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Cactus pear pruning residue in agriculture: Unveiling soil-specific responses to enhance water retention

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ABSTRACT

This study examines the effects of incorporating powdered cactus pear pruning waste (PCPPW) on the hydraulic properties of benchmark soils, in line with circular economy principles. The cultivation of cactus pear generates substantial amounts of pruning residues, which offer the potential for nutrient recovery and reuse. Our findings reveal that amending soils with this material has a positive impact on water retention, but it requires a substantial volume, exceeding 20%, which may not be practical for open-field applications. However, this presents promise for the horticultural and floricultural sectors. These results challenge previous assumptions about soil density, plant-available water capacity, and swelling potential, contributing to our understanding of agronomic applications. Notably, the enhancement of drainable water capacity is most significant in less clayey soils, while highly clayey soils experience fewer benefits. These results highlight the importance of considering specific soil conditions when implementing circular economy principles, particularly in soil amendment practices.

1. Introduction

Arid and semi-arid regions, constituting over forty per cent of the global land area, are key production areas for grains, fruits, and cash crops. Unfortunately, in these regions, agricultural development is limited by water shortages and poor soil fertility (Myers et al., 2017). So, water management in these soils is the key to agronomic success. In this regard, the use of amendments might be one of the most effective agronomic practices (Kranz et al., 2020, Ullah et al., 2021). For instance, biopolymers are ecologically friendly soil improvers that have been commonly employed to increase soil quality (Wang et al., 2023). Organic amendments contribute to the enrichment of soil fertility by increasing soil organic matter (SOM), thereby enhancing crop yield (Bastida et al., 2012, Larney and Angers, 2012). They also indirectly improve hydrological functions and soil structure (Dong et al., 2022; Reynolds et al., 2007) ameliorating the spatial arrangement, shape, and size of solid particles, voids, and SOM (Almendro-Candel et al., 2018). Amendments modify soil water status, evaporation, flow, and retention (Jury and Horton, 2004) despite the positive effects of organic matter on water holding capacity might be less than thought previously (Minasny and McBratney, 2018). Organic amendments can be residues or

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Abbreviations: BD, bulk density; BS, black soil Vertisol; DWC, drainable water capacity; PAWC, plant available water capacity; PCPPW, powdered cactus pear pruning waste; PSD, particle size distribution; PTF, pedotransfer functions; RS, red soil *Terra Rossa*; SOM, soil organic matter; SWRC, soil water retention curve.

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by-products from both agricultural and industrial processes. However, by-product availability cannot be the only selection criterion to use as several other factors, including quality, applicability, sustainability, cost, and positive impacts on the soil, should be considered (Siedt et al., 2021). Diverse organic wastes have been suggested as possible soil amendment, with various characteristics and locally available in different regions (Larney and Angers, 2012). Examples of fines include biochar (Guo et al., 2024; Ni et al., 2020), municipal waste and sewage sludge (Sadeghi et al., 2014; Paradelo et al., 2019), corn and sewage sludge (Głab et al., 2020), yard waste (Arthur et al., 2011; Curtis and Claassen, 2009), agricultural crop residues (Ibrahim and Horton, 2021), pruning waste (Benito et al., 2006; Auteri et al., 2022), or mixtures of these materials. Among the different types of soil improvers, pruning waste from agricultural activities is interesting as they are locally available and, therefore, generally sustainable in terms of costs. However, the large variability in the composition of pruning makes results hardly generalizable and studies conducted for a specific waste composition in a given pedoclimatic condition should be transferred with caution to other conditions.

Among the low-cost and large-available pruning waste, the residues of cactus pear (*Opuntia ficus-indica* (L.) Mill.), which thrives in most semi-arid countries and is greatly widespread in Central America and the Mediterranean basin, currently leads to the disposal of 13–15 t ha^{-1} of biomass per year (Enea, 2017). Cactus pear cladodes are succulent plant organs consisting of chlorenchyma, the outer layer in which photosynthesis occurs, and parenchyma, the innermost layer whose main function is to retain water. Both are composed of mucilage, which is a hydrocolloid forming stable (honeycomb-like) lattices capable of retaining large amounts of water. The presence of hydrocolloids explains the ability of Cactaceae to grow even in the most unfavorable climatic conditions. This characteristic makes it an interesting agricultural by-product. In addition to its potential as a soil amendment, some authors have evaluated dried and powdered cladodes of cactus pear as adsorbents for eliminating heavy metals or synthetic dyes from aqueous solutions (Nouri et al., 2021; Aziam et al., 2021).

Soil water retention curve (SWRC) expresses the empirical relationship between the matric potential and the volumetric water content of the soil, describing the ability of a given soil to store and release water. Its knowledge is important for agro-environmental modelling or irrigation scheduling and optimization (*e.g.*, Hillel, 1998; Angulo-Jaramillo et al., 2016). The experimental assessment of the SWRC is extremely time-consuming, thus attention has increased towards pedotransfer functions (PTFs) (Bouma, 1989). PTFs have the merit of predicting SWRC from easily measured and/or common soil data, such as bulk density (BD), SOM and particle size distribution (PSD) (Weynants et al., 2009; Castellini and Iovino, 2019). The extreme simplification with which the hydraulic properties are estimated by the existing PTFs considers soils mostly composed by mineral fraction while the effect of large amount of SOM added as soil conditioners is not specifically accounted for. Furthermore, PTFs neglect the presence of plants and the rhizospheric environment. Lateral thinking is that these amendments, even if grossly, can mimic a rhizospheric environment. Considering that 75% of the root mass for all vegetation and biome types is in the upper 40 cm, (Schenk and Jackson, 2002), neglecting the different properties of this layer of soil, especially in an agricultural environment, could be misleading.

The primary purpose of this research is to examine the impact of the amendment of powdered pruning waste from cactus pear (PCPPW) on the water retention characteristics of two contrasting soils widely diffused through the Mediterranean basin. The challenge of transferring our findings lies in the uncertain application to open field crops, whereas the transfer of knowledge proves feasible in plant nurseries, floriculture, or horticulture.

2. Materials and methods

2.1. Benchmark mediterranean soils

The Mediterranean Sea basin covers a surface of seven million square kilometres, encompasses latitude 30° to 40°N and extents from longitude 10°W to 40°E. Its soils are a quite disordered layer of evaporitic deposits originated during the Messinian Salinity Crisis, five and seven million years ago. These soils show analogous characteristics, including a specific climate in which the seasonal distribution of precipitation, rather than the total amount, is the main determinant, a contour of mountains, an abundance of desert dust, accumulations of secondary calcium carbonate or more soluble salts, and a millennial anthropogenic setting. Such a climate provokes the re-precipitation, in the form of nodules, of the partially dissolved carbonates (Carrubba and Scalenghe, 2012; Yaalon, 1997). In Mediterranean landscapes, two categories of soil stand out as archetypal: *terra rossa* (from Italian, red soils) and *terra fusca* (from Latin, black soils). Red soils form through the rubefication process of iron oxides, while black soils originate from the weathering of silicates (which leads to the formation of new inter-layered phyllosilicates) and the simultaneous dissolution of calcareous parent material (Peña and Torrent, 1990). Furthermore, a continuous provision of allochthonous (wind-transported) fine particles works together with pedogenesis, imparting a high water-holding capacity (Bilsel, 2004; Nettleton, 1991; Simonson, 1995).

We have chosen two contrasting soils, well-studied previously. The red soil (RS) is an Ap horizon from a Terric Chromic Cambisol (Loamic) (IUSS WG WRB, 2022; Alagna et al., 2018). The black soil (BS) is a Byss horizon from a Calcic Gypsic Vertisol (Hypereutric) soil (IUSS WG WRB, 2022; Laudicina et al., 2013 and, 2021; Scalenghe et al., 2016) (Table S1). The rationale for this choice depends on the different purposes of organic amendment with soil texture. In the case of coarse soils, organic amendments are frequently employed to augment the humus content and enhance the physical and chemical properties of coarse soils. Likewise, when applied to clayey or fine-textured soils, organic amendments enhance permeability, reduce the risk of soil surface crusting, improve air-water relations, and mitigate surface runoff in agricultural areas (Garbowski et al., 2023).

2.2. Characteristics of cactus pear (Opuntia ficus indica (L.) Mill.)

The cladodes of the cactus pear *cv* Gialla used in the study were collected during the fall season in Roccamena (IT) (472 m a.s.l.;

37°50’17"88 N, 13°9′20"16 E). We collected cladodes of different ages (1–3 years) and sizes (34.2 ± 2.1 ×21.3 ± 3.7 ×2.2 ± 0.3 cm), which would have been removed by normal annual pruning. The thornless cladodes, removed with a knife after collection, were underwent a washing process with tap water, followed by rinsing with deionized water, and were subsequently air-dried. Sequentially, the cladodes were manually dissected (≈ 35 min kg^{-1} cladode) and then dried at 105°C for 48 hours. The dried cladodes were grounded using a laboratory blender, obtaining particles of size Ø ≤ 2 mm, and stored at room temperature. The grain size distribution of powdered pruning cladodes was determined by manually sieving 50 g of PCPPW at a series of five sieves having diameters of 75, 106, 250, 425 and 860 μm and associating the percentage by mass to the mean geometric diameter in each class. The powder is rich in calcium but contains other elements, particularly manganese (Table S2).

2.3. Soil water retention curve (SWRC) measurement

Air-dried PCPPW was mixed with air-dried 2-mm sieved soil, in twelve different percentages by weight: 1, 2, 4, 6, 8, 10, 12, 15, 20, 30, 40, and 50%. Two control samples, i.e., not amended soil samples (100% RS and 100% BS), were also considered, thus resulting in a total of 26 repacked soil samples. Each sample was prepared by compacting a dry mass of the two constituents (soil and PCPPW), calculated using the following expressions, into cylinders with a diameter of 5 cm and a height of 4 cm:

$$Ms = \frac{V \quad BDp \quad BDs}{BDp + rBDs} Mp = rMs \tag{1}$$

in which M_p (g) and M_s (g) are, respectively, the oven-dried mass of PCPPW and soil, BD_p (Mg m^{-3}) and BD_s (Mg m^{-3}) are the oven-dry bulk densities of the two constituents, V (cm^3) is the sample volume (V = 78.5 cm^3), and *r* is the ratio between the oven-dry mass of PCPPW and the oven-dry mass of soil. The initial water content of both constituents was considered to calculate the corresponding oven-dried mass. The sample compaction procedure involved four consecutives increments of approximately 1 cm height. At each step a mass of mixture corresponding to one quarter of the calculated mass of the sample was poured into the cylinder and subjected to five strokes of beating from a height of 5 cm, followed by five rotations with a pestle. Finally, the sample bulk density was checked to ensure that it was the same as the theoretical one determined from Eq.(1). This sample preparation procedure was already adopted in former study on compost amendment (Bondì et al., 2022) allowing to obtain highly replicable samples. It is worth noting that the bulk density of the PCPPW (BD = 0.515 g cm^{-3}) was approximately 2.0 and 2.5 times lower than the dry BD of RS and BS (Table S1) thus, at the higher *r* values, the mixtures contained more amendment than soil on volume basis. These amendment levels could be unpractical for open field crops but are frequent for nursery and greenhouse application.

Laboratory determination of SWRC was conducted by the tension hanging water column apparatus (Dane and Hopmans, 2002a), for matric head values, *h*, between 0 and −1 m, and by the pressure plate extractor for lower *h* values down to −150 m (Dane and Hopmans, 2002b).

Soil samples, placed on the surface of the porous plate of a glass funnel, were saturated from below by applying four successive steps of *h* = −0.20, −0.10, and −0.05 m at 24 hr intervals followed by submersion (i.e., *h* = 0) for 2 hr. Starting from saturation, soil samples were subjected to desorption by applying a sequence of twelve decreasing matric head values: −0.025, −0.05, −0.075, −0.10, −0.15, −0.20, −0.25, −0.30, −0.40, −0.50, −0.70 and −1 m. Water drained from the sample was collected in a graduated burette that could be moved in height to regulate the imposed *h* values. Equilibrium was assumed when the reading at the burette graduate scale did not change during a time spell of 2 hr. It took from 6 to 72 hr to reach equilibrium depending on the soil type and the applied pressure head value. To avoid water losses due to evaporation, the funnel and burette were maintained sealed during the experiment. At each equilibrium *h* value, the drained water volume from the sample was noted and these volumes backwards added to the equilibrium volumetric water content, θ (m^3 m^{-3}), determined at the end of the drainage sequence (*h* = −1 m) by oven-drying the sample at 105°C for 24 h.

Bulk density variations were monitored by measuring the height of the samples by a gauge at three steps: i) after preparation, i.e., under initial air-dried condition (H0), ii) at the end of the saturation process (HS), and iii) at the end of the desorption process (HF).

Water retention data corresponding to the matric heads of −1, −30, and −150 m were collected using pressure plate extractors on three replicated samples measuring 5 cm in diameter and 1 cm in height, with the same bulk density as the 5 cm by 4 cm samples. In addition, the volumetric content of water at a matric head of −1 m was also determined on pressure plate to compare it with the same value measured in the tension apparatus. All measurements were performed under temperature-controlled conditions at 22 ± 1 °C.

2.4. Pore size distribution by mercury intrusion

Pore size distribution of samples with different PCPPW percentages (i.e., *r* = 0%, 20%, and 50%) for both RS and BS was measured by mercury intrusion (Pascal 140, Fison and Porosimeter 2000, Carlo Erba, Milan) in the range 0.007–200 μm equivalent cylindrical diameter. Pore volume is expressed on mass basis (mm^3 g^{-1}). The surface tension of mercury and contact angle used for calculation were 0.480 Nm^{-1} and 141.3°, respectively.

3. Results

3.1. Swelling and soil bulk density

Following saturation, the sample height increased for the control samples ($r = 0\%$) of both RS and BS (Fig. 1). As expected, the increase of sample height was more marked for the BS due to the higher clay percentage that promoted soil swelling. In particular, the sample height increased from 39 to 42 mm for the RS and from 38 to 44 mm for the BS. During the subsequent desorption process (from saturation to $h = -1$ m), the height of the RS did not change (HF = 42 mm) whereas continued to increase for the BS (HF = 46 mm). Saturation promoted a more marked increase in the sample height when the different mixtures with variable proportions of PCPPW were considered. In Fig. 1 the effect for the 50% PCPPW addition to soil is reported only, with the notation that all the intermediate PCPPW percentages determined swelling heights comprised between the control samples (i.e., 100% RS or 100% BS) and the corresponding 50% PCPPW mixtures. For the latter, following saturation, the height of the amended samples increased to 52–53 mm. Once saturated, the amended samples maintained the swelling height, or a little reduced it, during the following desorption phase. It is worth noting that the two mixtures (50% RS - 50% PCPPW and 50% BS - 50% PCPPW) followed a similar trend thus showing that the characteristics of the amended soils are mostly controlled by the properties of the PCPPW.

For both RS and BS, the soil dry BD significantly decreased at increasing the percentage of PCPPW (Fig. 2a). Due to the lower BD of the PCPPW (Table S1), the dry BD of the mixtures decreased from 1.032 to 0.698 Mg m^{-3} for RS and from 1.260 to 0.689 Mg m^{-3} for BS, when the percentage of PCPPW increased from 0% to 50% by weight (Fig. 2a). In other words, the dry BD decrease is an expected consequence of the lower weight of the amended soils when an increasing percentage of lighter material is added.

Under wet conditions, the BD was always lower than under dry conditions. Furthermore, no perceivable difference was observed for wet BD measured at saturation ($h = 0$) and field capacity ($h = -1$ m) (Fig. 2b). Under saturated conditions, BD decreased from 0.958 to 0.540 Mg m^{-3} for RS and from 1.088 to 0.530 Mg m^{-3} for BS. At field capacity ($h = -1$ m), BD decreased from 0.958 to 0.550 Mg m^{-3} for RS and from 1.041 to 0.530 Mg m^{-3} for BS. Significant linear regressions with the percentage of PCPPW were also found for wet BD (Fig. 2b). It is worth to be noted that, for both soils, the wet BD decreased to a greater extent than the dry BD at increasing the percentage of PCPPW, as depicted in Fig. 2a-b.

The difference between dry and wet bulk densities can be considered as an index of the swelling susceptibility induced by PCPPW. Indeed, if the swelling capacity of PCPPW were lower or equal to that of the control soils, the substitution of an increasing fraction of swelling soil with PCPPW would determine less (or equal) total swelling susceptibility. Therefore, the wet BD would decrease less than the dry BD at increasing the amending dose and the differences between the two BDs tend to reduce. The opposite is if the swelling capacity of PCPPW is greater than that of the considered soils.

Fig. 2c shows that the relative differences between dry and wet bulk densities were always positive and increased with increasing the PCPPW proportion. For both RS and BS, these differences were significantly correlated to the PCPPW to soil ratio. Compared to the control ($r = 0\%$), for which the differences between wet and dry BDs are exclusively due to swelling of clay particles, addition of PCPPW promoted increased swelling that can be attributed to hydration of the dried powdered cladodes of the cactus pear. For a given value of the PCPPW dose, the BS mixture generally showed larger relative differences between dry and wet BD than the RS because of the higher clay fraction. However, these differences tended to reduce for the highest values of the PCPPW ratio given the sample swelling was mostly controlled by the cactus pear hydration.

3.2. Soil water retention

Water retention data of the control samples of RS and BS soils provided different information (Fig. 3a). The two soils showed equivalent volumetric water content, θ, values for $h = -0.25$ m. For higher values of h, i.e., relatively wet conditions, the volumetric water content of BS was lower than that of RS. An opposite trend was observed at lower h values, i.e., relatively dry conditions, as BS

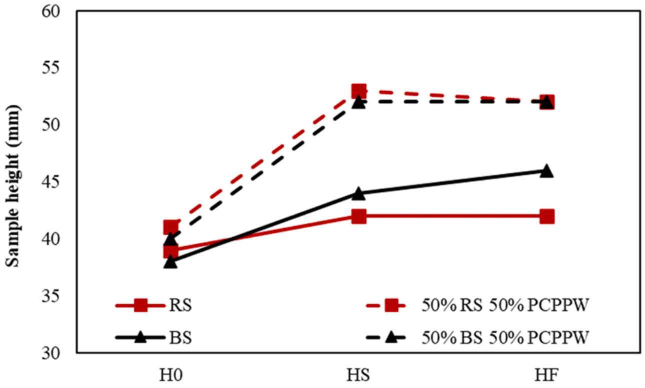

Fig. 1. Sample heights for the initial air-dried conditions (H0), at the end of the saturation process (HS), and at a water content corresponding to matric head $h = -1$ m (HF) for the red soil (RS) and the black soil (BS) and the mixtures of 50% soil and 50% PCPPW.

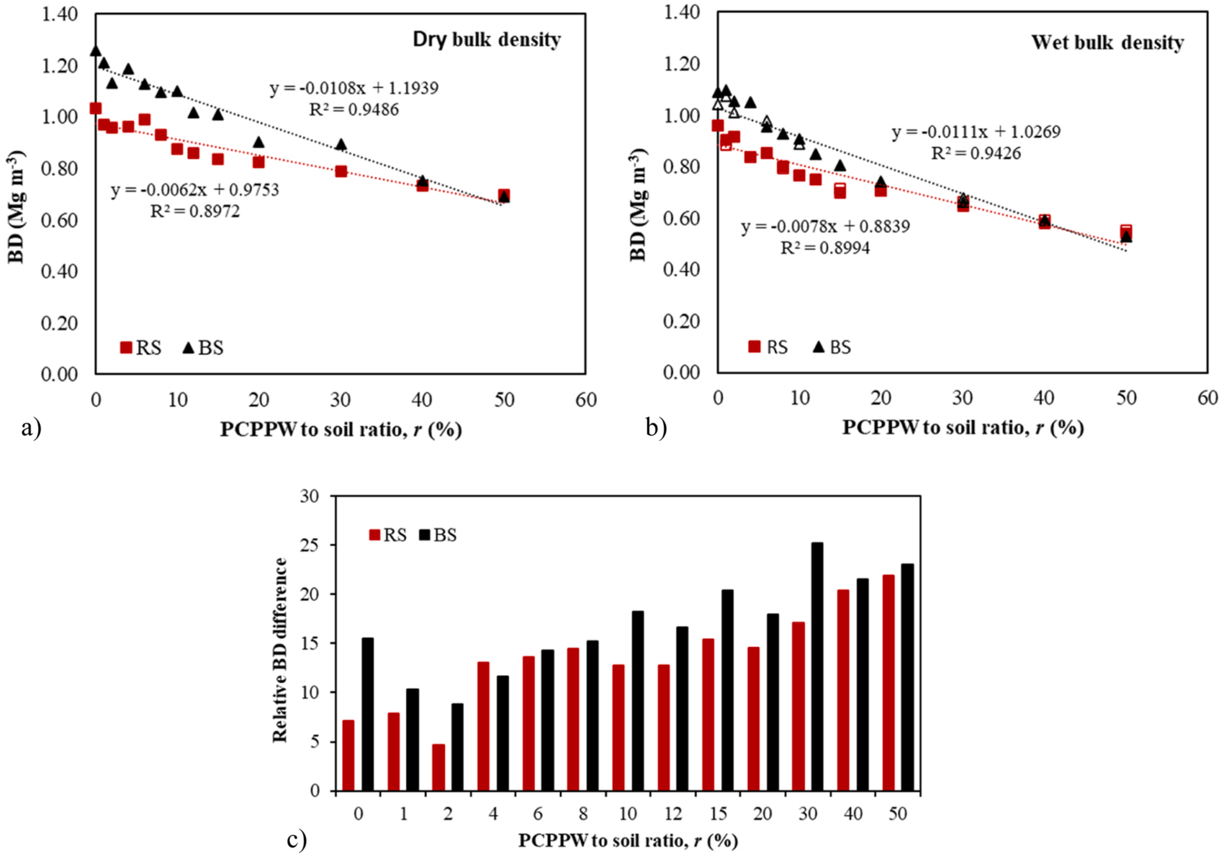

Fig. 2. Sample bulk density under dry (a), and wet (b), conditions as a function of percentages of PCPPW. For wet BD, filled and empty symbols represent saturated ($h = 0$) and field ($h = -1$ m) conditions, respectively. (**c**) Relative differences between the dry and wet BD for soil mixtures with different percentages of PCPPW. RS = red soil; BS = black soil. Regression lines are shown for saturated conditions only.

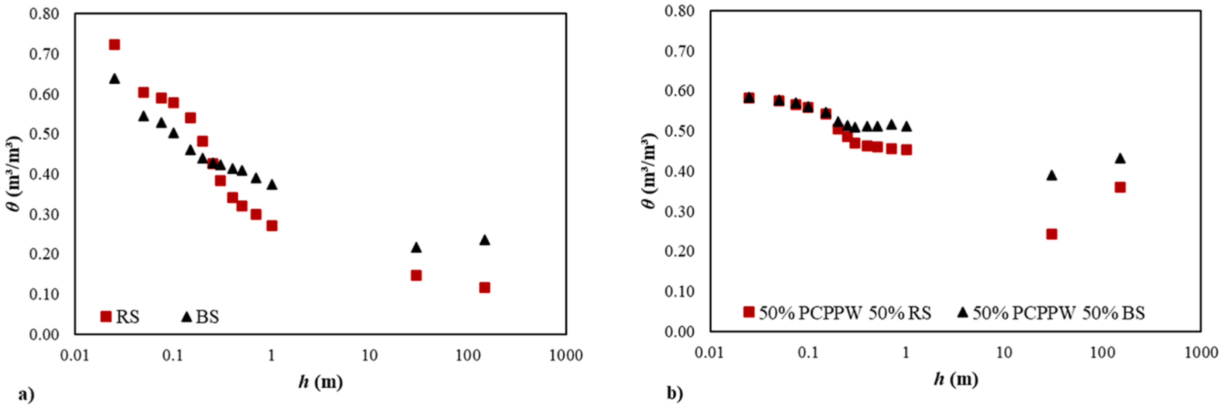

Fig. 3. Soil water retention data for a) the non-amended RS and BS soils and b) the 50% PCPPW to 50% soil mixtures.

showed a higher water retention capacity compared to RS (Fig. 3a). The observed behavior agrees with the different PSD of the two non-amended soils as BS, having a higher clay fraction, is likely characterized by a pore size distribution shifted towards relatively smaller diameters (Table S1). Thus, more water is retained in small pores than in large ones in BS. The opposite is for RS where the large pores predominate over the small ones (Nasta et al., 2009).

Comparison between non-amended soils and PCPPW-soil mixtures showed that soil water retention differed with PCPPW dose and soil type. In particular, the addition of 50% of PCPPW to the RS, resulted in increased θ values for $h < -0.15$ m whereas for higher matric head values (i.e., less negative), the volumetric water content slightly decreased (Fig. 3b). The maximum increase of θ

(0.018 m^3m^{-3}) was observed for $h = -1$ m. For the 50% PCPPW to 50% BS mixture, a generalized increase in the capacity to store water was observed and the volumetric water content increased, as compared to the non-amended BS, by a quantity variable from 0.032 m^3m^{-3} at $h = -0.05$ m to 0.196 m^3m^{-3} at $h = -150$ m. Therefore, our results showed that for both soils the powdered cactus pear improved the water retention capacity for relatively dry soil moisture conditions, which is for soil water content ranging from above the field capacity to the wilting point. However, for relatively wet conditions, the two soils did not show the same response to PCPPW addition. Indeed, for the RS soil a decrease in the water content corresponding to a given matric head was observed whereas, for BS, the addition of PCPPW increased the stored water.

Amending effects were confirmed by Pearson's correlation coefficients between θ values at a given matric head and the PCPPW dose (Table 1). Significant negative correlations were observed for RS at matric heads close to the upper range of matric pore domain ($h = -0.1$ m). For low h values ($h < -0.25$ m) an opposite sign of the correlation was observed with θ values that always increased at increasing the percentage of PCPPW. For BS, the volumetric water content always significantly increased with PCPPW in the range from $h = -0.1$ to -150 m (Table 1).

For both soils, correlations were significant at the matric head values of −0.1, −1.0, and −150 m, which correspond, respectively, to the volumetric water content equivalent to matric capacity, θ_m, field capacity, θ_f, permanent wilting point, θ_w, yielding the following regression lines:

Matric capacity, $h = -0.10$ m

RS: $\theta_m = 0.584 - 0.00121r$ BS: $\theta_m = 0.517 + 0.00101r$

Field capacity, $h = -1.0$ m

RS: $\theta_f = 0.350 + 0.00286r$ BS: $\theta_f = 0.424 + 0.00227r$

Wilting point, $h = -150$ m

RS: $\theta_w = 0.095 + 0.00478r$ BS: $\theta_w = 0.221 + 0.00390r$

A representation of the observed trends is given in Fig. 4**,** which shows how soil matric capacity is distributed between drainable water capacity (DWC) and plant available water capacity (PAWC). The first, given by difference $\theta_m - \theta_f$, is the water retained in pores that, according to the capillary law, have pore diameters in the range from 300 down to 30 μm. Such fraction corresponds to the soil water that is expected to drain below the root zone due to the synergistic impact of capillary and gravity flows. The latter, given by difference $\theta_f - \theta_w$, is the water retained in pores with a diameter from 30 down to 0.2 μm, and corresponds to the soil water available for crop growth (Reynolds et al., 2002).

For both soils, DWC tended to decrease at increasing the percentage of PCPPW, thus showing that amendment is expected to slow down the drainage below the root zone. A contrasting result (increasing DWC) was observed for RS only for very limited amending doses (*i.e.*, few per cent of PCPPW). The PAWC was to a less extent affected by PCPPW addition (Fig. 4). For the RS, PAWC tended to increase from 0.15 $m^3\,m^{-3}$ for $r = 0\%$ to a maximum of 0.26 $m^3\,m^{-3}$ for $r = 20\%$ and then it decreased to PAWC = 0.20 $m^3\,m^{-3}$ for $r = 50\%$. A comparable trend was noted for BS with the only difference that the maximum PAWC = 0.23 $m^3\,m^{-3}$ corresponded to $r = 30\%$.

3.3. Pore size distribution by mercury intrusion

Fig. 5 displays the pore size distribution in the range of pore size diameter from 0.007 to 200 μm of the control sample ($r = 0\%$), the 20% and 50% mixtures of PCPPW of both RS and BS soil.

The RS pore size distribution (Fig. 5a) displays a pattern with a shoulder with the maximum at around 1.5 μm of pore size diameter

Table 1

Pearson's correlation coefficients and corresponding p-values for the regression between volumetric water content at a given matric head and the PCPPW dose. Bold values indicate significant correlations.

h (m)	Red soil - RS		Black soil - BS	
	Pearson *R*	*p*-value	Pearson *R*	*p*-value
−0.025	−0.5487	0.0525	−0.1577	0.6085
−0.05	**−0.6216**	0.0235	0.3510	0.2396
−0.075	**−0.6393**	0.0187	0.5424	0.0555
−0.10	**−0.6357**	0.0197	**0.7103**	0.0065
−0.15	−0.4165	0.1574	**0.8014**	0.0010
−0.20	0.1531	0.6178	**0.7677**	0.0022
−0.25	**0.5736**	0.0404	**0.8052**	0.0009
−0.30	**0.6712**	0.0120	**0.8347**	0.0004
−0.40	**0.7156**	0.0060	**0.8657**	0.0001
−0.50	**0.7241**	0.0051	**0.8788**	0.0001
−0.70	**0.7441**	0.0035	**0.8736**	0.0001
−1	**0.7476**	0.0033	**0.8643**	0.0001
−30	**0.8816**	0.0001	**0.9798**	<.00001
−150	**0.9749**	<.00001	**0.9847**	<.00001

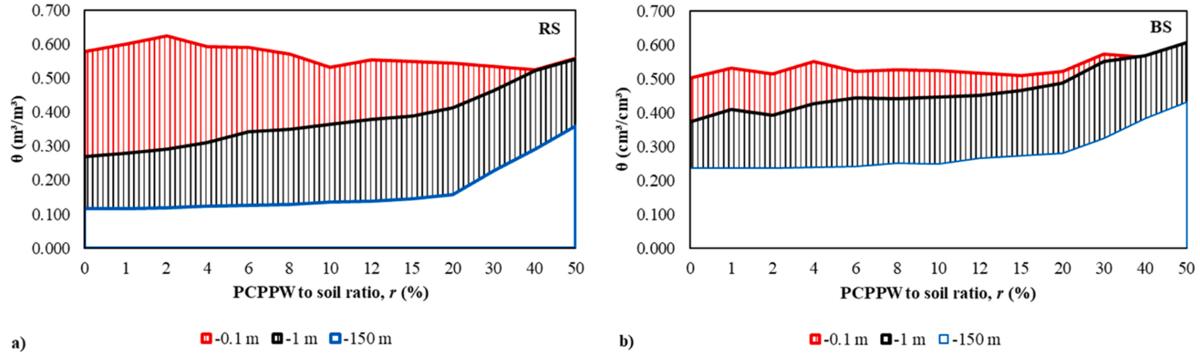

Fig. 4. Volumetric water content retained by PCPPW-soil mixtures for matric head values of −0.1 m (matric capacity), −1 m (field capacity) and −150 m (permanent wilting point). (a) RS (b) BS.

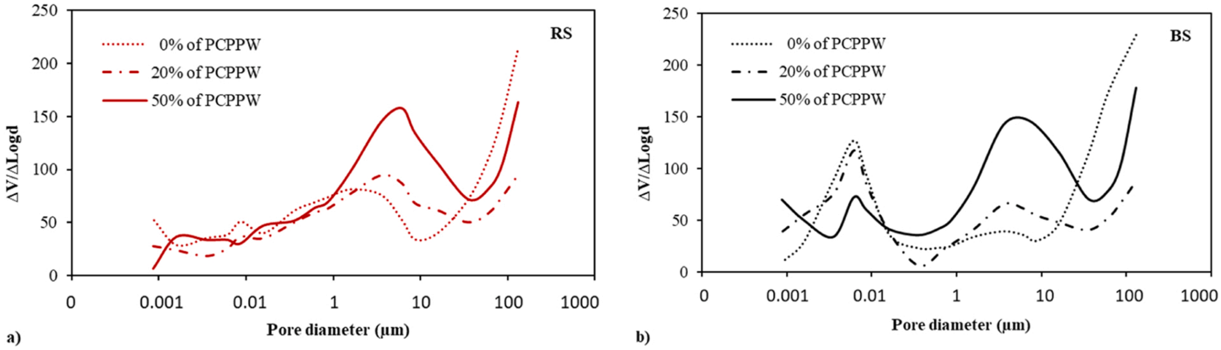

Fig. 5. Pore size distribution by mercury intrusion of a) RS and b) BS samples amended with different PCPPW doses (0%, 20%, and 50%).

for the control ($r = 0\%$) that shifts to higher values (2.5 μm and 5 μm for $r = 20\%$ and 50%, respectively) exhibiting more sharped peaks. Successively all the curves rise toward larger pores >75 μm. In the pore size range 0.007–25 μm, the samples with $r = 20\%$ and 50% increased the pores volume by 13% and 61%, respectively, as compared to the control (Fig. 6).

The BS pore size distribution (Fig. 5b) shows a bimodal pattern with *i)* a maximum of the first peak at around 0.05 μm of pore size diameter in the range of pores 0.007 – 0.25 μm for all samples. Instead, the pore volume in this region is similar for both control and $r = 20\%$ mixture but reduced (14%) for the $r = 50\%$ mixture (Fig. 6); *ii)* a maximum of the second peak at around 2.5 μm of pore size diameter for the mixtures and the control in the range of pores 0.25 – 7.5 μm. In this range, the pore volume increased by 78% for the $r = 20\%$ mixture and 315% for the $r = 50\%$ mixture (Fig. 6). Successively, as for RS, all the curves rise toward larger pores >75 μm. The addition of PCPPW promoted the increase of porosity especially in the range of pore diameters around 5 μm with a detrimental effect on the volume of pores with diameter larger than 75 μm. This effect was slightly for $r = 50\%$ mixture but marked for $r = 20\%$ mixture in both soils.

Soils are porous media, notably. Voids are sometimes measured as 'full of air' and other times derived from the measurement of the liquids they contain. In Fig. 6, both methods are considered. The results of both provide unique answers. One of the most important aspects is that the addition of PCPPW 'shifts' the porosity range (including the diameter size of the highest peak) towards regions where liquids are more available for plants. This has considerable relevance in the case of Vertisol, even if the total porosity does not vary significantly (probably because total porosity is mostly ruled by PCPPW addition), the water availability at the rhizospheric level increases. From these results, indications in terms of agronomic management can be extrapolated.

The total pore volume (Table 2), in the range of pores from 0.007 μm to 200 μm, after the amendment with 50% PCPPW increased by 18% in RS and 24% in BS. By contrast, with the $r = 20\%$ mixture the total pore volume reduced by 18% and 16% for RS and BS, respectively.

4. Discussion

Addition of powdered pruning waste of cactus pear to a loamy red soil and a clay black soil determined a decrease in soil BD under dry conditions. Significant negative correlations were found between dry BD and the PCPPW dose indicating that BD decreases at a rate of 0.062–0.078 Mg m^{-3}%PCPPW^{-1}. Similarly, Arvidsson (1998) showed that BD was largely dependent on SOM, with which it exhibited a strong negative correlation. Decreasing dry BD could be beneficial in fine-textured compacted or degraded soils showing BD values > 1.3 Mg m^{-3} in which root elongation may be impeded and soil aeration reduced (Reynolds et al., 2007). Instead, BD values

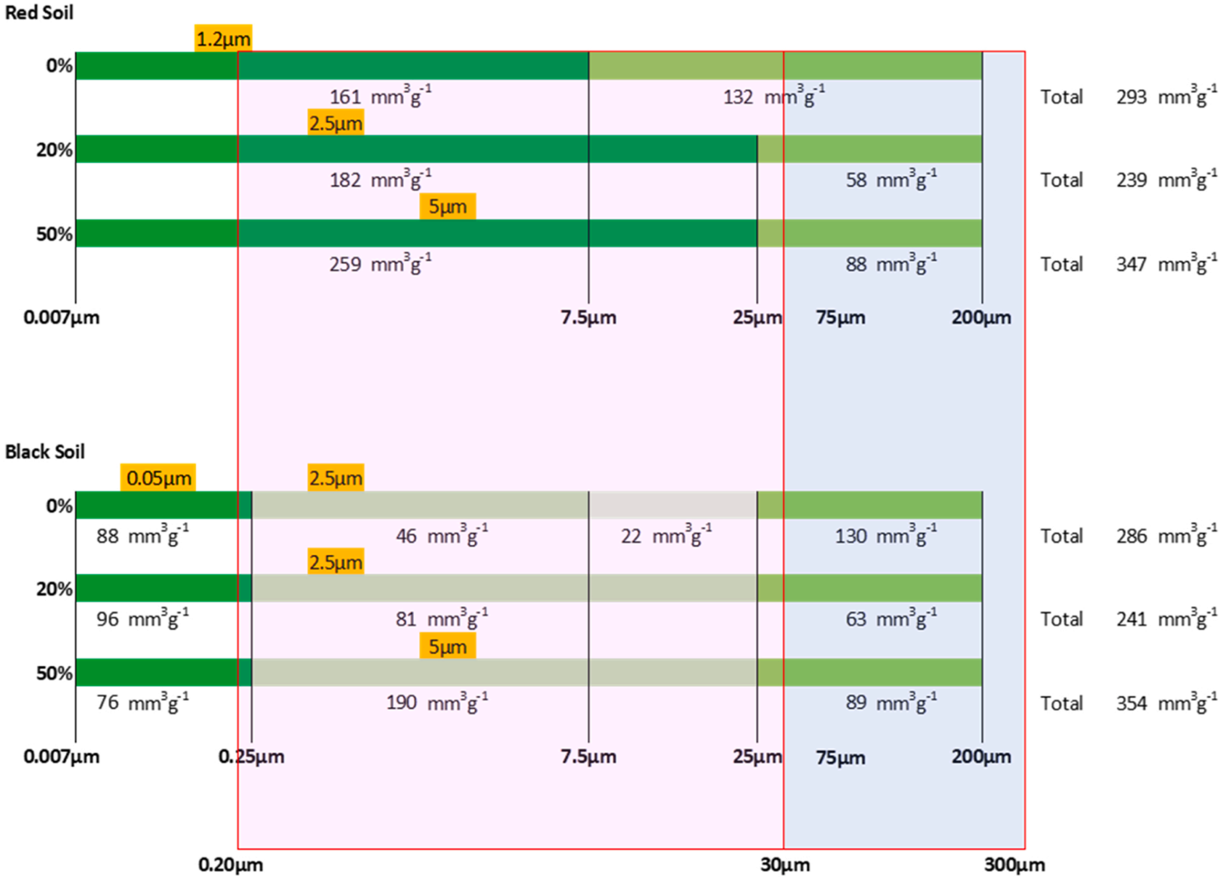

Fig. 6. Pore volume distributions as measured by Hg intrusion method in the different ranges determined based on the cumulative pore volume curve. Superimposition with the ranges measured by the volumetric water content corresponding to the selected matric heads of −0.1 m (300 µm), −1 m (30 µm) and −150 m (0.2 µm), respectively (see Fig. 4). Diameter size of the highest peak in each range (orange) and limits of the respective range (red inset). Figure not to scale.

Table 2
Total pore volume measured by mercury intrusion in the range of pore size diameter from 0.007 to 200 µm of the control (0% of PCPPW), the 20% and 50% mixtures of PCPPW of both RS and BS.

PCPPW	0%	20%	50%
	$mm^3\ g^{-1}$	$mm^3\ g^{-1}$	$mm^3\ g^{-1}$
RS	293	239	347
BS	286	241	354

below 0.8–0.9 Mg m^{-3} might result in inadequate root-soil contact and insufficient plant anchoring (Fan et al., 2021). Despite the present investigation was conducted on laboratory-repacked soil cores with limited compaction compared to natural soils, the observed relationships appear usable to predict the effect of the addition of a given quantity of PCPPW on the BD of natural soils. Furthermore, the two considered soils are widely diffused in the Mediterranean environment and, thus, the range defined by the two linear regression lines can be considered representative of the benefits expected when medium to fine-textured Mediterranean soils are amended with PCPPW.

Being a closed system, the powdered cactus pear had a relatively high swelling effect as, when added to the RS and BS, determined an additional decrease of the wet BD besides that determined by the soil clay particle swelling. The swelling capacity of the PCPPW is a consequence of the chemical structure of polysaccharides of the cactus pear (Amaya-Cruz et al., 2019). Cactus pear cladodes contain mucilage that is rich in galacturonic acid, contributing to improved water retention capabilities (Matsuhiro et al., 2006). The high swelling capacity that characterizes the PCPPW-soil mixtures should be considered with attention given that under constrained conditions, i.e., when the soil is not free to swell, may determine reduced soil porosity with negative effects on air and water circulation. For a limited percentage of PCPPW, the observed increased difference between dry and wet BD is probably positive as it increases the soil water retention.

Indeed, a significant positive correlation was found for water content at a given matric head and the PCPPW dose with the only exception of the matric capacity for the RS. In this last case, θ_m unexpectedly decreased at increasing r. It was hypothesized that the observed trend could be a consequence of specific interactions between PCPPW and RS at low matric head. In particular, the water drop penetration time test (Bisdom et al., 1993), conducted on the PCPPW, showed a slight repellency occurrence as the applied droplets ($N = 5$) infiltrated in time between 12 and 17 s. Therefore, it could be expected that addition of PCPPW hampered wettability particularly when the capillary forces are low (i.e., close to field capacity) and for high organic matter doses (Caltabellotta et al., 2022). However, this effect was not observed for BS. Another possible effect is related to PSD of PCPPW in relation to that of the two considered soils. Fig. 7 shows the percentage distribution by mass of PCPPW, particles compared to those of non-dispersed RS and BS soils. It is worth noting that the PCPPW particles prevailed for larger diameter classes ($d \geq 605$ μm), whereas the soil particles (both RS and BS) prevailed for $d \leq 163$ μm. The singularity is for $d = 326$ μm where the proportion of PCPPW particles prevailed over BS but not over RS ones. Given such particle diameter is very close to the sizes of pores that are saturated at matric capacity ($h = -0.1$ m), it could be supposed that PCPPW addition reduced the number of soil pores falling in that class for the RS thus determining the reduction of θ_m at increasing the PCPPW dose. An opposite trend, i.e.,θ_m increasing with the PCPPW dose, is justified for BS. However, the analyses conducted at the micrometric pore scale by Hg porosimetry similarly displayed the reduction of total pore volume after the addition of the 20% of PCPPW but, in this case, for both RS and BS soils with the successive volume increasing after further PCPPW addition (i.e., 50%) when compared with the respective controls (i.e, 0% of PCPPW).

The estimation of soil porosity has been achieved through two distinct methods: wet soil water retention and dry soil Hg intrusion. It is important to note that these approaches refer to wet and dry soil, respectively. As a result, the swelling effect that occurs in moist soil masks the displacement of the size pores from the smallest to the coarsest pores. This phenomenon is not observed when analyzing dry soil. In terms of retained water, a limited addition of PCPPW (few per cent units) seemed to increase the drainable water capacity (DWC) of the RS and did not affect BS. For higher PCPPW doses a decrease of DWC was observed for both soils, thus confirming that amending medium- to fine-textured soils with swelling PCPPW may hamper soil capacity to drain water and limit air circulation. Although the above statement holds true, the presence of water in the soil tends to mask the true size of the pores. This would explain some of the apparent discordances found between the two methods. The organic particles in the amended soil are larger in size (Fig. 7), and the addition promotes a dominating coarser porosity of the system, especially after 50% of PCPPW addition. This behavior is a result of the final architecture of the particles organization and is influenced by the intrinsic porosity of both soils.

The PAWC was also influenced by PCPPW addition, but observable benefits require very large PCPPW proportions (unlikely under field conditions), up to 20% in RS and even larger in BS. More in general, a redistribution between DWC and PAWC can be supposed with the average energy level of the retained water that becomes more and more negative and drainable water is transformed in plant available water up to a transition threshold of PCPPW dose of around 20% at which PAWC is maximum. Behind that threshold, DWC disappears, and PAWC reduces while most of the soil water is retained below the minimum soil matric head ($h = -150$ m) applicable by crops. For agronomic purposes, that threshold should be not overpassed, at least for these benchmark Mediterranean soils, rather heavily textured.

The ability of soil to retain water significantly affects plant growth, impacting carbon allocation, nutrient cycling, and photosynthesis rates. Research indicates that in various regions globally, soil water-holding capacity dictates crop yield and its stability. Yet, Minasny and McBratney (2018) drawing on data from 60 studies (50,000 measurements) have shown that a 1% increase in soil organic carbon, on average, results in a 1.16% volumetric increase in available water capacity, indicating a minor influence on soil water retention. They showed that overall, there are modest increases in θ when considering all textures. However, when categorized by texture, the rise is significantly greater in coarse-textured soil, followed by medium-textured soil, and least in fine-textured soil.

The significant linear regressions deduced for BD and the characteristic water retention points could help in selecting the most appropriate PCPPW dose to be applied to these soils. Despite the absolute values of BD, θ_m,$\theta\theta_f$ and θ_w can be affected by the empirical setup that made use of laboratory-repacked soil samples, it could be supposed that the relative effects, that is the gradient by which the selected soil property changes because of PCPPW addition, is not affected by the sample preparation. Therefore, if the soil properties under field conditions are known from other investigations, the short-term effect of a given PCPPW dose on bulk density, drainable water capacity and plant available water capacity can be predicted. In particular, the proposed relationships offer a large potentiality to be embedded into PTFs specifically developed for Mediterranean soils with the aim to predict the effects of PCPPW amending on the SWRC (Castellini and Iovino, 2019). A point that needs further investigation is the time stability of the modifications induced by PCPPW addition. In particular, it is expected that the physical and chemical properties of the PCPPW will change over time after soil embedment. However, to the best of our knowledge, no data on PCPPW degradation is available and, thus, long-term modifications could be learned only from studies conducted on similar organic amendment materials (i.e., compost) that showed how the maximum benefits regressed within approximately six months (Bondì et al., 2023; Cannavo et al., 2014; Guo et al., 2019; Weber et al., 2007).

In soil, the rhizospheric environment is complex and difficult to model and thus it is frequently overlooked. However, it is precisely at the level of the rhizosphere that it would be useful to be able to know, for example, the dynamics of water through the soil porous system. Currently, the knowledge of soils is extended to all parts of the world also thanks to the introduction of pedotransfer functions. Pedotransfer functions (PTFs) are used for converting existing data into data that we need but do not have available (Bouma, 1989). Regarding soil hydraulic properties, PTFs are generally based on PSD, BD, SOM, and cation exchange capacity (Tóth et al., 2015; Román Dobarco et al., 2019). For example, in Europe, EU-SoilHydroGrids offers data on soil hydraulic properties up to 2 m depth at 250 m resolution (Tóth et al., 2017). Despite being a powerful tool for planning and land management, most soil databases include the percent of clay and sand only as PTFs predictor variables (e.g., Román Dobarco et al., 2019). They necessarily simplify the complexity of the soil in an extreme manner, excluding the presence of plants. Plants that live in the soil, anchored by their root architecture, modify their intrinsic properties, in particular, the dynamics of liquids and gases. For example, roots secrete mucilage. Polymeric gels

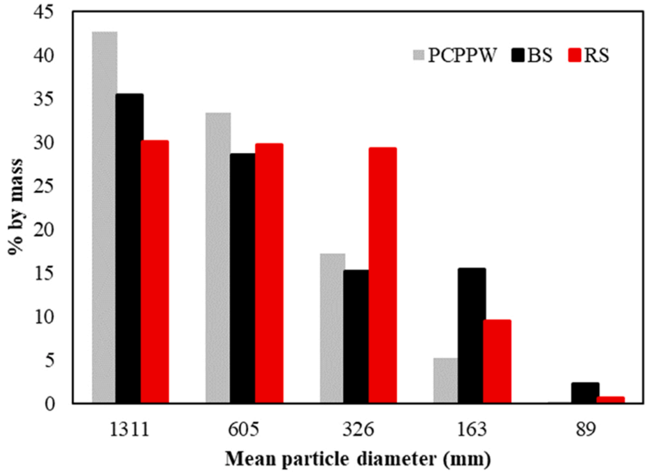

Fig. 7. Particle size distribution among selected diameter sizes in the range from 75 to 2000 μm.

known as mucilages, which are secreted by the cap cells of the root tip, have a crucial role in facilitating root-soil interactions (Ahmed et al., 2015). The physical and chemical properties of mucilage, along with their interactions, are essential in defining its diverse functions and playing a crucial role in hydraulic processes within the rhizosphere (Benard et al., 2019; Rosskopf et al., 2021). Adding plant biomass enhances soil physical properties through the development and stabilization of aggregates (Ansari et al., 2022). Soil macroaggregates (i.e., > 0.250 mm) are stabilized by roots, hyphae, and mucilages, particularly polysaccharides (Machado Vezzani et al., 2018).

The mucilages contained in cactus pear pruning, examined in this work with their potential as a soil conditioner, certainly mimic a rhizospheric environment, albeit oversimplified. Our results, limited to a Mediterranean environment, having chosen two extreme soils, can be used to improve the predictivity of PTFs, considering the presence of plants.

5. Synopsis and conclusions

We tested a by-product of a particular type of Mediterranean cultivation, the cactus pear, and its incorporation effect in benchmark soils. The amendment of powdered pruning waste of cactus pear (PCPPW) exhibited favorable impacts on the physical properties of two contrasting soils, (red soil, RS, and black soil, BS). In both soil types, the incorporation of the amendment led to a reduction in soil BD under dry conditions, which could be advantageous in fine-textured compacted or degraded soils, having BD values > 1.3 Mg m^{-3}, in which root elongation may be prevented and soil aeration reduced. However, PCPPW has a relatively high swelling effect that needs to be considered as, when the soil is confined, it can result in lower soil porosity, which negatively affects air and water circulation. Regarding soil water retention, a limited dose of PCPPW (a few percentage units) seemed to increase the drainable water capacity (DWC) of RS and did not affect BS. Instead, for higher doses of PCPPW, a decrease in DWC was observed for both soils, thus confirming that the emendation of medium to fine-textured soils with swelling PCPPW can hinder the drainage water from the soil and limit air circulation. Plant available water capacity (PAWC) was also found to be affected by the addition of PCPPW, however, observable benefits require very high PCPPW proportions, up to 20% in RS and even more in BS. It is reasonable to assume that a redistribution between DWC and PAWC occurs, with the average energy level of retained water becoming increasingly negative and drainable water converting into plant available water up to a transitional threshold of the PCPPW dose of about 20%, at which PAWC is maximum. Beyond this threshold, DWC disappears and PAWC also decreases, since most of the water is hygroscopic ($h > -150$ m) and not available for plants. For agronomic purposes, this threshold should not be exceeded, at least for these rather heavy textured Mediterranean reference soils. Overall, the findings indicated that the addition of PCPPW, in both soil types, could trigger benefits on hydrological processes and agronomic services by promoting the increase of PAWC, while maintaining the PCPPW content below 20%, and the infiltration of plant roots in the absence of swelling constraint conditions. In conclusion, PCPPW application, as a soil improver, can contribute to efficient water management in arid and semi-arid regions, characterized by limited water availability and low soil fertility.

Despite the general objective of the paper, emphasizing the need for tailored allochthonous material additions to specific soil types, the uncertain applicability of our results to open field crops is acknowledged. However, a potential avenue for knowledge transfer exists within controlled environments like plant nurseries, floriculture, or protected horticulture, where tested ratios are often exceeded, and some crops thrive in pure amendment conditions.

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CRediT authorship contribution statement

Bondì C.: Conceptualization, Investigation, Writing - original draft, Formal analysis. **Auteri N.:** Conceptualization, Investigation, Writing - original draft, Formal analysis. **Saiano F.:** Conceptualization, Writing - review & editing, Supervision. **Scalenghe R.:** Conceptualization, Writing - review & editing, Supervision. **D'Acqui L.P.:** Writing - review & editing, Formal analysis. **Bonetti A.:** Writing - review & editing, Formal analysis. **Iovino M.:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data have been uploaded to Zenodo. Available at DOI 10.5281/zenodo.7930425. Supplementaty material content related to this article was uploaded at the article submission.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eti.2024.103602.

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