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Optimizing Soil Water Retention through Compost and Vermicompost from Vert d'Iris Cooperative (Belgium): Chemical and Spectroscopic Characterization of Humic Acids (UV–Vis and FTIR Analysis)

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Abstract

The world faces major environmental challenges, including climate change, soil degradation, water scarcity, and pollution from unmanaged organic waste. Sustainable and scientifically validated strategies are therefore essential. This study evaluated the effect of a compost-vermicompost mixture (70:30, w/w), derived from food waste produced by the Vert d'Iris Cooperative (Belgium), on soil field capacity and humic acid quality.

The amendment was produced and characterized according to international standards before application to the Betteraves Enz garden (Anderlecht). Soil samples collected at 0–30 cm depth from amended plots ($n = 15$, n = number of samples) and control plots ($n = 15$) were analyzed for physicochemical properties and water retention. Humic acids were extracted following the International Humic Substances Society protocol and characterized by UV–visible and FTIR spectroscopy.

Amended soils showed a significantly higher field capacity than controls (38.4% vs. 27.3%), representing an increase of approximately 40% ($p < 0.001$, i.e., probability of error below 0.1%). Spectroscopic analyses indicated enhanced humification, reflected by significant variations ($p < 0.05$) in the absorbance ratios $A_{2/4}$ (E_2/E_4, 280/465 nm) and $A_{4/6}$ (E_4/E_6, 465/665 nm), as well as in the $\Delta\log K$ index ($\log A_{400} - \log A_{600}$), which are indicators of aromatic condensation, molecular size, and structural maturity of humic substances. FTIR spectra confirmed enrichment in aromatic and oxygenated functional groups.

These findings demonstrate that combining physicochemical and spectroscopic indicators provides robust evidence of improved soil water retention and long-term organic matter stabilization, supporting sustainable soil management strategies.

Keywords

waste management, water management, humic acids, UV–Vis spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, compost

1 Introduction

The rapid growth of the global population, projected to reach approximately 9.7–9.8 billion by 2050 [1], coupled with the escalating demands for food and water, underscores the urgent need for the rational and sustainable use of natural resources. However, these resources are increasingly threatened by climate change, pollution, and soil erosion, which collectively jeopardize global food security and ecosystem stability [2–5]. In urban and peri-urban regions, such pressures are further intensified by land-use constraints, soil sealing, and declining soil organic matter content.

According to the Food and Agriculture Organization (FAO), global food demand is expected to rise by 50% by 2030, while the International Food Policy Research Institute (IFPRI) forecasts a 30% increase in water demand within the same timeframe [1]. Addressing these challenges requires comprehensive strategies that prioritize

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the optimal and sustainable management of key resources, particularly through agricultural practices that enhance water-use efficiency. In urban environments such as the Brussels-Capital Region, about 53% of the soil surface is impermeabilized, severely limiting water infiltration and effective soil water storage capacity [6].

Alarmingly, an estimated 1.3 billion tons of food produced annually, equivalent to one-third of the global food supply for human consumption (approximately 3.9 billion tons), is lost or wasted [7, 8]. This issue affects both developed (672 million tons) and developing countries (625 million tons) [7–9], representing a significant waste of water, energy, and other resources invested in food production, processing, and distribution. Worldwide, food waste is predominantly (69%) directed to landfills, with 47% disposed in non-sanitary landfills and 22% in sanitary landfills, releasing substantial quantities of greenhouse gases that exacerbate climate change [10]. These 69% of food waste remains unrecycled or unrepurposed [10]. This issue is particularly evident in the Brussels-Capital Region, where the food waste recycling rate stands at only 27%, significantly lower than in other regions of Belgium [11]. This regional context highlights the urgent need for efficient organic waste recovery strategies.

Numerous studies have highlighted the environmental burden of landfilling and incinerating organic waste, which contributes to air, soil, and water pollution and poses serious risks to human health [12, 13]. Composting offers a promising alternative, enabling the conversion of organic waste into stable fertilizers that improve soil quality and fertility. However, the agronomic effectiveness of compost strongly depends on its chemical composition, stabilization degree, and humification level, and not all organic amendments provide comparable benefits.

In response to this challenge, the Vert d'Iris cooperative, a pioneering entity in organic farming and food distribution, has initiated a project to produce a compost-vermicompost mixture (70:30, w/w) from its own food waste and that of its partner clients in the Brussels food sector (around 150 tons of food waste per year). Such food waste–derived organic amendments have demonstrated significant benefits for soil enrichment, particularly in enhancing structural stability and water retention capacity, thereby reducing nutrient leaching beyond the root zone [14, 15]. Nevertheless, quantitative data on their effects on field capacity and humic substance quality in urban agricultural soils remain limited. Humic substances play a crucial role in the chemical, physical, and biological properties of soil [16–20]. Therefore, understanding the structure of humic substances, particularly humic acid (HA) (Fig. 1 [21]), is essential, as it is a fundamental indicator influencing soil properties.

Spectroscopic techniques such as UV–Vis and Fourier transform infrared (FTIR) provide valuable information on humic acid aromaticity, molecular complexity, and functional group composition, and are increasingly used for evaluating organic amendment quality. The aim of this study was to evaluate the impact of a food waste–derived compost-vermicompost mixture (70:30, w/w; 95% food waste, 5% wood waste) produced by the Vert d'Iris cooperative on soil field capacity and humic acid characteristics in the Betteraves Enz garden (Anderlecht, Belgium). Specifically, this work (i) quantifies changes in soil water retention, (ii) characterizes humic acid structure using UV–Vis and FTIR spectroscopy, and (iii) assesses the statistical significance and consistency of these effects.

2 Materials and methods

2.1 Experimental area and soil sampled

The experiments were conducted in May 2023 in the greenhouse of the Betteraves Enz garden, operated by the Vert d'Iris Cooperative (Fig. 2 [22, 23]), located in Anderlecht, Belgium, at geographic coordinates 50.82°N, 4.26°E.

This greenhouse spans an area of 720 m^2 and features a soil profile primarily composed of Luvisols [24], with a loamy texture. Granulometric analysis of the Betteraves Enz greenhouse soil revealed a composition of 65.8% silt, 25.1% sand, and 9.1% clay. The region is characterized by a temperate climate with warm conditions and consistent precipitation, even during dry months. The average annual precipitation is approximately 809.6 mm, while the mean annual temperature is around 11 °C. Precipitation levels fluctuate throughout the year, ranging from 45.4 mm in April to 86.9 mm in December.

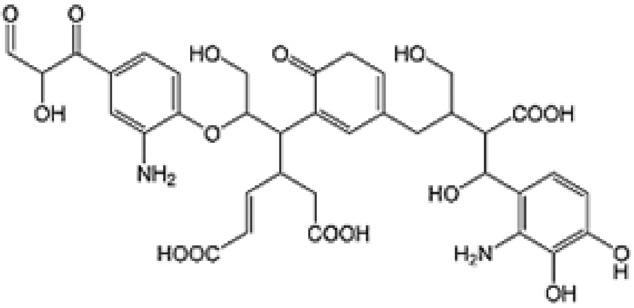

Fig. 1 Structural model of monomeric humic acid unit (molecular mass 731 g/mol) [21]

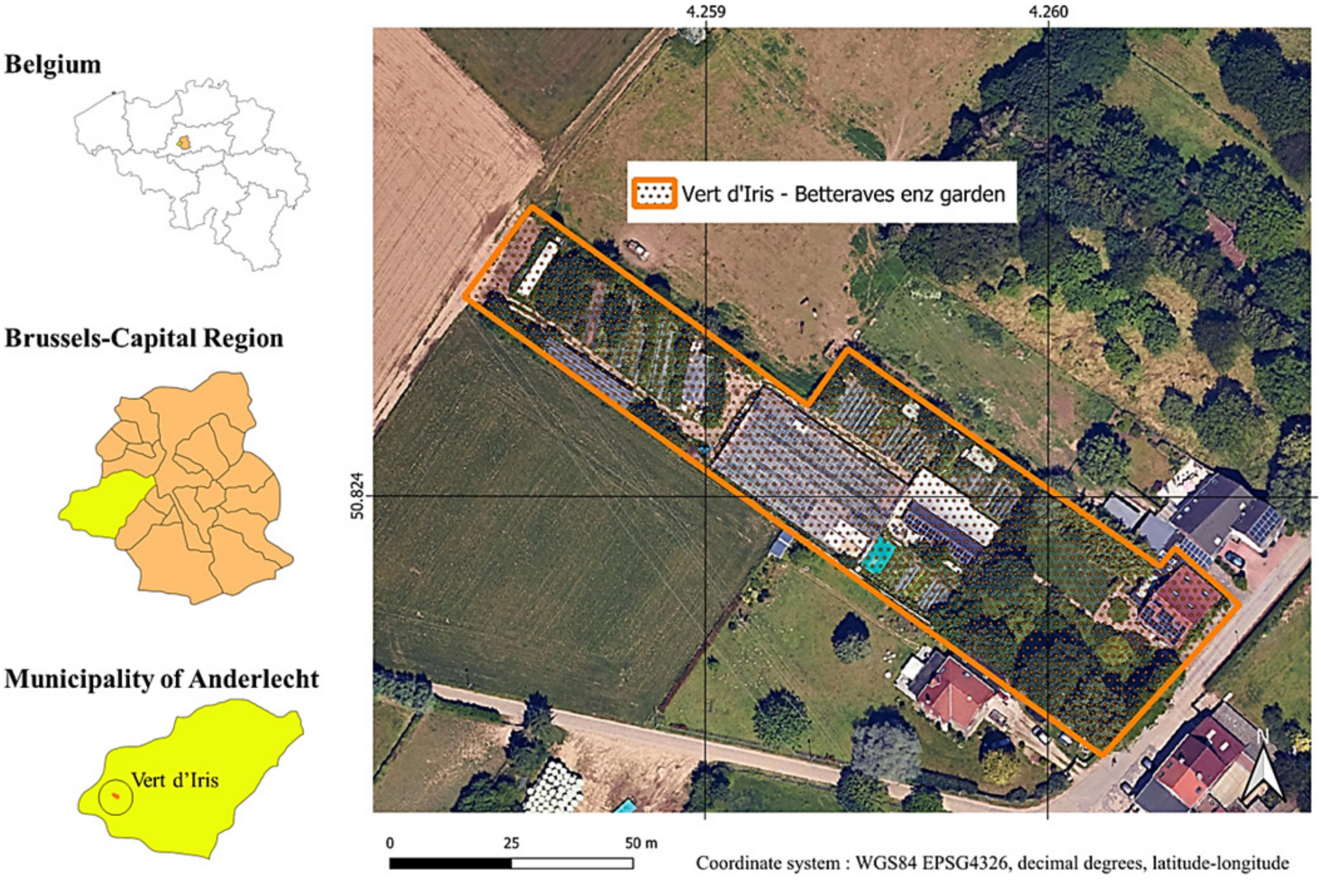

Fig. 2 Location of sampling points in Betteraves Enz garden (Anderlecht/Belgium) [22, 23]

The cultivated soil was classified as moderately structured with medium porosity and organic matter content typical of urban agricultural systems.

Soil sampling was conducted at the depth of 0–30 cm using stainless steel cylindrical cores (5 cm internal diameter, 30 cm length, sampling area 19.6 cm^2). Fifteen soil samples were collected within the greenhouse along a 10.5 m long plot using a systematic grid design. Undisturbed soil cores were collected in order to preserve soil structure and pore continuity.

The greenhouse soil had been amended in 2023 and May 2024 with 20 kg/m^2 of a mature compost-vermicompost mixture (70:30, w/w; maturity: 6–7 months) derived from food waste (95%) and wood waste (5%). In May 2024, the soil was cultivated with the *Solanum lycopersicum* cv. "Toronjina". In parallel, fifteen control soil samples were collected adjacent to the greenhouse following the same sampling protocol and from the same soil type, but without any history of organic amendment application. Five pure compost and four pure vermicompost samples were also collected for comparative characterization. However, preliminary statistical analyses indicated no significant differences between compost and vermicompost in their effects on soil field capacity and HA properties ($p > 0.05$, where p is the probability of error). Subsequent analyses presented in this paper focused only on their combined application. All collected samples were pretreated according to the NF ISO 11464 standard [25] (air drying at <40 °C and grinding to 2 mm) prior to physicochemical analyses [26].

2.2 Determination of soil and compost physicochemical properties

These analyses were carried out at the chemical laboratories of the Provincial Center for Agriculture and Rurality (CPAR, Brabant Wallon, Belgium) and the Center for Agronomy and Agro-Industry of the Province of Hainaut (Hainaut Analysis/CARAH). A detailed description of the analytical methods is provided in Table 1 [27–32].

Cation exchange capacity (CEC) values were converted from meq/100 g to SI unit (mol(+)/kg) according to international recommendations. (In the unit mol(+)/kg, "(+)" refers to moles of positive charge (charge equivalents), not simply moles of ions, as CEC quantifies the total exchangeable cationic charge per kilogram of soil.)

Potassium and sodium concentrations were determined by flame atomic absorption spectrometry in emission mode, which provides reliable sensitivity for alkali metals.

Table 1 Physicochemical parameters and methods used

Analysis	Method(s)	Reference
pH KCl 1M	PTCS3-NF EN ISO 10390	[27]
pH-water	PTCS3-NF EN ISO 10390	[27]
Organic carbon and humus	Organic carbon x 2.	[28]
Total carbon	PTCS17-Derived from NF EN 15936	[29]
Total nitrogen	PTCS17-Derived from NF ISO 13878	[30]
Phosphorus	PTCS10-Molybdenum Blue Colorimetry	
- Potassium (K^+) -Magnesium (Mg^{2+}) - Calcium (Ca^{2+}) - Iron (Fe) - Manganese (Mn) - Copper (Cu) - Zinc (Zn) - Sodium (Na)	PTCS12-Atomic Absorption Spectrophotometry CWEA S-11-12 and ISO 22036:2008	[31, 32]
Calcium carbonate ($CaCO_3$)	PTCS17-Derived from NF EN 15936	[29]
Cation exchange capacity (CEC) measured	Near-infrared spectroscopy	
Carbon/Nitrogen ratio	Calculated value	

2.3 Determination of field capacity

Field capacity (FC) represents the maximum water content retained by soil after gravitational drainage. It was assessed by saturating soil samples placed in perforated PVC pots (height: 15 cm; diameter: 10 cm; volume: 1.2 L) for 24 h, followed by a 24-h free drainage period and subsequent drying at 105 °C for 24 h. Each pot was filled with 500 g of air-dried soil packed to its natural bulk density. The retained moisture was calculated as the difference between wet and dry masses [33]. FC (%) was calculated as

$$\mathrm{FC}(\%) = \frac{(W_W - W_d)}{W_d} \times 100 \tag{1}$$

where W_W is the wet mass after 24 h drainage; and W_d is the dry mass after oven drying at 105 °C. This parameter is influenced by soil texture, organic matter content, aggregation, and porosity [34].

2.4 Isolation and determination of humic acids

The humic acids were extracted according to the literature [35–37].

The decalcification process was carried out 24 h using 0.05 M HCl (1:10 w/v). After centrifugation, the residue was thoroughly rinsed with distilled water until neutral. The remaining solid was then extracted for 24 h with 0.5 M NaOH (1:10 w/v), with intermittent mixing, followed by centrifugation. The humic acids were precipitated from the alkaline extract by adding 2 M HCl to adjust the pH to 2 and centrifuging the mixture. The resulting HAs were purified by treatment with a HCl/HF mixture (950 mL H_2O, 5 mL HCl, and 5 mL HF) for 24 h, followed by centrifugation. This purification procedure was repeated three times. The HAs residue was subsequently rinsed with distilled water until no chloride reaction was detected. Finally, the purified HAs were lyophilized and ground to a fine powder in an agate mortar.

2.5 Characterization of the humic acids

2.5.1 UV-Vis spectrophotometry analysis

The compost-vermicompost-amended and control soil samples were analyzed using a Lambda UV–VIS spectrophotometer (Perkin Elmer) with a wavelength range of 200–900 nm to assess the degree of aromaticity in the soils. Two milligrams of purified soil sample (amended or control) were added to 10 mL of 0.05 M $NaHCO_3$ solution. Absorbance (A) measurements were recorded at the following wavelengths: 280 nm ($A280$), 400 nm (A_{400}), 465 nm (A_{465}), 600 nm (A_{600}) and 665 nm (A_{665}). These absorbance values were subsequently used to calculate the aromaticity coefficient values: the absorbance ratio ($A_{4/6} = A_{465}/A_{665}$) and the Δlog$K$ value, determined using Eq. (2) [38]:

$$\Delta \log K = \log A_{400} - \log A_{600} \, . \tag{2}$$

2.5.2 Fourier transform infrared spectroscopy

The amended and control soil samples were analyzed using a Bruker Vertex 70 FTIR spectrometer equipped with a Platinum ATR (Attenuated Total Reflection) module, operating within the wavenumber range of 400 to 4000 cm^{-1}. The samples were prepared as tablets and compressed with KBr prior to analysis.

2.6 Statistical analysis

All analyses were performed on 15 independent samples per treatment. Results are reported as mean values accompanied by standard deviation. Statistical comparisons between compost-vermicompost-amended soils and control soils were performed using Student's t-test after verification of data normality. Differences were considered statistically significant at $p < 0.05$, statistically highly significant at $p < 0.01$, and statistically very highly significant at $p < 0.001$.

3 Results and discussion

3.1 Compost and vermicompost physicochemical properties

The physicochemical parameters of the pure compost and vermicompost samples provide critical insights into the quality and efficacy of these organic amendments. The compost and vermicompost were subsequently combined at a 70:30 (w/w) ratio prior to soil application.

These measured parameters are evaluated against the standards outlined in NF U44-051 [39], which serves as a reference for organic products used in agriculture. The results of these analyses are summarized in Table 2.

The organic matter contents of the compost and vermicompost were 25.89 ± 0.03% and 28.65 ± 0.06%, respectively, exceeding the minimum threshold of 20% established by the NF U44-051 [39] standard. This indicates a high degree of organic stabilization and suitability for long-term soil amendment. According to the literature, this high organic matter content is critical for enhancing soil structure, increasing water retention capacity, and providing a sustained supply of nutrients to plants over time [40]. Furthermore, the total nitrogen contents were 1.78 ± 0.04% for the compost and 1.41 ± 0.10% for the vermicompost, both remaining below the maximum threshold of 3% (or 30 kg/t) set by the standard. This moderate nitrogen content reduces the risk of nitrate leaching and excessive mineralization, favoring progressive humification.

3.2 Soil samples physico-chemical properties

These physico-chemical values are critical for assessing the impact of compost application on soil properties, including texture, and the resulting effects on key factors such as water retention and fertility. Additionally, they facilitate the evaluation of soil nutrient levels and other essential soil parameters influencing crop productivity. Statistical analysis demonstrated parameter-specific differences between treatments, ranging from significant to very highly significant ($p < 0.05$ to $p < 0.001$), as shown in Fig. 3 and Table 3.

Table 2 Results of the physicochemical analyses of the composts and vermicompost samples

Parameters	Compost type*		NF U44-051 [39]
	Compost	Vermicompost	
Dry matter content (%)	60.92 ± 0.09	38.41 ± 0.11	> 30%
Organic matter (%)	25.89 ± 0.03	28.65 ± 0.06	> 20%
Total ash (%)	35.03 ± 0.05	24.7 ± 0.08	
Total nitrogen (%)	1.78 ± 0.04	1.41 ± 0.10	< 3% or < 30 kg/t
C/N ratio	19.39 ± 0.21	16.52 ± 0.26	15 < C/N < 30
P_2O_5 (%)	0.92 ± 0.02	0.72 ± 0.07	< 3% or < 30 kg/t
CaO (in kg/t)	2.13 ± 0.06	1.94 ± 0.13	
MgO (in kg/t)	2.04 ± 0.04	0.87 ± 0.21	
pH	7.2 ± 0.02	6.9 ± 0.05	

[*] Values are mean and standard deviation.

Humus is a fundamental component for soil structure and fertility. As shown in Fig. 3, a significant increase in humus content to 13.7 ± 0.04% was observed in the compost-vermicompost-amended soils of the greenhouse, compared to the control soils, which had a humus content 7.9 ± 0.07%. This represents an increase of approximately 73%, highlighting the strong contribution of compost-derived organic matter. This enrichment directly contributes to enhanced soil aggregation and water retention [16, 17]. Nitrogen, an essential element for plant growth, exhibited

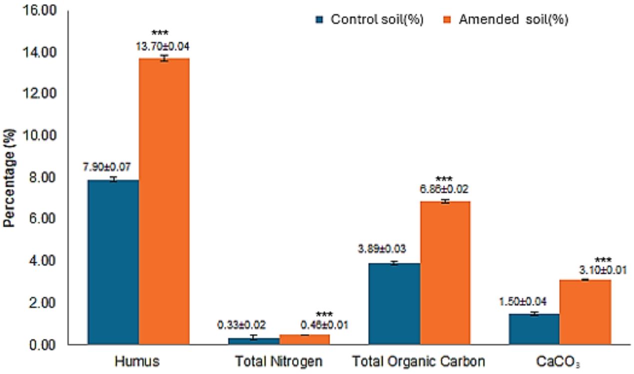

Fig. 3 Percentage composition of humus, total nitrogen, organic carbon, and $CaCO_3$ content in the soil samples. Error bars represent standard deviation ($n = 15$). The *** $p < 0.001$ indicates statistically very highly significant differences between compost-vermicompost-amended soils and control soils.

Table 3 Results of the macronutrient content, pH, C/N ratio, cation exchange capacity, and field capacity of the soil samples

Parameters	Control soils	Amended soils	Difference significance
Sodium (Na in mg/100 g)	1.6 ± 0.03	8.8 ± 0.06	***
Magnesium (mg/100 g)	32 ± 0.01	47 ± 0.05	***
Potassium (mg/100 g)	47 ± 0.06	52 ± 0.04	**
pH-KCl	7.1 ± 0.03	7.2 ± 0.02	*
pH-H_2O	7.6 ± 0.02	7.4 ± 0.02	*
CEC (mol(+)/kg)	11 ± 0.04	14 ± 0.06	***
Calculated C/N ratio	12	15	**
FC (%)	27.36 ± 0.06	38.4 ± 0.11	***

Values are means and standard deviations.
* ($p < 0.05$): statistically significant;
** ($p < 0.01$): statistically highly significant;
*** ($p < 0.001$): statistically very highly significant
+: In the unit mol(+)/kg, "(+)" refers to moles of positive charge (charge equivalents), not simply moles of ions, as CEC quantifies the total exchangeable cationic charge per kilogram of soil.

a similar pattern: the amended soils showed a higher nitrogen content (0.46 ± 0.01%) compared to the control soils (0.33 ± 0.02%), supporting improved nutrient availability and biological activity.

Moreover, the compost-vermicompost-amended soils demonstrated higher total organic carbon content (6.86 ± 0.02%) compared to control soils (3.89 ± 0.03%), reflecting a greater amount of organic matter in the amended soils. This near doubling of carbon content reflects substantial carbon sequestration potential. Regarding $CaCO_3$ content, the amended soils contained 3.1 ± 0.01% of $CaCO_3$, as opposed to 1.5 ± 0.04% in the control soils, thus highlighting the compost's role in enhancing soil porosity [41]. This improvement in porosity boosts the soil's ability to retain water through the formation of micropores [41, 42]. Additionally, $CaCO_3$ plays a crucial role in regulating soil pH, neutralizing its acidity and consequently increasing nutrient availability for plants [17, 43].

According to Table 3, the macro-nutrient levels in the amended soils (compost-vermicompost-amended soils) are 8.8 ± 0.06 mg/100 g for sodium, 47 ± 0.05 mg/100 g for magnesium and 52 ± 0.04 mg/100 g for potassium, respectively. These high levels in amended soils reflect an enhancement in soil fertility, promoting root development, plant growth and overall plant health [16, 17, 43].

Cation exchange capacity, which measures a soil's ability to retain and exchange essential plant nutrients, is a critical indicator of soil quality [17, 41]. Cation exchange capacity values were converted from meq/100 g to the SI unit mol(+)/kg for standardization. The amended soils exhibited a significantly higher CEC (≈ 1.4 mol(+)/kg) compared to the control soils (≈ 1.1 mol(+)/kg). This increase could enable the soil to retain more cations, enhancing its porosity and consequently improve its fertility and water retention capacity, as soils rich in cations tend to attract more water molecules [40, 41, 44]. Furthermore, pH values indicate that both soils are neutral to slightly alkaline, which is conducive to nutrient availability [45].

3.3 Soil samples field capacity

Water retention varies depending on the soil type and is influenced by the nature of the particles as well as the soil porosity [34]. The compost-vermicompost mixture significantly enhanced soil porosity and aggregate stability [16, 17, 42]. The field capacity values (%) of 15 control soil samples and 15 compost-vermicompost-amended soils samples are presented in Table 3 and Fig. 4.

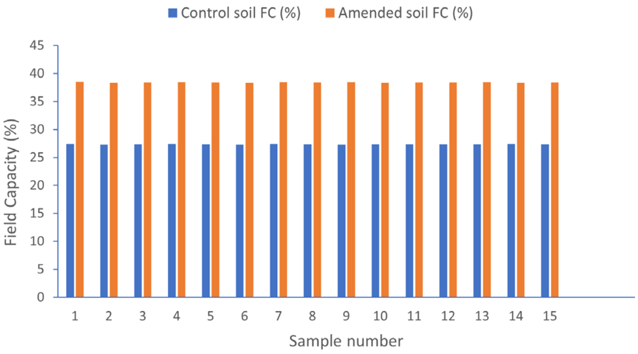

Fig. 4 The field capacity of the 15 control soil samples and 15 compost-treated soil samples

The FC values for the control and compost-amended soils were 27.36 ± 0.06% and 38.4 ± 0.11%, respectively. Student's *t*-test confirmed a highly significant difference between treatments ($p < 0.001$).

This represents an increase of approximately 40% in water retention capacity, directly attributable to increased humus content and improved pore continuity.

These results demonstrate that compost-vermicompost-based amendments constitute an effective strategy for improving soil water management under urban horticultural conditions.

3.4 Soil samples humic acids

3.4.1 UV–VIS analysis: determination of aromaticity

The absorption characteristics of humic acids in both amended and control soils are presented in Fig. 5 and Table 4.

Amended soils consistently exhibited higher absorbance values across all wavelengths, indicating greater chromophoric content.

Numerous studies have examined the absorption properties of humic acids in soil, demonstrating that absorption

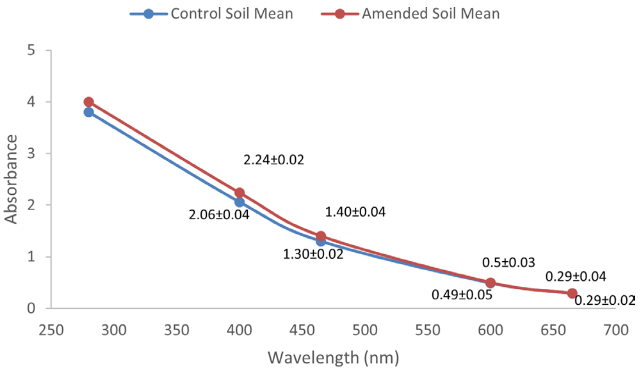

Fig. 5 UV–Vis is absorbance of humic acids in control and amended soils (mean spectra over the 15 control and 15 compost-vermicompost-amended soil samples)

Table 4 Ratio $A_{2/4}$, ratio $A_{4/6}$ and $\Delta\log K$ of humic acids (compost-vermicompost-amended and control soils)

Samples	Ratio $A_{2/4}$ (A_{280}/A_{465})	Ratio $A_{4/6}$ (A_{465}/A_{665})	$\Delta\log K$ $\log A_{400} - \log A_{600}$
HA amended soils	2.86 ± 0.08	4.83 ± 0.68	0.65 ± 0.03
HA control soils	2.92 ± 0.05	4.48 ± 0.32	0.62 ± 0.05
Difference significance	*		*

Values are means and standard deviations.
* corresponds to a statistically significant difference ($p < 0.05$).

intensity is directly correlated with the molecular composition of humic acids [46, 47].

The UV–Vis absorbance spectra of control and amended soil samples, as shown in Fig. 5, exhibit a progressive decline in absorbance with increasing wavelength from 250 to 650 nm. The consistently higher absorbance values observed in the amended soils indicate a greater presence of chromophoric organic compounds, particularly aromatic structures and conjugated systems, which are characteristic of humic substances [47]. This suggests that composting enhances organic matter enrichment by promoting the degradation of aliphatic structures and facilitating the accumulation of more recalcitrant aromatic compounds [46].

According to the literature, absorbance at 280 nm could be associated with lignin-derived structures, while absorbance at 465 nm corresponds to low-molecular-mass humic acids with a low degree of transformation [46, 47].

In contrast, absorbance at 665 nm reflects the presence of highly condensed humic acids, indicative of advanced humification [46, 47]. The significantly higher absorbance intensities in amended soils indicate enhanced aromaticity and molecular complexity.

The statistical analysis indicated that these differences were significant ($p < 0.05$). Together, these indices demonstrate that compost-vermicompost mixture application promotes the formation of chemically stable and highly humified organic matter. The $A_{2/4}$ ratio reflects the relative abundance of aliphatic structures (absorbing at 280 nm) versus aromatic and conjugated systems (absorbing at 465 nm). A lower $A_{2/4}$ value corresponds to higher aromaticity and structural condensation [38, 46, 48].

In this study, humic acid from amended soil exhibited a lower $A_{2/4}$ ratio (2.86 ± 0.08) compared to those from control soils (2.92 ± 0.05). This indicates a greater prevalence of aromatic structures and possibly a more advanced humification process in the amended soils.

However, the $A_{4/6}$ ratio is another indicator of condensation level of aromatic nuclei, and some studies have shown that higher $A_{4/6}$ ratios could reflect a greater heterogeneity in humic molecular structures, especially in systems undergoing active organic transformation such as amended soils [48–50].

The results presented in Table 4 indicate that the amended soils showed a higher $A_{4/6}$ ratio (4.83 ± 0.68) than the control soils (4.48 ± 0.32), suggesting that the compost-vermicompost amendment may contribute to the formation of a broader range of humic molecules, possibly including both younger and more transformed components.

Furthermore, the $\Delta\log K$ value, a recognized index of humic maturity by Kumada [38], is also higher in amended soils (0.65 ± 0.03) compared to control (0.62 ± 0.05), confirming a higher degree of humification in amended soils.

These findings underscore the critical role of composting in humification, by promoting the transformation of organic matter into more stable humic substances. This higher humification increases the soil cation exchange capacity, thereby improving its porosity, fertility, and water retention. Greater cation retention promotes higher water molecule attraction, leading to improve soil structure and resilience [40, 41, 44].

3.4.2 Fourier transform infrared spectroscopy

The FTIR spectra of humic acid samples from both amended and control soils are presented in Fig. 6.

All spectra exhibit the different characteristic peak intensities, the wavenumber ranges of which are summarized in Table 5.

The FTIR spectra of HAs extracted from amended soils and control soil samples reveal significant differences in the intensity of characteristic absorption bands, indicating changes in the chemical composition and functional groups present due to compost-vermicompost addition. The broad and intense absorption band observed in the 3700–3200 cm^{-1} range, attributed to O–H stretching vibrations of hydroxyl groups (phenolic and carboxylic) and N–H stretching from amine functional groups,

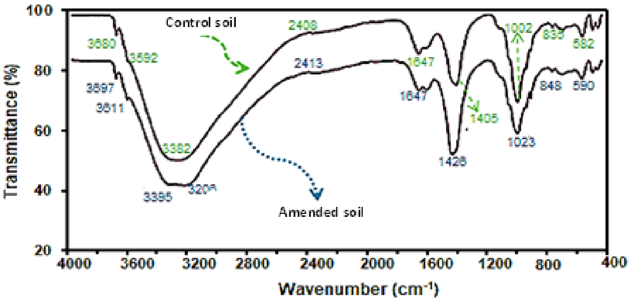

Fig. 6 FTIR spectra of humic acid samples from both compost-vermicompost-amended and control soils

Table 5 List of peaks (bands) present in FTIR spectra [51–53]

Wavenumber (cm^{-1})	Assignment
3700–3590	Free OH stretch
3400–3200	OH stretch, inter- and intra-molecular N–H, amine NH and phenol OH
1660–1620	Amide C=O stretch; quinone C=O and/or C=O bonded to H in paired ketones; C=C aromatic
1600–1580	C=C aromatic group stretching
1460–1430	C–H asymmetric of CH_3 and CH_2
1400–1380	Aliphatic C–H stretch
<1000	C–O stretches; aromatic C–H corresponding to polysaccharides and carbohydrates

is more pronounced in the amended soils, indicating an increased presence of hydrogen-bonded hydroxyls [51–53]. These polar groups enhance water adsorption and cation binding capacity. This increased absorption could reflect a higher content of water-retentive groups such as alcohols, phenols, and carboxylic acids, typically associated with humic substances derived from compost-vermicompost [16, 17, 51]. Similarly, the absorption band at 1660–1580 cm^{-1}, associated with C=O stretching of conjugated ketones, quinones, and amides, as well as C=C stretching of aromatic rings, exhibits greater absorption in the amended soils. This suggests a higher degree of aromatic condensation and structural stabilization [17, 52]. This supports UV–Vis evidence of advanced humification. Furthermore, the higher absorption at 1400–1000 cm^{-1} in amended soils, could be attributed to the increased C–O–C and C–O stretching vibrations associated with polysaccharides, alcohols, and carboxylates [52, 53]. This is characteristic of biologically derived organic matter, confirming the biochemical enrichment following compost application [16, 51, 52]. Absorption peaks at 1400–1380 cm^{-1}, could be attributed to aliphatic C–H stretching, indicating a depletion of aliphatic structures in favor of more recalcitrant aromatic components in amended soils, a key hallmark of advanced humification [51]. Whereas, the absorption peaks between 1460–1430 cm^{-1}, could be attributed to C–H asymmetric of CH_3 and CH_2 [52].

Additionally, the spectral region below 1000 cm^{-1}, which includes C–O stretching vibrations associated with polysaccharides and carbohydrate-like structures, shows a marked decrease in transmittance in the amended soils. This suggests the progressive degradation of labile organic fractions and the accumulation of chemically stable humic substances [52, 53]. The overall increase of transmittance in aromatic and carbonyl-associated absorption bands, coupled with the reduction of aliphatic and polysaccharidic signals, underscores the role of composting in accelerating [52, 53]. This transformation enhances the stability of soil organic matter, thereby improving cation retention, porosity, and overall soil fertility [16, 17, 40]. Overall, FTIR results confirm a shift from labile to recalcitrant organic matter fractions following compost-vermicompost amendment.

The combined physicochemical, spectroscopic, and hydraulic results demonstrate that the 70:30 compost-vermicompost mixture:

- Enhances organic carbon sequestration
- Promotes aromatic humic structures
- Increases CEC and porosity
- Significantly improves water retention.

These mechanisms collectively contribute to improved soil resilience, fertility, and long-term sustainability under urban agricultural systems.

4 Conclusion

This study highlights the significant benefits of a specifically formulated food waste compost-vermicompost mixture (70:30, w/w) in enhancing soil water retention and improving soil quality under urban horticultural conditions. Statistical analysis confirmed that amended soils exhibited a highly significant increase in field capacity compared to control soils ($p < 0.001$).

The increased presence of aromatic and structurally condensed humic fractions, as evidenced by UV–Vis and FTIR analyses, indicates advanced humification and improved organic matter stabilization. This enhanced humification contributed to a significant increase in cation exchange capacity, porosity, and water-holding potential, thereby strengthening soil physical and chemical resilience.

Importantly, these findings highlight the crucial role of compost quality, maturity, and aromatic composition in determining its effectiveness for improving soil hydraulic properties. Rather, composts derived from food waste and characterized by high aromaticity and molecular stability appear particularly effective in promoting long-term soil functionality and reducing the need for repeated applications.

These results underscore the role of quality-controlled composting and vermicomposting processes as sustainable strategies for soil and water management within circular economy frameworks. By combining organic waste valorization with soil restoration, such approaches provide a viable solution to mitigate environmental challenges associated with soil degradation, nutrient losses, and increasing water scarcity.

Future research should focus on long-term field-scale validation, crop productivity responses, and the interaction between compost quality and soil microbial dynamics to further optimize amendment strategies for sustainable agriculture.

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