on soil aggregate stability, three OPCs with different olive pomace proportions were applied in three doses (plus control) with fine and coarse grain sizes. Controlled laboratory conditions simulated field daily wetting-drying cycles during a 30-day experiment. As a short-term experiment, aggregate stability was determined on a macroaggregate size range.

2. Materials and Methods

2.1. Soil Sampling and Characterization

Two soils with different textures were selected for this experiment: sandy loam to loam and clay loam soil. Field observations grounded the hypothesis that the sandy loam to loam soil was poorly aggregated, whereas the clay loam was a well-aggregated soil. The first one, classified as Eutric Fluvisol [53], was collected from a cultivated maize area located at an experimental farm of the Polytechnic Institute of Bragança, NE Portugal (41°46′49.39″ N, 6°47′59.68″ W). The area is 690 m above sea level in a climate classified at Csb, according to the Köppen-Geiger classification system [54]. The second soil is classified as Schist-derived Eutric Leptosol [53,55] and was collected in a conventional olive orchard at Mirandela, NE Portugal (41°29′19.19″ N, 7°14′53.37″ W) [56]. This soil is representative of the olive groves found in approximately 80% of the area under olive cultivation of Trás-os-Montes [42,57]. It is a shallow soil with high stoniness and low organic matter content. Both soils were collected at 0–0.1 m depth, and the characteristics are presented in Table 1. Both air-dried soils were sieved to obtain aggregates of 1 to 2 mm. Soil texture was obtained through the pipette method, water pH by soil: distilled water suspension of 1:2.5 and pH KCl by suspension of 1:2.5 (soil: 0.1 N KCl); Electrical Conductivity was measured in a soil: distilled water suspension of 1:5 and Total N by elemental analysis (LECO CHNS-932). Soil Organic Carbon (SOC) was determined by the Walkley-Black oxidation method, and Organic Matter (OM) was estimated assuming 58% C content in OM [58]. The ammonium acetate method, buffered at pH 7, was used to assess extractable Al and potential CEC, determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) or Flame Atomic Absorption Spectrometry (FAAS). Effective CEC was obtained from the sum of the soil cations determined by ICP-OES or Flame FAAS.

2.2. Olive-Pomace-Based Organic Conditioners (OPC)

Olive-pomace-based organic conditioners (OPC) were obtained by composting two-phase olive pomace, almond shell, and sheep manure in different volumetric proportions, according to Table 2. Treatments were defined according to the percentage (%) of olive pomace in the initial mixture: OPC 44, OPC 31, and OPC 25. Composting was performed in three windrow trapezoidal piles with seven mechanical turnings for 180 days. After that, organic conditioner properties were determined, and the results are shown in Table 2. Total C and N were obtained by elemental analysis (LECO CHNS-932), and OM was obtained using the Walkley-black oxidation method. pH and EC were measured in a suspension of 1:2.5 and 1:5 (soil: distilled water), respectively. P (total P_2O_5) and K (total K_2O) were obtained by Egner-Riehm extraction. CaO was obtained using ammonium acetate 1M buffered at ph7 acid and detected by the FAAS technique.

Table 1. Soil properties of the selected soil for the aggregate stability experiment.

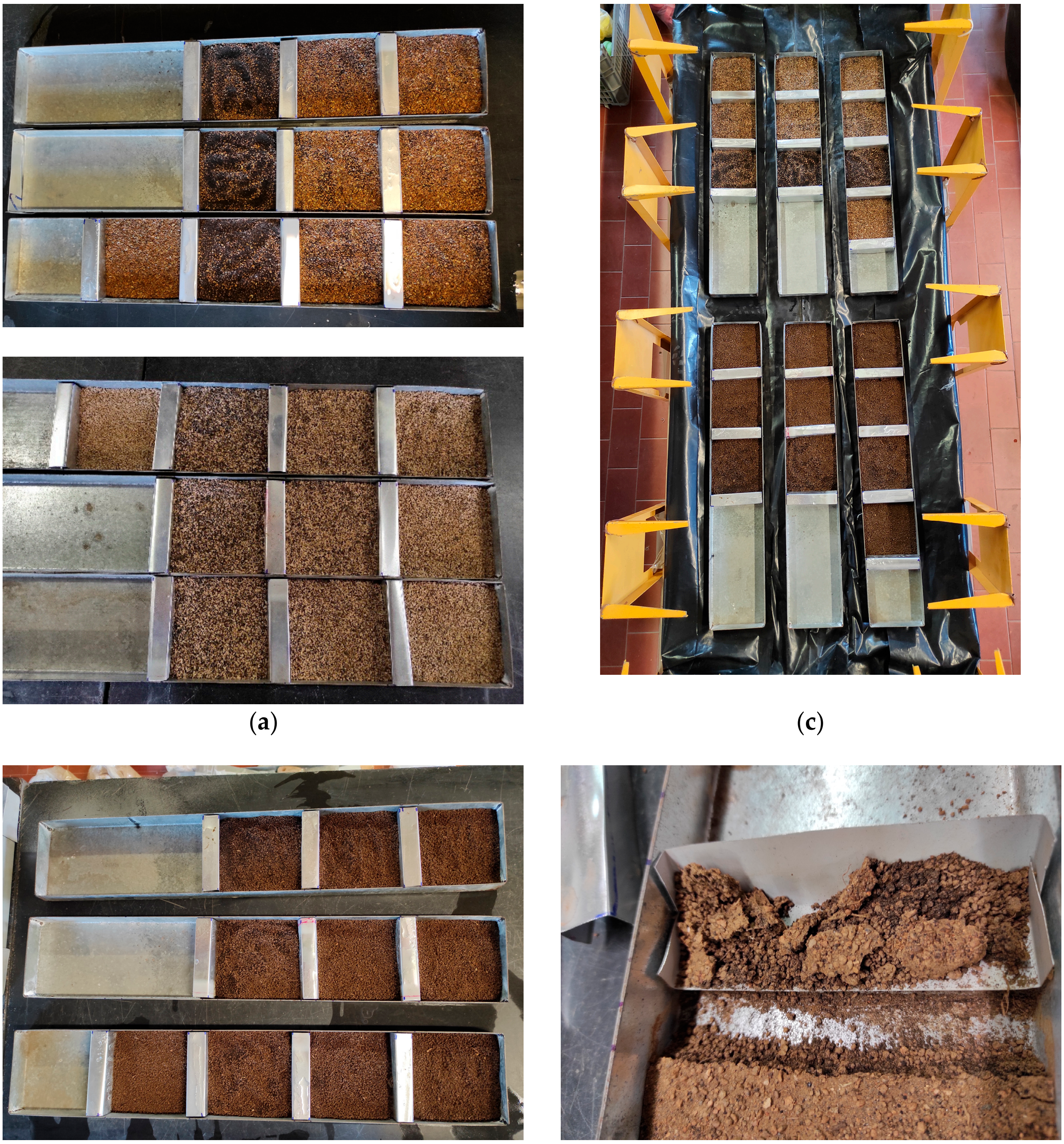
Soil	Fluvisol	Leptosol
Texture (ISSS)	Clay loam	Sandy loam to loam
Clay (%)	21	12
Silt (%)	25	21
Sand (%)	54	77
OM (%)	4.2	2.1
SOC (%)	2.4	1.2
pH (H_2O)	5.6	5.4
pH (KCl)	5	4
EC (25 °C, µS/cm)	90.3	100.6
Total N (g/kg)	2.3	1.5
Effective CEC (cmol+/kg)	26.64	5.8
Potential CEC (cmol(+)/kg)	33.4	10.6
Exchangeable Al (cmol(+)/kg)	0.012	0.007

Table 2. Characteristics of the three olive-pomace-based conditioners (OPC) used as an amendment in the experiment.

Olive-Pomace-Based Conditioners (OPC)	OPC 44	OPC 31	OPC 25
Initial ratio olive pomace: sheep manure: almond shell (*v*/*v*)	4:1:4	4:1:8	4:8:4
C/N	16	17	11
OM (%)	61	58	36
Total C (%)	32	31	19
Total N (%)	2.1	1.8	1.7
pH	8.0	7.9	9.5
EC (mS/cm)	1.94	2.61	5.24
P_2O_5 total (%)	0.26	0.22	0.49
K_2O total (%)	0.94	1.13	1.87
CaO total (%)	1.03	0.75	1.31

2.3. Experimental Design and Aggregate Stability (AS) Determination

The experiment was conducted under laboratory conditions in a micro-scale dimension. A hundred grams (100 g) of aggregates (1–2 mm) of each soil were mixed with the three OPC (OPC 44, OPC 31, and OPC 25) in four different doses: D0 or control (0 $t.ha^{-1}$), D1 (10 $t.ha^{-1}$), D2 (20 $t.ha^{-1}$), and D3 (40 $t.ha^{-1}$). The compost proportion in the mixture was 9%, 17%, and 29% by mass for the D1, D2, and D3, respectively. OPC conditioners were incorporated in coarse (<2 mm) and fine (milled at <0.75 mm) forms. Treatments (mixtures and control) were arranged in a metal tray with an area of 100 cm^2 (Figure 1). Treatments were subjected to wetting-drying cycles each day for 30 days. Each cycle consisted of wetting the treatments with a sprayer until a 40% moisture content was achieved, and they were subjected to a subsequent drying cycle in a term ventilator for 2 h. Figure 2 depicts an example of the wetting-drying cycle, showing the room and the soil temperature at the beginning of the cycle (on average, 14.8 ± 1.6 °C and 13.7 ± 1.3 °C, respectively), i.e., before wetting. Immediately after the heating period, the average temperature was 48.9 ± 4 °C in the room and 32.7 ± 3.6 °C in the soil surface. It is important to stress that soil temperature at the end of the drying period never reached more than 40 °C. Soil samples taken were stored at 4–6 °C until the aggregate stability analysis. Five samples were taken for each treatment, and the aggregate stability was measured considering four replicates per sample.



(**a**) (**c**) (**b**) (**d**)

Figure 1. Pictures of the experiment: (**a**) Leptosol amended with three OPCs and doses in fine wet (top) and after drying cycle (bottom); (**b**) Fluvisol amended in fine with three OPCs and respective doses; (**c**) samples disposal setup; and (**d**) sampling moment.

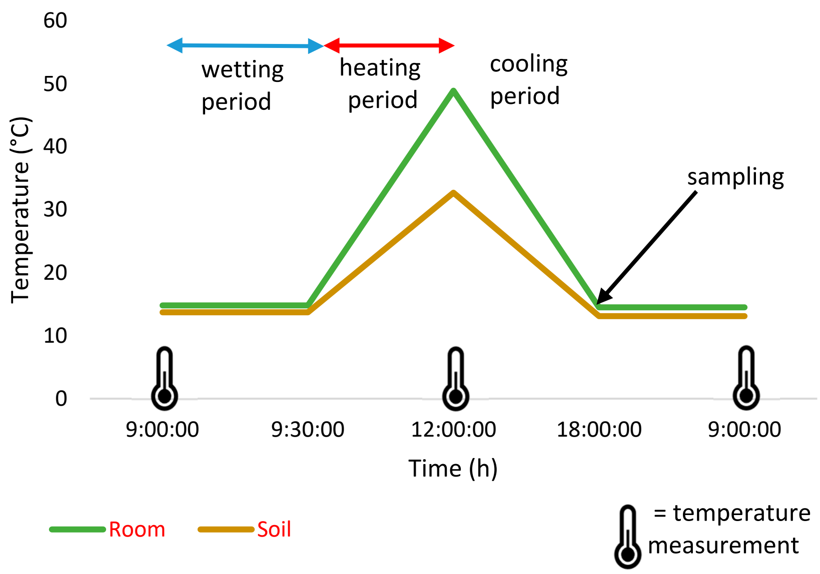


Figure 2. Example of a wetting-drying cycle and respective room and soil temperature during the experiment. The thermometers indicate the time of temperature measurements. Wetting, heating, cooling, and sampling moments are also indicated.

A wet sieving apparatus (Figure 3) was used to determine the aggregate stability (AS) [59]. Following the apparatus protocol, 4 g of sample added in each sieve (0.25 mm) were immersed in distilled water and shaken up and down in cyclical vertical movements for three minutes. After that, the distilled water was replaced by a sodium hexametaphosphate dispersant solution (2%), and the samples were shaken for more than 9 min to disperse the stable aggregates (>0.25 mm). The next step was to oven-dry all three fractions—the first fraction that passed the sieve with distilled water (DW_f), the fraction that passed the sieve when immersed in the dispersant solution (SH_f), and the remaining fraction above the sieve—at 105 °C for 24 h. All analyses were performed with four replications per sample. The moisture content of the original sample was also determined to make humidity corrections. The dry weights were used to calculate the indicator of aggregate stability (AS, %) as follows (1):

$$AS(\%) = \frac{SH_f}{DW_f + SH_f} \quad (1)$$

SH_f: dry weight of <0.25 mm fraction after agitation in sodium hexametaphosphate.
DW_f: dry weight of <0.25 mm fraction after agitation in distilled water.

Figure 3. Wet sieving equipment used to take the aggregate stability measurements.

2.4. Statistical Analysis

The Kolmogorov-Smirnov normality test was performed for each treatment (2 Soil × 3 OPC × 3 Doses × 2 Grain size + control). The data analysis was performed in software R. A multifactorial ANOVA and partial eta squared were used to perform and assess, respectively, the statistical significance of the factors tested and their relative contribution to statistically explain AS results obtained. A non-parametric Kruskal-Wallis test was also applied to compare the amended and unamended soil data. One and two-way ANOVA were applied to analyze specific data subsets, defined according to the research hypothesis under test in the experiment: the difference in AS between the two soils (a priori based on observational evidence); the OPC grain size effect on AS; and the effects of OPC type and dose, overall, and combined. The Tukey post hoc mean comparison test was used in case of a significant effect of a factor with more than two modalities (e.g., OPC type and dose) was detected in ANOVA.

3. Results

3.1. Relative Importance of Factors Affecting Aggregate Stability

All datasets were considered normal by the Kolmogorov-Smirnov Normality Test ($p > 0.05$). First, a multifactorial ANOVA with all factors (Soil × Grain size × OPC × Dose) was performed, coupled with a partial eta squared analysis to extract the main effects of each factor, and the summary of this approach is shown in Table 3. The significance order following the highest to lowest *p*-value is Grain size > Soil > Dose > OPC. This analysis confirms some of the hypotheses stated, where the Grain size and Soil factors have the most significant relevance. On the other hand, OPC shows no significance in the ANOVA without interaction, and the partial eta squared confirms that the OPC factor has a small effect size (Table 3).

Table 3. Statistical summary of the four- and three-way ANOVA. PES: Partial eta squared.

ANOVA—Four Way			ANOVA—Three Way Per Soil				
Factor	*p*-value	PES *	Factor	Leptosol		Fluvisol	
Grain size	**<0.001**	0.442		*p*-value	PES	*p*-value	PES
Soil	**<0.001**	0.369	Grain size	**<0.001**	0.215	**<0.001**	0.758
Dose	**<0.001**	0.259	Dose	**<0.001**	0.148	**<0.001**	0.563
OPC	0.339 NS	0.016	OPC	0.130 NS	0.060	0.085 NS	0.072

* Note: Partial eta squared = 0.01: Small effect size; 0.06: Medium effect size; 0.14 or higher: Large effect size. NS: not significant ($p > 0.05$).

Further, we compared the soils and their AS without the OPC amendments. As hypothesized, the difference was statistically significant and showed that the Fluvisol (63 ± 7%) is more aggregated than the Leptosol (39 ± 5%). As presented, soil mineral particle distribution and organic matter highly differ between soils (Table 1). It is important to notice that these data represent the control situation and will be used as a reference to analyze the following case comparisons.

Next, we confronted the unamended against the amended datasets to see if the amendment of soils affects the AS. The Kruskal-Wallis test returned a *p*-value < 0.05, confirming the hypothesis. The amendment of both OPCs—independently of treatment—causes a significative increase in AS for Leptosol (*p*-value < 0.05) but not for Fluvisol (Figure 4a). The AS increasing is far more expressive for the weakly aggregated soil and is close to the AS associated with the unamended well-aggregated soil.

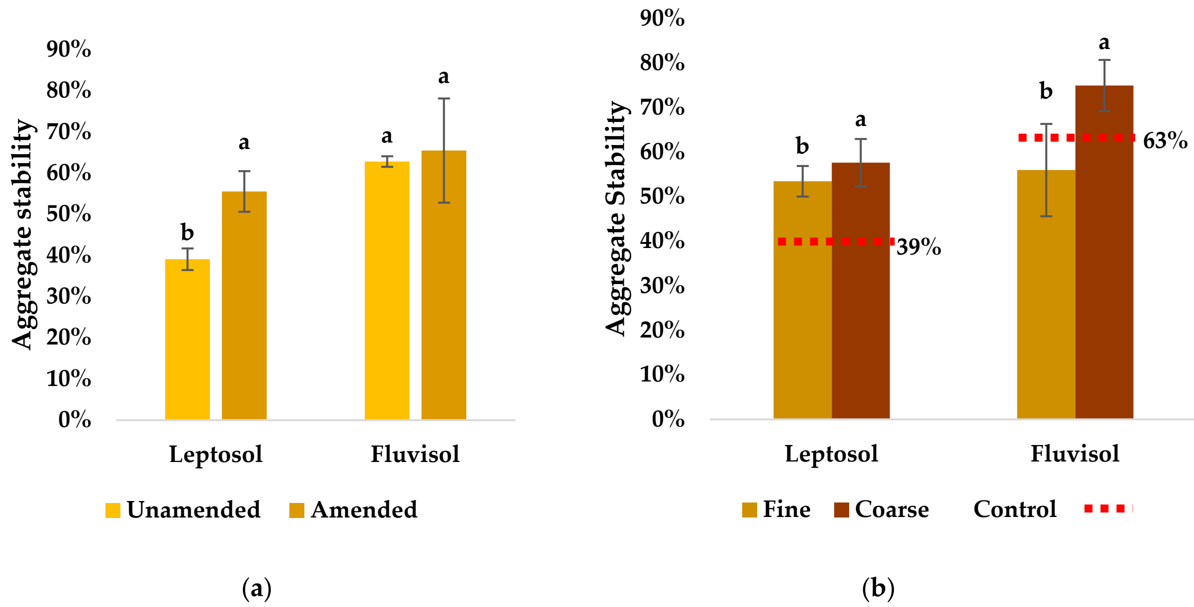


Figure 4. (**a**) Amended × Unamended data for each soil overview. (**b**) Aggregate stability for Leptosol and Fluvisol amended in fine (milled at 0.75 mm) and coarse (sieved at 2 mm) grain size. Different letters indicate significant differences ($p < 0.05$). Error bars correspond to the standard deviations.

As a prior difference in AS was detected for the unamended soil factor, a multifactorial ANOVA was performed by soil, considering three factors (Grain size × OPC × Dose) (Table 3). For Leptosol, without an interaction, the significance order following the highest to lowest partial eta squared is Grain size ($p = 0.215$) > Dose ($p = 0.148$) > OPC ($p = 0.060$), where OPC was not statistically significant. Partial eta squared shows that Grain size and Dose have a larger effect in AS, while OPC has quite a small effect. The same pattern was identified for Fluvisol: Grain size (0.758) > Dose (0.563) > OPC (0.072). Partial eta squared values in Table 3 reveal that Grain size has the greatest impact in AS, whereas Dose and OPC have a medium effect size.

3.2. Effects of Compost Characteristics on Soil Aggregate Stability

3.2.1. Compost Grain Size

Analyzing the grain size effect, the one-way ANOVA proved a significant statistical difference between the grain size tested, where coarse grain size represents the more expressive increase in AS for both unamended soils—Leptosol and Fluvisol (Figure 4b). The mean difference in AS between fine and coarse was 14% and 28% for Leptosol and Fluvisol, respectively.

Compared to control data, a progressive and significant increase in AS is observed for the sandy loam to loam soil for fine (14 ± 3%) and coarse (19 ± 5%) grain size (Figure 4b). Fluvisol had an opposite pattern: the aggregate stability oscillates down for fine OPC's amendment and increases when amended in coarse. For coarse grain size, the addition of OPC represents an increase of around 12% in soil AS, while the amendment in fine represents a decrease in AS (ca. 7%).

3.2.2. Compost Dose and Maturity

A one-way ANOVA was applied to each soil data to investigate the global conditioner's performance. Regarding the fine grain size, our results are contradictory. For Leptosol, the input of organic OPC—independently of which one—represents a statistically significant increase in AS ($p < 0.05$) compared to the unamended AS values. No significant difference between OPCs was detected for the poorly aggregated soil (Figure 5a). Both treatment's performance was very homogeneous. Fluvisol exhibited an opposite pattern: the stable water aggregates decreased with the incorporation of OPC, but this decrease in

AS was not significant (p-value = 0.252) (Figure 5a). Among the three OPC types, OPC 25 represents the highest AS percentage.

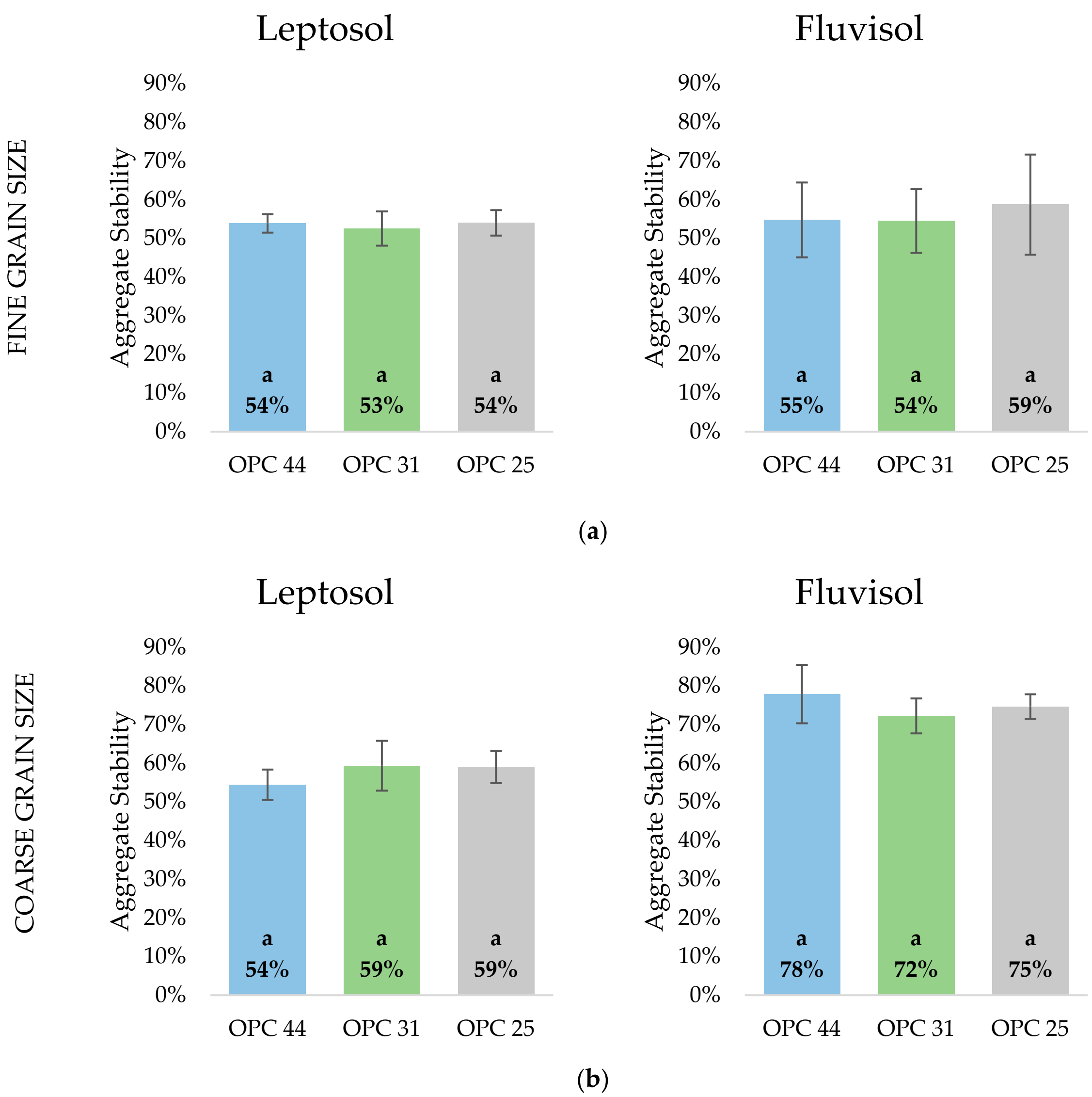


Figure 5. (**a**) Aggregate stability (%) for Leptosol and Fluvisol amended with OPCs 44, 31, and 25 in fine grain size (milled at 0.75 mm) and (**b**) in coarse grain size (sieved at 2 mm). Different letters indicate significant differences ($p < 0.05$) between OPCs. Error bars correspond to standard deviations.

OPC performance for coarse grain size is shown in Figure 5b. As for the fine grain size, no difference between OPC types was detected for Leptosol. However, the three OPCs tested significantly increased the AS by mean values of 18% compared to the unamended soil (Figure 5b). The mean AS achieved by amended Leptosol with OPC 31 and 25 (59%) in the coarse grain size is slightly close to the AS presented by unamended Fluvisol (63%). For Fluvisol (Figure 5b), the amendment with coarse grain size represents an increase in AS compared to the unamended soil—around 9–15%. This pattern is the opposite verified for the fine grain size, where a significant decrease in AS was observed. As stressed before, the most significant improvement in soil AS occurs by amending both soils with coarse OPC.

Regarding the doses, a global analysis showed a similar pattern for both soils amended in the fine grain size, comparing the global data. D3 had the significantly lowest AS increment for Leptosol and Fluvisol. However, this pattern changes according to OPC grain size, as shown in Figure 6. For Leptosol amended in fine, D2 represents the highest AS, although not statistically different from D1. D3 performed worst in both cases (Figure 6a).

For Fluvisol amended in the fine grain size, the dose increments significantly decreased the AS in soil, with D1 > D2 > D3, each one statistically different from the other (Figure 6a).

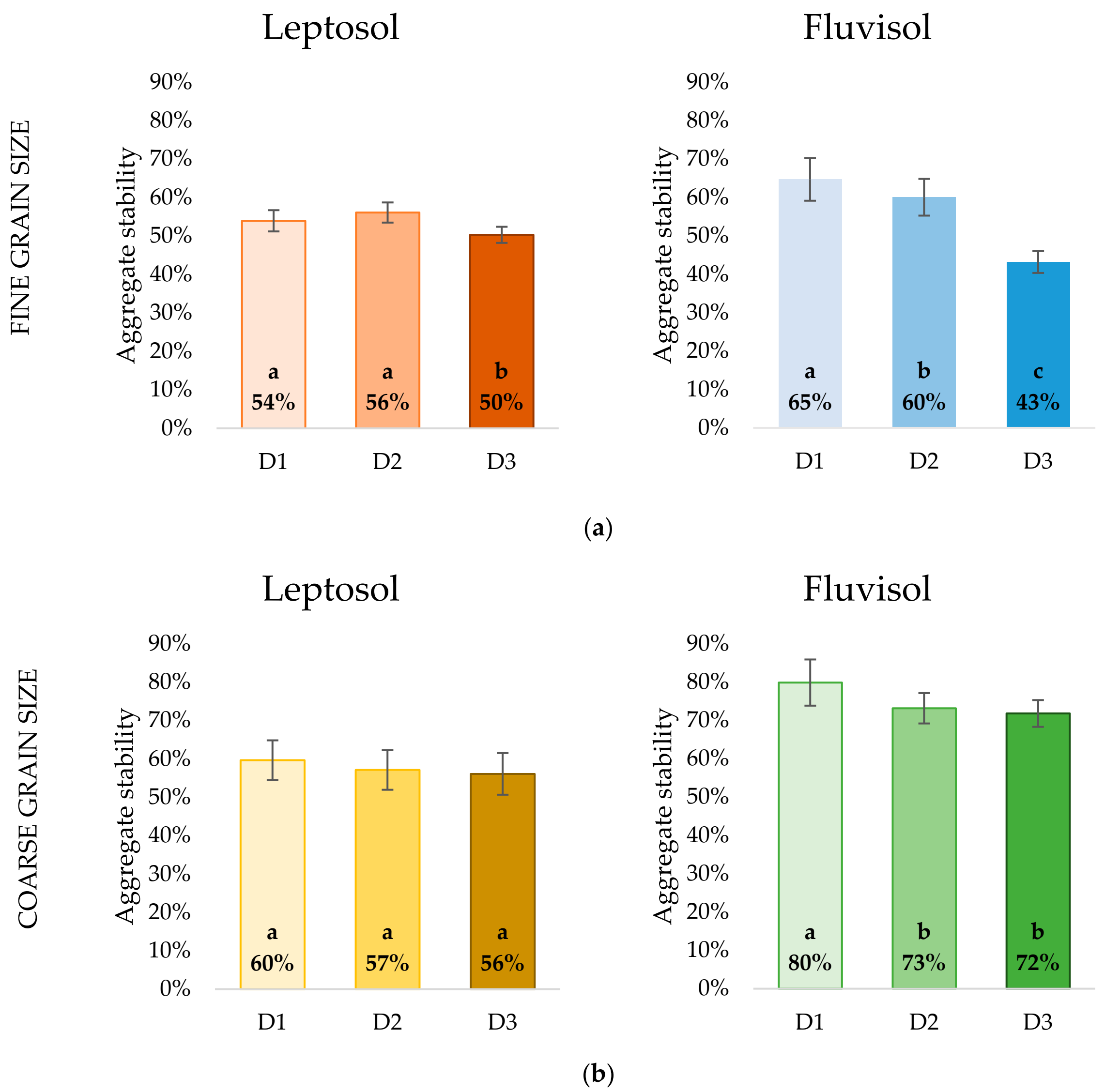


Figure 6. Overall performance of doses incorporated in a (**a**) fine and (**b**) coarse grain size into Leptosol and Fluvisol in aggregate stability. D1 = 10 $t.ha^{-1}$, D2 = 20 $t.ha^{-1}$, and D3 = 40 $t.ha^{-1}$. Different letters indicate significant differences ($p < 0.05$). Error bars correspond to standard deviations.

Regarding the coarse amendment form, the dose performance for Leptosol was similar among all rates tested. The increment in AS due to the amendment in the coarse grain size was around 19 ± 5%, which is a remarkable increase for this soil (Figure 6b). Fluvisol seems to be more sensitive to the doses tested for both granulometries. In Figure 6b, we observed that the lowest dose represents a significantly higher AS, followed by D2 and D3. Overall, our results suggest that the lowest dose tested (D1) had the best performance by enhancing AS in the soils, whereas D3 lowered AS values in soils, except for Leptosol amended in the coarse grain size.

The comparison between dose and OPC factors by soil and grain size is presented in Figure 7. Although the difference between conditioner types was not statistically significant ($p > 0.05$) for Leptosol amended with OPC in the fine grain size, the addition of conditioners represents an increase in AS compared to unamended soil in all types (Figure 7a). The dose significantly affects AS by increasing 11–17% of the average AS ($p = 0.000$). No interaction between OPC and Dose factors was detected. Results for Leptosol in Figure 7a suggest that the dose effect is non-monotonous. An increase in AS is observed until reaching a peak in D2, followed by a decline in D3—a pattern consistently observed across all three tested conditioners. As previously reported, D3 represents the worst performance in soil AS.

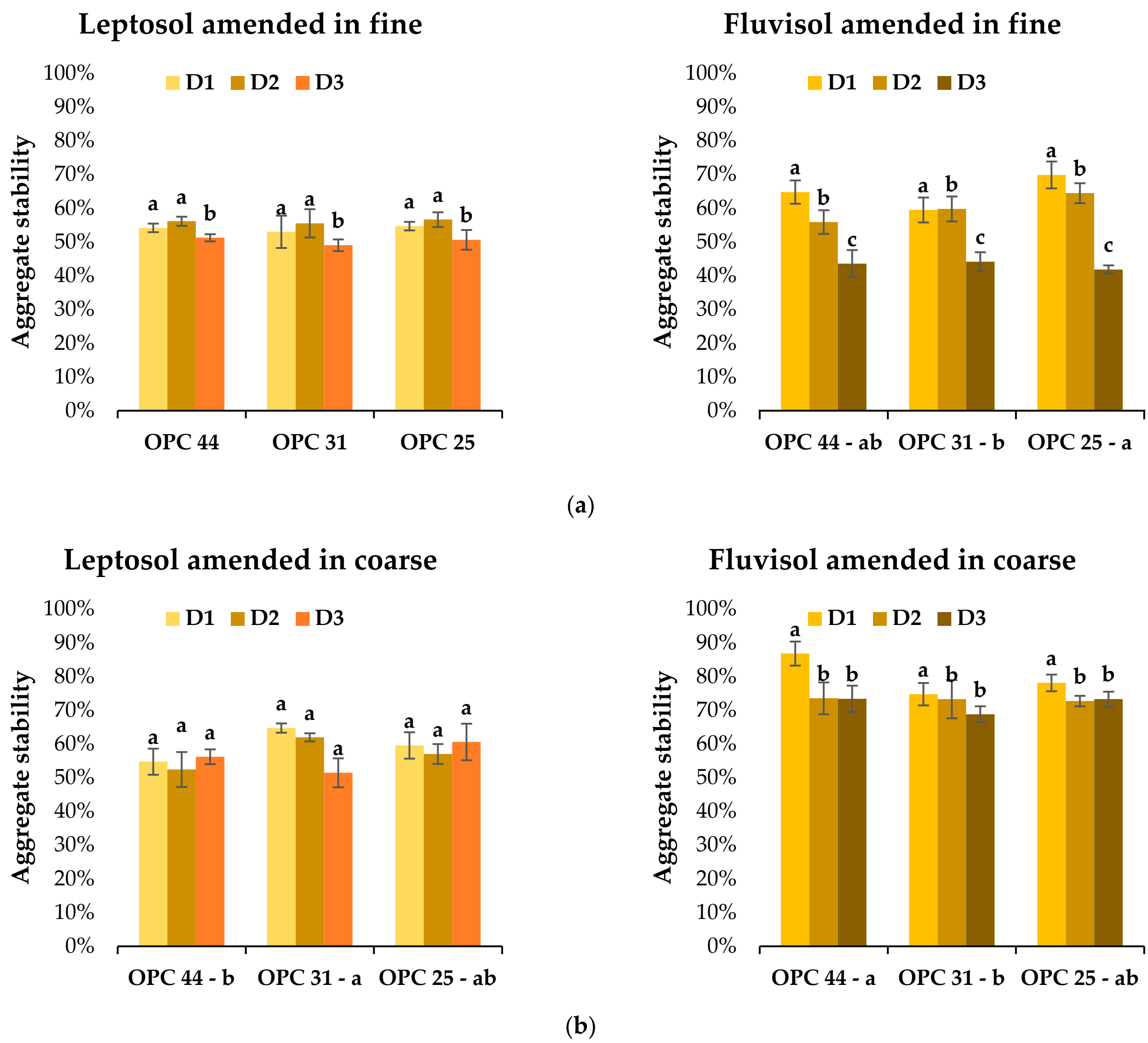


Figure 7. Aggregate stability for Leptosol and Fluvisol amended with olive-pomace-conditioners OPC 44, 31, and 25 in (**a**) fine grain size (milled at 0.75 mm) and in (**b**) coarse grain size (sieved at 2 mm), considering three doses: D1 (10 t.ha^{-1}), D2 (20 t.ha^{-1}), and D3 (40 t.ha^{-1}). Different letters indicate significant differences ($p < 0.05$) between Doses and OPCs. Error bars correspond to standard deviations.

In Fluvisol, adding conditioner's type in multiple doses significantly affects AS (p = 0.000), while the interaction was p = 0.479. Figure 7a shows that the doses present a similar effect, but the "peak" occurs earlier than Leptosol. The peak of AS corresponds to the reference dose (10 t.ha^{-1}) and decreases according to the dose increment. Dose D3 (40 t.ha^{-1}) reflects the worst performance, significantly decreasing the average AS of Fluvisol by 20%. All OPC incorporation in the fine grain size for Fluvisol decreases the AS measured in control samples. However, OPC 25 presented the best performance, followed by OPC 44 and OPC 31. Regarding the Fluvisol amended with OPC in the fine grain size, D3 presents a typical pattern in this treatment; for OPC 44, 31, and 25, D3 represents the poorest AS, even below the control dose. Also, this treatment shows the unique case where the unamended soil (D0) presents an AS similar to or even higher than the amended doses, i.e., the OPC amendment did not show an increase in AS; on the contrary, a decrease in AS values was observed.

In the case of Leptosol amended in coarse form, two-way ANOVA reveals that the doses did not significantly affect AS ($p > 0.05$). However, the conditioners did ($p < 0.01$), with significant interaction between the factors ($p < 0.001$) (Figure 7b). Both amended doses reflect a significant AS increment regarding the unamended data. The mean comparisons test shows that OPC 44 and OPC 31 differ statistically, while OPC 25 is similar to the other ones. For the Fluvisol amended in the coarse grain size, the statistical analysis shows that OPC and Doses significantly affect AS, while the interaction was $p > 0.05$. D1 presents a significantly higher AS for all OPC tested (Figure 7b). The amendments higher than 10 t ha^{-1} significantly decreased the AS compared to this reference dose. Regarding the OPCs, the best performance in AS was verified for OPC 44, followed by OPC 25 and OPC 31.

4. Discussion

As hypothesized, a priori clay loam soil (Fluvisol) presented higher AS than sandy loam to loam soil (Leptosol). In fact, it has been broadly reported that soils with more clay content are associated with higher AS [7,15,27,52]. Besides that, it is important to stress that sand particles contribute to aggregation, as demonstrated by [60–62]. A higher soil organic matter content is also directly associated with high AS. According to [16], the main soil properties influencing water aggregate stability in soils are soil texture, clay mineralogy, cation content, aluminum and iron oxides, and soil organic matter. Besides the higher OM, Fluvisol presents higher levels of N content, an effective CEC of almost 4.5 times, and a potential CEC three times higher than Leptosol (Table 1). These soil chemical properties contribute to the higher AS verified in the Fluvisol, quantitatively confirming the evidence observed in the field.

Soils with higher reactive minerals (i.e., illite, chlorite, smectite, vermiculite, and amorphous minerals) are expected to have a high specific surface area for adsorption of SOM, leading to aggregation of clay particles and SOM, which can stabilize C compounds within the aggregates and improve overall soil structure [3,6]. Ref. [4] argued that aggregate formation in soils with more clay content has more to do with the type of clay rather than clay quantity. They also pointed out that organic carbon inputs majorly influence the structure of coarse-textured soils. This is the case of Leptosol, in which primary minerals are predominant (Quartz (22%), Plagioclase (26%), and Mica (43%)) in the <20 μm fraction, and clay minerals (4%) are residual (Chlorite (4%) and Goethite (traces)) (soil mineralogy data provided by Teresa Valente). Although not qualified, Fluvisol mineralogy is likely to include smectite-type clay as soil surface cracking is field evidence during the dry season.

Given this, the clay loam soil amended with OPC in fine grain size performance was unexpected since a decrease in AS was detected. A very similar decrease of around 8% was detected by [52]. This pattern may have more than one explanation. A surface crust can be formatted due to several wetting-drying cycles and cause a reduction of water-stable aggregates, as reported by [14]. Ref. [8] says that aggregate breakdown depends on the wetting rate. Successively drying and wetting cycles in aggregated soils could decrease the proportion of soil aggregates, mainly due to the wetting rate, which might be non-uniform and insufficient to swell the clay fraction and promote colloidal particles or too rapid to cause the compression of occluded air in the capillary pores [8]. Studies by [33,34,52,63] also reported more pronounced results in loamy soils than in clay soil.

Globally, no significant differences were detected between the three OPC types tested in their effect on AS. OPC 44 and OPC 31 have similar chemical compositions regarding the C/N, OM, Total C, Total N, pH, and nutrient content. OPC 25 performed slightly better in the Fluvisol, although not significantly in all treatments tested. The mean AS achieved by amended Leptosol with OPC 31 and OPC 25 (59%) in coarse grain size almost reached the AS of unamended Fluvisol (63%). Although resulting from different proportions of the raw materials used in their elaboration (olive pomace, sheep manure, and almond shell), the three OPCs chemical characteristics, namely their C/N ratio, do not expressively differ so as to induce different responses to amendment in what regards AS in the short term and in the macroaggregate size range. Ref. [28] conducted an experiment using organic amendments with different natures (cauliflower residues, wheat straw, cattle manure, and poultry woody compost) and concluded that aggregate stability dynamics are strongly affected by the intrinsic decomposability of the organic material amended in the soil. Different types of organic amendments stimulate particular groups of the soil microbial population, having a different susceptibility to decomposition and, therefore, distinguished aggregate dynamics in the soil [16,34]. This concept applies to the same organic material with different maturity degrees [29,31] or distinct C pool fractions [60]. Analyzing the fungal lengths and aggregate stability, ref. [27] reported a good correlation between the two variables in sandy loam and silty loam soils and concluded that fungi activity is less critical for aggregate formation in more clayey soils. These authors also observed that adding particulate organic matter in different forms resulted in different compositions of the microbial communities established in the amended soils [27].

Regarding the incubation time, ref. [27] detected an increase in AS in sandy loam, silt loam, and silty clay loam soils in just three weeks. Even without repeated drying-wetting cycles after 30 days of incubation, ref. [60] concluded that it is possible to observe aggregate formation in a loamy-textured artificial soil, although it is significant compared to the control samples. So, in the present study, the 30 days may not have been sufficient for the Fluvisol either, especially in the fine amendment form, because it already had high aggregate stability and good soil structure or because the added organic materials just contributed to creating disruptive zones. Ref. [33] conducted an experiment that tested two soil textures, and their results were also more pronounced in the loamy soil than in the clay soil.

Some studies pointed out that the aggregate stability increased linearly with increasing organic amendment amounts [27,64]. In most cases of this work, the AS increases with increasing dose up to D2 (20 t.ha^{-1}), but conversely, the maximum rate of OPC input reveals a decrease in AS compared to the lower rates tested. The observed dynamics in AS for D3 are a common pattern, as it consistently exhibits the most negligible effectiveness in enhancing soil aggregate stability across all scenarios. Better, a decrease in AS was detected. This breakdown effect is supported by the work of [8], where an imbalance between inorganic and organic particles is verified, and break zones are created. This pattern suggests a saturation level for the soil, from which the increment of organic material will no longer improve soil aggregate stability. In fact, ref. [8] reported this pattern for soils with high levels of aggregation, when the carbon mineralization rate will be similar to new organic carbon inputs and, therefore, no aggregate formation is observed. Other studies have reported this pattern, proving that the addition of organic amendments in soil with high carbon content and good structure does not contribute to increased soil aggregation [34,65]. In this sense, our results for the Fluvisol amended with the coarse grain size are aligned with the literature because no significant increase in AS was verified.

Analyzing the Q1 of the AS data, all increase was associated with Leptosol, with AS gains in the order of 44 to 66%. Coarse grain size had the best performance in 75% of the cases. Considering the soil AS gains greater than 40%, the OPC performance order was OPC 25, OPC 31, and OPC 44. D1 performed better in 44% of situations, followed by D2 (38%) and D3 (19%). Among treatments, Fluvisol amended with fine grain size presented a decrease in soil AS, especially in the higher dose tested (40 t.ha^{-1}). The optimal dose could be estimated using a regression function fitted to the experimental data. This strategy may help to reduce costs related to soil conditioner application. However, the global overview indicates that the most remarkable improvements in soil AS are associated with the lowest dose (10 t ha^{-1}), regardless of the soil, grain size, and OPC type. Ref. [45] applied two different mixtures of olive mill solid waste for five years at a rate of 9 t.ha^{-1}, and results showed a significant improvement in total organic carbon and humic substance values. In this sense, our results are in accordance with the amount recommended by the Portuguese law (10 t.ha^{-1}) [66]. Although the presented approach simulates an accelerated process of aggregate formation (30 forced wetting–drying cycles), an annual amendment of 10 t ha^{-1} certainly will improve soil structure in the field, where more binding agents—such as those derived from biota and plant roots activity—will act. However, this conclusion should not be extrapolated to longer-term scenarios because a physical-chemical evolution of the applied compost is expected to occur as part of the dynamics of soil organic matter, essentially determined by soil microbiota activity.

Aggregate stability significantly increased in the sandy loam to loam soil (Leptosol) amended by OPCs in the fine grain size (increased by 15 ± 3%) and coarse grain size (increased by 19 ± 5%). In the Fluvisol (clay loam), aggregate stability decreased with the OPC's fine grain size amendment and increased when amended in the coarse grain size, yet neither treatment was statistically different from the unamended soil. The relation between the grain size of compost incorporated and aggregates stability is poorly addressed in the literature, while some studies indicate that compost inputs increase the macro-aggregates fraction (>200 μm) [31,60,65]. These findings are in line with the better performance of coarse grain size amendments obtained in the present experiment.

Ref. [63] investigated the effects of OPC on soil water retention and infiltration, depth of penetration, and accumulated intake in a clay and a silty loam soil type. The results for the related properties were more pronounced in the silty loam soil, and the general improvements were proportional to the application rate. Ref. [51] measured the AS in clay loam soil amended in two doses of compost from olive pomace and noticed a significant increase for the lowest dose applied. Corroborating soil chemical properties results from this study proved that a double quantity of organic input does not induce a proportional increase in soil aggregate stability index and soil organic matter content. Ref. [52] measured AS in three soil textures (clay, loam, and sandy loam) amended with two doses, 3% OPC and 6% OPC. For the clay soil, the highest AS was related to the lower doses, and on the opposite, the lowest AS was found for the 6% OPC. They also stress that the AS changes were more pronounced in coarse-textured soils than in clayey ones.

The three OPCs differ in terms of the proportions of olive pomace in the initial composted mixture. OPC presented 44, 31, and 25% olive-pomace in the initial mixtures. In this context, the higher the quantity of olive pomace in the compost, the more noteworthy its impact on both waste management challenges and the circular economy. As there were few significant differences between OPC in soil and AS, we can recommend the OPC containing a higher proportion of OP, as it represents the best solution for the olive oil production chain.

The significant increase in AS for Leptosol amended with olive-pomace-based conditioners may be extremely important for the semi-arid and arid regions, especially the Iberian Peninsula (Portugal and Spain) and other olive oil country producers in the Mediterranean climate zone, like Italy, Greece, Tunisia, Turkey, and Morocco. These countries represent a high percentage of olive oil production globally and are, therefore, the biggest olive pomace producers. Soil conditioners obtained from olive pomace and other agrifood byproducts composting are an alternative to soil and water conservation, as well as a contribution to reducing emissions costs and establishing a circular economy. It can also be an opportunity to mitigate climate change by recycling and keeping C in the protected pools in soil aggregates. Moreover, ref. [56] reported soil losses in olive groves under conventional tillage ranging from 250 to 600 kg ha^{-1} year^{-1}. Although this value is lower than the recommended soil loss tolerance rate (2 Mg ha^{-1} year^{-1}), it represents a loss more significant than the soil formation rate, considering the shallow and stony soils where the experiment was carried out. Thus, soil management practices such as the amendment with natural-based solutions—like OPC—are interesting techniques to reduce soil loss.

5. Conclusions

This study demonstrates the high potential of two-phase olive-pomace-based compost (OPC) as an organic soil conditioner. The olive-pomace-based compost enhanced soil aggregation at the macroaggregates fraction (>0.25 mm) in the short-term evaluation, especially in soils with poor aggregation and low organic matter content. The coarse grain size of OPC proves more effective in increasing soil aggregate stability, especially in Leptosol coarse-textured soil (increased by 19.5 ± 5%). In well-aggregated Fluvisol, amendment induced a significant increase in AS only in the compost coarse grain size (+12%). In addition, the coarse grain size OPC amendment is more feasible, practical, and less costly, which does not justify a reduction in grain size when preparing compost for application at farm scale.

Lower application rates (10 $t.ha^{-1}$) are recommended for optimum performance, as higher doses (40 $t.ha^{-1}$) have less of an aggregating effect. Thus, as less cost-effective, high application rates are not recommended in what concerns their effective contribution to improving aggregate stability. Although the three OPCs tested are chemically different, the experiment did not provide sufficient evidence to define which OPC performed better in improving AS. In the short term, the compost's physical properties, such as grain size, have more remarkable effects than its chemical properties.

The study was undertaken in a controlled small-scale experimental setup, therefore requiring adequate results transfer for field conditions. This is an important step towards a better understanding of the role in soil management of organic amendments derived from agri-food-chain byproducts or residue valorization, as is the case of olive-pomace-based composting. Incorporating olive-pomace-based composts contributes to the circular economy and faces the challenges of the actual olive chain. OPC applications in poorly aggregated soils are a promising soil management strategy for enhancing soil resistance to physical degradation and reducing soil organic matter decline rates in Mediterranean farmland. Expectedly, these results might stimulate future research on the topic and the farming stakeholders' decisions to enhance soil conservation practices that contribute to soil health and climate adaptation in the Mediterranean region.

Author Contributions: Conceptualization, T.d.F.; methodology, T.d.F.; formal analysis, T.d.F.; investigation, A.C.R.; resources, Z.H. and F.F.; data curation, T.d.F. and A.C.R.; writing—original draft preparation, A.C.R.; writing—review and editing, T.d.F.; visualization, A.C.R.; supervision, T.d.F. and M.L.; project administration, Z.H., T.d.F. and F.F.; funding acquisition, Z.H., T.d.F. and M.L. are supervisors of A.C.R., a UDC PhD student at CIMO. All authors have read and agreed to the published version of the manuscript.

Funding: The authors are grateful for the financial support of the research carried out by projects "BIOMA—Circular Economy and the digital transformation in Agrifood sector, POCI-01-0247-FEDER-046112", and "ForestWaterUp—Nature-based solutions for the ecological restoration of degraded soils in the Sabor Lakes, POCI-07-62G4-FEDER-181557". The authors are also grateful to the Foundation for Science and Technology (FCT, Portugal) for the financial support through national funds FCT/MCTES (PIDDAC) to CIMO (UIDB/00690/2020 and UIDP/00690/2020) and SusTEC (LA/P/0007/2020). Ana Caroline Royer thanks the national funding by FCT, the Foundation for Science and Technology, through the individual research grant 2022.11024.BD.

Data Availability Statement: All collected and relevant data is already presented in this work.

Acknowledgments: The authors wish to express a special thanks to Laura Silvestre for her direct involvement in the experiment and in the laboratory analysis that followed. Authors wish also thank Teresa Valente, from the University of Minho, for gently providing information on the mineralogy of one of the test soils. The authors acknowledge Renecleide Viana dos Santos and Daniel Figueiredo for their support in fieldwork and sample collection. We are thankful to our project partner, "ACUSHLA azeites S.A.", for their involvement in composting olive pomace and all colleagues that helped on the composting process.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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