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Temporal variability of physical quality of a sandy loam soil amended with compost

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Abstract
Compost can enhance the soil's ability to retain water, resulting in an overall improvement of soil physical quality (SPQ). The purpose of this study was to evaluate the temporal variability of physical and hydraulic properties of a sandy loam soil amended with a compost obtained from orange juice processing wastes and garden cleaning. The soil water retention curve of repacked soil samples at varying compost to soil ratios, *r*, was determined at the time of compost embedding (M0) and after six months (M6), and twelve months (M12). Indicators of SPQ linked to soil water retention curve such as air capacity (*AC*), macroporosity (P_{mac}), plant available water capacity (*PAWC*), relative field capacity (RFC) and Dexter S-index (S), were estimated. The effect of compost addiction of the pore volume distribution function was also evaluated.
The elapsed time from compost application influenced all SPQ indicators but the maximum beneficial effects of compost amendment were achieved within approximately the first six months. Indicators linked the macro- and mesoporosity (P_{mac} and *AC*) decreased with *r* whereas indicators linked to plant water availability (*PAWC* and *RFC*) increased with *r*. The combined effect of time and rate was statistically observed only for P_{mac}, *PAWC* and *S*.
Compost addiction reduced the soil compaction and modified the pore system, as the fraction of structural porosity (i.e., macropores) decreased and the fraction of textural porosity (i.e., micropores) increased. It was concluded that even a single application of compost could have a significant impact on soil water retention and microstructure with positive implications for soil health, precision agriculture and crop productivity.

Keywords Compost amendment · Soil physical quality (SPQ) · Soil water retention · Temporal variability

Introduction

In sandy soils, organic amendments are mainly used for enhancing the organic matter levels of the soil and improving its physical and chemical properties (Garbowski et al. 2023).

In this regard, compost is undoubtedly an effective and sustainable organic soil amendment that can increase humus content, improve soil fertility, and boost the soil's ability to retain water and nutrients, thereby enhancing the soil physical quality (SPQ) (Ampim et al. 2010; Paradelo et al. 2019; Wang et al. 2022). Compost is the result of the composting process, i.e., the aerobic, thermophilic decomposition of organic wastes by different species of microorganisms under controlled conditions (Parr et al. 1978). The process of decomposition transforms potentially toxic organic matter into a stabilized state that can be used to improve soil condition for plant growth.

Regarding the soil physical properties, numerous studies have highlighted various benefits of using compost as an organic soil amendment, such as: improvement of aggregation and aggregate stability (Annabi et al. 2007; Dong et al. 2021; Sarker et al. 2022), increase in total porosity (Arthur et al. 2011; Wallace et al. 2019), decrease in bulk density (Somerville et al. 2018; McGrath et al. 2020), improvement of pore size distribution (Aggelides and Londra 2000), increase in water retention capacity (Logsdon et al. 2017; Schmid et al. 2017; Głąb et al. 2020). Compost can also enhance soil air permeability, reduce compaction, and provide a favorable environment for plant root growth (Olson et al. 2013; Maškova et al. 2021). Apart from the specific

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climatic characteristics of each environment which drive the degradation rate of the soil organic matter, the impact of compost can vary over time depending on various factors such as the quality and the quantity of the compost used, the soil texture and the soil management adopted (Rupasinghe and Leelamanie 2020; Kranz et al. 2023).

The soil physical properties play a crucial role in determining the interactions between soil, water, and plants, thereby influencing the growth and germination of plants (Dexter 2004). The physical, chemical, and biological processes occurring in the plant root zone are mainly driven by the SPQ. It primarily refers to soil strength, water and air transmission, and storage characteristics (Topp et al. 1997). Physical quality is closely related to the soil water retention curve, which expresses the volumetric water content, θ, as a function of the pressure head, *h*. The soil water retention curve provides an indirect method for estimating pore size distribution (Hillel 1998) and can be used to determine capacity based SPQ indicators directly linked to the soil's ability to retain and supply water and air to plants. These indicators, that can be used in practical applications, include air capacity (*AC*), macroporosity (P_{mac}), plant available water capacity (*PAWC*), relative field capacity (RFC) (Reynolds 2002, 2003). Dexter (2004) introduced a conceptually different SPQ indicator, namely the S-index, which provides information on the distribution of soil pore sizes.

SPQ is affected by various factors, including soil structure, density, porosity, permeability, water retention capacity, pH, and organic matter content. Soil quality worldwide has been declining due to multiple reasons, including improper land use, poor agricultural management, excessive use of pesticides and fertilizers, soil compaction due to machinery, erosion, loss of organic matter, and climate change (Mojiri et al. 2012; Ferreira et al. 2022). Soils with poor physical characteristics generally exhibit high compaction or low porosity with limited water retention and slowed fluid transmission (Dexter 2004). This can result in inadequate root development and reduced soil aeration, both of which can hinder plant growth and productivity. Conversely, excessively high porosity can cause anchoring problems for crops or plants. Accordingly, the rational use of compost can be a valuable support to cultivation techniques for improving SPQ.

The duration of beneficial effects of compost amendment is not fully investigated as most of the studies focused the long-term effects that implies repeated inputs, generally every year, whereas very few studies have addressed the effects of a single input of organic matter (Cannavo et al. 2014; Sax et al. 2017). To the best of our knowledge, there is a limited number of studies focused on the use of SPQ indicators for evaluating the effects of compost amendment (Reynolds et al. 2009, 2015). Arthur et al. (2011) quantified the long-term effects of adding three different types of compost on the physical properties of a sandy soil by SPQ indicators. Castellini et al. (2022) evaluated the short- and medium-term effects of a compost addition on the physical and hydraulic properties of a clay soil. They reported that soil water retention and bulk density can be enhanced when high rates of compost, equal to 15 and 75 kg m^{-2}, were used. Bondì et al. (2022) assessed the reliability of SPQ indicators and pores size distribution parameters to evaluate the effectiveness of compost amendment on a sandy loam soil. They found that the addition of compost effectively altered the soil pore distribution system and associated SPQ indicators, resulting in possible positive effects on soil hydrological processes and agronomic services. Existing studies proved that SPQ indicators can be valuable tools for assessing the impacts of compost on soil.

The objective of this study was to assess the short-term effects of compost amendment on the physical and hydraulic properties of sandy loam soil. In particular, the temporal effect of a single application of compost at different rates was evaluated through measurements of SPQ indicators conducted at the time of embedding and after six and twelve months. Information on the temporal persistence of the benefits of compost amendment is crucially important for planning the most effective soil management practices.

Materials and Methods

Sample preparation

A sandy loam soil was amended with 5-months-aged compost derived from orange juice processing waste (75%) and garden cleaning (25%). Orange juice processing waste were composed of about 60% peel, 30% pulp and 10% pips, while garden cleaning contained triturated pruning residues and mown grasses (Palazzolo et al. 2019).

The sandy loam soil, classified by Alagna et al. (2018) as a Typic Rhodoxeralf, was sampled in a citrus orchard at the Department of Agriculture and Forestry Sciences of the University of Palermo, Italy (UTM 33S 355511E, 4218990N). Physicochemical attributes of soil and compost are shown in Table 1, taken from Bondì et al. (2022). Both components, before being mixed, were sieved through a 2 mm sieve, and air-dried.

Compost was blended with soil in five different rates by weight: $r = 10\%$, 20%, 30%, 50%, and 75%. Additionally, for comparative purposes, the two unmixed matrices were also considered: i.e., the not amended soil ($r = 0$) and pure compost ($r = 100\%$). In total, 42 samples were prepared, with two replicates for each compost rate and each duration of the compost embedment. The samples were prepared by compacting the dry mass of soil and compost into metal cylinders having diameter and height of 5 cm with a porous nylon

Table 1 Physicochemical attributes of soil and compost (from Bondì et al. 2022)

Soil		Compost	
Clay (%)	17.6	pH	7.2
Silt (%)	29.8	EC (dS m^{-1})	0.54
Sand (%)	52.6	C (%)	9.91
OM (%)	2.1	N (%)	0.64
pH	7.8	P (%)	0.45
EC (dS m^{-1})	0.48	Ash (%)	82.5
CEC (cmol kg^{-1})	25.31	C/N ratio	15.1

cloth at the bottom. The packing methodology described by Bondi et al. (2022) was used that proved to be effective in obtaining replicable results as showed by coefficients of variation, *CV*, for bulk density and water retention far below the acceptable limit of 15% (Warrick 1998).

Use of a limited number of replicates (i.e., $N = 2–3$) is a frequent option when operating with repacked soil cores (Arthur et al. 2011; Reynolds et al. 2015; Ibrahim and Horton 2021) given the variability due to natural aggregation is loss in these samples. On the other hand, using repacked samples is preferable in studies aimed at estimating the effects of soil amendments rate as they allow to compare soil physical and hydraulic characteristics associated to exactly the same amendment dose.

In November 2021, soon after preparation, 14 samples, two for each mixture, were analyzed to determine the soil water retention curve at time M0. The remaining samples were placed directly on the surface of the extensive green roof plot at the University of Palermo and analyzed after six (M6) and twelve months (M12). The samples were subjected to meteoric events, thus undergoing natural drainage and wetting cycles, with variation of soil moisture content, which also caused swelling and shrinkage phenomena in the samples.

Rainfall and temperature data, during the embedding period were recorded by a weather station of the Servizio Informativo Agrometeorologico Sicialiano (SIAS), located about 3 km far from the green roof. The thermopluviometric chart for the study period is showed in Fig. 1.

In May 2022 and in November 2022, i.e., respectively after six and twelve months from compost embedding, determination of soil water retention curve were repeated, following the same experimental procedure.

Soil water retention curve measurement and parameterization

The soil water retention curve was determined experimentally by the hanging water column apparatus (Dane and Hopmans 2002a), for pressure head, h (m), values ranging from −0.01 to −1 m, and by the pressure extractor method (Dane and Hopmans 2002b) for lower h values ranging from −1 to −150 m. With the hanging water column technique, the soil samples were placed on the surface of the porous plate of a glass funnel and saturated from below by applying four successive equilibrium steps of 24 h each at h values of −0.2, −0.1, and −0.05 m followed by submersion (i.e., $h = 0$). Starting from saturation, soil samples were drained by imposing a decreasing sequence of 11 h values: −0.05, −0.075, −0.10, −0.15, −0.20, −0.25, −0.30, −0.40, −0.50, −0.70 and −1 m. For each equilibrium h value, the volume of water drained was recorded and these volumes were added backwards to the equilibrium volumetric water content, θ (m^3 m^{-3}), determined at $h = −1$ m by weighting the sample after oven-drying at 105 °C for 24 h.

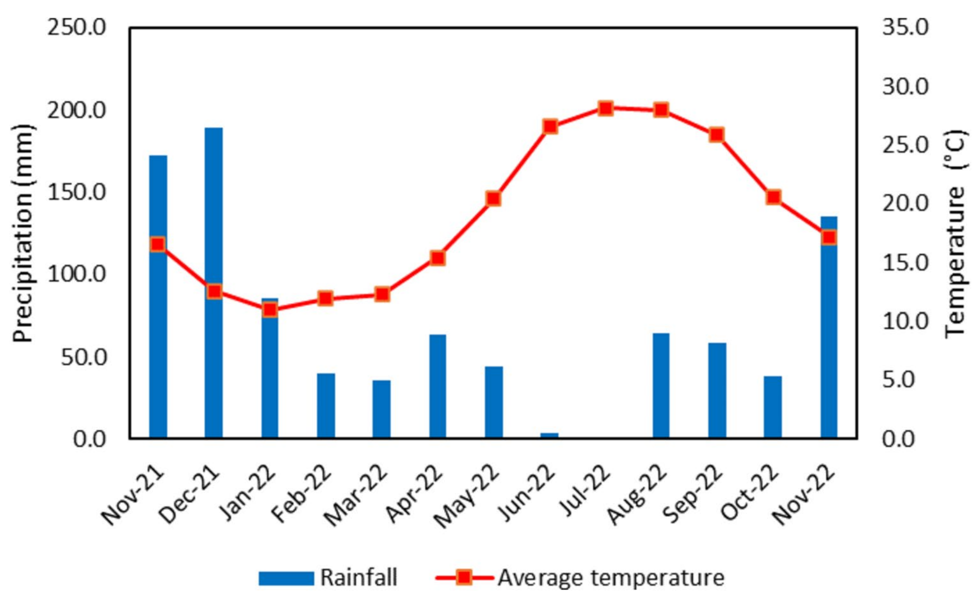

Fig 1 Thermopluviometric chart of the weather station in Palermo (50 m a.s.l., UTM ED50 353448E, 4221667N)

At the end of the experiment ($h = -1$ m), the height of the sample was measured at nine fixed points on sample surface by using a gauge with a precision of 0.5 mm and an average value was determined through the application of the arithmetic mean. This value was used to calculate the sample volume, V (cm^3), and, consequently, the sample dry soil bulk density, BD ($g\ cm^{-3}$).

For the pressure head values of −1, −10, −30 and −150 m, the water retention data were determined in pressure plate extractors on two replicated samples of 5-cm-diameter by 1-cm-height, prepared at the same bulk density value of the larger samples. Determination of volumetric water content at $h = -1$ m was included in pressure plate experiments for comparison with the θ value measured at the same potential in the tension apparatus. All the measurements were conducted under temperature-controlled conditions at 22 ± 1 °C. The van Genuchten's empirical unimodal model (1980) was used to fit the experimental water retention data:

$$\theta(h) = \theta_r + \left(\theta_s - \theta_r\right)\left(1 + |\alpha h|^n\right)^{-m} \quad (1)$$

where θ_s ($m^3\ m^{-3}$) and θ_r ($m^3\ m^{-3}$) are the saturated and residual volumetric water contents, respectively, α (m^{-1}) is a scale parameter, and n and m with $m = 1-1/n$ are shape parameters. The water retention data were fitted separately for the two replicates of each mixture by using SWRC fit software (Seki 2007). The shape and scale parameters (α, n, θ_s, and θ_r) were estimated without any constraint to their possible range. The reliability of the estimates was assessed by common statistical indicators such as the correlation coefficient, R, the mean error, ME and the root mean square error, $RMSE$ (Bondì et al. 2022).

Estimation of SPQ indicators

Bulk density, BD ($g\ cm^{-3}$), is an indirect indicator of aeration, strength, and ability to store and transmit water (Reynolds et al. 2008):

$$Bulk\ density\ BD = \frac{M_s}{V_b} \quad (2)$$

where M_s (g) is oven-dry soil mass and V_b (cm^3) is the corresponding bulk soil volume.

From the fitted van Genuchten water retention curves, the following capacity-based indicators of SPQ were calculated (Reynolds et al. 2002, 2003):

$$Air\ capacity\ AC = \theta_s - \theta_{FC} \quad (3)$$

$$Macroporosity\ P_{mac} = \theta_s - \theta_m \quad (4)$$

$$Plant\ available\ water\ capacity\ PAWC = \theta_{FC} - \theta_{PWP} \quad (5)$$

$$Relative\ field\ capacity\ RFC = \frac{\theta_{FC}}{\theta_s} \quad (6)$$

where θ_{FC} ($m^3\ m^{-3}$) is the volumetric water content corresponding to so-called field capacity (h = -1 m), θ_m ($m^3\ m^{-3}$) is the volumetric water content of the soil matrix (h = -0.1 m), and θ_{PWP} ($m^3\ m^{-3}$) is the volumetric water content corresponding to the permanent wilting point (h = -150 m).

Air capacity, AC ($m^3\ m^{-3}$), is expressive of the ability of the soil to ensure the necessary aeration to the root systems. Macroporosity, P_{mac} ($m^3\ m^{-3}$), is representative of the volume of macropores (i.e., >1300 µm equivalent pore diameter) of the soil and, indirectly, provides an indication of the soil's ability to favor the drainage processes and the root proliferation. Plant available water capacity, $PAWC$ ($m^3\ m^{-3}$), is expressive of the soil's ability to store and provide water that is available to plant roots. Relative field capacity, RFC (-), indicates the soil's ability to store water and air in relation to the total porosity which is assumed to be expressed by θ_s.

Dexter (2004) proposed to evaluate SPQ from the slope of the retention curve at the inflection point when the curve is expressed as gravimetric water content, U ($g\ g^{-1}$), versus the natural logarithm of h.

$$S - index\ S = -n\left(U_s - U_r\right) \cdot \left[1 + \frac{1}{m}\right]^{-(1+m)} \quad (7)$$

where U_s ($g\ g^{-1}$) and U_r ($g\ g^{-1}$) are the gravimetric saturated and residual water contents that, under the assumption of rigid soil, can be calculated from θ_s and θ_r.

The judgment on SPQ is made comparing the measured value of a given SPQ indicator with the classification range proposed in the literature (Olness et al. 1998; Reynolds et al. 2002, 2009; Dexter 2004).

The pore volume distribution function, $S_v(h)$, may be defined as the slope of the soil water retention curve expressed as volumetric water content versus ln(h), and plotted against the equivalent pore diameter, d_e (µm). To allow comparison of different porous materials, Reynolds et al. (2009) proposed a normalized soil pore volume distribution, $S^*(h)$ being $0 \le S^*(h) \le 1$.

Evaluation of SPQ involves comparison of "location" and "shape" parameters, derived from the normalized pore volume distribution, with optimal values suggested by Reynolds et al. (2009).

Location parameters are the mode diameter, d_{mode} (µm), the median diameter, d_{median} (µm), and mean diameter, d_{mean} (µm), shape parameters are standard deviation, SD (-), skewness, SK (-), and kurtosis, KU (-). For brevity reasons, the expressions for estimating the location and shape parameters are not given here but the reader is referred to Reynolds et al. (2009).

Statistical analysis

A pairwise t-test was applied to establish statistical comparisons between two datasets corresponding to different times from compost application date. The influence of compost addition on the considered SPQ indicators was evaluated by analyzing the significance of Pearson correlation coefficient, *R*, calculated between each SPQ indicator and the compost to soil ratio, *r*. A two-way ANOVA was employed to assess the individual and combined effects of time and compost rate on the SPQ indicators. All statistical tests were carried out with Microsoft Excel at a significance level $p = 0.05$.

Results and discussion

Influence of time from compost application on SPQ indicators

The water retention data were adequately fitted by the unimodal model of van Genuchten as showed by the high values of *R* and the low values of *ME* and *RMSE* (Table 2).

The average values of SPQ indicators obtained at the three sampling dates are reported in Table 3 whereas mean and standard deviation values corresponding to the different soil-compost rates are listed in Table S1 (supplementary material). The coefficients of variations for the soil bulk density and the capacity-based indicators of SPQ were generally within the limit of 15% considered acceptable for these soil properties (Warrick 1998) with the only exception of P_{mac} and *AC* that were respectively characterized by mean *CV* values in the range 20.9–36.8% and 5.0–17.3%, depending on the sampling time. Variability of replicated measurements also tended to increase with time from compost application (Table S1).

For all the considered indicators, statistically significant differences were observed between the value at the time of compost embedment and the values measured after six (M6) and twelve (M12) months, respectively. This indicated a clear temporal effect that influences the soil's physical properties and pore distribution, which ultimately impact plant growth and overall soil health.

In particular, the SPQ indicators associated to total porosity or macro-porosity (*BD*, *AC*, P_{mac}) decreased whereas SPQ indicators associated to the smaller pore size domain (*PAWC* and *RFC*) increased. Also, the S-index, which is representative of the entire pore size distribution, increased. No statistically significant differences were observed in the mean values of *PAWC* and *RFC* between M6 and M12. The other indicators showed significant differences between M6 and M12 that, however, were of opposite sign compared to the differences observed between M0 and M6. This result indicates that the maximum benefits of compost amendment was achieved within six months whereas the soil physical quality remained unchanged or regressed in the following six months. Our results are consistent with those of Weber et al. (2007) who observed short-term beneficial effects of compost on soil water retention. Specifically, they observed that total porosity and plant available water increased only within the first five months after compost application. The short-term effects of adding compost to the soil were evaluated in another study by Guo et al. (2019) on a tomato crop in China that showed improved soil structure, increased water retention capacity, and enhanced soil fertility six months after the compost application. Therefore, it can be inferred that the positive effects of compost on soil water availability may not last for more than approximately six months and it will require regular application to maintain the benefits over time. The temporal effects of a single compost application on soil bulk density and water retention were modelled by simple asymptotic and exponential functions by Cannavo et al. (2014). According to their published data for a compost made of sewage sludge and wood chips applied at 40% v/v rate to an urban soil, *BD* is expected to increase by 7.2% after 6 months, P_{mac} and *AC* to decrease by 18% and 5%. Our results are in good agreement with the short-term effects observed by Cannavo et al. (2014). However, while their results suggest that the soil physical properties are monotonically increasing or decreasing even after the first six months, signs of inverted trends were observed in the present study. A possible factor of discrepancy could be the influence of root system that, under field conditions, could contrast the effects of soil compaction and compost

Table 2 Statistics of coefficient of correlation, *R*, mean error, *ME*, and root mean square error, *RMSE*, for the estimated water retention curves

	R	*ME*	*RMSE*
Min	0.9307	-1.52×10^{-3}	4.04×10^{-3}
Max	0.9996	1.26×10^{-3}	1.03×10^{-2}
Mean	0.9930	3.40×10^{-5}	7.12×10^{-3}

Table 3 Mean values of SPQ indicators obtained for M0, M6 and M12. Mean values followed by the same letter did not differ significantly according to Student's t-test ($p < 0.05$). Values in parentheses were standard deviations ($N = 2$)

	M0	M6	M12
BD	1.07a (0.02)	1.17c (0.04)	1.13b (0.05)
AC	0.12c (0.02)	0.09a (0.03)	0.10b (0.02)
P_{mac}	0.006c (0.003)	0.001a (0.001)	0.003b (0.002)
PAWC	0.22a (0.03)	0.29b (0.04)	0.30b (0.03)
RFC	0.76a (0.04)	0.82b (0.006)	0.80b (0.05)
S-index	0.10a (0.02)	0.16c (0.03)	0.13b (0.01)

decomposition thus extending over time the benefits of soil amendment.

Compost rate effect on SPQ indicators

Table 4 shows the Pearson's correlation coefficients, *R*, between the SPQ indicators and the compost to soil ratio, *r*. In Fig. 2 the regression lines between the SPQ indicators and *r,* are plotted together with classification ranges according to criteria found in the literature (Reynolds et al. 2002, 2009; Dexter 2004; Agnese et al. 2011).

The soil *BD* showed a significant negative correlation with *r* only at M6 and M12 sampling dates. At M0, the compost rate did not statistically influenced *BD* as the densities of the compost and the soil were similar (i.e, soil *BD* = 1.07 g cm^{-3}, compost *BD* = 1.04 g cm^{-3}, see supplementary material Table S1). Differently, at M6 and M12, compost amendment was effective in contrasting the soil compaction due to the mechanical effects of rainfall that was observed for low compost rates (r < 20%) (Fig. 2a). For both dates, the *BD* decreased at increasing the compost rate thus indicating that less compacted conditions were maintained over time in amended soils. This result is in line with the conclusions of Khaleel et al. (1981), Sax et al. (2017), Somerville et al. (2018) and Castellini et al. (2022), who suggested that the use of compost decreases the soil bulk density and, consequently, reduces soil compaction.

Specifically, the dry *BD* values ranged from 1.04 to 1.12 g cm^{-3} with a mean value of 1.07 g cm^{-3} (coefficient of variation, *CV* = 2.09%). After six months (M6), *BD* increased with values ranging from 1.12 to 1.24 g cm^{-3} and mean value equal to 1.17 g cm^{-3} (*CV* = 3.40%). After twelve months (M12), the *BD* values decreased slightly, although remaining greater than the initial values (M0), with a range of values between 1.06 to 1.21 g cm^{-3} with a mean value of 1.13 g cm^{-3} (*CV* = 4.53%). Differences in *BD* values observed across the three sampling dates were mainly due to compaction phenomena caused by the impacts of raindrops that break soil aggregates (Vaezi et al. 2017). Indeed, a seasonal trend could be observed in *BD* with compaction mainly occurring in the first six rainy months (M0-M6) followed by a partial recovery during the dry season (M6-M12) (Fig. 1). It is worth to be remarked that the study neglects the role of vegetation that can contribute to maintain a loose soil structure due to the effect of roots system as well as to protect soil surface by raindrop compaction (Curtis and Claassen 2009). However, regardless of the time period and *r*, the soil *BD* values remained, generally, within the range considered optimal for field crop production, i.e., 0.9–1.2 g cm^{-3}, as suggested by Agnese et al. (2011).

Table 4 Pearson's correlation coefficients between SPQ indicators and the compost to soil ratio, *r*. Values in bold indicate statistically significant correlation ($p < 0.05$)

	M0	M6	M12
BD	-0.467	**-0.578**	**-0.682**
AC	**-0.951**	-0.498	**-0.774**
P_{mac}	**-0.851**	-0.232	**-0.667**
PAWC	**0.958**	**0.874**	**0.723**
RFC	**0.979**	**0.623**	**0.775**
S-index	**0.800**	0.319	**0.566**

At M0 and M12, the capacity-based indicators linked to the macro- and mesoporosity (P_{mac} and *AC*), exhibited significant negative correlations with *r*. At the intermediate sampling date (M6), the correlations were similarly negative despite not significant. In any case, classification of soil physical quality according to P_{mac} and *AC* was always non-optimal (Fig. 2). This finding was not unexpected since the soil samples used in this study were repacked in the laboratory, resulting in a structureless samples.

The plant available water capacity (*PAWC*) was always positively correlated with *r* (Table 4) thus showing that, independently of the sampling date, the compost amendment determined more favorable conditions for plant as already showed by several studies (Celik et al. 2004; Sax et al. 2017; Seker et al. 2020; Rivier et al. 2022) that reported how compost addition can increase soil water retention, thereby increasing the *PAWC*. For a sandy loam soil amended at 25% by volume with a windrowed yard waste compost, Curtis and Claassen (2009) observed a *PAWC* increase of 32% compared to 21% estimated from the regression line in Fig. 2 (M0). Overall, the results of the present study further support previous findings showing that compost application yielded *PAWC* values that were all above the optimal threshold suggested in the literature (Fig. 2).

The relative field capacity (*RFC*) was significantly influenced by the compost rate with *RFC* values that, independently of the sampling date, increased at increasing *r*. The values of this SPQ indicator remained always outside the optimal range recommended in the literature (Fig. 2), indicating that the soil has a relatively high field capacity compared to total porosity. Given the results were obtained on repacked structure less samples, this condition highlights how the loose of natural aggregation may lead to limited soil aeration with negative impact on plant growth.

The values of *S* always increased at increasing the compost rate (Fig. 2) and were consistently above the optimal threshold value of 0.05 indicating the presence of a well-defined microstructure as suggested by Dexter (2004).

Overall, the rate of compost application tended to decrease the macro- and mesoporosity and to increase the microporosity thus improving the availability of water for plant. At the time of compost embedment (M0), the

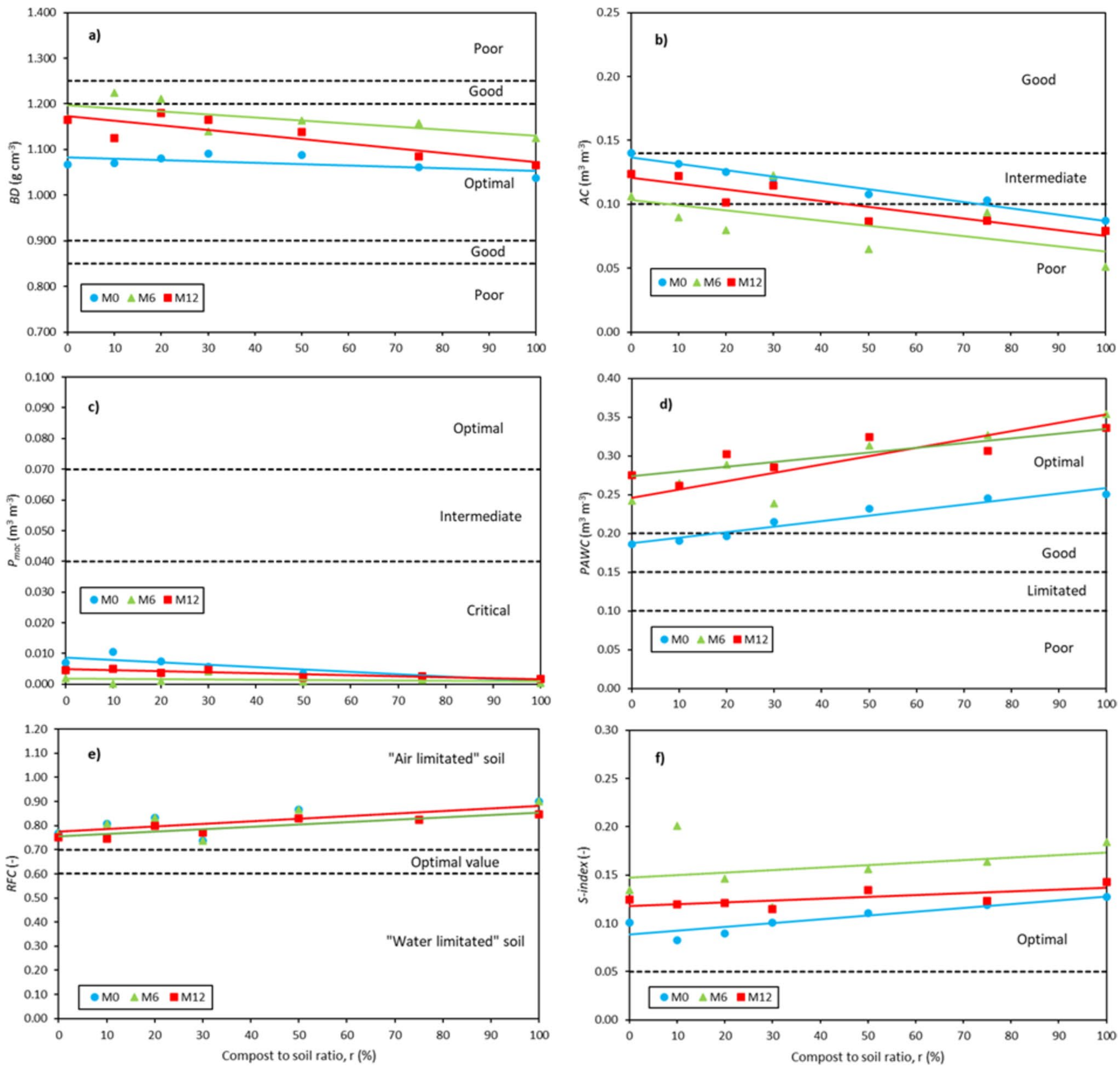

Fig 2 Regression lines between the SPQ indicators and the compost to soil ratio, *r*, with corresponding classification ranges according to criteria found in the literature. **a**) bulk density; **b**) air capacity; **c**) macroporosity; **d**) plant available water capacity; **e**) relative field capacity; **f**) *S*-index

strength of the correlation between SPQ indicators and *r* was maximum whereas *R* decreased, and also became not significant, with time. This result confirm that the effects of compost are short-term effects and frequent applications of compost are necessary to maintain the benefits over time.

Two-way ANOVA

For each considered SPQ indicator, the two-way ANOVA (time, rate, time x rate) was used to analyze the effects of time elapsed from compost embedment and added dose of compost. Table 5 reports the results of ANOVA. A significant separated effect ($p < 0.05$) of each individual factor on all the considered SPQ indicators was observed. The combined effect was found to be statistically significant only for P_{mac}, *PAWC* and *S* indicators, which means that the effect of

Table 5 Two-way ANOVA of time and compost rate effects on the SPQ indicators

	Sum of square	*Df*	*Mean Square*	*F*	*p-Value*	*F crit.*
			BD			
Time	0.070	2	0.035	36.996	<0.050	3.467
Rate	0.026	6	0.004	4.547	<0.050	2.573
Time x Rate	0.016	12	0.001	1.388	0.246	2.250
Within	0.020	21	0.001			
Total	0.131	41				
			AC			
Time	0.006	2	0.003	12.177	<0.050	3.467
Rate	0.012	6	0.002	8.210	<0.050	2.573
Time x Rate	0.003	12	2.18×10^{-4}	0.870	0.586	2.250
Within	0.005	21	2.52×10^{-4}			
Total	0.026	41				
			P_{mac}			
Time	1.14×10^{-4}	2	5.74×10^{-5}	37.314	<0.050	3.467
Rate	9.16×10^{-5}	6	1.53×10^{-5}	9.935	<0.050	2.573
Time x Rate	7.19×10^{-5}	12	5.99×10^{-6}	3.898	<0.050	2.250
Within	3.23×10^{-5}	21	1.54×10^{-6}			
Total	3.10×10^{-4}	41				
			PAWC			
Time	0.057	2	0.029	132.471	<0.050	3.467
Rate	0.034	6	0.006	26.126	<0.050	2.573
Time x Rate	0.006	12	0.001	2.407	<0.050	2.250
Within	0.005	21	2.15×10^{-4}			
Total	0.101	41				
			RFC			
Time	0.028	2	0.014	17.295	<0.050	3.467
Rate	0.069	6	0.011	13.921	<0.050	2.573
Time x Rate	0.012	12	0.001	1.252	0.315	2.250
Within	0.017	21	0.001			
Total	0.127	41				
			S-index			
Time	0.020	2	0.010	105.272	<0.050	3.467
Rate	0.007	6	0.001	11.718	<0.050	2.573
Time x Rate	0.007	12	0.001	6.404	<0.050	2.250
Within	0.002	21	9.56×10^{-5}			
Total	0.036	41				

an individual factor depends on the level of the other individual factor. For *BD*, *AC* and *RFC* no statistically significant combined effect was found, i.e., the differences in the levels of factors time and rate, taken together, do not have a significant impact on these SPQ indicators. This may be due to an antagonistic effect of the two factors that showed opposite influence on these SPQ indicators.

Effect of compost addition on the pore size distribution

To investigate the influence of compost amendment, the trend of the location and shape parameters of the normalized pore volume distribution curves as a function of the compost dose was analysed. Except for *SK*, all the examined parameters exhibited a negative correlation with *r* (Table 6), with statistically significant *R* values ($p < 0.05$) for the location parameters, namely d_{mode}, d_{median} and d_{mean}. Compost amendment significantly affected shape parameters only at the time of application (M0) thus suggesting that the effects of compost on the shape parameters are probably weak or, alternatively, that these parameters are less sensitive to compost rate.

Figure 3 shows the mean values of the location parameters for the three sampling dates. The mode diameter, d_{mode}, which represents the most frequently occurring equivalent

Table 6 Pearson's correlation coefficients between the location and the shape parameters and *r*. Values in bold indicate statistically significant correlation ($p < 0.05$)

	M0	M6	M12
d_{mode}	**-0.952**	**-0.680**	**-0.722**
d_{median}	**-0.775**	**-0.749**	**-0.711**
d_{mean}	**-0.533**	**-0.748**	**-0.685**
SD	**-0.630**	-0.099	-0.482
SK	**0.728**	0.053	**0.579**
KU	**-0.770**	-0.037	-0.526

pore diameter, decreased from M0 to M6 and then remained roughly constant in M12. Castellini et al. (2022) identified a positive, and significant, relationship between saturated hydraulic conductivity and d_{mode}, therefore reporting a similar result. Differently, the median, d_{median}, and the mean, d_{mean}, equivalent diameters progressively decreased from M0 to M12. Also, Al-Omran et al. (2021) found that application of date palm biochar and compost, both separately or in combination, reduced the equivalent pore diameters and the locations parameters, and this resulted in improved water retention and water use efficiency of sandy soils. Therefore, embedment of compost yielded a porous medium characterized by smaller pore size and lower heterogeneity as detected by the negative correlation with location and shape parameters. Such effects are not to be considered entirely positive, unless the pores system established is well interconnected, ensuring adequate hydrodynamic soil properties. These effects continued over time with reference to location parameters but not to the shape ones. Our findings agree with the results obtained by Ibrahim and Horton (2021), demonstrating that the application of compost led to a decrease in soil pore equivalent diameters, resulting in altered soil pore distributions. In agreement with the results obtained for capacitive SPQ indicators, it can be hypothesized that the addition of compost caused a relocation of pore size distribution from structural porosity (i.e., macropores), that decreased, to textural porosity (i.e., micropores), that increased.

Conclusions

The SPQ of a sandy loam soil was influenced by a single application of compost obtained from orange juice processing wastes and garden cleaning, dosed at different rates. The study revealed a clear influence of the elapsed time from compost application as significant differences were observed for all SPQ indicators between M0 and, respectively, M6 and M12. Between M6 and M12, SPQ indicators showed no significant differences (*PAWC* and *RFC*) or even an opposite sign as compared to the differences observed between M0 and M6. It was concluded that the maximum benefits of compost embedding were achieved within approximately the first six months of application. Consequently, to maintain these benefits over time, regular compost application would be necessary.

At the time of application (M0), the soil bulk density was not influenced by the compost rate. Interestingly, a negative correlation with *r* was observed at M6 and M12 that was attributed to the effective role of compost in reducing soil compaction due to rainfall impact thus showing a seasonal influence on porosity and related indicators of SPQ. Compost application dose negatively affected the SPQ indicators linked the macro- and mesoporosity, such as P_{mac} and *AC*, and positively influenced SPQ indicators linked to plant water availability, such as *PAWC* and *RFC*.

The two-way ANOVA showed a significant separated effect of both time and rate on all the considered SPQ indicators. The combined effect was significant only for P_{mac},

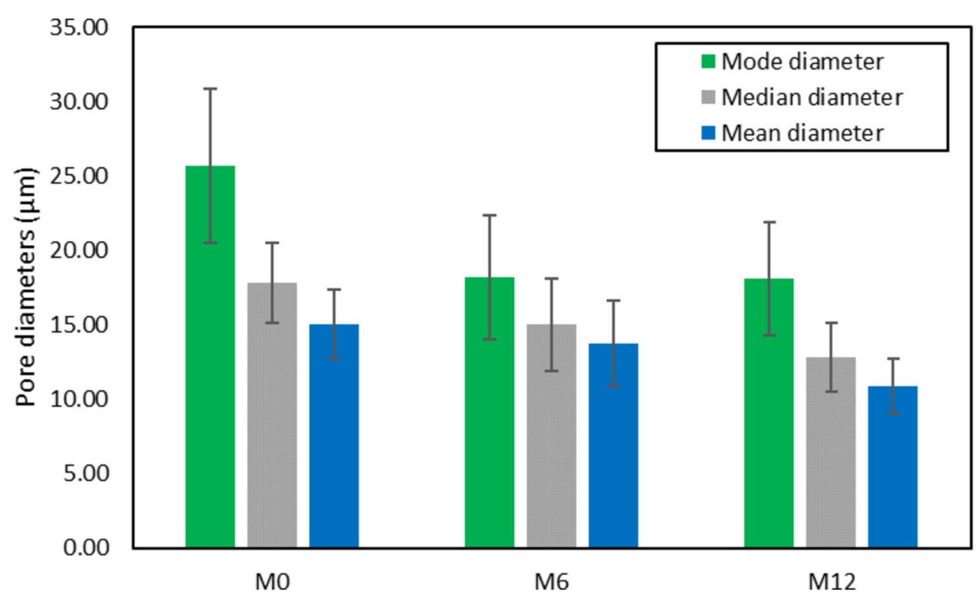

Fig 3 Mean values of the location parameters (d_{mode}, d_{median} *and* d_{mean}) obtained for M0, M6 and M12. Error bars indicate standard deviation

PAWC and *S*, while for the remaining indicators an antagonistic effect of the two factors was observed.

The pore size distribution was affected by compost rate as, at M0, both location and shape parameters decreased with *r*. Compost addiction involved a smaller and less heterogeneous pore system, thereby influencing the soil water retention capacity as the fraction of structural porosity (i.e., macropores) decreased and the fraction of textural porosity (i.e., micropores) increased. However, these modifications generally tended to vanish with time from compost application.

Overall, it can be concluded that a single application of compost has a significant impact on soil water retention and pore system of a sandy loam soil for at least six months from compost embedding. A possible downside of this investigation is that it neglects the influence of vegetation in maintaining a stable and interconnected porosity and protecting the soil form compaction due to raindrop impact. Given the important implications that these results bear for soil health, precision agriculture and crop productivity further field investigations are necessary to investigate the role of soil natural aggregation and root system on the physical quality of soils amended with compost of different characteristics.

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Declarations

The authors have no relevant financial or non-financial interests to disclose.

Conflicts of Interest The authors declare no conflict of interest.

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