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Hydrodynamic behavior of a near-saturated sandy-loam soil shortly after incorporating compost or zeolite

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A R T I C L E I N F O

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A B S T R A C T

Little is known about short-term effects of compost and zeolite addition on hydrodynamic properties of near-saturated coarse-textured soils. These effects were tested for a sandy-loam soil by a Mini-Disk Infiltrometer at three pressure heads (-6, −3 and −1 cm) and a wide range of amendment percentages, p_a. Soil hydraulic conductivity was determined on two dates separated by nearly one month whereas soil sorptivity was determined at the end of the sampling period. Overall, the effect of the compost varied from null to appreciable since increasing p_a from 0 % to 40 % did not affect the considered parameter or induced a decrease by up to eight times. Instead, the zeolite was largely ineffective since the tested parameters did not vary with p_a. At the end of the experiment, the soil amended with zeolite was up to 70–90 % more sorptive and conductive than that amended with the compost. Perhaps the particles of compost represented a physical obstacle to water flow and probably also induced some soil water repellency. Instead, the particles of zeolite were wettable, and they did not appreciably alter the pore size distribution. Adding compost can determine a decrease in the ability of a near-saturated soil to draw and conduct water but this ability does not change with zeolite. Other investigations are required to confirm these results, test the suggested explanation and finally draw general conclusions. The applied methodology in this investigation is easy, cheap and suitable for prolonged monitoring without causing an appreciable alteration of the sampled soil.

1. Introduction

Soils with a coarse texture, typically dominated by sand and deficient in organic matter, present several limitations to sustainable land use. Their loose structure, poor water retention, rapid drainage, and high vulnerability to nutrient leaching and erosion reduce both their agronomic potential and ecological stability (Garbowski et al., 2023). To address these constraints, the application of soil amendments, whether organic (e.g., compost, vermicompost, biochar, peat) or mineral (e.g., lime, volcanic rocks, zeolites, clay minerals), has emerged as a promising strategy for improving the physical, chemical, and biological quality of such soils (Reynolds et al., 2009; Castellini et al., 2024) and can also be used to prepare engineered growing substrates (Autovino et al., 2024a).

Composting refers to the process of humification and stabilization of organic wastes including sewage sludge, manure, municipal solid waste and green waste (Huang et al., 2016). Under the action of micro-organisms and enzymes, organic wastes are degraded and transformed into CO_2, H_2O, mineral ions and humic substances. Compost application to coarse-textured soils can be expected to improve soil organic matter content (Dong et al., 2022), bulk density (Mandal et al., 2013), soil structure (Rivier et al., 2022), total porosity (Arthur et al., 2011), pore size distribution (Bondì et al., 2022) and water holding capacity (Curtis and Claassen, 2009). Applying compost to these soils can determine a decrease (Whelan et al., 2013) or an increase (Kranz et al., 2020) of saturated soil hydraulic conductivity, K_s.

Among the mineral soil amendments, zeolites have assumed an increasingly significant role in recent years. Zeolites are a family of silica polymorphs or crystalline aluminosilicates composed of corner-sharing TO_4 tetrahedra (T = typically Si or Al), forming a three-dimensional, four-connected framework with uniformly sized, molecular-scale pores (Ghasemi et al., 2016). A wide range of natural and synthetic zeolites exists, characterized by differing Si/Al ratios that determine their ion exchange capacity and can differently influence soil behavior and plant responses (Cataldo et al., 2021), also depending on soil texture (Gholizadeh-Sarabi and Sepaskhah, 2012). Adding zeolite in sandy and

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loamy soils can be expected to improve soil water retention and holding capacity while simultaneously reducing K_s and infiltration rate (Colombani et al., 2015). However, a high application rate of zeolite particles could also induce particle dispersion, structural degradation and an increase of K_s of sandy-loam soils due to the coarseness of the zeolite particles and the addition of Na^+ ions (Ghorbani et al., 2022). According to Ibrahim and Alghamdi (2021), application of natural clinoptilolite zeolite in the ultra-fine nanoparticle size can be expected to increase water-holding capacity and reduce hydraulic conductivity of coarse-textured soils.

The experimental information currently available on soil-water relationships in coarse-textured porous media amended with compost or zeolite seems mainly focused on water retention characteristics and, for the hydrodynamic aspects, on K_s. There is less data regarding soil's hydrodynamic properties in close to saturation conditions. Further, there is almost nothing on hydrodynamic parameters controlling early-time infiltration. Instead, this information is expected to have a noticeable hydrological relevance for different reasons.

A reason is that full saturation of well permeable soils rarely occurs under natural field conditions (Dohnal et al., 2016). Therefore, K_s data alone are not enough to characterize the soil's hydrodynamic behavior. Moreover, K_s data are expected to be largely influenced by fragile, unstable and often highly variable macropores of different nature (Dohnal et al., 2010; Jarvis et al., 2013). Hence, these data are expressive of the bulk soil, but they could not appropriately describe the effect of the amendment on the soil matrix (Logsdon and Jaynes, 1993). Matrix pores are small enough to remain water-filled at pore water pressure head values varying between −3 cm and −10 cm, depending on the investigation, and the hydraulic conductivity, K, corresponding to these pressure heads represents the saturated hydraulic conductivity of the soil matrix (Topp et al., 1997; Reynolds, Topp, 2008). Therefore, determining this soil hydrodynamic parameter requires collecting data corresponding to little negative pressure heads.

Soil sorptivity, S, should also be determined since this parameter, representing the soil's ability to draw water (Stewart et al., 2013), is dominated by soil capillarity forces (Cook and Broeren, 1994) and it affects estimation of other soil hydraulic properties (Minasny and McBratney, 2000). Sorptivity controls early-time infiltration and both S and K have to be determined for predicting one- and three-dimensional infiltration with physically-based models (Philip, 1957; Haverkamp et al., 1994).

Amendment effects on sorptivity and hydraulic conductivity of near-saturated soils can be tested, both in the laboratory and the field, with the Mini-Disk Infiltrometer (MDI, Meter Group, 2021). This device provides a simple, rapid and cost-effective method for measuring, with a minimal disturbance of the sampled soil volume, three-dimensional infiltration under a fixed negative pressure head, h_0 (-6 cm $\leq h_0 \leq$ −0.5 cm), established on the infiltration surface. One of the most important features of the MDI, and generally of tension infiltrometer methods, is that the use of a slightly negative h_0 value for the run makes it possible to measure the hydrodynamic response of the soil matrix independently of preferential flow effects (Dohnal et al., 2010; Wilson and Luxmoore, 1988). With the device, the sorptivity and hydraulic conductivity values that control infiltration under the established h_0 value can be calculated (Zhang, 1997; Dohnal et al., 2010). Therefore, there is a direct correspondence between the soil hydrodynamic parameters and the experimentally measured infiltration process.

The general aim of this investigation was to evaluate short-term effects of two commercial soil amendments, that are an organic compost and a mineral zeolite, on hydraulic conductivity and sorptivity of a near-saturated sandy-loam soil sampled with an MDI. The specific objectives were to: (i) determine the effects of the two amendments, applied at seven different rates, on the considered soil hydrodynamic parameters; (ii) establish differences between the two treatments; and (iii) assess short-term temporal variation in amendment effects.

2. Theory

Transient cumulative infiltration, I (L), measured with the MDI can be described by the following well known relationship (Philip, 1957):

$$I = C_1 t^{1/2} + C_2 t \tag{1}$$

where t (T) is the time and C_1 (L T$^{-1/2}$) and C_2 (L T^{-1}) are coefficients that can be estimated by different methods (Vandervaere et al., 2000), including minimizing the sum of the squared residuals between the measured $I(t)$ values and those predicted by Eq.(1) (Lassabatère et al. 2006).

According to Zhang (1997), for a homogeneous and isotropic soil and a uniform initial soil water content, the C_1 and C_2 values obtained by a three-dimensional infiltration process at a given pressure head, h_0 (L) ($h_0 \leq 0$), on the soil surface can be described as a function of soil sorptivity, S_0 (L T$^{-1/2}$), and hydraulic conductivity, K_0 (L T^{-1}), respectively, as:

$$C_1 = A_1 S_0 \tag{2}$$

$$C_2 = A_2 K_0 \tag{3}$$

where A_1 and A_2 are dimensionless coefficients that depend on soil water content, soil water retention and infiltrometer parameters. For soils with the van Genuchten (1980) water retention function, the expressions of these coefficients were determined using numerically simulated infiltration data (Zhang, 1997):

$$A_1 = \frac{1.4 b^{0.5} (\theta_0 - \theta_i)^{0.25} \exp[3(n-1.9)\alpha_{vG} h_0]}{(\alpha_{vG} r)^{0.15}} \tag{4}$$

$$A_2 = \frac{11.65(n^{0.1}-1)\exp[2.92(n-1.9)\alpha_{vG} h_0]}{(\alpha_{vG} r)^{0.91}} \quad \text{for } n \geq 1.9 \tag{5a}$$

$$A_2 = \frac{11.65(n^{0.1}-1)\exp[7.5(n-1.9)\alpha_{vG} h_0]}{(\alpha_{vG} r)^{0.91}} \quad \text{for } n < 1.9 \tag{5b}$$

where h_0 (cm) is the applied pressure head during the infiltration process (h_0 is negative for unsaturated conditions), n and α_{vG} (cm^{-1}) are the water retention parameters, r (cm) is the radius of the infiltrometer, θ_0 (cm^{3}cm^{-3}) is the soil water content at h_0, θ_i (cm^{3}cm^{-3}) is the initial soil water content, and b is a parameter set at 0.55 (Warrick and Broadbridge, 1992). Determination of S_0 and K_0 consists of using Eqs.(2) and (3) once C_1 and C_2 have been calculated. The van Genuchten parameters required by the procedure can be estimated from soil texture (e.g., Carsel and Parrish, 1988) or they can be obtained by fitting laboratory determined soil water retention data, although in this last case the procedure of soil hydraulic characterization becomes more complicated from an experimental point of view. Dohnal et al. (2010) improved Eq.(5b) suggesting, for low n values, the following alternative expression of A_2, that was optimized specifically for a small disk size (15.2 cm^2) and a range of pressure head values varying between −0.5 and −6 cm:

$$A_2 = \frac{11.65(n^{0.82}-1)\exp[34.65(n-1.19)\alpha_{vG} h_0]}{(\alpha_{vG} r)^{0.6}} \quad \text{for } n \leq 1.35 \tag{5c}$$

According to the α_{vG} and n parameters of the van Genuchten water retention curve listed by Dohnal et al. (2010), Eq.(5c) should be used for sandy-clay-loam, sandy-clay, silty-clay and clay soils.

Therefore, transient infiltration and both initial and final soil water content values are necessary to determine S_0 by Eqs.(2) and (4). Instead, only infiltration data are required to obtain K_0 by Eq.(3) and (5).

3. Materials and methods

3.1. Soil and amendments

A coarse-textured soil was collected from a citrus orchard located at the Department of Agriculture, Food and Forest Sciences of the University of Palermo, Italy (UTM 33S 355511E - 4218990 N). Approximately 200 kg of soil were sampled from the upper 15 cm of the soil profile, sieved through a 1 cm mesh to remove gravel and large vegetation residues and subsequently air-dried under controlled laboratory conditions at approximately 20 °C for nearly three weeks.

The particle size distribution (PSD) of the soil sieved at 2 mm was determined by standard laboratory procedures (Gee and Or, 2002). In particular, 50 g samples were pre-treated with hydrogen peroxide and sodium polyphosphate to remove organic matter and induce colloid deflocculation, respectively. The fine particle fractions were determined by the hydrometer method whereas the coarse fractions were obtained by mechanical sieving. According to the USDA soil texture classification system, the soil was sandy-loam with clay, silt and sand contents equal to 15.1 %, 29.0 % and 55.9 %, respectively. Based on the IUSS Working Group WRB (2022) guidelines, the soil was classified as a Terric Chromic Cambisol (Loamic).

Two soil amendments of distinct origin were employed in this study. An organic amendment was a commercial compost (C) supplied by GECOS (Italy). This compost was obtained through a controlled process of transformation and stabilization of wastewater and sludge, combined with organic matrices such as untreated wood and pruning residues from ornamental greenery. A mineral amendment was a natural zeolite (Z), manufactured by GECOS (Italy), based on chabazite and free from pollutants. According to the manufacturer, the particles of Z ranged between 0.7 and 2 mm but no information on the particle size range was provided for the C. The main chemical characteristics of the used amendments were reported in Table 1.

To determine the actual size of the fine (< 2 mm) soil, C and Z particles used for the experiment, their PSD was also determined by sieving without performing any pre-treatment. In particular, 50 g of air-dried material were passed through a stack of sieves with decreasing mesh openings (2, 0.85, 0.425, 0.25, 0.106 and 0.074 mm) and vibrated for 5 min. The PSD was determined as the percentage by weight of particles within the following six size classes: 2–0.85, 0.85–0.425, 0.425–0.25, 0.25–0.106, 0.106–0.074 and < 0.074 mm. All measurements were performed in duplicate. Both amendments were coarser than the soil (Fig. 1). The particles with an equivalent diameter ≥ 0.25 mm represented the 98.3 % for the C, the 73.1 % for the Z and the 59.4 % for the soil. Therefore, as compared with the soil, the percentage of coarse particles was larger by 38.9 percentage units with the C and 13.7 units with the Z. Particles smaller than 0.25 mm were detected for both the soil and the Z but not for the C. Thus, the C was clearly coarser than the soil. Instead, the Z and the soil had a similar PSD.

Loss on ignition (LOI) was also determined for the soil, the C and the Z using 3 g (±0.006 g) samples weighed into porcelain crucibles. The samples were oven-dried at 105 °C for 24 h, cooled in a desiccator for 30 min and the dry weight (w_{105}) was recorded. Subsequently, the samples were combusted in a preheated muffle furnace at 400 °C for 16 h, cooled in a desiccator, and the final weight (w_{400}) was recorded. The LOI was calculated as the percentage difference between w_{105} and w_{400} referred to w_{105}. The resulting LOI values were 5.6 % for the soil, 31.1 % for the C and 8.9 % for the Z. These values reflect not only the oxidation of organic matter but also the thermal decomposition of

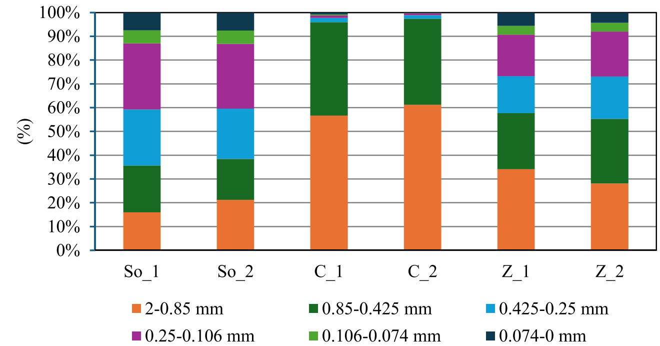

Fig. 1. Percentages by weight of soil (So), compost (C) and zeolite (Z) particles of a given size range determined in duplicate (1 and 2) by sieving.

inorganic soil constituents such as hydrated aluminosilicates, structural water, carbonates, and hydrates (Nelson and Sommers, 1996). In the case of the Z, that is an aluminosilicate, the LOI value primarily indicates the quantity of structural water incorporated within its framework (Luukkonen et al., 2017).

Table 1
Properties of the amendments used in this investigation provided by the manufacturer.

Compost	EC ($dS\ m^{-1}$)	C (%)	N (%)	pH	P (%)	Ash (%)
	2.0	48	2.6	8.4	< 1.0	12.3
Zeolite	**CEC ($Cmol\ kg^{-1}$)**	**SiO_2 (%)**	**Al_2O_3 (%)**	**K_2O (%)**	**CaO (%)**	**Fe_2O_3 (%)**
	230	50	17	6	6	3

EC = electrical conductivity; *CEC* = cation exchange capacity.

3.2. Preparing mixtures and microplots

The two soil amendments, previously air-dried, were mixed with the soil at eight different percentages, p_a, by weight: 0 % (i.e., control soil without amendment), 5 %, 10 %, 15 %, 20 %, 25 %, 30 %, and 40 %. High p_a values were included in this investigation even if, due to economic and practical reasons, smaller percentages could be used in the field (Abildayev et al., 2025; Arthur et al., 2011; Eden et al., 2017; Kukowska and Szewczuk-Karpisz, 2025; Mohammadi et al., 2025; Pratt et al.; 2025). This choice was made since relatively large amendment percentages could however be used in some circumstances, such as for greenhouse cultivation (Prisa, 2020) or other pot experiments (Chatzistathis et al., 2020). Moreover, considering a wide range of p_a values was expected to yield a detailed representation of the effects of the treatment on a considered soil property, in accordance with other recent investigations (Bondì et al., 2022, 2024, 2025; Castellini et al., 2025).

The dry mass of both components was determined using the following equations (Bondì et al., 2022):

$$M_s = \frac{V\ \rho_{b,a}\ \rho_{b,s}}{\rho_{b,a} + r\ \rho_{b,s}} \tag{6a}$$

$$M_a = rM_s \tag{6b}$$

in which M_a (g) and M_s (g) represent the dry masses of amendment (C or Z) and soil, respectively, $\rho_{b,a}$ (g cm^{-3}) and $\rho_{b,s}$ (g cm^{-3}) are the dry bulk densities of the two constituents, determined using the core sampling method followed by oven-drying at 105 °C, V (cm^3) is the sample volume, and r is the amendment-to-soil ratio. The air-dried masses were corrected to account for the initial volumetric water content of the soil.

The soil was mixed with the amendment until a homogeneous mixture was obtained. A total of sixteen microplots (8 amendment rates × 2 amendments) were established in polypropylene boxes with dimensions of 60 cm × 40 cm and a height of 13 cm. Microplots for control were replicated twice considering that two different controls would be used by two research groups working on the same soil with different amendments and in different laboratories. Each microplot comprised an 8 cm layer of the soil–amendment mixture placed above a 3 cm drainage layer composed of expanded clay granules supplied by GECOS (Italy). To prevent migration of fine particles from the substrate into the drainage layer, a thin (<1 cm) polypropylene geotextile was placed between the two layers. Two additional boxes were prepared with non-amended soil above the drainage layer to initially perform some checks of the applied experimental method for measuring infiltration.

Mixtures were gradually transferred into the containers using a hand scoop, followed by manual compaction to ensure uniform settling. In particular, to ensure a uniform vertical soil distribution, the mixture was applied in three steps, and each layer was lightly compacted by hands and a shovel. Compaction was light to prevent hydraulic discontinuities between two adjacent layers as far as possible (Autovino et al., 2024b). A single operator filled the boxes in order to favour uniformity across the different boxes (Bagarello et al., 2025). Microplots were then left air exposed to ambient laboratory conditions during the two measurement campaigns. After the last infiltration measurements, the boxes were exposed to open air.

3.3. Soil sampling experimental methods

Three-dimensional infiltration experiments were performed on the packed soil in a microplot by an MDI having a disk diameter of 4.5 cm. Two sampling campaigns were carried out. The first campaign (I) started immediately after preparing the microplots and its overall duration was four days. The second campaign (II) started nearly 30 days after concluding the first campaign and its overall duration was six days. At the end of the first measurement campaign, 1 L of water was uniformly poured onto each microplot in order to promote a uniform soil wetting and drying process during the time interval between the two measurement campaigns. A 30-day interval between the sampling campaigns was considered appropriate to try capturing short-term variations in amendment effects on the measured soil properties in more or less similar initial soil water content conditions.

For each microplot, that is for a given soil/amendment mixture, infiltration data were collected at three different pressure head, h_0, values, equal to -6 cm, -3 cm and -1 cm. Each individual infiltration process for an established h_0 value was carried out at a different sampling point, so as to obtain all infiltration curves in a microplot under similar initial soil water content conditions. For a given h_0 value and a microplot, the experiment was replicated at two different, randomly chosen, sampling points, for a total of six MDI infiltration runs in a microplot. The soil surface at a sampling point was gently leveled with a trowel and small amounts of loose soil were used when necessary to improve the contact between the MDI and the infiltration surface. The device was fixed to a support to keep it still during the run and infiltration was measured until the reservoir emptied. Readings were taken visually at time intervals varying from 5 s for the first 30 s to 2 min after the twentieth minute of the run. A cumulative infiltration, I (L), vs. time, t (T), curve was obtained at each sampling point.

A few MDI runs were initially carried out in the two additional boxes with non-amended soil until the reservoir was empty. This initial check of the applied experimental methodology confirmed that every point of the wetting front remained within the soil volume by the end of the run. In other terms, the infiltration data were not noised by edge or bottom effects.

Obtaining K_0 data only requires MDI data whereas MDI and soil water content data are necessary for also determining S_0 (Zhang, 1997). Especially for the final water content, the destructive thermo-gravimetric method seems an appropriate method to be applied since the actually wetted soil volume under the device can be sampled. In light of these considerations, only K_0 was determined in the first sampling campaign so as not to cause alterations to the soil in different positions of the microplot which could have compromised or hindered the second campaign of measurements. In other words, sorptivity was not determined in the first sampling campaign in order not to disturb excessively the soil in an intermediate stage of the experiment.

The soil was sampled immediately before performing the second series of MDI runs to determine the dry soil bulk density, ρ_b (g cm^{-3}), and the initial gravimetric soil water content, w_i (g g^{-1}). Two undisturbed soil samples were collected by manually pressing two metal cylinders with a height of 2 cm and a diameter of 5 cm into the soil. The initial volumetric soil water content, θ_i (m^{3}m^{-3}) was then determined from ρ_b and w_i. The two ρ_b, w_i and θ_i values were averaged to characterize the soil in a microplot.

After an MDI run, the wetted soil under the device was sampled with a teaspoon to determine the final gravimetric soil water content, w_0 (g g^{-1}). The final volumetric soil water content, θ_0 (m^{3}m^{-3}), was determined from w_0 and the ρ_b value for the considered microplot, determined before the run. The diameter of the wetted bulb at the soil surface, d_b (cm), was also measured along two orthogonal directions. A representative d_b value for the run was obtained by averaging these two measurements.

Overall, 192 MDI runs were performed in this investigation, i.e. 2 sampling campaigns × 3 pressure heads × 2 replicated runs per microplot × 8 mixtures per amendment × 2 amendments.

After about a month of exposure of the boxes to open air, soil water repellency data were collected by the widely applied water drop penetration time (WDPT) test (Doerr, 1998; Letey et al., 2000). In particular, 60 drops of deionized water were evenly applied with a medical dropper at the surface of each box from a height of 10 mm and the time for their complete penetration was recorded. Two disturbed soil samples were also collected to determine the gravimetric soil water content, w_{WDPT} (g g^{-1}), immediately before the WDPT experiment since soil water repellency is expected to depend on soil water content at the time of its determination (e.g., Hermansen et al., 2019; Bayad et al., 2020). Therefore, a total of 16 w_{WDPT} values were determined for each treatment.

3.4. Calculations and data analysis

For each MDI infiltration run, Eq.(1) was fitted to the cumulative infiltration, I (mm), vs. time, t (h), data by minimizing the sum of the squared residuals between the measured and the predicted I values (Lassabatère et al., 2006) to simultaneously estimate the C_1 (mm h$^{-1/2}$) and C_2 (mm h^{-1}) parameters of the model. In a single case (second campaign with the compost, $h_0 = -1$ cm, $p_a = 40$ %) the adaptation of the model to the data failed ($C_1 = 0$). In the other cases, the relative error, Er (%), calculated according to Lassabatère et al. (2006) varied from 0.6 % to 4.7 % with a mean value of 1.5 %. According to Lassabatère et al. (2006), an Er value that does not exceed 5.5 % denotes an acceptable fitting of an infiltration model to the data. Therefore, the fitting of the model to the infiltration data was satisfactory for all individual runs. The soil hydraulic conductivity, K_0 (mm h^{-1}), and sorptivity, S_0 (mm h$^{-1/2}$), values corresponding to a run with a given pressure head were then calculated according to Zhang (1997) and Dohnal et al. (2010), i.e. using Eq.(2)-(5). The required soil water retention parameters for the calculations were chosen from Table 1 by Dohnal et al. (2010).

With reference to a given soil property, the data were analyzed in order to establish i) the amendment effect; ii) if the effect was similar between the two amendments; and iii) if the effect changed with time.

Amendment effects were tested by performing a linear regression analysis of the considered soil property vs. p_a and determining the statistical significance of the correlation coefficient, R, by a two-tailed t test at $P = 0.05$ (Glantz, 2012). The intercept of a statistically significant relationship represents the value of the considered soil property without any treatment whereas the slope is expressive of the rate at which that property varies by adding the amendment (Bondì et al., 2022, 2024, 2025; Castellini et al., 2025).

To establish similarity between the amendments and to evaluate time effects, two means of a soil property were compared by F and two-tailed t tests at $P = 0.05$. This choice was made instead of comparing two regression lines (Glantz, 2012) since a statistical significance of both regression lines between a soil parameter and p_a was only detected in a few cases.

In this investigation, a given variable (e.g., soil sorptivity or soil hydraulic conductivity at an established pressure head) was determined by using different percentages of amendment, p_a (%) (from 0 % to 40 %) for two reasons: i) making this choice was necessary for testing the relationship between the considered variable and the intensity of the treatment (Bondì et al., 2022, 2024, 2025; Castellini et al., 2025); and ii) for a fixed amount of applied amendment (e.g., given mass per unit surface area and incorporation depth), it is unlikely that every point of a field soil will receive exactly the same treatment. Instead, some heterogeneity in the distribution of the amendment will be more or less unavoidable. An experiment making use of different amendment doses seems therefore appropriate to predict the overall response of the field soil with reference to the variables of interest.

The WDPT data were summarized considering the five soil water repellency classes by Bisdom et al. (1993): wettable (WDPT < 5 s), slightly water repellent (WDPT = 5–60 s); strongly water repellent (WDPT = 60–600 s); severely water repellent (WDPT = 600–3600 s), and extremely water repellent (WDPT > 3600 s). For each microplot, the percentage of WDPT values falling in each class was determined.

4. Results

For each sampling campaign (I or II), amendment (C = compost; Z = zeolite) and percentage of amendment, p_a (%), soil hydraulic conductivity generally increased according to the sequence K_{-1} (K for $h_0 = -1$ cm) > K_{-3} (K for $h_0 = -3$ cm) > K_{-6} (K for $h_0 = -6$ cm) (Fig. 2). For each amendment and p_a value, soil sorptivity, that was only determined in the second campaign, generally increased according to the sequence S_{-1} (S for $h_0 = -1$ cm) > S_{-3} (S for $h_0 = -3$ cm) > S_{-6} (S for $h_0 = -6$ cm) (Fig. 3). Larger soil hydraulic conductivity and sorptivity values with greater (less negative) h_0 values are physically expected. Therefore, this initial check of the data did not suggest any anomaly in the developed dataset.

4.1. First sampling campaign

With the C, the relationship between K_{-6} and p_a was statistically significant (coefficient of determination, $R^2 = 0.69$, $R > 0$) but p_a did not influence significantly either K_{-3} or K_{-1} ($R^2 = 0.11$–0.13, depending on h_0; Fig. 2**a**). In particular, K_{-6} decreased by 3.1 times as p_a increased from zero to 40 %.

With the Z, none of the tested relationships between K and p_a was statistically significant ($0.0001 \leq R^2 \leq 0.15$; Fig. 2**b**), indicating that soil hydraulic conductivity did not vary with the amount of Z regardless of the established pressure head.

For each pressure head, a comparison was carried out between the K values obtained with the two amendments. The hydraulic conductivity of the soil treated with the Z was greater than that obtained using the C by 10.0–21.7 %, depending on h_0 (Table 2), but the differences between the two treatments were not statistically significant. Using the Z instead of the C implied detecting a smaller coefficient of variation, CV, of K for the smallest h_0 value ($h_0 = -6$ cm), a little higher CV value for the intermediate pressure head ($h_0 = -3$ cm) and an appreciably higher CV value for the highest pressure head ($h_0 = -1$ cm).

Therefore, signs of a treatment effect on K were weak since they included a significant relationship between K and p_a for only one of the six tested relationships and consistently higher values of K with one of the two soil amendments, but only a little and not significantly. Overall, the data suggested that adding an amendment at different rates or using an amendment instead of another did not influence K. Therefore, amending the soil was largely ineffective immediately after performing the treatment.

4.2. Second sampling campaign

With both amendments, ρ_b decreased significantly as p_a increased (Fig. 4**a**). On average, the dry soil bulk density differed with the used amendment by 2.2 % and the difference between the two treatments was not statistically significant (Table 3).

The antecedent gravimetric soil water content, w_i, increased significantly with p_a for both amendments even if the w_i vs. p_a relationships were rather scattered, with R^2 values of 0.35 for the C and 0.29 for the Z (Fig. 4**b**). The mean w_i value of the soil treated with the C was larger than that of the soil treated with the Z by 53.1 % and the difference between

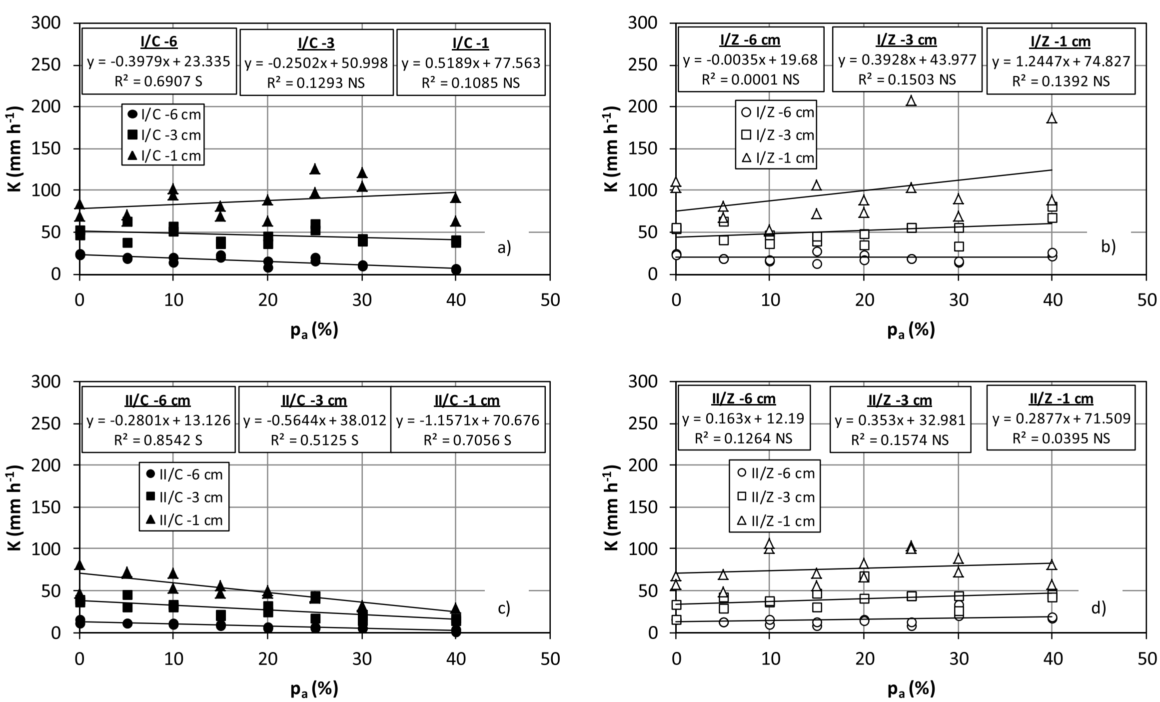

Fig. 2. Relationship between the soil hydraulic conductivity, K, and the percentage, p_a, of amendment (C = compost; Z = zeolite) for the three established pressure head, h_0, values (-6, −3 and −1 cm) in the first (I) and second (II) sampling campaigns (soil hydraulic conductivity corresponding to $h_0 = -6$, −3 and −1 cm denoted as K_{-6}, K_{-3} and K_{-1}, respectively, in the text; S: coefficient of correlation, R, significantly greater than zero at $P = 0.05$; NS: R not significantly greater than zero).

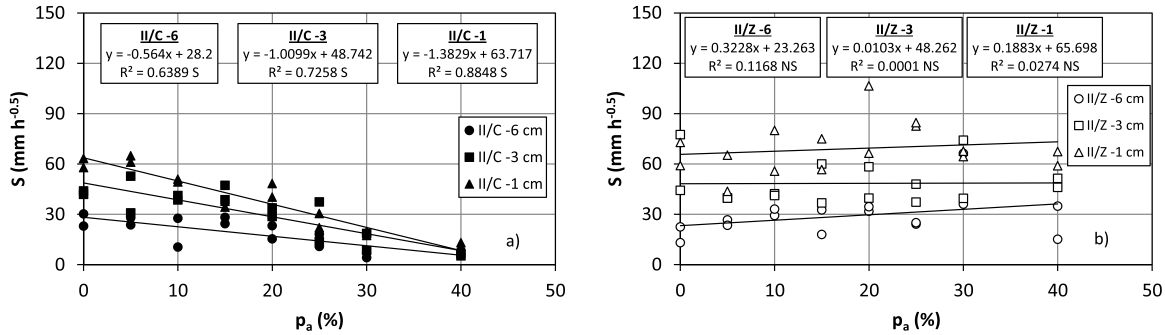

Fig. 3. Relationship between the soil sorptivity, S, and the percentage, p_a, of amendment (C = compost; Z = zeolite) for the three established pressure head, h_0, values (-6, −3 and −1 cm) in the second (II) sampling campaign (soil sorptivity corresponding to $h_0 = -6$, −3 and −1 cm denoted as S_{-6}, S_{-3} and S_{-1}, respectively, in the text; S: coefficient of correlation, R, significantly greater than zero at $P = 0.05$; NS: R not significantly greater than zero).

Table 2
Summary statistics of the soil hydraulic conductivity values, K_{-6}, K_{-3} and K_{-1} (mm/h), obtained on the soil treated with compost, C, or zeolite, Z, by establishing, in two sampling campaigns, three different pressure head, h_0, values with the Mini-Disk Infiltrometer (sample size, $N = 16$ for each dataset except for C and $h_0 = -1$ cm in the second sampling campaign for which N was equal to 15).

Statistic	h_0 = -6 cm				h_0 = -3 cm				h_0 = -1 cm			
	First sampling campaign		Second sampling campaign		First sampling campaign		Second sampling campaign		First sampling campaign		Second sampling campaign	
	C	Z	C	Z	C	Z	C	Z	C	Z	C	Z
Min	5.7	12.6	1.0	7.8	36.1	34.2	14.1	15.5	62.8	52.1	28.5	48.1
Max	24.9	27.7	16.3	33.2	63.5	81.2	45.0	68.4	126.3	207.4	81.5	106.7
Mean	16.1 a A	19.6 a A	8.0 b A	15.1 b B	46.5 a A	51.1 a A	27.8 b A	39.4 b B	87.0 a A	97.4 a A	51.4 b A	76.7 a B
CV (%)	38.3	21.9	48.6	39.0	19.3	25.6	36.6	29.1	23.4	44.2	31.9	24.3

Min = minimum value; *Max* = maximum value; *CV* = coefficient of variation.
For a given pressure head and sampling date, two means followed by the same upper case letter were not significantly different according to an F test and a two-tailed t test at $P = 0.05$. Two means followed by a different upper case letter were significantly different.
For a given pressure head and amendment, the lower case letter was the same when two means were not significantly different according to an F test and a two-tailed t test at $P = 0.05$, and different when the two means were significantly different.

the two treatments was statistically significant (Table 3).

For both treatments, the relationship between θ_i and p_a was not significant (Fig. 4**c**). The soil treated with the C had a 43.6 % larger mean of θ_i than the soil treated with the Z and the difference between the two treatments was significant (Table 3).

Neglecting from the calculations an apparently anomalous soil water content value for the C treatment (Fig. 4**b,c**) yielded smaller differences between the treatments, equal to 34.6 % for w_i and 28.0 % for θ_i. However, even in this case, differences between treatments were significant.

The soil treated with the Z was more homogeneous (smaller *CV* values) than that treated with the C with reference to ρ_b, w_i and θ_i.

Therefore, before performing the second sampling campaign with the MDI, the soil amended with the C was on average wetter than the soil amended with the Z. The θ_i values were nearly independent of p_a since an increase of p_a determined an increase of w_i and a decrease of ρ_b.

The final gravimetric soil water content, w_0, increased significantly with p_a with a single exception since it did not vary significantly with p_a for the Z and h_0 = -1 cm (Fig. 5**a-c**). At the end of the MDI runs, the soil treated with the C had a significantly larger w_0 value than that treated with the Z (Table 4). In particular, w_0 was larger by 18.0–20.3 %, depending on h_0, in the former case than the latter one.

Instead, the final volumetric soil water content, θ_0, did not vary significantly with p_a in the soil treated with the C, regardless of h_0 (Fig. 5**d-f**). With the Z treatment, the θ_0 vs. p_a relationship was inverse and significant, even if rather weak ($0.28 \leq R^2 \leq 0.30$) for $h_0 = -3$ and −1 cm and not significant for h_0 = -6 cm. The soil treated with the C was significantly wetter than that treated with the Z by a percentage varying with h_0 between 13.5 % and 15.0 % (Table 4).

Therefore, the volumetric soil water content at the end of the run with the MDI did not vary with p_a or it decreased as p_a increased. Using the C instead of the Z determined larger θ_0 values regardless of h_0.

The slope of the relationship between d_b and p_a was numerically negative in all cases, that is for the two amendments and the three established pressure heads (Fig. 6), but the d_b vs. p_a relationships were not statistically significant with a single exception. This relationship was significant but rather weak ($R^2 = 0.39$, $R > 0$) for the C amendment with h_0 = -1 cm. Therefore, the analysis generally suggested that, for given amendment and pressure head value, d_b did not vary with p_a.

For both amendments, d_b decreased monotonically as h_0 increased from −6 cm to −1 cm (Table 5). However, the means of d_b obtained with a given amendment and the three h_0 values did not differ significantly one from the other with a single exception. With the C amendment, establishing h_0 = -6 cm instead of −1 cm yielded an 8.2 % higher d_b value. Therefore, d_b generally decreased with larger h_0 values but this decrease was statistically significant for only one of the six established comparisons. The most common result was that, with a given amendment, d_b did not vary significantly with h_0.

For a given pressure head, the C treatment yielded larger d_b values than the Z one and the differences between the two amendments were statistically significant for all h_0 values (Table 5). In particular, the percentage differences between the d_b values for the C and Z treatments varied in the 9.5–12.9 % range depending on h_0.

Overall, there were some signs that d_b decreased with larger p_a and h_0 values but these signs were weak and statistically supported only in a few cases. Instead, the effect of the amendment on d_b was clearer and also significant. Specifically, using the Z amendment instead of the C one consistently implied measuring smaller wetted bulbs at the soil surface.

With the C, all tested relationships between S and p_a were statistically significant and they indicated that S decreased as p_a increased

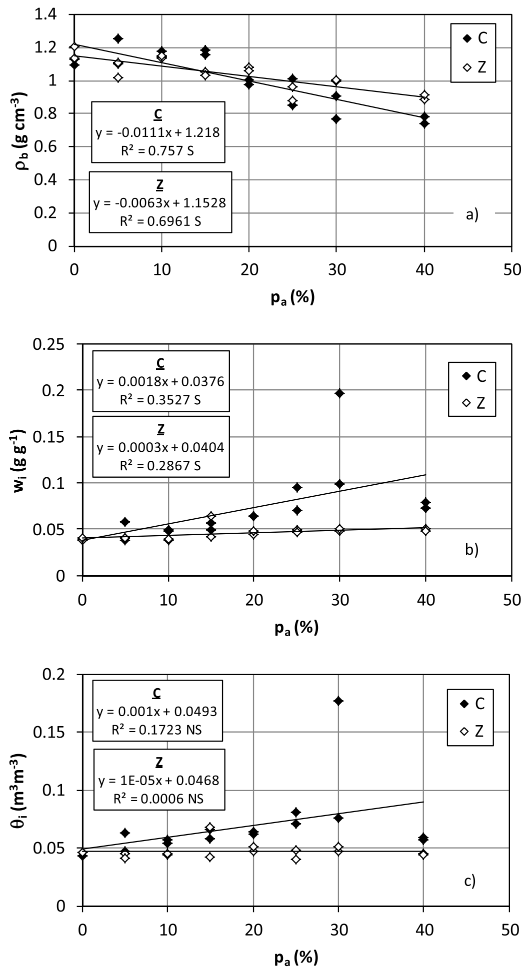

Fig. 4. Dry soil bulk density, ρ_b, gravimetric, w_i, and volumetric, θ_i, soil water content before starting the second campaign of MDI runs against percentage of applied amendment, p_a (C = compost; Z = zeolite; S: coefficient of correlation, R, significantly greater than zero at $P = 0.05$; NS: R not significantly greater than zero).

Table 3
Summary statistics of the dry soil bulk density, ρ_b, gravimetric, w_i, and volumetric, θ_i, soil water content values before starting the second campaign of MDI runs for the two amendments (sample size, $N = 16$ for each dataset).

Parameter	Statistic	Compost	Zeolite
ρ_b	Min	0.74	0.88
(g cm^{-3})	Max	1.26	1.21
	Mean	1.02 a	1.04 a
	CV (%)	16.1	9.3
w_i	Min	0.038	0.038
(g g^{-1})	Max	0.196	0.064
	Mean	0.070 a	0.046 b
	CV (%)	55.2	14.8
θ_i	Min	0.043	0.041
(m^{3}m^{-3})	Max	0.178	0.068
	Mean	0.068 a	0.047 b
	CV (%)	46.1	13.5

For a given parameter, two means followed by the same lower case letter were not significantly different according to an F test and a two-tailed t test at $P = 0.05$. Two means followed by a different lower case letter were significantly different.

(Fig. 3**a**). In particular, S_{-6}, S_{-3} and S_{-1} decreased by 5.0, 5.8 and 7.6 times, respectively, as p_a increased from zero to 40 %. Therefore, adding more C implied making the soil less sorptive, more appreciably with reference to the highest (less negative) pressure heads.

With the Z, none of the tested relationships between S and p_a was statistically significant (Fig. 3**b**), indicating that soil sorptivity at a given h_0 value did not vary with the amount of Z.

For each pressure head, the sorptivity of the soil treated with the Z was significantly greater than that obtained using the C (Table 6). Two corresponding S values differed by 59.2–69.9 %, depending on h_0. Therefore, treating the soil with the Z made the soil more sorptive as compared with a treatment with the C.

The coefficients of variation, CV, of the data were smaller with the Z as compared with the C and differences between the two treatments were more appreciable for the higher h_0 values. Therefore, the soil treated with the Z was also more homogeneous than that treated with the C with reference to the ability of the soil to draw water.

With the C, all tested relationships between K and p_a were statistically significant, indicating that K decreased as p_a increased (Fig. 2**c**). In particular, K_{-6} decreased by 6.8 times as p_a increased from zero to 40 %. A smaller decrease was detected for K_{-3} (by 2.5 times) and K_{-1} (by 2.9 times).

With the Z, none of the tested relationships between K and p_a was statistically significant (Fig. 2**d**), indicating that soil hydraulic conductivity did not vary with the amount of Z regardless of the considered pressure head. Therefore, using different percentages of Z did not have any effect, to a scale corresponding to that of an MDI run, on the ability of the soil pores to conduct water.

The hydraulic conductivity of the soil amended with the Z was larger by 41.7–88.1 %, depending on h_0, than that of the soil amended with the C and all differences between the two treatments were statistically significant (Table 2). Therefore, treating the soil with the Z made the soil more conductive as compared with a treatment with the C.

Even with reference to the soil hydraulic conductivity values, the soil treated with the Z was more homogeneous (smaller CV values) than that treated with the C regardless of h_0.

4.3. Comparing the two sampling campaigns

For each amendment and pressure head, a comparison was carried out between the K values obtained in the two sampling campaigns to verify if a short-term temporal variability of K occurred. In all cases, i.e. for both amendments and the three h_0 values, the soil hydraulic conductivity obtained in the second date was numerically smaller than that obtained in the first date (Table 2). However, there was a difference between the amendments.

With the C, the K values obtained in the second date were smaller by 40.2–50.1 % than those obtained in the first date, depending on h_0, and the differences between the two sampling campaigns were statistically significant in all cases.

With the Z, the K values obtained on the second date were smaller by 21.2–22.9 % than those obtained on the first date, depending on h_0, and the differences between the two sampling dates were statistically significant for $h_0 = -6$ and -3 cm but not for $h_0 = -1$ cm.

With a single exception (Z, $h_0 = -1$ cm), relative variability of the K data increased from the first to the second sampling date.

4.4. Soil water repellency

After the second campaign with the MDI and an additional month of exposure of the soil boxes to open air, the gravimetric soil water content did not differ significantly between the C and Z treatments since the mean and the CV of w_{WDPT} were equal to 0.22 g g^{-1} and 22.3 %, respectively, in the former case and to 0.20 g g^{-1} and 18.0 % in the latter case.

In the absence of any treatment, the 35 %-45 % of the WDPT tests did not suggest any soil water repellency whereas the remaining 55 %-65 % of the tests suggested a slight water repellency (Fig. 7). The treatment with the C at different rates i) did not modify soil water repellency as

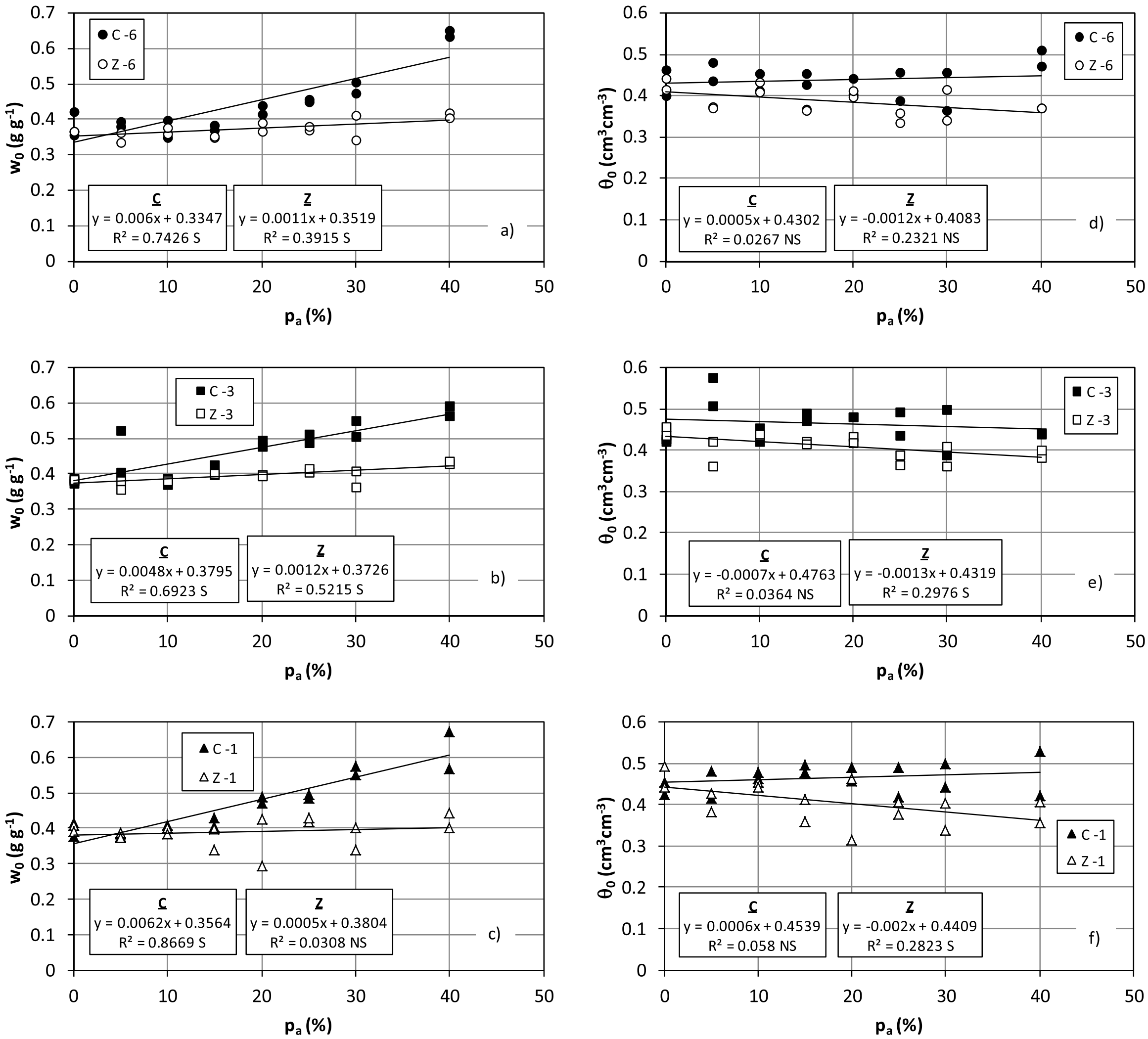

Fig. 5. Gravimetric, w_0, and volumetric, θ_0, final soil water content against percentage of amendment, p_a, for the two treatments (C = compost; Z = zeolite) and the three established pressure heads with the MDI, h_0 ($h_0 = -6$, -3 and -1 cm; S: coefficient of correlation, R, significantly greater than zero at $P = 0.05$; NS: R not significantly greater than zero).

Table 4
Summary statistics of the gravimetric, w_0, and volumetric, θ_0, final soil water content values after a MDI run at different pressure heads, h_0, on a soil treated with compost, C, or zeolite, Z (sample size, $N = 16$ for each dataset).

Statistic	h_0 = -6 cm				h_0 = -3 cm				h_0 = -1 cm			
	w_0 (g g^{-1})		θ_0 (m^{3}m^{-3})		w_0 (g g^{-1})		θ_0 (m^{3}m^{-3})		w_0 (g g^{-1})		θ_0 (m^{3}m^{-3})	
	C	Z	C	Z	C	Z	C	Z	C	Z	C	Z
Min	0.350	0.336	0.365	0.334	0.370	0.355	0.390	0.362	0.377	0.295	0.417	0.313
Max	0.650	0.418	0.510	0.443	0.591	0.437	0.577	0.458	0.673	0.443	0.528	0.492
Mean	0.443a	0.373b	0.439a	0.386b	0.466a	0.395b	0.464a	0.409b	0.469a	0.390b	0.465a	0.404b
CV (%)	20.1	6.3	8.5	8.4	15.8	5.5	9.7	7.3	18.3	9.7	7.2	12.1

Min = minimum value; *Max* = maximum value; *CV* = coefficient of variation.
For given pressure head and variable (w_0 or θ_0), two means followed by a different lower case letter were significantly different according to an F test and a two-tailed t test at $P = 0.05$.

compared with the untreated soil in a case, ii) suggested that the treatment improved a little soil wettability in another case, and iii) determined an increase of the WDPT tests indicating water repellency in five cases. Even in these last cases, water repellency was slight with the exception of a very few tests suggesting a strong water repellency. Instead, the treatment with the Z at different rates suggested that, although not monotonically, larger concentrations of amendment improved soil wettability. In detail, with the largest concentration of Z, all WDPT tests suggested wettable conditions.

Therefore, the data overall indicated that the soil was naturally wettable or slightly water repellent. Addition of C did not modify appreciably soil water repellency or it determined a limited increase, remaining however in a situation of slight water repellency. Instead, addition of Z determined a decrease and also disappearance of any water repellency.

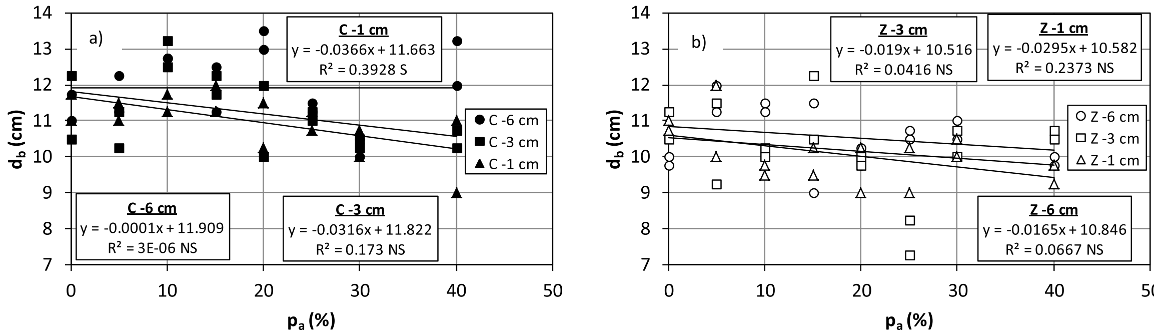

Fig. 6. Relationship between the diameter of the wetted bulb at the soil surface after the MDI run, d_b (cm), and the percentage, p_a, of amendment (C = compost; Z = zeolite) for the three established pressure heads on the soil surface, h_0 ($h_0 = -6$, -3 and -1 cm; S: coefficient of correlation, R, significantly greater than zero at $P = 0.05$; NS: R not significantly greater than zero).

Table 5
Summary statistics of the values of the diameter of the wetted bulb at the soil surface after the MDI run, d_b (cm), for the two amendments and the three established pressure heads on the soil surface, h_0 (sample size, $N = 16$ for each dataset).

Parameter	Compost			Zeolite		
	$h_0 = -6$ cm	$h_0 = -3$ cm	$h_0 = -1$ cm	$h_0 = -6$ cm	$h_0 = -3$ cm	$h_0 = -1$ cm
Min	10.0	10.0	9.0	9.0	7.3	9.0
Max	13.5	13.3	12.0	12.0	12.3	12.0
Mean	11.9 a A	11.3 ab A	11.0 b A	10.5 a B	10.2 a B	10.0 a B
CV (%)	8.5	8.7	6.8	7.8	11.8	7.8

For a given amendment, two means followed by the same lower case letter were not significantly different according to an F test and a two-tailed t test at $P = 0.05$. Two means followed by a different lower case letter were significantly different.
For a given pressure head, two means followed by a different upper case letter were significantly different according to an F test and a two-tailed t test at $P = 0.05$.

Table 6
Summary statistics of the soil sorptivity values, S_{-6}, S_{-3} and S_{-1} (mm h$^{-0.5}$), obtained, in the second sampling campaign, on a soil treated with compost, C, or zeolite, Z, by establishing three different pressure head, h_0, values (sample size, $N = 16$ for each dataset except for C and $h_0 = -1$ for which N was equal to 15).

Statistic	Pressure head					
	-6 cm		-3 cm		-1 cm	
	C	Z	C	Z	C	Z
Min	4.1	13.0	5.3	36.8	13.0	43.7
Max	30.2	66.2	52.6	77.4	64.8	106.5
Mean	18.0 a	29.1 b	30.4 a	48.4 b	40.7 a	69.1 b
CV (%)	50.6	41.8	50.2	26.2	43.0	21.2

Min = minimum value; *Max* = maximum value; *CV* = coefficient of variation.
For a given pressure head, two means followed by the a different lower case letter were significantly different according to an F test and a two-tailed t test at $P = 0.05$.

4.5. Summary of the amendment effects on the soil hydrodynamic behavior

Overall, the two amendments yielded different results. Using the C induced a decrease of near-saturated soil hydrodynamic parameters with larger amendment rates, p_a. Initially, this decrease was limited to some of the tested parameters but then it was detected for all parameters (Figs. 2 and 3). Instead, adding the Z did not influence any of the tested parameters regardless of both p_a and the sampling date.

With the C, near-saturated soil hydraulic conductivity decreased appreciably in the relatively short time period between the two sampling campaigns (Table 2). Instead, using the Z made this decrease smaller.

Nearly 1.5 months after preparing the samples, the soil treated with Z was more sorptive (Table 6) and more conductive (Table 2) than the same soil treated with C. Moreover, the former soil was drier than the latter one both before (Table 3) and after (Table 4) the MDI run.

The effect of the amendment was also visually perceivable since, at the end of the MDI runs, the diameter of the wetted bulb at the soil surface was larger with the C treatment than the Z one (Table 5).

Therefore, the hydrodynamic response of the soil treated with the C was more dependent on both the time from the beginning of the experiment and the amount of the amendment used than that of the same soil treated with the Z.

Both sorptivity and hydraulic conductivity are expected to be smaller in finer soils (Moret-Fernández et al., 2020; Yilmaz et al., 2023) and capillary forces, controlling lateral expansion of the wetting front around a near-point source of water, are greater in finer soils with smaller pores. Therefore, the soil treated with the C was functionally finer than that treated with the Z.

Finally, soil water repellency was at the most slight in untreated conditions (Fig. 7). Addition of Z determined disappearance of any water repellency. Adding C did not modify or it induced a limited increase of soil water repellency.

5. Discussion

Some experimental evidence that a treatment with C or other organic amendments can induce a decrease of the unsaturated soil hydraulic conductivity can be found in the literature (Aggelides and Londra, 2000; Wanniarachchi et al., 2019) and this investigation supported previous findings. However, we did not find data about the Z effects on hydrodynamic properties of near-saturated coarse-textured soils. This investigation suggested that these effects could be negligible.

Trying to explain these results, it was preliminarily recognized that the overall duration of the experiment was short, that is a couple of months. Therefore, the occurrence of relevant soil aggregation processes promoted in some different manner by the two amendments appeared unlikely.

Instead, the following considerations were made: i) the soil was packed manually and some soil settling and compaction phenomena likely occurred during the experimental period due to gravity, wetting and drying (Murphy et al., 1993; Busscher et al., 2002); ii) in coarse soils, some physical pore obstruction due to amendment addition can be expected to occur (Villagra-Mendoza and Horn, 2018; Wanniarachchi et al., 2019); iii) soil pore size distribution depends on the soil particle size distribution (Arya et al., 1999; Arya and Heitman, 2015; Lebron et al., 2002; Nimmo, 2004). With reference to the particles smaller of 2 mm, the soil and the Z had a relatively similar particle size distribution whereas the C was overall coarser than both the soil and the other

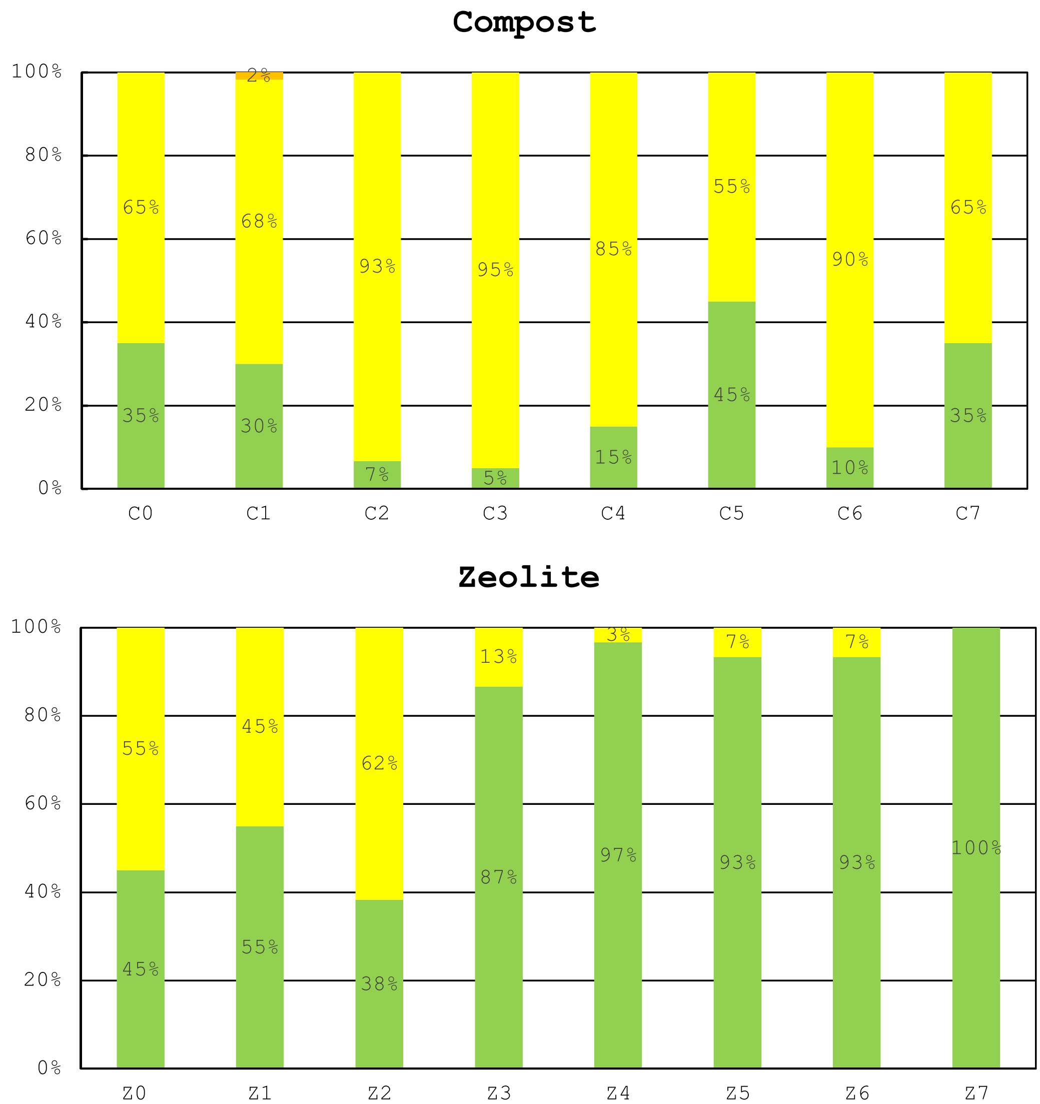

Fig. 7. Classification of soil water repellency according to Bisdom et al. (1993) for different concentrations of compost and zeolite (green: wettable; yellow: slightly water repellent; orange: strongly water repellent).

amendment (Fig. 1); and iv) using the C implied introducing in the soil particles that were essentially non-porous and impermeable to water. Instead, the used Z particles likely had pores and channels within their structure (Nakhli et al., 2017; Satriani et al., 2024). Consequently, all other things being equal, it can be presumed that a particle of C might hinder flow more effectively than a particle of Z.

In light of these considerations, a possible explanation of the results obtained in this investigation was the following. Relatively small sorptivity and hydraulic conductivity values were obtained with the C and with large amounts of this amendment since the large particles of C obstructed the relatively large conductive soil pores and hence, they constituted a physical obstacle to water flow. Instead, with the Z, appreciable obstruction phenomena did not occur, and the pore size distribution did not change appreciably. Hence, the treatment with the Z did not impede water transport and neither *S* nor *K* changed substantially after the treatment.

In the first sampling campaign, the C effect was only detected for the smallest (most negative) pressure head since the smaller conductive soil pores were more easily obstructed than the larger pores. Soil settling and compaction phenomena occurring between the two sampling campaigns determined a decrease of pore sizes and also a closer contact between the soil and the particles of amendment. The decrease of *K* between the two sampling campaigns was more appreciable with the C than with the Z since, in the former case, settling and compaction phenomena also enhanced the ability of the amendment to retard flow. In the latter case, instead, settling and compaction phenomena were not, or were less, associated with an enhanced ability of the amendment to retard flow. Moreover, the Z made perhaps the soil matrix more rigid as compared with the C.

Finally, differences between the two treatments increased from the first to the second sampling campaign because the hydraulic conductivity of the soil treated with the C decreased more than that of the soil treated with the Z.

This explanation shows some similarity with that by Belviso et al. (2022), which suggested that a particle of amendment can limit water transport into the soil by favoring development of a clay-like porous medium due to an increase in meso-micropores combined with macropore loss. The larger θ_i (Table 3) and θ_0 (Table 4) values obtained with the C than the Z suggest an improved ability of the soil treated with the organic amendment to retain water. Hence, the data obtained in this investigation are consistent with the interpretation by these authors. However, there are also some differences between this investigation and that by Belviso et al. (2022) since these authors considered a silty-loam soil amended with zeolite but just this amendment did not influence soil hydrodynamic properties in this investigation. In other words, C but not Z addition favored development of a clay-like porous medium.

Another possible reason why soil hydrodynamic parameters became smaller with larger percentages of C but not with more Z was that the former amendment induced some soil water repellency that instead did not occur with the latter amendment.

This explanation, that is not necessarily alternative to the previous one, was considered plausible taking into account that: i) an increase in soil water repellency can determine smaller values of both sorptivity and hydraulic conductivity close to soil saturation (Wahl et al., 2003; Ebel and Moody, 2020); ii) an increase in soil water repellency can occur with more compost (Müller and Deurer, 2011; Głąb, 2014; Leelamanie and Manawardana, 2019) but the zeolite could not have the same effect. For example, Müller and Deurer (2011) listed zeolite as one of the possible surfactants to be used for alleviating soil water repellency and Gholami et al. (2024) recognized that a treatment with zeolite effectively mitigated the adverse hydrological effects of soil water repellency in fire affected soils; and iii) the WDPT data collected a few weeks after the MDI runs suggested more water repellency in the soil treated with C than in that treated with Z (Fig. 7).

However, this explanation is not free from uncertainties since, with the C treatment, the *K* and *S* values obtained in the second campaign decreased with more amendment (Figs. 2 and 3), but more C did not suggest a continuous increase of soil water repellency (Fig. 7). Another more general reason is that, according to other investigations, the soil water repellency attributable to organic amendments could overall be negligible under field conditions (Castellini et al., 2024) and zeolite could also exhibit some hydrophobicity, depending on the Si/Al ratio and the surface hydroxyl group content (Tatlier et al., 2022). In other words, it cannot be excluded at all that the soil hydrodynamic response did not depend, or depended only a little, on soil water repellency.

Taking into account that WDPT and MDI data are collected at different scales (point for the WDPT test and small area for the MDI), developments of this investigation should be performed by also considering the need to determine soil water repellency and infiltration at more directly comparable scales.

Numerical simulation of hydrological states and fluxes requires describing appropriately the spatially and temporally variable soil hydraulic parameters (Christiaens and Feyen, 2000; Assouline and Mualem, 2006; Baroni et al., 2017; Šípek et al., 2019). This investigation contributed to understanding how the soil should be described soon after application of a large amount of amendment in the upper zone of a tilled layer.

With the C, the tilled soil should be considered as a two-layered system, with different soil hydrodynamic parameters for the upper amended layer and the non-amended deeper layer. Time changes of soil properties in the amended layer can be appreciable and hence they should also be considered.

Instead, with the Z, the tilled soil could be considered vertically almost homogeneous, regardless of whether the soil contains the amendment or not. Further, time changes of soil hydrodynamic parameters can be expected to be smaller and perhaps it could not be strictly necessary taking these changes into account.

Therefore, soil parameterization for numerical modelling purposes seems simpler if the Z is used as amendment instead of the C. Of course, this suggestion is based on a single experiment, and it is valid for a soil similar to the sampled one and a relatively short time period, that is one or two months after adding the amendment. Considering other soils and performing longer experiments could help to draw general conclusions.

The MDI appears to be a good method for performing these developments for different reasons. The device is simple and cheap, and its application determines a minimal, or even negligible, disturbance of the sampled soil volume. Therefore, the data are expressive of the soil response and not of any soil alteration due to the run.

The non-destructive nature of the run implies that the same sampled soil can also be subjected to subsequent determinations. In other terms, soil monitoring campaigns can easily be realized. This is an important aspect of the methodology since amendment effects on soil-water relationships can be expected to vary with the elapsed time after the treatment (Bondì et al., 2022).

The operating principle of the MDI is the same as that of the classical tension infiltrometer (Perroux and White, 1988), that can be used in the field to explore larger and more representative areas by a single run. Therefore, performing comparisons between laboratory and field experiments should be easy.

The data obtained under close to zero, but negative pressure heads can be expected to be more representative of common field situations as compared with those obtained by ponding infiltration experiments, taking into account that ponded infiltration is an extreme case which is rarely seen in the field (Dohnal et al., 2016).

Finally, the MDI can also be used for detecting soil water repellency (Lichner et al., 2018; Alagna et al., 2019).

Evidently, tension infiltrometers are not perfect devices since they also have limitations such as, for example, the risk of poor contact between the disc and the soil that could compromise the quality of the data (Close et al., 1998). However, it seems plausible to suggest that the advantages outweigh the disadvantages.

Finally, it has to be acknowledged that the use of two sampling points within each microplot could be expected to introduce pseudoreplication, which may limit the statistical independence of the observations. Likely, future studies should consider replicating entire microplots to improve statistical power and also account for packing-related heterogeneity. Taking into account that, in common field situations, the expectation is to incorporate relatively small amounts of amendment into the soil, additional investigation should also consider smaller *pa* values than those considered in this investigation.

6. Conclusions

Understanding soil hydraulic properties changes is essential for sustainable land management, especially in arid and semi-arid regions, where water availability is a limiting factor. The two tested amendments can be expected to have a different short-term impact on the hydrodynamic properties of a near-saturated coarse-textured soil. According to this investigation, the soil sorptivity and hydraulic conductivity values corresponding to high pressure head values (-6 cm $\leq h_0 \leq -1$ cm) decrease with larger compost rates whereas they do not vary with different amounts of zeolite. Overall, adding compost makes the soil functionally finer as compared with the soil treated with zeolite. Moreover, the soil amended with compost experiences more appreciable short-term temporal variations of soil hydrodynamic parameters than that amended with the zeolite.

In summary, the compost can be expected to favor development of a clay-like porous medium if the particles of this amendment act as a physical obstacle to water flow. Development of a clay-like porous medium is not expected with the zeolite if the particles of this amendment do not alter appreciably the pore size distribution.

Characterizing a soil profile for numerical simulation purposes appears easier if the zeolite is used as an amendment instead of the compost.

From a practical point of view, using compost, especially in large percentages, can be expected to induce a slowdown of the water transport processes towards the deeper layers in conditions of near-saturation of the soil, especially a few weeks after the treatment. This circumstance could help to maintain a water reserve usable by plants in the treated soil layer. The same conclusion cannot be drawn for the zeolite since, in this case, hydrodynamic processes in near-saturated soil conditions can be expected not to change appreciably, regardless of the amount of amendment used and the time elapsed since the treatment.

Of course, trying to draw general conclusions requires testing experimentally the suggested interpretations, considering other soils, performing longer measurement campaigns and making use of other amendments.

The experimental methodology applied in this investigation could also be applied by other research groups, as it seems appropriate for developing larger and more complete soil datasets. Exposing some soil boxes to open air for long periods and possibly sowing appropriate plant species could make it possible to also establish if and how the effects of the applied soil amendments vary with meteorological forcing and development of vegetation.

CRediT authorship contribution statement

D. Autovino: Writing – original draft, Validation, Investigation, Data curation. **C. Bondì:** Writing – original draft, Validation, Investigation, Data curation. **V. Bagarello:** Writing – original draft, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **F. Zanna:** Writing – original draft. **G. Russo:** Writing – original draft, Validation, Investigation, Data curation. **K. Zhioua:** Writing – original draft, Validation, Investigation, Data curation.

Declaration of Competing Interest

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

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Data availability

Data will be made available on request.

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