

Research article

Impact of vermicompost addition on water availability of differently textured soils

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ABSTRACT

Vermicompost is an organic material that is abundant in humic acids and nutrients. It is obtained through the bio-oxidation and stabilization processes carried out by earthworms. It has been proven to bring several benefits to different soil properties, including bulk density, soil structure, and plant available water capacity (PAWC). This investigation was conducted to fill the knowledge gap in some critical factors related to vermicompost application, specifically the short-term influence of a single vermicompost application with increasing doses on soil wettability and physical quality of differently textured soils. Water repellency of vermicompost and soil/vermicompost mixtures was investigated at different moisture contents by the water drop penetration time test, whereas physical quality was assessed by 35 soil indicators related to bulk density, soil water retention curve, and pore size distribution function.

Despite vermicompost showed from strong to severe hydrophobicity at moisture content lower than the field capacity, amended soils were at the most slightly water repellent thus indicating that, under field conditions, the hydrophobicity attributable to soil amendment with vermicompost could be considered negligible. Soil physical quality was effectively affected by vermicompost addition with different outcomes depending on soil texture. Indicators linked to PAWC generally increased at increasing the vermicompost rate in the coarse soils whereas no significant effect was observed for intermediate and fine soils. For example, plant available water capacity of coarse-textured soils increased from an average initial value of $0.056 \text{ cm}^3 \text{ cm}^{-3}$ to an optimal value of $0.15 \text{ cm}^3 \text{ cm}^{-3}$ when a vermicompost addition dose of about one-third by volume (34 %) was applied. In the finest soil, drainable porosity significantly increased from an initial value of $0.09 \text{ cm}^3 \text{ cm}^{-3}$ to $0.23 \text{ cm}^3 \text{ cm}^{-3}$ when the maximum vermicompost dose (43 %) was applied thus indicating that amendment could be effective in enhancing water and air circulation.

1. Introduction

Soil organic matter is a dynamic soil component that represents a main source for several ecosystem services critically important for human well-being and nature conservancy [1]. It is well known that intensive agriculture can be a major cause of fertility loss and soil degradation [2]. By worsening the physical, chemical, biological, and ecological components of the soil, soil degradation implies an overall decline in soil quality and a possible consequent reduction in ecosystem functions and services [2,3]. Several technological

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options were suggested in the literature for soil organic matter management and, therefore, for improving soil quality [4]. Practically, they consist of controlling the organic carbon losses by reducing soil erosion, decreasing leaching, and minimizing soil organic matter decomposition or, alternatively, increasing soil organic matter content through the use of amendments [4–6]. It has been widely proven that amendments have beneficial effects on soil quality and water availability, thus resulting in higher crop yields [7–9]. Depending on the agricultural sectors considered (i.e., conventional open-field or greenhouse agriculture) or plant type (food crops or ornamental plants), several organic soil amendments are available to increase soil water availability [10]. For example, coconut fiber, sphagnum, and peat represent the basis for substrates creation in nursery, and for high-income ornamental crops [11–13]. On the other hand, under extensive field crops, traditional amendments such as aged manure and compost, or more innovative ones such as biochar, are generally reported in the literature as effective in improving the physical-chemical soil properties [14–17].

Recently, the use of vermicompost as an organic soil conditioner has progressively increased also due to its contribution to sustainable management and recycling of organic waste [6–18]. Vermicompost, or called worm humus, is the product of the bio-oxidation and stabilization processes of organic material (e.g., food waste, horticultural waste, poultry droppings, food industry sludge, and so on) by earthworms, to obtain an organic material highly rich in humic acids and nutrients. In terms of benefits for crops, vermicompost is considered a sustainable source of macro- and micro-nutrients, because it is a source of mineral nutrient elements that are easily available for plants growth [19]. Application of vermicompost favored the survival of soil bacteria and actinomycetes and reduced the number of soil fungi [20]. Earthworms act as a natural bioreactor. Their activity stimulates the rate of decomposition of organic residues but, thanks to their motion into the soil, improves its structure and aeration, resulting in increased porosity, infiltration, and water retention [21,22]. Therefore, vermicompost is usually considered a natural and sustainable soil improver [23,24]. Several investigations reported the benefits of vermicompost application on different soil properties, including bulk density [25] or water use efficiency [26], but little literature has considered thoroughly the impact of vermicompost addition on soil water retention [27]. For two different soils, for example, Rivier et al. [28] evaluated the effect of compost and vermicompost addition on soil structure, soil water retention and water use efficiency. They reported that the application of both organic amendments improved soil water holding capacity, increased the macro-aggregates, and reduced soil bulk density, even at small application rates. Liu et al. [29] reported that vermicompost can significantly improve soil water permeability and retention thus ultimately improving the available water content.

Using vermicompost could be recommended to improve the water retention of coarse-intermediate textured soils or, more generally, to balance the water-to-air ratio in intermediate-fine textured ones [30]. However, to our knowledge, few in-depth evaluations of vermicompost effect on agricultural soils are available, and none of them aimed to compare the effects on contrasting soil texture. In fact, most studies have considered the impact on one-two soil's physical properties, e.g., stability of soil aggregates [31,32], bulk density [32–34] soil porosity [33–35] or water content at field capacity and wilting point [25–32], but there are no studies that simultaneously evaluated the effects on several physical soil properties as a function of both different soil textures and increasing amendment rates. A possible drawback of vermicompost amendment, not adequately considered in the available literature, could be related to the reduced soil wettability given it is commonly accepted that soil water repellency (SWR) is caused by organic compounds derived from living or decomposing plants or microorganisms [36]. However, the composition of organic matter rather than its total amount was found to influence SWR [37,38]. Furthermore, evaluating the short-term impact of amendment deserves interest given the soil wettability and the related physical properties can be modified, even immediately after vermicompost incorporation, with unpredictable effects on the soil hydrological processes. A simple assessment of SWR can be conducted by the water drop penetration time (WDPT) test which consists of placing a drop of water on the soil surface and measuring the time for it to penetrate [39]. Despite the WDPT test has been criticized [40,41] it still remains the most widely applied option for SWR assessment [42,43].

Evaluation of the effects of organic amendments on soil physical properties and water retention, can be made by estimating several soil indicators from the soil water retention curve [5,44–46]. For instance, Reynolds et al. [5] suggested using some capacity-based indicators accounting for the soil's ability to store and provide water and air to the crops, such as macroporosity, air capacity, relative field capacity, and plant available water capacity. On the other hand, when the entire soil water retention curve is available, it is possible to derive the pore volume distribution function and its related “location” and “shape” parameters [5]. The aforementioned soil physical indicators were widely and profitably used also to evaluate the impact of soil organic matter on the soil water retention of natural [15–45] and repacked [13–47] soil samples. A third approach for water retention curve analysis is based on the S-theory proposed by Dexter [44]. The S-index represents the magnitude of the slope of the soil water retention curve at the inflection point when such curve is expressed as gravimetric water content vs. the natural logarithm of the pressure head. According to Dexter [44], the inflection point should be able to discriminate the non-capillary from capillary porosity. Han et al. [48] suggested estimating some inflection point indicators from the soil water retention curve parameters expressed by the van Genuchten [49] model, including the effective porosity and a pore distribution index.

This investigation was conducted to evaluate the impact of increasing levels of vermicompost addition on the physical properties of five soils with different textures, from coarse to intermediate and fine. Specifically, hydrophobicity of vermicompost and soil/vermicompost mixtures was preliminarily evaluated in the range of moisture content from field capacity to oven-dry. Then, the impact of amendment rates up to about 50 % was evaluated in terms of modification of soil bulk density, water retention, and 15 indicators of soil physical quality. Therefore, the investigation structure can be summarized by the following steps: i) selection of five soils with different physical properties, with particular attention to the water retention capacity; ii) preparation of soil/vermicompost mixtures, until relatively high levels of soil amendment are achieved (0–43 %); iii) evaluation of soil/vermicompost mixtures effects on soil properties, including hydrophobicity, bulk density, macroporosity, air capacity, relative field capacity, plant available water capacity, indicators from the pore volume distribution function and from the inflection point of the water retention curve; iv) discussion about the practical impact of soil amendment on water availability for plants growth.

2. Material and methods

2.1. Soils and experimental materials

Five soils of different textures were collected in Sicily and Apulia, namely at Palermo Orleans (OR), Bari CREA (CR), Palermo Campus UNIPA (UN), Taranto Ginosa (GI) and Taranto Castellaneta (CA). Soil use of the selected fields was fallow, grass lawn, or orchard (Table 1). For each site, about 20 kg of soil was taken in the upper layer of soil profile (up to 20 cm) and stored in the laboratory, where it was air-dried and sieved to a diameter of 2 mm. Soils were characterized by standard laboratory techniques to determine the particle distribution [50] and the main chemical soil properties, including organic matter, pH, electrical conductivity, cation exchange capacity, and nitrogen content.

The vermicompost used in this investigation is a by-product of the digestion of cow manure by earthworms (*Eisenia foetida*) manufactured by CONITALO, Italian Lombrichi Breeding Consortium. The physico-chemical characteristics of the vermicompost were conducted using standard laboratory techniques. In particular, after oven dried at 70 °C for 24 h, vermicompost was grounded to pass a <1-mm sieve. Total organic carbon (TOC) and N contents were determined through the Dumas method (dry combustion method), using a CHNS Analyzer (Flash EA 1112-CHNS, Thermo Electron Corporation). For the determination of total contents of Ca, K, Mg, Na, P, Fe, Mn, Cu and Zn the samples were mineralized using microwave assisted pressure digestion and quantified by an ICP-OES optical spectrometer (Varian Inc., Vista MPX). The remaining parameters listed in Table 2 were retrieved from the manufacturer's technical sheet.

2.2. Soil/vermicompost mixtures

Soils and vermicompost were preliminary air-dried and sieved at 2-mm- sieve to remove coarse fragments and large vegetal residues and then mixed at 19 amendment different proportions by weight: 0 (i.e., soil without amendment), 0.5, 1, 2, 4, 5, 6, 6.5, 7, 8, 9, 10, 12, 13, 15, 17, 22, 33, 43 %. Therefore, a total of 95 repacked soil samples (19 concentrations x 5 soils) were prepared. Samples of each soil/amendment mixture were obtained by compacting into 5 cm diameter by 5 cm height metal cylinders a dry mass of the two constituents given by the following relationships [47]:

$$M_s = \frac{V \rho_{b,v} \rho_{b,s}}{\rho_{b,v} + r \rho_{b,s}} \quad (1)$$

$$M_v = r M_s \quad (2)$$

where M_v (g) and M_s (g) are the dry masses of vermicompost and soil, respectively, $\rho_{b,v}$ (g cm^{-3}) and $\rho_{b,s}$ (g cm^{-3}) are the dry bulk densities of the two constituents, V (cm^3) is the sample volume, and r is the ratio between dry masses of amendment and soil. Sample preparation was conducted by filling the cylinder with the mixture in four successive steps and, for each step, by lightly pressing the sample surface with a twisting motion using a pestle [47]. A flow chart explaining the procedural steps for determining soil physical quality indicators is reported in Fig. 1. Considering steps 1–3 of the flow chart (i.e., starting from the preparation of the samples, going through their saturation phase, and the subsequent water retention curve determination), the incubation time of soil samples was less than approximately two months. When transferred to field conditions, the amendment rates considered in this investigation corresponded to an air-dried vermicompost dose between 3–4 and 176–213 t ha^{-1} , depending on the considered soil, for an application depth of 5 cm.

Table 1
Sampling sites and main physical and chemical characteristics of the considered soils.

	OR	CR	UN	GI	CA
Site	Palermo Orleans	Bari CREA	Palermo Campus UNIPA	Taranto Ginosa	Taranto Castellaneta
Latitude, Longitude	38.107208N 13.349832 E	41.110366N 16.877836 E	38.107184N 13.351942E	40.461383N 16.84105 E	40.51246N 16.886826 E
Land use	Grass lawn	Fallow	Citrus orchard	Vineyard	Citrus orchard
Clay, Cl (%)	30	17	18	16	6
Silt, Si (%)	34	40	30	13	21
Sand, Sa (%)	36	43	52	71	73
Texture USDA	clay loam	loam	sandy loam	sandy loam	sandy loam
Texture group	fine	intermediate	coarse	coarse	coarse
Organic Matter, OM (%)	3.65	4.57	6.15	1.55	0.60
pH	7.69	7.53	7.99	7.90	7.35
EC (dS m^{-1})	0.29	0.42	0.34	0.13	0.20
CEC (cmol kg^{-1})	28.7	11.76	25.31	6.14	5.40
N (%)	0.21	0.24	0.32	0.099	0.029
C (%)	2.12	2.65	3.57	0.90	0.35
C/N ratio	10.10	11.04	11.16	9.09	12.07
WRB classification [51]	Chromic Cambisol (Loamic)	Chromic Cambisol (Loamic)	Terric Chromic Cambisol (Loamic)	Chromic Cambisol (Loamic)	Terric Chromic Cambisol (Loamic)

Table 2
Chemical characteristics of the considered vermicompost.

Water content (%)	Ash content (%)	pH (-)	EC (dS/m)	TOC (%)	N (%)	Ca (g/kg)	K (g/kg)	Mg (g/kg)	Na (g/kg)	P (g/kg)	Fe (g/kg)	Cu (mg/kg)	Mn (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
7.6	56.7	7.5	3.1	19.7	15.6	39.9	15.2	12.7	3.7	9.5	14.2	67.0	718.4	n.f.	265.6

EC = electric conductivity; TOC = total organic carbon; N = total nitrogen; Ca = total calcium; K = total potassium; Mg = total magnesium; Na = total sodium; P = total phosphorus; Fe = total iron; Cu = total copper; Mn = total manganese; Pb = total lead; Zn = total zinc (n.f. = not found).

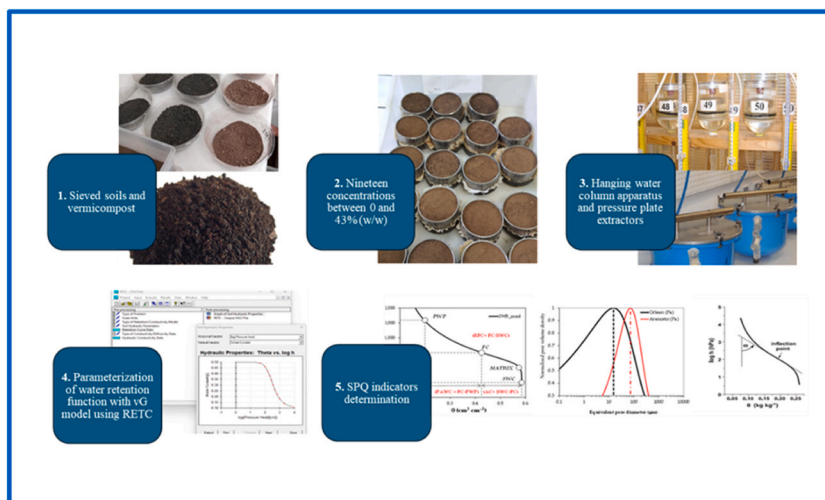


Fig. 1. Flow chart of the procedural steps for soil physical quality (SPQ) indicators determination: 1. Preparation of sieved soil and vermicompost, 2. Soil/vermicompost mixture in cylindrical samplers, 3. Soil water retention determination, 4. Parameterization of soil water retention function and 5. Determination of the three groups of SPQ indicators, i.e., capacitive indicators, location and shape parameters of pore volume distribution function, and related to the inflection point of soil water retention function.

2.3. Assessment of vermicompost wettability

The water drop penetration time (WDPT) test [36–50,52] was applied to evaluate the hydrophobicity of vermicompost at four reference water content values. Specifically, sieved vermicompost was compacted to a height of approximately 1 cm into metallic trays having dimensions of $10.5 \times 17.0 \text{ cm}^2$. Two samples were established at air-dried (AD) and oven-dried (OD) conditions. In the latter case, the sample was dried for 24 h at 105°C and then cooled for 2 h in a silica gel desiccator before conducting the WDPT test. Two samples were preliminary saturated and equilibrated into a pressure plate apparatus (Soil Moisture Equipment Corp., Santa Barbara, CA) at pressure head values of $h = -100$ and -15000 cm , i.e., at field capacity (FC) and permanent wilting point (WP). For each pressure head value, the soil water content was determined by the thermogravimetric method after subtracting the total weight of water added for the WDPT test. For each vermicompost sample, 20 drops of distilled water, each having a $60 \pm 5 \mu\text{L}$ volume, were placed on the sample surface, and the time for complete infiltration was recorded. Drops were placed according to a square grid of $20 \times 20 \text{ mm}^2$ by micropipette from a height of 10 mm to avoid excessive kinetic energy.

To evaluate the influence of vermicompost on the wettability of the amended soils, five $10.5 \times 17.0 \times 1.0 \text{ cm}^3$ repacked samples of air-dried soil/vermicompost mixtures at 43 % proportion by weight were prepared and the WDPT test conducted according to the same experimental procedure. Given all the considered soils were not hydrophobic under air-dried conditions ($\text{WDPT} \approx 0$), only the highest concentration was considered to assess the maximum possible effect of vermicompost in triggering soil water repellency.

The SWR classification suggested by Bisdorff et al. [53] was used to classify soils according to different WDPTs, that is $< 5 \text{ s}$ (wettable, W), 5–60 s (slightly hydrophobic, SLH), 60–600 s (strongly hydrophobic, STH), 600–3600 s (severely hydrophobic, SEH) and $> 3600 \text{ s}$ (extremely hydrophobic, EXH). The repellency class was determined for each of the 20 droplets and the frequency distribution of the repellency classes for each sample was calculated [54].

2.4. Soil water retention curve and bulk density determination

Soil water retention curve in the range of soil pressure head (h) values $-100 \leq h \leq -5 \text{ cm}$ was determined by a hanging water column apparatus [55]. The apparatus consisted of a sintered porous plate with an air entry value of -200 cm connected to a graduated burette that may move vertically allowing to set different pressure head values and to measure the water drained from the sample. After preparation, each soil sample was placed on the porous plate surface and progressively wetted by capillary rise until full

saturation. Saturation was carefully completed in four successive equilibrium steps of 24 h each at h values of -20 , -10 , and -5 cm followed by sample submersion ($h = 0$). Then, the samples were subjected to a drainage cycle consisting of a sequence of 11 decreasing pressure head values ($h = -5, -7.5, -10, -15, -20, -25, -30, -40, -50, -70$, and -100 cm) and the volume of water drained into the burette at equilibrium recorded. The volumetric water content, θ ($\text{cm}^3 \text{cm}^{-3}$), at each equilibrium stage was calculated by adding the drained volumes to the final θ value determined at $h = -100$ cm by weighting the sample after oven-drying at 105°C for 24 h. The sample dry soil bulk density, ρ_b (g cm^{-3}) was also calculated from the oven-dried weight [56]. For each vermicompost/soil mixture considered, the water retention data at pressure heads in the range $-15000 \leq h \leq 330$ cm were determined in pressure plate extractors on three replicated samples of 5-cm-diameter by 1-cm-height [57]. Therefore, 15 pairs of volumetric soil water content-soil pressure head, θ - h values were measured for each soil/vermicompost mixture.

The unimodal van Genuchten (vG) water retention function [49] was fitted to the data by the RETC software [58]. To accurately estimate the water retention curve, model fitting was performed by optimizing all the parameters (i.e., θ_r , θ_s , α and n) of the vG model [59].

2.5. Soil physical quality indicators

Three groups of soil physical quality indicators, derived from the measured soil water retention curve, were considered in this investigation [15–50,52–60]. The first group consists of widely used soil indicators accounting for the soil's ability to store and provide water and air to the crops [5], such as macroporosity, air capacity, relative field capacity, and plant available water capacity. The second group includes “location” and “shape” parameters of the pore volume distribution function, as suggested by Reynolds et al. [5]. The third group includes indicators related to the inflection point of the water retention function: soil pressure head, soil water content, slope of the water retention curve, soil porosity, and pore distribution index. According to Dexter [44] and Han et al. [48], the inflection discriminates the non-capillary (macropores) from capillary porosity. Overall, a total of 15 soil indicators were therefore considered. The specific characteristics of the considered soil physical quality indicators are given below.

2.5.1. Capacitive-based indicators

Four capacitive indicators of soil physical quality, that account for the water-air ratio into the soil, were considered in this first group, namely macroporosity, P_{MAC} ($\text{cm}^3 \text{cm}^{-3}$), air capacity, AC ($\text{cm}^3 \text{cm}^{-3}$), relative field capacity, RFC , and plant available water capacity, $PAWC$ ($\text{cm}^3 \text{cm}^{-3}$):

$$P_{MAC} = \theta_s - \theta_m \quad (3)$$

$$AC = \theta_s - \theta_{fc} \quad (4)$$

$$RFC = \frac{\theta_{fc}}{\theta_s} \quad (5)$$

$$PAWC = \theta_{fc} - \theta_{pwp} \quad (6)$$

where θ_s , θ_m , θ_{fc} and θ_{pwp} are the volumetric water contents ($\text{cm}^3 \text{cm}^{-3}$) corresponding to a pressure head $h = 0, -10, -100$ and -15000 cm, respectively [5].

2.5.2. Pore volume distribution indicators

Location parameters (modal, d_{mod} (μm), median, d_{med} (μm), and mean, d_m (μm) diameters) indicative of central tendency, and shape parameters (standard deviation, SD (μm), skewness, Sk , and kurtosis, Ku) indicative of spread, asymmetry, and peakedness, respectively, of the soil pore volume distribution function, were calculated as follows [5]:

$$d_{mod} = \frac{2980\alpha}{m^{-1/n}} \quad (7)$$

$$d_{med} = \frac{2980\alpha}{(0.5^{-1/m} - 1)^{1/n}} \quad (8)$$

$$d_m = \exp\left(\frac{\ln d_{0.16} + \ln d_{0.50} + \ln d_{0.84}}{3}\right) \quad (9)$$

$$SD = \exp\left(\frac{\ln d_{0.84} - \ln d_{0.16}}{4} + \frac{\ln d_{0.95} - \ln d_{0.05}}{6.6}\right) \quad (10)$$

$$Sk = \frac{1}{2} \left[\frac{\ln d_{0.16} + \ln d_{0.84} - 2(\ln d_{0.50})}{(\ln d_{0.84} - \ln d_{0.16})} + \frac{\ln d_{0.05} + \ln d_{0.95} - 2(\ln d_{0.50})}{(\ln d_{0.95} - \ln d_{0.05})} \right] \quad (11)$$

$$Ku = \frac{\ln d_{0.05} - \ln d_{0.95}}{2.44(\ln d_{0.25} - \ln d_{0.75})} \quad (12)$$

where $m = 1 - 1/n$ and $d_{0.05}$, $d_{0.16}$, $d_{0.25}$, $d_{0.50}$, $d_{0.75}$, $d_{0.84}$, $d_{0.95}$, are equivalent pore diameters (μm) obtained from the capillary rise equation for given normalized water content values. The reader is referred to Reynolds et al. [5] for further details.

2.5.3. Inflection point indicators

Considering the vG model for the soil water retention curve, the soil parameters at the inflection point, i.e., pressure head value, h_{inf} (cm), water content, θ_{inf} ($\text{cm}^3 \text{cm}^{-3}$), slope of the water retention curve, S , porosity from saturation to infection point, POR_{inf} ($\text{cm}^3 \text{cm}^{-3}$) and pore distribution index, λ_{inf} were calculated according to Han et al. [48]:

$$h_{inf} = \frac{1}{\alpha} \left(\frac{1}{m} \right)^{\frac{1}{n}} \quad (13)$$

$$\theta_{inf} = (\theta_s - \theta_r) \left[1 + \frac{1}{m} \right]^{-m} + \theta_r \quad (14)$$

$$S = n(\theta_s - \theta_r) \left[\frac{2n - 1}{n - 1} \right] \left(\frac{1}{n-2} \right) \quad (15)$$

$$POR_{inf} = (\theta_s - \theta_{inf}) \quad (16)$$

$$\lambda_{inf} = S / \theta_{inf} \quad (17)$$

2.6. Data analysis

For each soil, a linear regression analysis was performed between each considered soil variable and the vermicompost application rate, r . Specifically, the considered soil variables were: volumetric soil water content at selected pressure head values (i.e., θ_5 , $\theta_{7.5}$, θ_{10} , θ_{15} , θ_{20} , θ_{25} , θ_{30} , θ_{40} , θ_{50} , θ_{70} , θ_{100} , θ_{330} , θ_{1030} , θ_{3060} , and θ_{15300}), parameters of vG model (θ_r , θ_s , α and n), soil bulk density (ρ_b), capacitive-based indicators (P_{MAC} , AC , RFC , $PAWC$), location and shape parameters of pore volume distribution function (d_{mod} , d_{med} , d_m , SD , Sk , Ku) and inflection point indicators (h_{inf} , θ_{inf} , S , POR_{inf} , λ_{inf}). Therefore, 175 correlations (35 soil indicators x 5 soils) were considered. The influence of vermicompost addition was investigated by assessing the significance of the regression coefficients between the considered soil variables and the vermicompost to soil ratio, r ($p = 0.05$). Furthermore, for the significant correlations, the range of variability of each considered variable was calculated in the range between zero (non-amended soil or control) and the maximum vermicompost application rate (i.e., $r = 43\%$).

3. Results

3.1. Soil and vermicompost characteristics

According to the USDA classification, the five soils were sandy-loam (Castellaneta, CA, Ginosa, GI, and UNIPA, UN), loam (CREA, CR), and clay-loam (Orleans, OR) (Table 1). The percentage of fine particles, i.e., the sum of clay and silt content, ranged from 26 to 64 % following the order CA < GI < UN < CR < OR. According to common and practical criteria for soil textural grouping e.g., [61], three soils (CA, GI, UN) were coarse-textured soils and the remaining intermediate (CR) or fine (OR) textured soils. The selected soils belong to the Reference Soil Group of the Chromic Cambisols, according to the classification of the IUSS WRB Working Group [62].

Overall, the soils had very low organic matter (OM) contents (Table 1). With the only exception of the coarse soil at the UN site (OM = 6.14 %), the coarse soils showed lower organic matter contents (OM = 0.6–1.6 %) than the intermediate-fine soils (OM = 3.7–4.6 %). According to literature references suggesting a lower critical threshold of OM equal to 4 %, and optimal values in the range of 5–9% [5, 51], only UN and CR soils had adequate levels of organic matter, while the other soils were poorly rated. The soil pH ranged from neutral to moderately alkaline (7.3–8.0) and electrical conductivity was in general very low ($< 0.42 \text{ dS m}^{-1}$).

The vermicompost had levels of moisture and ash contents of 7.6 and 56.7 %, respectively, and a pH of 7.5; also, TOC and N contents were equal to 20 % and 16 %, respectively (Table 2). Therefore, due to oxidative processes, it has lost some organic matter, as compared both to the values reported in the manufacturer's technical sheet and the references (i.e., European standard NF U44-051 sets minimum thresholds of C/N at 8 and dry matter at 30 %). In accordance with the European law for "organic soil improvers-designations, specifications and marking", threshold limits for metallic trace elements (e.g., Cu and Pb) were always below the limits (Table 2). Likewise, P, K, and N were lower than the references, i.e., not higher than 3 % [24].

3.2. Influence of vermicompost on soil wettability

For the vermicompost, the median water drop penetration time was minimum at field capacity (FC) (WDPT = 3 s) and maximum under air-dried (AD) conditions (WDPT = 778 s). Intermediate median values of WDPT were obtained at permanent wilting point (WP) (WDPT = 169 s) and after oven-drying (OD) (WDPT = 250 s) (Table 3). According to the soil water repellency classification by Bisdom

et al. [53], 95 % of the individual WDPT values fell in the non-repellent class (WDPT <5 s) when the vermicompost was wetted at FC ($h = -100$ cm) (Fig. 2a). Vermicompost wettability decreased at WP ($h = -15000$ cm), given all individual droplets fell in the strongly hydrophobic class ($60 \leq \text{WDPT} < 600$ s), and was minimum for AD in which 95 % of the droplets showed severe hydrophobicity ($600 \leq \text{WDPT} < 3600$ s). Therefore, our results agree with literature that generally reported that dry soils exhibit the highest level of SWR whereas, above a critical moisture content, soils appear to be wettable [63]. In the case of vermicompost, the critical moisture threshold is located between FC and WP. It is not surprising that under OD condition vermicompost hydrophobicity was lower than under AD one. Indeed, it is likely that the organic matter content was partially volatilized during oven-drying treatment thus resulting in a lower hydrophobicity. For instance, reusing the same sample after oven-drying at 105 °C resulted in a decrease of the soil water repellency of two forest soils with similar OM content [54].

The median WDPT of soil/vermicompost mixtures ranged from 9 s (CA) to 33 s (OR) and generally increased following the same order of the percentage of fine particles, i.e. $CA < UN < GI < CR < OR$ (Table 3). According to Bisdom et al. [53] classification, 100 % of the individual WDPT values for all the considered soils fell in the slightly repellent class (Fig. 2b). Therefore, addition of vermicompost at the highest proportion rate determined the occurrence of a limited hydrophobicity in the tested soils. However, given the water repellency of vermicompost was maximum under air-dried conditions and declined as the vermicompost wetted, it can be argued that, under normal operative conditions, i.e., for lower vermicompost proportions and higher soil water contents, the hydrophobicity attributable to soil amendment with vermicompost could be considered negligible.

3.3. Vermicompost effects on water retention curve parameterization and soil bulk density

The vG unimodal model for the water retention curve adequately fitted the experimental data, with maximum average error (MAE) and root mean square error (RMSE) that were in the range $0.005\text{--}0.0022 \text{ cm}^3 \text{ cm}^{-3}$ for MAE, and $0.010\text{--}0.0018 \text{ cm}^3 \text{ cm}^{-3}$ for RMSE. Practically, individual maximum discrepancies between measured and estimated values were at most equal to $0.04 \text{ cm}^3 \text{ cm}^{-3}$ (only at a single soil pressure head value for UN).

For each considered soil and amendment rate, the results of water retention curves parameterization, carried out with vG model, are reported in Fig. 3. As expected, the retention curve scale parameter, n , of non-amended (control) soils increased from finer to coarser soils, ranging from 1.38 (OR) to 2.06 (GI). No particular trend was observed for θ_s , θ_r , and α parameters of control soils even if the former increased, as expected, from coarse soils to intermediate ones. The residual water content, θ_r , should be considered as a fitting parameter without a clear physical meaning.

Regardless of the considered soil, θ_r and θ_s significantly increased as the vermicompost to soil ratio increased, with determination coefficients (R^2) of the regression lines that generally increased from finer to coarser soils (Fig. 3). The same increasing and significant trend was detected for the α parameter of CA and GI soils but not for the other soils. Both increasing and decreasing trends, depending on the soil texture class, were obtained for n parameter (Fig. 3). A singular feature was observed for this parameter with a significantly increasing (or decreasing) trend for vermicompost concentrations up to about 15–17 % ($R^2 = 0.86\text{--}0.88$) followed by a plateau that highlights how higher vermicompost concentrations were no more effective in modifying the shape of the water retention curve. It was therefore concluded that vermicompost amendment had a significant general effect on the water retention curve of the considered soils.

A highly significant decreasing relationship between soil bulk density (ρ_b) and vermicompost to soil ratio was observed for the five soils with coefficients of determination in the range of 0.80–0.95 (Fig. 4). The soil ρ_b decrease is an expected consequence of the lower weight of the amended soils when an increasing percentage of vermicompost ($\rho_b = 0.409 \text{ g cm}^{-3}$) is added.

The volumetric water content generally increased with increasing the vermicompost dose with the only exception of the OR soil at very low soil pressure head values (i.e., between -330 and -15300 cm), where a decreasing trend was detected. Table 4 reports the coefficients of determination for the linear regressions between the volumetric water content, θ , at three reference values of applied pressure head ($h = -10$, -100 , and -15000 cm) and the vermicompost to soil ratio, r . The generally observed positive correlation between θ and r highlights that the vermicompost addition was effective in increasing the water retained by the soils. The reliability of the regression model was affected by soil texture and the considered pressure head value, given the coefficients of determination changed depending on these variables (Fig. 5). On average, the coefficients of determination were highest for CA and lowest for UN soils (i.e., 0.73 and 0.13, respectively). A minimum R^2 value was always detected that fell in the range from -20 to -100 cm of soil water pressure head (Fig. 5a). According to capillary law, this range of h corresponds to the size of the largest pores that are full of

Table 3

Statistics of water drop penetration time, WDPT, test (s), of vermicompost at different reference water content and the soil/vermicompost mixture at 43 % proportion by weight (OD = oven dried; AD = air dried; WP = wilting point; FC = field capacity; OR = Orleans; CR = CREA; UN = Campus UNIPA, GI = Ginosa; CA = Castellaneta).

	Vermicompost				Soil/vermicompost mixtures				
	OD	AD	WP	FC	OR	CR	UN	GI	CA
min	182	588	90	2	25	16	6	12	8
max	369	888	527	7	44	27	15	16	11
mean	256	756	210	3	34	21	11	14	9
median	250	778	169	3	33	19	11	14	9
CV%	22	12	64	37	18	17	25	11	12

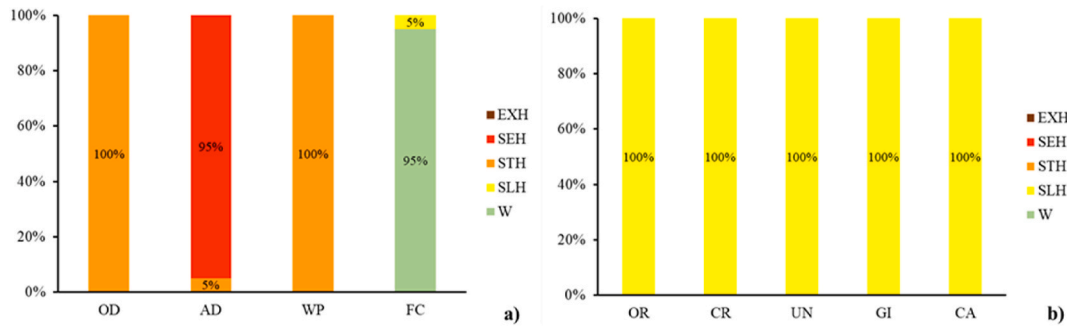


Fig. 2. Classification of SWR for a) the vermicompost at different reference water contents and b) the soil/vermicompost mixtures at 43 % proportion by weight (W = wettable; SLH = slightly hydrophobic; STH = strongly hydrophobic; SEH = severely hydrophobic; EXH = extremely hydrophobic; OD = oven dried; AD = air dried; WP = wilting point; FC = field capacity; OR = Orleans; CR = CREA; UN = Campus UNIPA, GI = Ginosà; CA = Castellaneta).

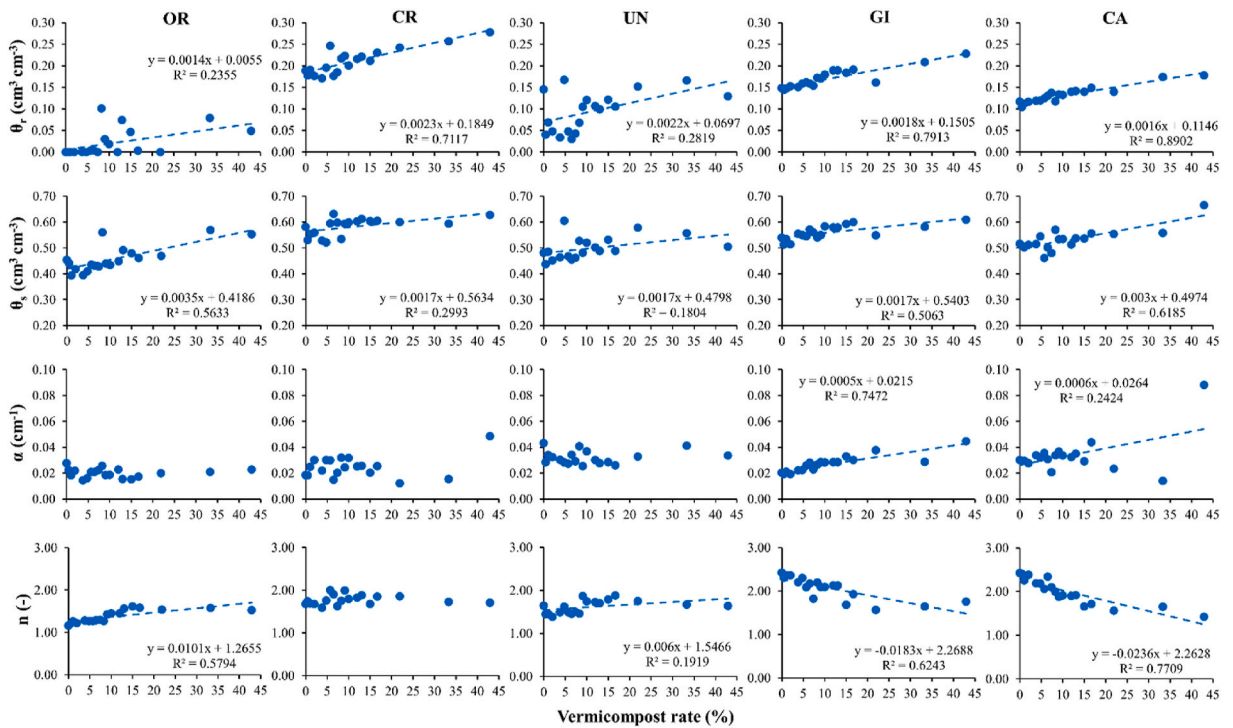


Fig. 3. Linear correlation between parameters of water retention curve vG model and vermicompost application rate. For a given soil and vG-parameter, only significant regression lines were depicted ($p = 0.05$) (OR = Orleans; CR = CREA; UN = Campus UNIPA, GI = Ginosà; CA = Castellaneta).

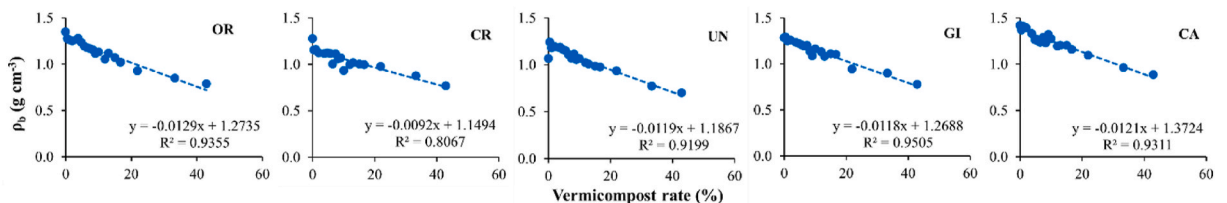


Fig. 4. Linear regressions between soil bulk density (ρ_b) and vermicompost application rate. For a given soil, significant regression lines were depicted ($P = 0.05$) (OR = Palermo Orleans; CR = Bari CREA; UN = Palermo Campus UNIPA, GI = Taranto Ginosà; CA = Taranto Castellaneta).

water between 30 and 150 μm thus indicating that vermicompost addition is less effective in determining modification of water retention in this pore size class. The pressure head h value corresponding to the minimum R^2 value increased as the clay content of soil increased (but similar findings were obtained when the percentage of fine particles was considered), suggesting that the effectiveness of vermicompost addition also depended on the soil texture (Fig. 5b).

3.4. Vermicompost effects on soil physical quality indicators

3.4.1. Capacitive-based indicators

For coarse (GI and CA) and fine (OR) soils, macroporosity (P_{MAC}) significantly increased as the vermicompost dose increased while no trend was observed for the remaining soils (CR and UN) (Table 5). The increase in soil macroporosity was larger for coarse than fine soils, given P_{MAC} increased from 0 to 0.03 $\text{cm}^3 \text{cm}^{-3}$ and from 0.01 to 0.05 $\text{cm}^3 \text{cm}^{-3}$ for GI and CA, respectively, as a consequence of vermicompost addition at a rate of 43 % while, for the same application dose, the increase in P_{MAC} was only of 0.004 $\text{cm}^3 \text{cm}^{-3}$ for OR soil.

Vermicompost amendment determined an increase in air capacity (AC) for OR and UN soils and a decrease in AC for CA soil (Table 5). The increase in soil air capacity was larger for the fine OR ($\Delta_{AC} = 0.14 \text{ cm}^3 \text{cm}^{-3}$) than the coarse UN soil ($\Delta_{AC} = 0.05 \text{ cm}^3 \text{cm}^{-3}$). The capacity-based indicators P_{MAC} and AC (eqs. (3) and (4)) are expressive of the water retained in pores with equivalent diameter higher than, respectively, 300 and 30 μm . Therefore, vermicompost addition was effective in increasing the relative volume of both the porosity classes in the fine OR soil, of only the smaller porosity class in the intermediate UN soil, whereas it increased the larger class (P_{MAC}) and decreased the smaller one (AC) in the coarse CA soil. Independently of the statistical significance, it is worth noting that P_{MAC} trend was always positive with r , i.e., it increased with vermicompost addition, whereas the AC trend inverted its sign in the passage from fine to coarse soils. Indeed, the highest positive correlation coefficient was obtained for OR soil (percentage of fine particles, Si + Cl = 64 %) and the lowest negative correlation coefficient for CA soil (Si + Cl = 26 %) (Table 5).

The relative field capacity (RFC; eq. (5)) significantly increased with vermicompost for the coarse soils (CA, GI) and significantly decreased for the fine one (OR), showing no trend for the remaining soils. Modeled data suggested that RFC increased from 0.41 to 0.72 for CA and from 0.52 to 0.63 for GI, while it decreased from 0.78 to 0.57 for OR. Considering that the optimal balance between the root-zone soil water capacity and the soil air capacity occurs in the range $0.6 \leq RFC \leq 0.7$ [64], amendment with vermicompost resulted effective in correcting the water-limited or the air-limited conditions occurring, respectively, in coarse and fine soils.

Plant available water capacity (PAWC; eq. (6)) significantly increased only for coarse soils (GI and CA) with a more marked effect on the coarsest soil given that, compared to the control, PAWC increased by 0.24 $\text{cm}^3 \text{cm}^{-3}$ (Table 5). The ideal condition for maximal root growth and function corresponds to $PAWC \geq 0.20 \text{ cm}^3 \text{cm}^{-3}$ [64]. Thus, vermicompost amendment yielded a remarkable improvement of the soil physical quality classification according to this indicator that shifted from “poor” ($PAWC < 0.10 \text{ cm}^3 \text{cm}^{-3}$) to optimal for coarse-textured soils.

3.4.2. Pore volume distribution indicators

The location parameters of the pore volume distribution function, d_{mod} , d_{med} and d_m (eqs. (7)–(9)), always increased significantly with the vermicompost rate for OR and UN soils; the former soil showed the largest increments in d_{mod} , d_{med} and d_m , that increased by a factor 2, 6 and 10, respectively, from $r = 0$ –43 % (Table 5). The opposite result was found for the CA soil that showed d_{med} and d_m values that significantly decreased with the vermicompost rate and a negative, but not significant, trend for d_{mod} . No correlation was in general observed between the location parameters and r for the CR and GI soils. Lastly, d_{mod} always significantly increased, except for CA and CR soils for which a significant relationship was not observed (Table 5). The effect of vermicompost addition on shape indicators SD and Sk (eqs. (10) and (11)) agreed with those obtained for capacitive indicators, with an opposite behaviour between coarse and fine soils (Table 5). Finally, kurtosis (Ku ; eq. (12)) was found to significantly increase for the two coarsest soils (GI and CA) while no significant relationships were observed for the other soils (CR, UN and OR).

In agreement with the optimal values proposed in the literature for these indicators [5], results suggested that improvements in modal diameter were obtained only for coarse soils (UN and GI) because d_{mod} exceeded the suggested minimum optimal value of 60 μm only when the highest dose was applied. The other indicators related to central values of the pore size distribution (d_{med} and d_m) generally exceeded the literature references suggested for agricultural soils [5]. Parameter SD quantifies the size range of equivalent pore diameters, i.e., the sorting of pore diameters, with $SD = 1$ indicating no variation in pores diameter (pores with the same size). Therefore, increasing SD indicates an increasing range in pore diameters [5]. This occurred only for coarse soils (GI and CA), while the opposite result was detected for UN and OR sites. Negative Sk values indicate a pore size distribution shifted to small pores whereas positive Sk values shifted to large pores. Therefore, the observed significant correlations suggested that the addition of vermicompost

Table 4

Coefficients of determination (R^2) for the correlations between modeled soil water retention values and vermicompost application doses for three selected pressure head values corresponding to matrix capacity (θ_{10}), field capacity (θ_{100}) and permanent wilting point (θ_{15300}). R^2 values with the minus sign indicate decreasing correlations. The significant correlations were marked with asterisks (** $p < 0.01$; * $p < 0.05$).

	Orleans (OR)	CREA (CR)	UNIPA (UN)	Ginosa (GI)	Castellaneta (CA)
θ_{10}	0.5597**	0.2255*	0.1795	0.3188*	0.5566**
θ_{100}	0.0013	0.1862	0.0200	0.6316**	0.8263**
θ_{15300}	-0.1498	0.7486**	0.2450*	0.8584**	0.9580**

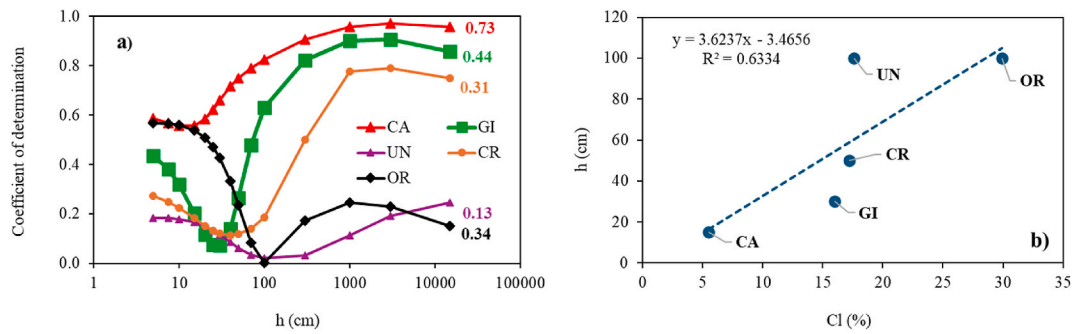


Fig. 5. Values of the coefficient of determination (R^2) for the linear regression between soil water content and vermicompost application rate as a function of soil pressure head values h (a) (curve labels indicate the mean R^2 over the entire h range), and relationship between the h values corresponding to the minimum R^2 values in figure a) and the soil clay fraction (Cl) (b) (OR = Orleans; CR = CREA; UN = Campus UNIPA, GI = Ginosà; CA = Castellaneta).

Table 5

Coefficients of determination (R^2) for the correlation between soil physical indicators and vermicompost rate. R^2 values with the minus sign indicate decreasing correlations. The significant regressions were marked with asterisks (** $p < 0.01$; * $p < 0.05$). For each significant regression, the calculated values between minimum and maximum vermicompost concentration ($r = 0$ and 43 %) are reported in brackets.

	Orleans (OR)	CREA (CR)	UNIPA (UN)	Ginosà (GI)	Castellaneta (CA)
P_{MAC} ($cm^3\ cm^{-3}$)	0.2525* (0.01–0.014)	0.1170 (n.a.)	0.0115 (n.a.)	0.7809** (0–0.03)	0.3924** (0.01–0.05)
AC ($cm^3\ cm^{-3}$)	0.8542** (0.09–0.23)	0.0001 (n.a.)	0.2652* (0.20–0.25)	–0.0621 (n.a.)	–0.2813* (0.29–0.18)
RFC (–)	–0.6625** (0.78–0.57)	0.0266 (n.a.)	–0.1394 (n.a.)	0.3424** (0.52–0.63)	0.5933** (0.41–0.72)
PAWC ($cm^3\ cm^{-3}$)	0.0013 (n.a.)	0.1862 (n.a.)	0.0200 (n.a.)	0.6316** (0.08–0.18)	0.8263** (0.002–0.24)
d_{mod} (μm)	0.7747** (16–38)	0.0787 (n.a.)	0.2138* (46–65)	0.3833** (50–72)	–0.0005 (n.a.)
d_{med} (μm)	0.7554** (4–26)	0.0681 (n.a.)	0.2705* (28–49)	0.0251 (n.a.)	–0.3511** (61–28)
d_m (μm)	0.7454** (2–21)	0.0615 (n.a.)	0.2709* (22–42)	–0.0018 (n.a.)	–0.5343** (57–18)
SD (–)	–0.2116* (62 to –36)	–0.0126 (n.a.)	–0.2446* (13–8)	0.5222** (3–6)	0.8521** (2–9)
Sk (–)	0.5755** (–0.6 to –0.3)	0.0059 (n.a.)	0.2223* (–0.4 to –0.3)	–0.5953** (–0.2 to –0.4)	–0.8699** (–0.2 to –0.5)
Ku (–)	0.0346 (n.a.)	–0.0035 (n.a.)	–0.1868 (n.a.)	0.6153** (1.13–1.15)	0.8145** (1.13–1.16)
h_{inf} (cm)	–0.6001** (181–50)	–0.0002 (n.a.)	–0.2616* (66–43)	–0.2929* (59–41)	0.1569 (n.a.)
θ_{inf} ($cm^3\ cm^{-3}$)	0.8326** (0.22–0.46)	0.3911** (0.35–0.62)	0.7913** (0.26–0.54)	0.9300** (0.28–0.57)	0.8492** (0.23–0.52)
S (–)	0.9123** (0.04–0.18)	0.2202* (0.10–0.14)	0.7288** (0.08–0.17)	–0.0514 (n.a.)	–0.2518* (0.13–0.10)
POR_{inf} ($cm^3\ cm^{-3}$)	–0.0182 (n.a.)	<0.0001 (n.a.)	–0.0584 (n.a.)	–0.3351** (0.37–0.32)	–0.3972** (0.35–0.31)
λ_{inf} (–)	0.5791** (0.22–0.51)	0.0026 (n.a.)	0.1968 (n.a.)	–0.6231** (0.81–0.38)	–0.7850** (0.81–0.24)

P_{MAC} , macroporosity; AC, air capacity; RFC, relative field capacity; PAWC, plant available water capacity; d_{mod} , modal diameter; d_{med} median diameter; d_m , mean diameter; SD, standard deviation, Sk, asymmetry, Ku, kurtosis of soil pores distribution; h_{inf} , soil pressure head at the water retention curve inflection point; θ_{inf} , soil water content at the inflection point; S, Dexter’s S index; POR_{inf} , soil porosity at the inflection point; λ_{inf} , pore distribution index.

improved the relatively higher proportion of larger pores of UN and OR soils (Table 5). It is interesting to note that, for OR soil, a threshold behaviour was identified because, starting from a value of –0.65 (control), Sk values linearly increased to about –0.37 (vermicompost rate of about 17 %) to remain stable up to the highest vermicompost concentrations. Since this value approached the optimal values suggested for this soil indicator ($Sk = -0.43$ to -0.41), the positive impact of the amendment is confirmed. The pore distributions were leptokurtic ($Ku > 1$) for coarse soils (GI and CA), namely more peaked in the center and more tailed in the extremes than the lognormal curve [5], with Ku values that were optimal ($Ku = 1.13$ – 1.14) approximately up to 20 % of vermicompost rate, depending on the considered soil.

3.4.3. Inflection point indicators

Soil pressure head, h_{inf} (eq. (13)), at the inflection point of the water retention curve decreased significantly as the vermicompost rate increased for GI, UN, and OR, while no trend was observed for the other soils. In particular, greater changes were detected for the fine (about 130 cm) than coarse or intermediate (about 20 cm) textured soils (Table 5). Similarly to the θ - h results earlier reported, the water content θ_{inf} corresponding to the inflection point (eq. (14)) always significantly increased with vermicompost rate. According to the soil texture, the improvements in estimated θ_{inf} , i.e., differences between max and min values, increased from fine soils ($\Delta\theta_{inf} = 0.24\ cm^3\ cm^{-3}$ for OR), to intermediate ($\Delta\theta_{inf} = 0.27$ and $0.28\ cm^3\ cm^{-3}$, respectively, for CR and UN) to coarse soils ($\Delta\theta_{inf} = 0.29\ cm^3\ cm^{-3}$ for both CA and GI); this confirms that the assumed sequence for soil texture groupings reasonably explains the effects of vermicompost addition with the higher improvements observed for coarse soils (Table 5). The slope of the water retention curve at the inflection point (eq. (15)), increased as the vermicompost rate increased for OR, CR and UN and decreased only for CA soil. It is worth noting that the regression equation shifted its slope by increasing the fine particle content from significantly negative ($R^2 = 0.25$) for CA to significantly positive ($R^2 = 0.91$) for OR (Table 5). Soil porosity from saturation to inflection point, POR_{inf} (eq. (16)) significantly

decreased as the vermicompost rate increased only for the coarsest soils (GI and CA), suggesting an impoverishment in soil porosity (up to 4–5%) when these soils amended with the highest dose of vermicompost. The pore distribution index, λ_{inf} (eq. (17)), significantly decreased with the vermicompost rate for coarse soils (GI and CA) and increased significantly for fine (OR) soil (Table 5). In agreement with the coarse texture of the GI and CA soils, λ_{inf} started from a common value of 0.81 for the control ($r = 0$), to reach 0.38 or 0.24 for GI and CA, respectively, when amended at $r = 43\%$. Overall, references of literature for this indicator suggest that it may decrease from coarser to finer sandy soils [48]. Therefore, a decrease of λ_{inf} as a function of amendment rate appears plausible, as a consequence of the reduction in soil porosity. On the other hand, for the fine OR soil λ_{inf} significantly increased from 0.22 of the control to 0.51 at $r = 43\%$. It is worth noting that the pore distribution index of a not amended fine soil could be comparable with that of sandy soil amended at the higher vermicompost concentrations, as very similar results were detected between CA and OR (Table 5).

4. Discussion

According to literature findings, vermicompost addition can significantly mitigate the loss of organic carbon due to soil tillage [65]. However, the scientific literature relating to this soil amendment is particularly lacking regarding the overall effect on the main soil physical and hydraulic properties, and a very limited literature reports its effects in the short-term. Specifically, most studies have considered one or, at the most, two soil properties (i.e., bulk density, porosity, or aggregates stability), but there are no studies that simultaneously evaluated the effects on several soil physical properties as a function of both different soil textures and increasing amendment rates. For instance, Albiach et al. [31] evaluated the effect of $2.4 \text{ t ha}^{-1} \text{ yr}^{-1}$ of a commercial vermicompost on the aggregates structural stability of a medium textured soil. They found that vermicompost did not produce any significant change in stability of soil aggregates, suggesting that rates recommended by the producers are too low to be effective. Arabi et al. [34] evaluated the effects of $2\text{--}6 \text{ t ha}^{-1}$ of vermicompost on the bulk density of a silty clay loam. According to their results, vermicompost significantly improved the soil bulk density (already at the minimum rate of 2 t ha^{-1}) and enhanced the water retention in aggregates compared with the not amended soil. Mengistu et al. [33] studied the effects of $3.7\text{--}15 \text{ t ha}^{-1}$ of vermicompost on the bulk density and porosity of a sandy clay loam. The independently determined soil bulk density and porosity tended to decrease and increase, respectively, with an increased rate of vermicompost application. However, such response was significant only when the vermicompost was applied at a relatively higher rate ($\geq 11.25 \text{ t ha}^{-1}$). Consistent effects on soil porosity were reported by Azarmi et al. [35] for a loamy soil amended with rates of $5\text{--}15 \text{ t ha}^{-1}$. Baghbani-Arani et al. [25] concluded that the treatments with vermicompost (2.7 t ha^{-1}) were able to alleviate water deficit stress. Vermicompost improved the biological yield of fenugreek by improving the physicochemical conditions of the soil (e.g., water contents at field capacity and wilting point), especially in the water deficit stress conditions, thus reducing the usage of chemical fertilizers in line with the goals of sustainable agriculture. An investigation on the effects of vermicompost on multiple soil variables (i.e., water holding capacity, infiltration rate, bulk density, aggregate stability, and water use efficiency) for a sandy clay loam soil was conducted by Sharma et al. [32], although they considered a biochar-vermicompost mixture for which the vermicompost rate was selected only according to the recommended nitrogen dose.

Evaluating the short, or very short-term, effects of soil amendment could be decisive for water availability assessment in arid environments or, more generally, during prolonged dry periods. However, although the medium-long-term effect on soil physical and hydraulic properties is well documented, as reported for example by the review of Kranz et al. [6], the short-term impact has been poorly considered. For example, Black et al. [66] reported that the effect on PAWC should be assessed within a few months of implementation. Indeed, they studied the effects of compost at several application rates and showed that the PAWC of amended plots was greater than not amended plots, but much of such increase was lost within about 6 months. Even shorter response times were sometimes considered when the effect on soil bulk density was studied [6]. For instance, Somerville et al. [67] compared the amendment effects on three textured soils after 3 months, showing a reduction in bulk density values of 15–25 % in amended soils. A significant reduction of bulk density after 7 months of investigation was reported by Mohammadshirazi et al. [68] when they compared tillage with and without compost application to a compacted control soil. Consequently, the present research accounts for the effects on multiple soil indicators in the very short-time after amendment (<1–2 months), providing findings that fill a gap of knowledge in this field of research.

Generally, the agronomic practice aimed at improving the soil physical properties using organic amendments also considers the induced effects on soil fertility. In this case, the amendment rate for field application is more calibrated to improve the availability of chemical elements than to improve the soil physical properties. For instance, Khalifa et al. [30] applied 5 and 10 t ha^{-1} of vermicompost to reduce the water stress impact on some soil properties and on water productivity in terms of barley yield. The results showed that vermicompost improved the physical and chemical properties of soils, as compared with compost, because soil bulk density decreased by 2.2 %; also, there was a significant increase in soil organic carbon, available nitrogen, and field capacity by 44 %, 14 %, and 19 %, respectively [30]. However, to our knowledge, the amendment rate is never diversified according to the considered soil texture or the expected effects. In their review on the effects of compost incorporation on soil physical properties in urban soils, Kranz et al. [6] emphasized the fact that, among the current research gaps on this topic, the rates and depths of compost incorporation were not experimentally determined or optimized using laboratory or field experiments.

In this investigation we considered two of the most critical experimental factors reported in the literature, namely the soil texture and the amendment rate, to investigate the vermicompost effects on the soil water/air relationship and learn from the findings obtained how far the estimates suggested for field amendments differ from those obtained in the laboratory. Since compost can have hydrophobic behaviour, the amendment effects on the soil retention were evaluated in the very short-term, especially to account for the possible negative implications when periods of prolonged dryness occur.

The selected soils included three relatively coarse-textured (sandy loam) soils (i.e., sand content between 53 and 74 %), as such

soils are the most deficient in water retention and, consequently, they could mostly benefit from amendment. The minimum level of $PAWC$ should be at least equal to $0.15 \text{ cm}^3 \text{ cm}^{-3}$ [5], being considered “poor” or “arid” those soils that can store, and provide, less than $0.10 \text{ cm}^3 \text{ cm}^{-3}$ of water to plant roots. The three sandy loam soils had poor characteristics as, on average, they had $PAWC$ of about $0.056 \text{ cm}^3 \text{ cm}^{-3}$ far below the optimal range (Fig. 6). This means that, referring to rainfed agriculture, they would need a vermicompost addition dose of about one-third by volume (34 %) in the root zone to reach the goal of $PAWC = 0.15 \text{ cm}^3 \text{ cm}^{-3}$. Conversely, incorporating an average vermicompost amount of 15 t ha^{-1} , as suggested in many applications, would not have a substantial impact, as $PAWC$ would increase only by about $0.066 \text{ cm}^3 \text{ cm}^{-3}$ (Fig. 6).

Reynolds et al. [5] applied $75 \text{ e } 300 \text{ t ha}^{-1}$ of compost in the first 10 cm of a clay loam soil to assess the impact in terms of physical quality and productivity. Regarding $PAWC$, they showed a lack of improvement ($PAWC = 0.13 \text{ cm}^3 \text{ cm}^{-3}$) when they considered the lowest amendment rate and an optimal improvement ($PAWC = 0.22 \text{ cm}^3 \text{ cm}^{-3}$) when considered the highest level. Compared to the control, the maize yield increased, respectively, by 1.4 or 2.1 t ha^{-1} when the lowest and highest compost rates were added [5].

Our laboratory data for the sandy loam soils agreed with those by Reynolds et al. [5] because, concerning the first 5 cm of the soil, it is expected to reach an acceptable level of $PAWC$ by implementing about 146 t ha^{-1} of vermicompost. However, such effect of organic amendment should be limited to a soil condition shortly after the main tillage, because the effect due to soil consolidation was not considered in this investigation. Moreover, such estimation does not take into account the effect of hysteresis of the soil water retention curve. For the UN sandy loam soil, Bondi et al. [47] showed that $PAWC$ is strongly influenced by hysteresis with an average $PAWC$ value measured during the drainage that was 112 % higher than during wetting. Therefore, this effect could be easily considered by determining, for example, the mean changes between the two main processes.

As expected, different soil physical quality parameters were affected by vermicompost addition in the fine OR soil. The macropore and drainable porosity increased as also confirmed by the central diameters of the pore size distribution function. Conversely, the $PAWC$ was practically unaffected. The decrease of SD and Ku and the shift of S highlighted that the pore size distribution tended to become more uniform and skewed towards the larger pore diameters. The physical quality of the intermediate CR soil was minimally affected by the vermicompost amendment. Therefore, the results unequivocally show that vermicompost influenced different soil physical qualities depending on the soil texture, i.e., mostly water availability for plants in sandy loam soils and water/air circulation capacity in clay loam soil. For the intermediate loam CR soil, addition of vermicompost was less effective, and further investigation is needed in these soils.

Another point that deserves further investigation is related to the temporal persistence of the amendment benefits. Overall, a reduction in the soil water retention in larger pores could be expected some months (between 6 and 12) after organic amendment, as reported for both coarse [69] and fine [15] textured soils. In both cases, soil reconsolidation determined an increase of soil bulk density with a corresponding decrease of the capacitive indicators related to drainable porosity (AC and P_{MAC}) and an increase of those related to water availability for plants ($PAWC$). Consistent results were obtained also with specific reference to the GI soil amended with 5 % vermicompost (unpublished data). In this case, nine months after amendment, soil water content significantly reduced by 6 % at saturation and 5 % at field capacity, thus determining a reduction of AC (from 0.02 to $0.01 \text{ cm}^3 \text{ cm}^{-3}$) and P_{MAC} (from 0.26 to $0.25 \text{ cm}^3 \text{ cm}^{-3}$), and an increase of $PAWC$ (from 0.16 to $0.24 \text{ cm}^3 \text{ cm}^{-3}$).

5. Conclusions

The application of vermicompost can effectively improve the physical quality of soils in terms of increased plant water availability and equilibrate air-to-water ratio in the root zone. However, a possible drawback of vermicompost amendment could be related to the induced soil hydrophobicity.

Despite being the subject of several studies, thorough evaluations of the impact of vermicompost addition on the soil hydrophobicity and water retention under different application rates and contrasting soil textures are lacking in the literature. This investigation was conducted to fill the knowledge gap in these factors related to vermicompost application. At this aim, hydrophobicity of vermicompost and soil/vermicompost mixtures and 35 soil physical indicators related to bulk density, soil water retention curve and pore size distribution functions were calculated for five differently textured soils (from sandy loam to clay loam) amended with vermicompost rates up to 43 % by weight that, for an application depth of 5 cm, corresponded to field doses up to $176\text{--}213 \text{ t ha}^{-1}$.

Vermicompost was wettable at field capacity but showed strong to severe hydrophobicity for lower moisture contents. However, even under the most severe conditions of moisture content (air dried condition) and application rate ($r = 43 \%$), all the soil/vermicompost mixtures were slightly water repellent thus indicating that, for lower vermicompost doses and higher soil water contents, the hydrophobicity attributable to soil amendment with vermicompost could be considered negligible.

An expected decrease in soil bulk density was observed as a consequence of the lower weight of the amended soils when an increasing percentage of vermicompost was applied. This resulted in increased water retained in the entire range of the explored pressure head values for the two coarsest soils (GI and CA) and in an increase of the water content only at higher h values (i.e., for larger pores) for the finest OR soil. A limited effectiveness of vermicompost in improving water retained at intermediate pressure head values (i.e., for h values between -20 and -100 cm) was also detected.

Consequently, different effects in terms of soil physical indicators were observed depending on the soil texture. In the coarse soils, indicators linked to water availability for plants ($PAWC$ and RFC) generally increased whereas the location indicators of pore size distribution decreased, thus indicating that the most frequent pore diameter shifted towards lower sizes. The opposite result was observed for the fine OR soil whereas no apparent effect of vermicompost addition was observed for the intermediate CR soil. For the three sandy loam soils, vermicompost application at rates of about 34 % allowed to improve the poor plant available water capacity ($PAWC < 0.10 \text{ cm}^3 \text{ cm}^{-3}$) up to values close to optimal conditions recommended in the literature ($PAWC \geq 0.15 \text{ cm}^3 \text{ cm}^{-3}$). In the fine

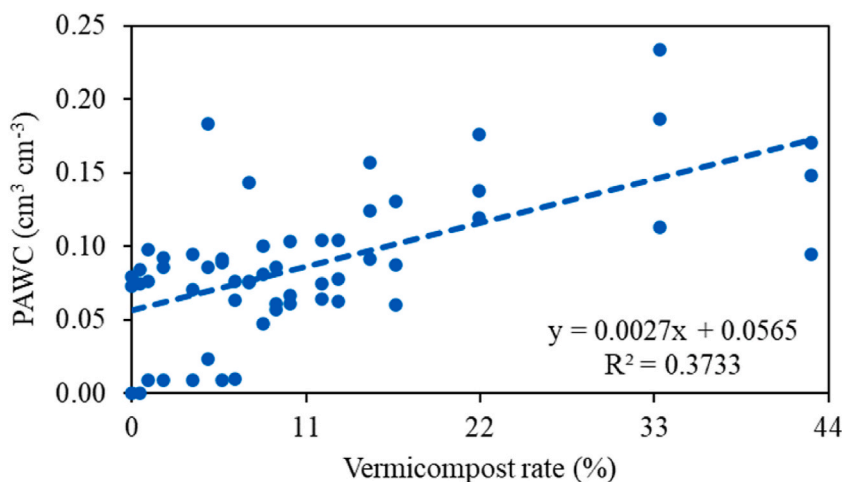


Fig. 6. Relationship between the plant available water capacity (PAWC) and the dose of vermicompost added to the sandy loam soils.

OR soil, the PAWC was unaffected by vermicompost amendment but macropores and drainable porosity increased thus determining more favourable conditions for air and water circulation.

There is still a need for verification in actual agricultural field conditions because a variety of factors, including vermicompost properties and site-specific climate, may influence the temporal persistence of the amendment benefits. However, the present study, despite being conducted at a laboratory scale, can be considered a first comprehensive step towards understanding the role of vermicompost in soil physical quality improvement under different application rates and textural classes. Moreover, the results are novel as, to our knowledge, a throughout assessment of short-term effects of vermicompost addition on soil hydrophobicity, water retention, and related soil physical quality indicators, involving five differently textured soils and a range of amendment from 3 up to 200 t ha⁻¹ has never been conducted before. Applying the same experimental approach, further steps could be made, for example, to quantify the possible amendment effects after a longer period, typically after about a year, to check the residual effects on water retention and hydrophobicity and the improvements due to structural restoration of the soil.

Data availability statement

The entire raw database has been uploaded to Zenodo. Available at <http://doi.org/10.5281/zenodo.11198042>.

CRedit authorship contribution statement

Mirko Castellini: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, conceptualization. **Cristina Bondi:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation. **Luisa Giglio:** Investigation, Formal analysis, Data curation. **Massimo Iovino:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

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.

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References

- [1] R. Lal, Soil Organic Matter and Feeding the Future: Environmental and Agronomic Impacts, first ed., CRC Press, 2021 <https://doi.org/10.1201/9781003102762>.
- [2] R. Lal, Restoring soil quality to mitigate soil degradation, Sustainability 7 (2015) 5875–5895, <https://doi.org/10.3390/su7055875>.
- [3] M. Castellini, M. Iovino, M. Pirastu, M. Niedda, V. Bagarello, Use of BEST procedure to assess soil physical quality in the Baratz Lake catchment (Sardinia, Italy), Soil Sci. Soc. Am. J. 80 (2016) 742–755, <https://doi.org/10.2136/sssaj2015.11.0389>.
- [4] R. Lal, Challenges and opportunities in soil organic matter research, Eur. J. Soil Sci. 60 (2) (2009) 158–169, <https://doi.org/10.1111/j.1365-2389.2008.01114.x>.
- [5] W.D. Reynolds, C.F. Drury, C.S. Tan, C.A. Fox, X.M. Yang, Use of indicators and pore volume-function characteristics to quantify soil physical quality, Geoderma 152 (2009) 252–263, <https://doi.org/10.1016/j.geoderma.2009.06.009>.
- [6] C.N. Kranz, R.A. McLaughlin, A. Johnson, G. Miller, J.L. Heitman, The effects of compost incorporation on soil physical properties in urban soils – a concise review, J. Environ. Manag. 261 (2020) 110209, <https://doi.org/10.1016/j.jenvman.2020.110209>.
- [7] S.K. Lam, L. Xia, D. Chen, Boosting the benefits of compost, Nat Food 3 (2022) 682–683, <https://doi.org/10.1038/s43016-022-00597-6>.
- [8] J. Viaene, J. Van Lancker, B. Vandecasteele, K. Willekens, J. Bijtbeier, G. Ruysschaert, B. Reubens, Opportunities and barriers to on-farm composting and compost application: a case study from northwestern Europe, Waste Manag. 48 (2016) 181–192, <https://doi.org/10.1016/j.wasman.2015.09.021>.
- [9] M. Ros, S. Klammer, B. Knapp, K. Aichberger, H. Insam, Long-term effects of compost amendment of soil on functional and structural diversity and microbial activity, Soil Use Manag. 22 (2006) 209–218, <https://doi.org/10.1111/j.1475-2743.2006.00027.x>.
- [10] T. Garbowski, D. Bar-Michalczuk, S. Charazińska, B. Grabowska-Polanowska, A. Kowalczyk, P. Lochyński, An overview of natural soil amendments in agriculture, Soil Tillage Res. 225 (2023) 105462, <https://doi.org/10.1016/j.still.2022.105462>.
- [11] P.A.Y. Ampim, J.J. Sloan, R.I. Cabrera, D.A. Harp, F.H. Jaber, Green roof growing substrates: types, ingredients, composition and properties 1, J. Environ. Hortic. 28 (4) (2010), <https://doi.org/10.24266/0738-2898-28.4.244>, 244–242.
- [12] L.J.M. Githinji, J.H. Dane, R.H. Walker, Physical and hydraulic properties of inorganic amendments and modeling their effects on water movement in sand-based root zones, Irrigat. Sci. 29 (1) (2011) 65–77, <https://doi.org/10.1007/s00271-010-0218-4>.
- [13] G. Gugliuzza, A. Verduci, M. Iovino, Water retention characteristics of substrates containing biochar and compost as peat and perlite replacements for ornamental plant production, Acta Hortic. 1305 (2021) 507–511, <https://doi.org/10.17660/ActaHortic.2021.1305.67>.
- [14] A. Ibrahim, R. Horton, Biochar and compost amendment impacts on soil water and pore size distribution of a loamy sand soil, Soil Sci. Soc. Am. J. 85 (4) (2021) 1021–1036, <https://doi.org/10.1002/saj2.20242>.
- [15] M. Castellini, M. Diacono, A. Preite, F. Montemurro, Short- and medium-term effects of on-farm compost addition on the physical and hydraulic properties of a clay soil, Agronomy 12 (2022) 1446, <https://doi.org/10.3390/agronomy12061446>.
- [16] L. Dong, W. Zhang, Y. Xiong, J. Zou, Q. Huang, X. Xu, P. Ren, G. Huang, Impact of short-term organic amendments incorporation on soil structure and hydrology in semi-arid agricultural lands, Int. Soil Water Conserv. Res. 10 (2022) 457–469, <https://doi.org/10.1016/j.iswcr.2021.10.003>.
- [17] C. Védère, M. Lebrun, P. Biron, S. Planchais, M. Bordenave-Jacquemin, N. Honvault, C. Rumpel, The older, the better: ageing improves the efficiency of biochar-compost mixture to alleviate drought stress in plant and soil, Sci. Total Environ. 856 (2023) 158920, <https://doi.org/10.1016/j.scitotenv.2022.158920>.
- [18] D. Das, K. Abhisheka, P. Banik, P. Bhattacharyay, A valorisation approach in recycling of organic wastes using low-grade rock minerals and microbial culture through vermicomposting, Environ. challenges 5 (2021) 100225, <https://doi.org/10.1016/j.envc.2021.100225>.
- [19] H.T. Zhao, T.P. Li, Y. Zhang, J. Hu, Y.C. Bai, Y.H. Shan, F. Ke, Effects of vermicompost amendment as a basal fertilizer on soil properties and cucumber yield and quality under continuous cropping conditions in a greenhouse, J. Soils Sediments 17 (12) (2017) 2718–2730, <https://doi.org/10.1007/s11368-017-1744-y>.
- [20] S. Hou, R. Zhang, C. Zhang, L. Wang, H. Wang, Role of vermicompost and biochar in soil quality improvement by promoting *Bupleurum falcatum* L. nutrient absorption, Soil Use Manag. 39 (4) (2023) 1600–1617, <https://doi.org/10.1111/sum.12955>.
- [21] C. Fischer, C. Roscher, B. Jensen, N. Eisenhauer, J. Baade, S. Attinger, A. Hildebrandt, How do earthworms, soil texture and plant composition affect infiltration along an experimental plant diversity gradient in grassland? PLoS One 9 (6) (2014) e98987 <https://doi.org/10.1371/journal.pone.0098987>.
- [22] J. Hallam, J. Holden, D.A. Robinson, M.E. Hodson, Effects of winter wheat and endogeic earthworms on soil physical and hydraulic properties, Geoderma 400 (2021) 115126, <https://doi.org/10.1016/j.geoderma.2021.115126>.
- [23] M. Blouin, J. Barrere, N. Meyer, S. Lartigue, S. Barot, J. Mathieu, Vermicompost significantly affects plant growth. A meta-analysis, Agron. Sustain. Dev. 39 (2019) 34, <https://doi.org/10.1007/s13593-019-0579-x>.
- [24] V. Ducasse, Y. Capowiez, J. Peigné, Vermicomposting of municipal solid waste as a possible lever for the development of sustainable agriculture. A review, Agron. Sustain. Dev. 42 (2022) 89, <https://doi.org/10.1007/s13593-022-00819-y>.
- [25] A. Baghbani-Arani, S.A.M. Modarres-Sanavy, M. Poureisa, Improvement of the soil physicochemical properties and fenugreek growth using zeolite and vermicompost under water deficit conditions, J. Soil Sci. Plant Nutr. 21 (2021) 1213–1228, <https://doi.org/10.1007/s42729-021-00434-y>.
- [26] M. Ebrahimi, M.K. Souiri, A. Mousavi, N. Sahebani, Biochar and vermicompost improve growth and physiological traits of eggplant (*Solanum melongena* L.) under deficit irrigation, Chem. Biol. Technol. Agric. 8 (2021) 19, <https://doi.org/10.1186/s40538-021-00216-9>.
- [27] H. Ma, S. Zhao, J. Hou, T. FeYissa, Z. Duan, Z. Pan, K. Zhang, W. Zhang, Vermicompost improves physicochemical properties of growing medium and promotes plant growth: a meta-analysis, J. Soil Sci. Plant Nutr. 22 (2022) 3745–3755, <https://doi.org/10.1007/s42729-022-00924-7>.
- [28] P.A. Rivier, D. Janniczky, A. Nemes, A. Makó, G. Barna, N. Uzinger, C. Farkas, Short-term effects of compost amendments to soil on soil structure, hydraulic properties, and water regime, J. Hydrol. Hydromechanics 70 (1) (2022) 74–88, <https://doi.org/10.2478/johh-2022-0004>.
- [29] X.N. Liu, J. Zhang, Q. Wang, H. Shagheh, T.T. Chang, Y.A. Hamoud, Modification of soil physical properties by maize straw biochar and earthworm manure to enhance hydraulic characteristics under greenhouse condition, Sustainability 14 (20) (2022) 13590, <https://doi.org/10.3390/su142013590>.
- [30] T.H. Khalifa, S.A. Mariey, Z.E. Ghareeb, I.A. Khatib, A. Alyamani, Effect of organic amendments and nano-zinc foliar application on alleviation of water stress in some soil properties and water productivity of barley yield, Agronomy 12 (2022) 585, <https://doi.org/10.3390/agronomy12030585>.
- [31] R. Albiach, R. Canet, F. Pomares, F. Ingelmo, Organic matter components and aggregate stability after the application of different amendments to a horticultural soil, Bioresour. Technol. 76 (2) (2001) 125, [https://doi.org/10.1016/S0960-8524\(00\)00090-0](https://doi.org/10.1016/S0960-8524(00)00090-0).
- [32] P. Sharma, V. Abrol, V. Sharma, S. Chadda, C.S. Rao, A.Q. Gaine, D.I. Hefft, M.A. El-Sheikh, S. Mansoor, Effectiveness of biochar and compost on improving soil hydro-physical properties, crop yield and monetary returns in inceptisol subtropics, Saudi J. Biol. Sci. 28 (12) (2021), <https://doi.org/10.1016/j.sjbs.2021.09.043>, 7549–7549.
- [33] T. Mengistu, H. Gebrekidan, K. Kibret, K. Woldetsadik, B. Shimelis, H. Yadav, The integrated use of excreta-based vermicompost and inorganic NP fertilizer on tomato (*Solanum lycopersicum* L.) fruit yield, quality and soil fertility, Int. J. Recycl. Org. Waste Agric. 6 (2017) 63–77, <https://doi.org/10.1007/s40093-017-0153-y>.
- [34] Z. Arabi, A. Moghaddam, M. Hoseini, A. Faraji, Effects of vermicompost and biochar on yield and yield components of maize line AR68 and on some soil physicochemical properties, Arabian J. Geosci. 16 (2023) 677, <https://doi.org/10.1007/s12517-023-11774-7>.
- [35] Rasool Azarmi, M.T. Giglou, R.D. Taleshmikail, Influence of vermicompost on soil chemical and physical properties in tomato (*Lycopersicon esculentum*) field, Afr. J. Biotechnol. 7 (14) (2008) 2397–2401. <http://www.academicjournals.org/AJB>.
- [36] S.H. Doerr, R.A. Shakesby, R.P.D. Walsh, Spatial variability of soil hydrophobicity in fire-prone eucalyptus and pine forests, Portugal, Soil Sci. 163 (1998) 313–324.
- [37] E.S. Vogelmann, J.M. Reichert, J. Prevedello, C.O.B. Consensa, A.É. Oliveira, G.O. Awe, J. Mataix-Solera, Threshold water content beyond which hydrophobic soils become hydrophilic: the role of soil texture and organic matter content, Geoderma 209–210 (2013) 177–187, <https://doi.org/10.1016/j.geoderma.2013.06.019>.
- [38] V. Alagna, M. Iovino, V. Bagarello, J. Mataix-Solera, L. Lichner, Application of minidisk infiltrometer to estimate water repellency in Mediterranean pine forest soils, J. Hydrol. Hydromechanics 65 (3) (2017) 254–263, <https://doi.org/10.1515/johh-2017-0009>.

- [39] C.L. Watson, J. Letey, Indices for characterizing soil-water repellency based upon contact angle-surface tension relationships, *Soil Sci. Soc. Am. J.* 34 (6) (1970) 841–844, <https://doi.org/10.2136/sssaj1970.03615995003400060011x>.
- [40] V. Alagna, M. Iovino, V. Bagarello, J. Mataix-Solera, L. Lichner, Alternative analysis of transient infiltration experiment to estimate soil water repellency, *Hydrol. Process.* 33 (4) (2019) 661–674, <https://doi.org/10.1002/hyp.13352>.
- [41] B. Ebel, J.A. Moody, Rethinking infiltration in wildfire-affected soils, *Hydrol. Process.* 27 (10) (2013) 1510–1514, <https://doi.org/10.1002/hyp.9696>.
- [42] L.W. Dekker, C.J. Ritsema, K. Oostindie, D. Moore, J.G. Wesseling, Methods for determining soil water repellency on field-moist samples, *Water Resour. Res.* 45 (4) (2009), <https://doi.org/10.1029/2008WR007070>.
- [43] I. Tinebra, V. Alagna, M. Iovino, V. Bagarello, Comparing different application procedures of the water drop penetration time test to assess soil water repellency in a fire affected Sicilian area, *Catena* 177 (2019) 41–48, <https://doi.org/10.1016/j.catena.2019.02.005>.
- [44] A.R. Dexter, Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth, *Geoderma* 120 (2004) 201–214, <https://doi.org/10.1016/j.geoderma.2003.09.004>.
- [45] A.M. Stellacci, M. Castellini, M. Diacono, R. Rossi, C.E. Gattullo, Assessment of soil quality under different soil management strategies: combined use of statistical approaches to select the most informative soil physico-chemical indicators, *Appl. Sci.* 11 (2021) 5099, <https://doi.org/10.3390/app11115099>.
- [46] J. Pranagal, A. Wozniak, 30 years of wheat monoculture and reduced tillage and physical condition of Rendzic Phaeozem, *Agric. Water Manag.* 243 (2021) 106408, <https://doi.org/10.1016/j.agwat.2020.106408>.
- [47] C. Bondi, M. Castellini, M. Iovino, Compost amendment impact on soil physical quality estimated from hysteretic water retention curve, *Water* 14 (2022) 1002, <https://doi.org/10.3390/w14071002>.
- [48] H. Han, D. Giménez, A. Lilly, Textural averages of saturated soil hydraulic conductivity predicted from water retention data, *Geoderma* 146 (2008) 121–128, <https://doi.org/10.1016/j.geoderma.2008.05.017>.
- [49] M.T. van Genuchten, A closed form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J.* 44 (1980) 892–898, <https://doi.org/10.2136/sssaj1980.03615995004400050002x>.
- [50] G.W. Gee, D. Or, Particle size analysis, in: J.H. Dane, G.C. Topp (Eds.), *Methods of Soil Analysis, Part 4, Physical Methods*, Soils Science Society of America, Madison, WI, 2002, pp. 255–293, <https://doi.org/10.2136/sssabookser5.4.c12>.
- [51] P.J. Craul, *Urban Soils: Applications and Practices*, Wiley, Toronto, 1999.
- [52] J. Letey, M.L.K. Carrillo, X.P. Pang, Approaches to characterize the degree of water repellency, *J. Hydrol.* 231–232 (2000) 61–65, [https://doi.org/10.1016/S0022-1694\(00\)00183-9](https://doi.org/10.1016/S0022-1694(00)00183-9).
- [53] E.B.A. Bisdorn, L.W. Dekker, J.F.T. Schoute, Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure, *Geoderma* 56 (1993) 105–118, <https://doi.org/10.1016/B978-0-444-81490-6.50013-3>.
- [54] G. Caltabellotta, M. Iovino, V. Bagarello, Intensity and persistence of water repellency at different soil moisture contents and depths after a forest wildfire, *J. Hydrol. Hydromechanics* 70 (4) (2022) 410–420, <https://doi.org/10.2478/johh-2022-0031>.
- [55] J.H. Dane, J.W. Hopmans, 3.3.2.2 Hanging water column. p.680-683, in: J.H. Dane, G.C. Topp (Eds.), *Methods of Soil Analysis, Part 4, Physical Methods, Number 5 in the Soil Science Society of America Book Series*, Soil Science Society of America, Inc., Madison, WI, USA, 2002.
- [56] V. Bagarello, M. Castellini, M. Iovino, Influence of the pressure head sequence on the soil hydraulic conductivity determined with tension infiltrometer, *Appl. Eng. Agric.* 21 (3) (2005) 383–391, <https://doi.org/10.13031/2013.18457>.
- [57] J.H. Dane, J.W. Hopmans, 3.3.2.4 Pressure plate extractor. p.688-690, in: J.H. Dane, G.C. Topp (Eds.), *Methods of Soil Analysis, Part 4, Physical Methods, Number 5 in the Soil Science Society of America Book Series*, Soil Science Society of America, Inc., Madison, WI, USA, 2002.
- [58] M.T. van Genuchten, F.J. Leij, S.R. Yates, *The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils*, Riverside (CA): U.S. Department of Agriculture, Agricultural Research Service. U.S. Salinity Laboratory, 1991. EPA/600/2-91/065.
- [59] M. Castellini, M. Iovino, Pedotransfer functions for estimating soil water retention curve of Sicilian soils, *Arch. Agron Soil Sci.* 65 (2019) 1401–1416, <https://doi.org/10.1080/03650340.2019.1566710>.
- [60] L.M. Manici, M. Castellini, F. Caputo, Soil-inhabiting fungi can integrate soil physical indicators in multivariate analysis of Mediterranean agroecosystem dominated by old olive groves, *Ecol. Indic.* 106 (2019) 105490, <https://doi.org/10.1016/j.ecolind.2019.105490>.
- [61] J.P. Amsili, H.M. van Es, R.R. Schindelbeck, Cropping system and soil texture shape soil health outcomes and scoring functions, *Soil Security* 4 (2021) 100012, <https://doi.org/10.1016/j.soisec.2021.100012>.
- [62] IUSS Working Group WRB, *World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, fourth ed., International Union of Soil Sciences (IUSS), Vienna, Austria, 2022.
- [63] L.W. Dekker, C.J. Ritsema, How water moves in a water repellent sandy soil: 1. Potential and actual water repellency, *Water Resour. Res.* 30 (9) (1994) 2507–2517.
- [64] W.D. Reynolds, C.F. Drury, X.M. Yang, C.S. Tan, Optimal soil physical quality inferred through structural regression and parameter interactions, *Geoderma* 146 (2008) 466–474, <https://doi.org/10.1016/j.geoderma.2008.06.017>.
- [65] Z. Ding, A.M. Kheir, O.A. Ali, E.M. Hafez, E.A. ElShamey, Z. Zhou, M.F. Seleiman, A vermicompost and deep tillage system to improve saline-sodic soil quality and wheat productivity, *J. Environ. Manag.* 277 (2021) 111388, <https://doi.org/10.1016/j.jenvman.2020.111388>.
- [66] R.J. Black, G. Kidder, D.A. Graetz, G.L. Miller, B. Dehgan, Evaluation of Composted Materials to Be Utilized in Florida Roadside and Median Plantings, WPI-0520743, Final Report. Department of Environmental Horticultural, Soil and Water Sciences Department, University of Florida, 1999.
- [67] P.D. Somerville, P.B. May, S.J. Livesley, Effects of deep tillage and municipal green waste compost amendments on soil properties and tree growth in compacted urban soils, *J. Environ. Manag.* 227 (2018) 365–374, <https://doi.org/10.1016/j.jenvman.2018.09.004>.
- [68] F. Mohammadshirazi, R.A. McLaughlin, J.L. Heitman, V.K. Brown, A multi-year study of tillage and amendment effects on compacted soils, *J. Environ. Manag.* 203 (2017) 533–541, <https://doi.org/10.1016/j.jenvman.2017.07.031>.
- [69] C. Bondi, M. Castellini, M. Iovino, Temporal variability of physical quality of a sandy loam soil amended with compost, *Biologia* (2024), <https://doi.org/10.1007/s11756-024-01637-1>.