

Factors that affect physicochemical and acid-base properties of compost and vermicompost and its potential use as a soil amendment

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Highlights

- The compost feedstock determines the characteristics of the soluble OM
- Worms in vermicompost contribute to a more efficient degradation of the OM
- Correlations can be established between the origin and the reactivity of compost DOM
- The content of acid groups of the HS-like extracts increases with composting time
- The quality of unproductive mine soils can be improved with compost amendments

Factors that affect physicochemical and acid-base properties of compost and vermicompost and its potential use as a soil amendment

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Abstract

Composting and vermicomposting have attracted attention in relation to both waste management and the potential to produce organic amendments that could improve soil quality. The main differences between compost depend on the feedstock, the production process, and the degree of maturity. In the present study, samples of compost of different origin (food and green waste, livestock waste, algae waste, urban waste or sewage sludge) or subjected to different composting methods (traditional or using earthworms) were collected for analysis. Additionally, samples collected at various stages of the composting process were compared (raw material, 15 and 30 days of composting, and final compost). Different analysis and techniques were used to establish the chemical composition, physicochemical and acid-base properties of compost samples and the organic matter extracts. The correlations obtained (between the abundance of acid groups in different extracts of the compost or between the cation exchange capacity and the C/N atomic ratio) would allow for predicting the compost behaviour based on certain characteristics, and a reduction in the number of parameters determined experimentally, thus facilitating comparisons between different compost. In addition, the potential value of the compost as amendment was tested with a Haplic Cambisol from a mining area. The application of compost increased the pH, the organic matter and nutrient content, and promoted seed germination and root growth.

Keywords: Compost, feedstock, organic waste, humic substances, soil amendment, vermicompost

1. Introduction

Waste management is required to maintain natural resources and to protect the environment. Recycling, reuse and valorization of waste are possible solutions potentiating the circular economy (Hollins et al., 2017). Although most of the waste generated by anthropogenic activities is biodegradable, it should not be directly applied because its uncontrolled decomposition can have negative effects on soil systems (Hanc et al., 2019a). Organic matter from waste can be decomposed and stabilized in a process in which microorganisms play an important role. Thus, biodegradable organic residues can be stabilized and repurposed via composting and vermicomposting processes. Both processes are aerobic and bio-oxidative but differ in the involvement of earthworms in vermicomposting. The involvement of earthworms in the composting process promotes the aeration and fragmentation of the organic matter, thus increasing the rate of mineralization (Hanc and Vasak, 2015)

The use of compost and vermicompost to improve soil quality has increased in recent years. Numerous studies have investigated the use of compost as a soil amendment with the aim of immobilising potentially toxic elements or increasing nutrient or organic matter content (Forjan et al., 2017; Palansooriya et al., 2020). To use the compost as a soil amendment it should have reached a certain degree of maturity and stability. Maturity is associated with the capacity of a compost to favour plant growth and with the absence of phytotoxic compounds, whereas stability is associated with a decrease in microbial activity during composting (Cerdá et al., 2018). The stability is related to the transformation of fresh organic matter into recalcitrant aliphatic compounds and highly humified aromatic structures (Droussi et al., 2009). Different physical, chemical and biological parameters can be used to determine the degree of maturity and stability of compost, including odour, cation exchange capacity, nitrogen and carbon contents or degree of humification (Bernal et al., 1998; Droussi et al., 2009).

The degree of humification of organic matter is related to the production of humic substances (HS) and to the degree of maturity or stability reached during composting (Jurado et al., 2015). As the aim is to yield a stable product rich in humic substances, these substances are often extracted from compost for characterization (Amir et al., 2003). Some studies indicate that the humic substances extracted from compost improve the soil properties more effectively than other more conventional amendments (Wu et al., 2021). Humic substances can benefit soil systems by regulating pH, acting as redox agents, complexing metallic ions, and stimulating plant growth (Fuentes et al., 2018; Guo et al., 2019). Thus, humic substances show great potential for elaborating biofertilizers and for removing heavy metals from soils. The contribution of humic substances to the fate and bioavailability of macro and micronutrients and toxic species, such as heavy metals and pesticides, can be attributed to the abundance of aromatic structures and carboxylic and phenolic groups in their structure (Lee et al., 2020). Although there is no much information available on the acid-base properties of HS-like substances and dissolved organic matter from composted material, it is a matter of considerable interest since it can provide useful information to improve the performance of the compost for agronomic purposes in soils and to control the bioavailability, distribution and toxicity of metals in environment (Yan and Korshin, 2014). As concluded by Fernández et al. (2007) the acid-base properties of the HS-like extracted from compost resemble those typical of native soil HS, thus inducing fewer changes in amended soil HS.

Various studies have focused on analysing compost and vermicompost derived from animal and plant waste (Chatterjee et al., 2021; Kucbel et al., 2019). Other studies

have compared the composting systems (Soobhany et al., 2017), while others have characterized the HS extracted (Guo et al., 2019), monitored the changes in organic matter throughout the composting process (Lalremruati and Devi, 2021) and, eventually, evaluated the effects of incorporating the resulting material on soils (Forjan et al., 2017; Teodoro et al., 2020).

Since it is not easy to find complete studies including characterization and comparison of compost and their extracts, the present research aims to conduct an integral study of the aforementioned aspects, in order to obtain more detailed information about the products generated by composting and vermicomposting and their potential use as amendment and/or fertilizers. For this purpose, samples of compost and vermicompost were selected to compare both the effect of the composting process and the effect of the feedstock material. The evolution of the organic matter was also monitored at different stages of the composting process. Although soil-compost interactions mainly occur in aqueous media, information about humic-like substances and dissolved organic carbon of these types of material is scarce. We therefore decided to compare the composition and acid-base behaviour of the dissolved organic carbon in the equilibrium solution with the corresponding humic-like extracts. Finally, with the aim of evaluating the effects of the application of stabilized organic residues on degraded soils, compost and vermicompost samples were applied as amendments to an unproductive mine soil.

2. Materials and Methods

2.1. Samples

Six compost samples were analysed: four were commercial products (CLW (livestock waste), CUW (urban waste), CSS (sewage sludge) and CVA (algae) and two were produced in traditional composting or vermicomposting systems (CDDW, from domestic waste and CVDW, from domestic waste using earthworms). In addition, with the aim of studying the changes in the organic matter throughout the composting process, samples were obtained at different stages (UW0 (fresh urban waste), CUW15 (after 15 days composting) and CUW30 (after 30 days of composting)), as outlined in Figure S1 (Supporting Information). A detailed description of the samples is included in Table S1 (Supporting Information).

The compost samples were used to extract the dissolved organic carbon (equilibrium solutions) by adding 150 mL of water to 7.5 g of compost. The resulting suspension was homogenized by an initial vigorous shaking and then equilibrated for 5 days (open atmosphere). The solution was then separated by centrifugation at 6000 rpm.

The humified organic matter was extracted from compost to yield the humic substance-like (HS-like) fractions. The extraction was carried out following the protocol established by the International Humic Substances Society (IHSS) (Swift, 1996).

2.2. Characterization

The compost, equilibrium solutions and HS-like fractions were characterized using common methods for these types of materials. Briefly, C, H, N and S contents were determined in an element analyzer (TruSpec CHN-1000, LecoSC-144DR); ash content was determined gravimetrically by combustion at 650 °C; oxygen content was determined as $O = 100 - (C + N + H + S + \text{ash})$; oxidizable C was determined by Sauerlandt's method (Walkley, 1947) and C in solution was determined using a total organic carbon analyzer

(TOC-L CSN Shimadzu); concentrations of the major elements were determined by ICP-OES (Perkin-Elmer Optima 3300DV); P concentration was determined in the compost and in the equilibrium solution by the molybdenum blue method (Murphy and Riley, 1962); concentration of ammonium in the equilibrium solution was determined with a selective electrode (Elit electrode Nico 2000); pH and electrical conductivity were measured in the equilibrium solution with a combined electrode (Crison, pH 0-14) and a conductivity meter (Crison GLP 32), respectively.

Due to the heterogeneity of the samples, all the analysis were replicated until a standard deviation below 10 % was achieved. The bivariate Pearson correlation analysis was conducted with SPSS 25 to evaluate the relationship between the different physico-chemical parameters analyzed. Significance was assumed if $p < 0.05$.

2.3. Acid-base properties

Acid-base titrations were conducted with the equilibrium solutions (~ 5 g solid/L) and of the different HS-like fractions (0.1 g HS/L), following the protocol proposed by López et al. (2012). The titration of the equilibrium solutions was conducted at 0.1 M ionic strength in KNO₃. The titration of the HS-like fractions was also conducted at 0.01 M to obtain the intrinsic parameters of protonation. Because of the high pH of the equilibrium solutions, two aliquots were taken from the same sample to study protonation (titration with 0.1M HCl) and deprotonation (titration with 0.1 M KOH).

2.4. Application of the amendments

Compost samples were applied to an unproductive mine soil, with the aim of evaluating the efficacy of these samples as soil amendments. The soil was a Haplic Cambisol (Ch2) collected in a uranium mine site (Mina Fé, Saelices el Chico, Spain) and characterized by Arán et al. (2020). The compost samples were applied as individual amendments by manually mixing the soil and compost. Thus, 150-200 g of soil were amended with the amount of compost required to reach a variable content between 2% and 10% (w:w). The soil-compost samples were then incubated at room temperature for 2-3 weeks, during which the moisture content was maintained at between 50 and 70% of the water holding capacity. At the end of the incubation period, the samples were dried, and the pH, C and N contents, total P, Olsen P, and the exchange cations were determined by standard methods (Sparks et al., 1996). A sample of unamended soil was used as a control.

Aqueous equilibrium solutions were made from the compost and the amended samples by the same method as outlined above. The resulting equilibrium solutions were used in germination assays on filter paper, following a similar protocol to that described by Di Salvatore et al. (2008). The ryegrass *Lolium perenne* was selected for use in the assays since it is relatively insensitive to high concentrations of metal, as usually observed in mine soils (Teodoro et al., 2020). Twenty *Lolium perenne* seeds were placed on three layers of filter paper held in Petri dishes (120 x 20 mm) and watered with 8 mL of equilibrium solution or distilled water (control). The Petri dishes were then sealed and placed in a germination chamber, where they were held at 22 °C, in darkness, for 7 days. Then, the germinated seeds were counted, and the root length was measured. Seeds were considered to have germinated when the root was at least 1 mm long. Each treatment was carried out in triplicate. To facilitate comparison of the results of the germination assays, the percentages of relative radicle growth (RRG), relative seed germination (RSG) and

germination index (GI) was calculated (Walter et al., 2006). The normalized residual elongation (NRE) index was also determined (Bagur-González et al., 2011):

$$RRG(\%) = \frac{\text{Mean root length in sample}}{\text{Mean root length in control}} \times 100 \quad (1)$$

$$RSG(\%) = \frac{\text{Number of seed germinated in sample}}{\text{Number of seed germinated in control}} \times 100 \quad (2)$$

$$GI(\%) = \frac{RRG \times RSG}{100} \quad (3)$$

$$NRE = \frac{\text{Mean root length in sample} - \text{Mean root length in control}}{\text{Mean root length in control}} \quad (4)$$

3. Results and discussion

The results and discussion of physicochemical characterization, acid-base properties and application of the compost as soil amendment are presented in different sections. Within each section, different sub-sections are devoted to the results from compost, equilibrium solution and HS-like fractions, respectively. In each sub-section, results are displayed into three discussion blocks:

- Origin: Samples of different feedstock subjected to a similar composting process: CLW, CUW, CDDW and CSS; CVA and CVDW
- Process: Samples of the same feedstock subjected to different composting processes: CDDW (traditional composting) and CVDW (vermicomposting)
- Maturation: Samples obtained at different times throughout the composting process: UW0, CUW15, CUW30 and CUW

3.1. Characterization

3.1.1. Compost

The results of the chemical analysis are included, along with the values of other relevant parameters, in Table 1. Results for the Pearson's correlation between these parameters are shown in Table S2 (Supporting Information), while the metal contents of the different compost are shown in Table S3 (Supporting Information). The percentage of carbon in the samples produced by a traditional composting process with different types of waste material varied between 22.8 and 34.0%. The sample with the highest content of carbon corresponded to that obtained from a combination of green and food waste (CUW). The sample with the lowest percentage of carbon was produced from livestock manure (CLW). Comparison of samples CDDW and CVDW, produced from similar feedstock and subjected to traditional composting or vermicomposting, respectively, revealed a substantial increase in both the total and oxidizable carbon due to the vermicomposting process. The vermicomposting process reduces the proportion of carbon that can be oxidised relative to traditional composting: 75.4% and 81.0%, respectively. Analysis of the changes in the carbon content during the composting process

(UW0, CUW15, CUW30 and CUW) revealed a decrease in both the total and oxidizable carbon, particularly during the maturation stage, i.e. oxidizable carbon was 86.1 % of the total carbon at the end of the process, while it remained above 95% during the initial decomposition stage.

The C/N ratio (Table 1) is widely used as an indicator of compost maturity. Thus, various studies report that values below 20 indicate that the maturity of the compost is acceptable, but those compost showing a C/N ratio below 15 are recommended for agronomic use (Soobhany et al., 2017). The C/N ratio ranged between 8.6 (CSS) and 12.8 (CLW) for the samples produced from different types of feedstock. A value of 8.5 was found for sample CVDW, lower than that determined for sample CDDW (10.3) produced by a different composting process. This finding appears to be consistent with previous studies and can be attributed to the earthworms, which supply N and may mineralize the organic nitrogen in the form of mucus excretions and nitrogenous excrements during vermicomposting along with the loss of organic matter (Negi and Suthar, 2018). Although the C/N ratio in the raw sample UW0, mainly constituted by a mixture of green and food waste, is low relative to the optimal values for a composting process to be considered effective ($20 < C/N < 30$), other authors showed this type of waste may be effectively broken down by the composting process (Kumar et al., 2010; Wang et al., 2019). As the composting process advanced, the values of the C/N ratio decreased due to the loss of carbon as CO₂, caused by the decomposition or breakdown of the compostable organic components. As indicated by Bernal et al. (1998), the greatest decrease occurred during the active phase, while the maturation stage scarcely influenced the ratio.

The cation exchange capacity (CEC) has been widely used to evaluate the maturity of the compost and the degree of humification of the organic matter, as functional groups that increased the CEC are generated during this process. Thus, high CEC values may be related to a higher maturity degree and to the increase of humic substances in the compost. Pearson correlation analysis indicated a positive correlation between CEC and the C/N ratio when compost feedstock was considered. Thus, samples with the highest C/N ratio, CLW and CUW, showed larger CEC values (Figure 1). The CEC increased during the composting process, as observed by comparison of the uncomposted material (UW0) and the final product (CUW) (Table 1). After the first cycle of composting, the CEC decreased (comparing UW0 and CUW15) and then increased gradually with composting time. A negative correlation between CEC and C/N ratio has been found with composting time (or composting maturity), similar to that found by Harada and Inoko (1980), although in their study the range for the C/N ratio was larger. This trend appears to indicate that after the first composting cycle, the carbon is mainly derived from humified organic matter, in which the acid sites are occupied by exchange cations. As the composting process advances, the formation of humic substances is favoured, increasing the content of carboxylic and phenolic groups. The Pearson correlation analysis also showed that a negative correlation exists between total P and C/N or C, pointing out to the mineralization of the organic P forms

3.1.2. *Equilibrium solutions*

The values of the parameters used to characterize the equilibrium solutions of the samples are given in Table 2. The concentrations of the metals determined in the equilibrium solutions are included in Table S4 (Supporting Information). The pH of the equilibrium solutions ranged between 6.3 and 8.5. The lowest values corresponded to the two vermicompost samples. Comparison of the compost and vermicompost samples made from the same feedstock showed that the pH of the equilibrium solution was lower

after vermicomposting. During the composting process, the pH increased slightly in the first cycle and then increased sharply, by approximately one unit, in the second cycle, before remaining almost constant throughout the maturation stage. This increase of pH can be attributed to the decomposition of organic components like proteins, amino acids or peptides and the release of ammonium ions or volatile ammonia (Jamroz et al., 2020).

The electrical conductivity (EC) was used as an indicator of salinity, in order to evaluate any potential problems on using the compost as soil amendment. The EC should remain below 4 mS/cm to be tolerated by plants (Lasaridi et al., 2006). This value was only exceeded in sample CLW, due to high concentrations of sodium and potassium. On the other hand, this parameter did not follow any clear pattern throughout the composting process. However, the EC was much lower in the commercial product than in the uncomposted sample, and the largest decrease occurred during the first composting cycle, suggesting a significant reduction in the amount of soluble salts in the composted material. The pH and EC were correlated in mature compost samples, which may be explained by differences in pH-dependent occupation of acid sites in the organic matter by cations (Figure 2). The relationship was again different in the composted and vermicomposted samples. The pH of sample CSS was lower than expected from the EC, which can be explained by the high concentration of NH_4^+ in this sample (159.1 mg/L) relative to the other samples (between 4.6 and 21.2 mg/L).

The major elements that mobilize into the equilibrium solution are shown in Figure S2 (Supporting Information). The highest percentages generally corresponded to Na and K, except in sample CSS, in which Na, K and Mg occurred in almost the same proportion (~20%). The presence of a high concentration of Na in solution may be problematic regarding the use of compost as a soil amendment as this cation is rapidly absorbed by plants, thus preventing absorption of Ca and Mg (Kuchel et al., 2019). Comparison of the compost and vermicompost produced from the same waste material (CDDW and CVDW) revealed very similar results regarding the major elements released to the solution, suggesting that the feedstock is the main factor responsible for the availability of the major elements. In general, the concentration of major cations of the water extracts of the samples collected at the different stages of the composting process decreased with the composting time, which was also observed by Jamroz et al. (2020).

The sample with the highest concentration of dissolved organic carbon was that obtained from livestock waste (CLW), even though the carbon content of the compost was low. The percentage of oxidizable carbon was lowest in the solid sample of this compost, which led to the percentage of dissolved organic carbon being the highest. The equilibrium solution samples with the lowest content of dissolved organic carbon were CDDW and CVA. Comparison of the uncomposted sample (UW0) and the final composted sample (CUW) revealed a marked decrease in the dissolved organic carbon of the water extracts. Very similar findings have been reported by different authors (Said-Pullicino et al., 2007; Hunce et al., 2020; Jamroz et al., 2020). This can be explained by the biochemical transformations of the organic components through composting. Initially, the concentration of the more labile organic components is relatively high. These components, with hydrophylic character, are mainly composed of polysaccharides, proteins, peptides, and amino acids. As the composting process advances, the mineralization, re-polymerization and condensation of these labile components, lead to the formation of HS-like components, resistant to degradation and with lower solubility (Jamroz et al., 2020).

Semi-empirical relationships between parameters determined by UV-visible spectroscopy are often used to characterize organic matter in solution. These include the

correlation between the coefficient of molar absorptivity at 280 nm (ϵ_{280}) and the percentage aromaticity ($\% \text{ aromaticity} = 0.05 \times \epsilon_{280} + 6.74$) and between this coefficient and the molar mass ($\text{molar mass} = 3.99 \times \epsilon_{280} + 490$) (Fuentes et al., 2006). The lowest values of ϵ_{280} corresponded to the uncomposted sample UW0 and sample CSS (Table S5, Supporting Information), which is representative of an immature compost. The highest value corresponded to sample CDDW, followed by the two vermicompost samples (CVA and CVDW). In the equilibrium solutions of the mature samples, except that of sample CSS, the percentage aromaticity was between 20 and 27 %, which agrees the presence of hydrophobic moieties, more resistant to degradation, at the end of the composting process (Jamroz et al., 2020). Accordingly, the relative aromaticity of the DOC increased throughout the composting process, from 10.5% to 20.1%. These results suggest that these semi-empirical parameters are good indicators of the degree of humification and maturity of the soluble organic matter.

3.1.3. *HS-like fractions*

As in other studies with compost (Fuentes et al., 2018; Veeken et al., 2000), the protocol used for extracting the HS-like components is that recommended by the IHSS for extracting humic substances from soil. This protocol yields good results when applied to mature organic matter but is probably not as effective for immature organic matter. It is therefore possible that the method will quantify carbohydrates, proteins and amino acids as HS-like compounds, even though these are precursors of HS-like compounds and have not yet decomposed.

The percentages of major elements and the corresponding atomic ratios for the HS-like fractions extracted are shown in Table 3. Analysis of the extraction yields of HS-like components reveals that sample CLW had the highest content of HS-like compounds (42 g/kg of compost). The total carbon content was lowest in this compost, but the DOC was highest. Analysis of these data revealed a correlation between the amount of HS-like compounds extracted from the compost of different origin and the percentage of organic carbon in the equilibrium solution (Figure 3 a). Inclusion of the other samples in the same plot shows that the concentration of DOC present in the equilibrium solution provides a good estimate of the content of HS-like compounds. The only exception is sample CVA, for which a lower DOC was measured. Although organic matter humification should occur as the composting process advances (Amir et al., 2010; Li et al., 2017), the extraction yield of HS-like compounds was very high for the fresh material at the beginning of the composting process. After the first composting cycle, the percentage of HS-like compounds extracted increased and then remained almost constant throughout the maturation stage. This agrees with the loss of organic carbon with the composting time (Table 1). The decrease of HS-like substances may be consequence of the mineralization rate and decomposition rate of labile HS constituents, which may be higher than the HS formation rate at the initial stages of the composting process (Chen et al., 2021; Wang et al., 2019). Also, this can be explained by considering that the protocol used extracts small organic acids as HS-like compounds. In addition to the previously mentioned correlation, the relationship between the yield of HS-like compounds and the pH of the equilibrium solution distinguished the two types of process: composting and vermicomposting (Figure 3 b).

Analysis of the HS-like fractions revealed a greater carbon content in the humic acid (HA) than in the fulvic acid (FA) fraction, whereas the latter is richer in oxygen. Regarding the content of other elements, generally the proportion of nitrogen was much

higher in the HA extracted from mature compost. Changes in the N content and C/N ratio for the HA extracts during composting, is consisting with previous studies, and might be attributed to the degradation of labile OM molecules and the transformation to saturated structures (Li et al., 2017). Comparison of the HS-like compounds extracted from compost and vermicompost from the same feedstock showed that the nitrogen content was higher in the vermicompost, which can be attributed to the fact that the solid sample also contained more nitrogen due to the direct action of earthworms. The atomic ratios in the FA and HA fractions obtained from the mature compost were plotted in a van Krevelen diagram, along with the ratios reported in other studies (Figure S3, Supporting Information). We can see that the samples are more widely dispersed in the FA fraction than in the HA fraction. Generally, the HAs are displaced towards lower values of the O/C ratio. This is usually attributed to the enrichment in oxygenated acidic groups for the FA fraction, which is expected to be higher in this fraction. This also agrees with the aromaticity degree, which is generally higher in the HA-like fraction (Figure S4, Supporting Information). The variation in the atomic ratios during the different stages of composting is similar to that reported in previous studies (Amir et al., 2010; Hanc et al., 2019b). Both fractions are displaced towards higher values of the O/C atomic ratio, which may be related to an increase in acidic groups throughout the composting process due to the gradual transformation of polysaccharides and other similar compounds into oxygenated compounds such as carboxylic and phenolic compounds (Hanc et al., 2019b).

3.2. Acid-base properties

3.2.1. Equilibrium solutions

Acid-base titrations were conducted to evaluate the concentration and type of acid groups present in the dissolved organic matter (DOM). The charge curve for sample CLW, resulting from the difference in the mmoles of acid or base consumed in the titration of the sample and those consumed by the electrolyte is shown in Figure 4 a. The figure includes the derivative obtained from the charge curve, in which three well-defined peaks were observed. All samples, except CSS, showed similar behaviour independently of the composting process and the feedstock material (Figure 4 b and Figure S5, Supporting Information). Despite the scarcity of information, Sciubba et al. (2015) also identified the presence of three types of acid positions on the DOM extracted from compost and attributed these to carboxylic groups in amino acids (pKa between 2 and 3), carboxylic groups in organic acids (pKa between 4 and 6) and phenolic hydroxyl groups, hydroxyl in carbohydrate units and amino groups from amino acids (pKa between 8 and 11), respectively. The pH interval in the present study only enabled observation of positions type 2 and type 3 identified by Sciubba et al. (2015).

The 3-site Langmuir isotherm was used to obtain the acid-base parameters of the DOM (equation 5):

$$Q = Q_0 + \frac{M_1}{1 + K_1[H^+]} + \frac{M_2}{1 + K_2[H^+]} + \frac{M_3}{1 + K_3[H^+]} \quad (5)$$

where K_i represents the protonation constant of the different groups, M_i represents the abundance of each type of group, and Q_0 is the charge due to occupation of the acid sites by cations that must be displaced by protonation. The model fitting results are shown in Table 4. For correct interpretation it should be noted that the charge generated on the

organic matter is due to the deprotonation of acid sites and it is therefore negative. The Q_0 value shown in Table 4 can be interpreted as a net positive charge that is occupying acid sites, as positive charges are usually used to facilitate data handling.

DOM containing the highest and lowest number of acid sites (M_T) is that corresponding to samples CSS and CVA, respectively. In all cases, the most acidic groups are the least abundant, whereas the abundance of the other two types of groups was very similar (Table 4). Again, sample CSS is the exception. The presence of some cations in the solution may alter these results, as we attributed the consumption of acid/base to the protonation/deprotonation of the acid sites in the organic matter, without considering possible hydrolysis reactions and/or precipitation of cations. The possible effect of hydrolysis reactions may be important in samples such as CSS, due to the high concentration of NH_4^+ (Table 2).

The log K values (Table 4) did not follow any trend in relation to the origin of the compost. However, in the vermicompost samples, the DOM contains more acid groups when the original material contains a high proportion of manure (i.e. sample CVA). The result of applying the different composting processes to similar types of material, as in samples CDDW and CVDW, demonstrates that vermicomposting generates DOM with higher content of functional groups, although these groups show a less acidic character. Similar results were found by Campitelli et al. (2012), when studying the HA extracted from compost and vermicompost obtained from rabbit manure. The content of carboxylic and phenolic groups was higher for the HA extracted from the vermicompost, while the acidity constants were slightly lower. Sample CSS was once again an exception, as it yielded the highest log K value for the first type of sites (4.24 relative to a mean value of 3.43 ± 0.27 for the other samples) and the lowest values for sites 2 and 3 (6.27 and 9.65 relative to mean values for the other samples of 6.54 ± 0.08 and 10.17 ± 0.13 , respectively).

The same type of comparison can be carried out for the DOM of the samples obtained at the different stages of composting (Figure S6, Supporting Information). There were notable differences in the curves of the fresh material and the material collected at the different stages of the process. The modelling parameters showed a decrease in the number of acid sites during composting (Table 4), indicating differences between DOM at the beginning of the process, when labile organic matter is also mobilized into the solution, and that after the first composting cycle. The variation in the acidity of the groups with the composting time also indicated a clear difference between UW0 and the other samples, as it corresponded to the highest log K value for the first site (4.50 relative to a mean value for the other samples, of 3.75 ± 0.22) and lower values for sites 2 and 3 (6.05 and 9.73 compared with 6.57 ± 0.08 and 10.08 ± 0.03 , respectively). The most acidic groups were the most abundant in UW0 (almost 50% of the total), whereas they became the least abundant after the first composting cycle. The high abundance of these sites in sample UW0 is attributed to the contribution of amino acids, which disappear as the organic matter matures.

3.2.2. HS-like fractions

As expected, the FA charge was larger than the HA charge over the entire pH range (Figure 5 and Figure S7, Supporting Information). The distribution of affinities indicates the presence of two types of acid sites, while in the case of DOM three different acid sites were obtained. These acid sites can be attributed to carboxylic and phenolic

groups (Milne et al., 2001; Plaza et al., 2005). The charge generated due to the deprotonation of the acid groups can be described by equation 6:

$$Q = Q_0 + \frac{M_1}{1 + (K_1 [H^+])^{m_1}} + \frac{M_2}{1 + (K_2 [H^+])^{m_2}} \quad (6)$$

where K_i is the protonation constant of the carboxylic and phenolic groups, M_i is the abundance of each type of acid site, and m_i represents the width of the distributions. The parameters obtained by fitting are shown in Table S6 (Supporting Information). The Q_0 values are not shown as they are equal or close to zero. The results show that the model provided a good fit to the experimental data and demonstrate that the total number of acid sites (M_T) is greater in the FA fraction. The ratio between the total number of sites in both fractions ($M_T(\text{FA})/M_T(\text{HA})$) was around 1.1 for the HS-like extracted from the compost samples, with the exception of sample CSS, which has a value slightly higher than 2, and around 1.5 for the corresponding extracts from vermicompost.

To enable comparison with DOM, the site abundance of the HS-like fractions is expressed in mmol of charge per g of compost, by using the extraction yield (Table 3). Considering the different solubility of the HS-like extracts, the DOM present in the equilibrium solution will be mainly constituted by FA molecules. The comparison (Figure S8, Supporting Information) revealed similar trends, although the sites are more abundant in the DOM. This difference can be attributed to the low extraction yield for the HS-like fraction and to the presence in the water extracts of non-humified organic matter, small organic acids and cations, which may all contribute to the overestimation of acid sites in the DOM. The mean log K values of the bimodal distributions that characterize the FA fraction are very similar to the values of type 1 and 3 sites in the DOM (Table 4 and Table S6, Supporting Information). In all samples, the most acidic sites in the DOM showed lower log K values than those obtained for the FA fraction. By contrast, the log K values for the weakest sites are lower in the FA fraction than in the DOM. Some of these differences could be attributed to the methodology followed for the potentiometric titrations (Figure S9, Supporting Information).

The charge curves of the HS-like fractions extracted from the samples collected throughout the composting process revealed clear differences in the FA and HA fractions (Figure 6). Regarding the FA fraction, a drastic change in the charge curves was observed between UW0 and CUW15. In both samples, the initial charges were similar, but then differed as the pH increased until reaching a value of 6, after which the values increased in parallel. After the first composting cycle, the differences were only observed at low pH values. This indicates that no significant changes in the chemical composition or molecular structure occur in this fraction after the 15-day decomposition phase. By contrast, the HA fraction underwent a gradual increase of charge throughout the pH range as the composting process advanced, along with an increase in the total number of acid sites (Table S6). These changes in the charging behaviour may be attributed to the degradation of molecules with a low degree of humification and to the changes produced in the chemical composition of the HA-like extracts during composting.

A rigorous study of the acid-base properties of HS-like extracts requires determining the intrinsic protonation constants and considering the electrostatic effect of the organic polyelectrolytes. The Donnan model was used in this work, which considers HS to form an electrically neutral gel-like phase (Kinniburgh et al., 1996). The Donnan volume (V_D) is related to the ionic strength through equation 7.

$$V_D = b (1 - \log \log I) - 1 \quad (7)$$

where b is an empiric parameter characteristic of a particular substance and describes V_D variation with the ionic strength. The optimization of b allows for calculating the electrostatic potential in the Donnan phase and the intrinsic protonation parameters (Table 5). These parameters can be compared to the intrinsic parameters specifically obtained for other compost derived HS-like (Table S7, Supporting Information). The average values obtained for the parameter b , 0.62 for FA-like and 0.45 for HA-like, are higher for the FA-like fraction, similarly to the values reported by Plaza et al. (2005) for the HS extracted from compost derived from olive mill wastewater. An exception to this trend has been reported by Fernández et al. (2007) and by van Zomeren et al. (2009), who found very similar values for this parameter in the fulvic and humic fractions extracted from compost (Table S7, Supporting Information). Analysis of the results obtained for the HS-like fractions extracted at different stages of the composting process indicates that b decreases throughout the maturation process. The same variation was reported by Plaza et al. (2005). The higher b values observed for the HS-like in the first stages of composting suggest a high contribution of small molecular weight particles. This situation reverses as HS-like condensation occurs during the composting process.

The average content of total acid sites, M_T , obtained for all the samples, 5.58 and 4.00 mmol/g for FA-like and for HA-like, respectively, was small compared to the literature data (Table S7, Supporting Information). However, when the abundance of carboxylic and phenolic groups is expressed as a percentage of the total content of acid groups, the results are almost identical to the percentages reported by Plaza et al. (2005), with carboxylic groups representing approximately 65% of the total acid sites in both FA and HA fractions. Campitelli et al. (2012) and Li et al. (2011) obtained a similar ratio of carboxylic and phenolic groups for HA extracts from compost and vermicompost, although the method used to quantify the acid sites was different. Compared to other HS-like derived from compost (Fernández et al. 2007, van Zomeren et al., 2009), our samples have lower percentage of carboxylic groups. The distribution of acid groups, between carboxylic and phenolic type, in HS-like extracted during the maturation process is not very different. An increase in the total content of acid groups, as opposed to the DOM, was observed during the composting process, which agrees with the behaviour displayed by the charge curves of the HS-like extracts (Figure 6). As previously reported by Plaza et al. (2005), a loss of aliphatic structures and carbohydrates, along with an increase in acid functional groups and groups containing N and S occur during the composting process. This increase in the site abundance was more evident in the HA-like extracts, from 3.57 to 4.74 mmol/g, than in the FA-like extracts, from 5.00 to 5.11 mmol/g, agreeing with the separation observed between the charge curves with the composting time (Figure 6).

Average values for $\log K$ of carboxylic and phenolic groups were 2.96 and 7.86 for FA-like, and 3.49 and 8.21 for HA-like, respectively. These are comparable to the values specifically obtained with the NICA-Donnan model for HS-like extracted from compost found in the literature (Table S7, Supporting Information). On the other hand, the $\log K$ values calculated with the Henderson-Hasselbalch equation for other compost HA were almost 2 log units higher (Campitelli et al., 2012). When compared with the generic values obtained for aquatic and terrestrial HS (Milne et al. 2005), the values obtained are rather similar, indicating that the nature of the acid sites present in the HS molecules is related. As the composting process advances, $\log K$ experienced a shift toward a more acidic character (Table 5). The same trend was described by Plaza et al.

(2005), although the decrease in their log K values for the HA-like was more pronounced. This result indicates that, in general, the HS-like become more acidic during the composting process possibly due to the oxidation reactions in the lignin or to the microbial degradation of carbohydrates (Sánchez-Monedero et al., 2002).

3.3. Testing the compost as soil amendment

The physico-chemical characteristics of the Haplic Cambisol and the variations in these after amendment with compost of different feedstock (except compost CVDW, which was not applied due to limited sample availability) are shown in Table 6. Soil Ch2 showed an acidic character, characteristic of mine soils developed in areas rich in mineral sulphides. The carbon content was lower than 1% and the values of available phosphorus (Olsen P) and CEC were relatively low, reflecting the low productivity of the soil (Hazelton and Murphy, 2007).

Application of compost led to an improvement of different soil quality indicators, particularly pH, available phosphorus and CEC. This effect increased with the amount of compost in the amendment. The pH of the compost samples ranged between 6.16 and 9.76, and application of the amendment therefore had a positive effect on the soil. Sample CSS was the only compost that did not increase the soil pH above 7, although this compost, together with compost CUW, supplied the greatest amounts of organic matter. Application of amendments containing 10% of CUW or CSS increased the carbon content from 0.66% to 3.28% and 3.47%, respectively. Also, application of sample CSS produced the greatest increase in total P on the amended soil, but the relative concentration of available P forms is lower than with the other compost. Thus, application of composts CDDW and CLW produced an increase in the concentration of Olsen P from 4.6 mg/kg to 206.6 and 365 mg/kg, respectively. Both samples contain more than 10% of the total P as available P forms (Table 1), which may favour plant productivity. Finally, compost CLW also generated the greatest increase in the CEC relative to the control, from 1.27 to 37.3 cmol(+)/kg. The concentration of exchangeable cations in the amended soil increased significantly with the content of compost, irrespective of the feedstock (Table S8, Supporting Information).

Seed germination was favoured by increasing the content of compost in the amended soil, as reflected by the increase in GI, although the intensity of the increase depended on the compost used (Table 6). Thus, the GI values were highest in samples amended with CLW and CDDW. Application of both composts generated the highest increase in the concentration of available P and exchangeable cations, and yielded the optimal pH for plant growth. On the other hand, the smallest increase in GI occurred with compost CSS. Although this compost yielded the greatest increase in C, N and total P in the soil, it did not generate such a large increase in pH as the other compost. Compost CSS was produced from sewage sludge, and therefore the concentration of species that are potentially toxic to *Lolium perenne* may be significant. When the germination tests were conducted with the water extracts from the compost, similar tendencies were observed. Samples CLW and CDDW showed the GI values above 100 %, while sample CSS yielded the lowest GI, ~60 % (Figure S11, Supporting Information). The low GI for sample CSS confirms the existence of phytotoxic effects and the lack of maturity of this compost (Cesaro et al., 2019). The other compost, on the other hand, could be considered free of phytotoxic substances. Other factors that inhibit seed germination include high salinity and excess of ammonium (Hoekstra et al., 2002). The concentration of ammonium in the solutions used in the germination assay was not determined, although

it reached values higher than 150 mg/L in the original CSS sample (Table 2). The lower positive effect of CSS on the amended soil was also reflected in the values of the NRE index (related to root growth), which reached a maximum value of 0.17 in the soil amended with 10% of compost. Root growth is a more sensitive parameter, although it is more difficult to quantify than seed germination. For the other samples, the values of NRE ranged between 0.33 and 0.53, and application of compost CLW had the most positive effect.

The effects of the application of compost on shoot and root growth are shown in Figure S10 (Supporting Information). No clear trend was observed in the growth of the aerial part of the seedlings in relation to the different amendments, nor in the different compost percentages in each. However, the effect on root growth decreased in the order CLW > CVA > CUW > CDDW > CSS. A good correlation between the NRE index and the %N in the compost was observed (Figure S12, Supporting Information), although the variables were inversely related, so that as the N content increased, the root growth decreased. The correlations between total P and K, were lower (R^2 , 0.28-0.60). The increase in K led to an increase in the NRE index, whereas the opposite effect was observed in the case of total P. Therefore, a compost with a well-balanced NPK index (Figure S12, Supporting Information) is needed in order to obtain a positive effect on the root growth. Thus, sample CSS (NPK, 3.6-4.8-0.5) with high N and low L content produced a smaller increase, while the opposite was found for sample CLW (NPK, 1.8-31-3.6).

4. Conclusions

Compost and vermicompost samples were studied to evaluate both the effect of the composting process and the effect of the feedstock material. The evolution of the organic matter stabilization was also monitored during composting. A decrease of the C/N ratio led to a CEC increase as the composting process progressed, whereas a linear increase of CEC as a function of C/N ratio was observed when mature compost samples from different feedstock were analysed. In both cases the correlation can be interpreted as an increase in the degree of maturity. The concentration of DOC in water extracts can be used to quantify the content of HS-like compounds in the compost, which is especially relevant since the extraction procedure for humic substances is time-consuming.

The potentiometric study of the acid-base properties of HS-like fractions extracted from compost revealed an increase in the total amount of acidic sites during the maturation of the compost, thus enhancing the possibility of interaction and removal of heavy metals from soils. Also, considering the interaction between the soil fractions and the compost, it may be useful to study the acid-base behaviour of the DOM in the equilibrium solution, since these are the processes that are more likely to take place in the environment. The worms that participate in the vermicomposting process seem to perform a more efficient degradation of the original aliphatic materials, as it can be deduced by the higher abundance of acidic groups compared to traditionally composted samples.

The use of the compost as amendment improve the quality of unproductive mine soils. Depending on the feedstock material, different parameters were improved, i.e. urban waste compost generated a greater increase in the organic carbon, while domestic waste compost and livestock manure compost increase the concentration of bioavailable nutrients in the soil. Seed germination was favoured after the application of these compost samples, indicating that the nutrient content of the selected compost must be balanced to optimize soil fertility and plant growth.

627

628 Acknowledgments

629 This work was financially supported by the Interreg VA Spain-Portugal Programme (EU)
630 through the project Res2ValHum (0366_RES2VALHUM_1_P). R.L, J.A and S.F. are
631 members of the CRETUS Institute (CRETUS, AGRUP2015/02, ref. 2018-PG10) and
632 were also supported by the Group of Excellence GI-1245 financed by the Government of
633 Galicia (ED431C 2018/12). A.C. Silva acknowledges receipt of a PhD grant
634 (UMINHO/BD/40/2016) financed by the Operational Program Norte 2020 (through the
635 Project NORTE-08-5369-FSE-000033). LIPOR and other companies are also
636 acknowledged for the supply of the compost samples. The authors thank M. Santiso, F
637 Casas, J. Maceira, M. Orge and D. Fiuza for their assistance in characterizing the compost
638 and soil samples.

639 CRediT authorship contribution statement

640 **Rocío López:** Conceptualization, methodology, investigation, formal analysis, data
641 curation, writing – original draft. **Juan Antelo:** Methodology, investigation, data
642 curation, writing – review & editing. **Ana Catarina Silva:** Methodology, investigation,
643 data curation, writing – review & editing. **Fátima Bento:** Conceptualization, funding
644 acquisition, resources, validation, writing – review & editing. **Sarah Fiol:** Methodology,
645 funding acquisition, resources, project administration, writing – review & editing.

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Figure captions

Figure 1: Correlation between cationic exchange capacity (CEC) and C/N ratio of the compost. The solid line corresponds to the positive correlation observed for compost of different feedstock (filled symbols) and the dashed line shows a negative correlation during the composting process (empty symbols).

Figure 2. Variation of the electric conductivity (EC) as a function of the pH in the equilibrium solution of the compost samples.

Figure 3. Relationship of the yield in the HS-like extraction and a) the oxidizable carbon (C_{oxi}) content in the equilibrium solution and b) the pH of the equilibrium solution.

Figure 4. a) Charge curve and proton affinity distributions in the Dissolved Organic Matter (DOM) of the equilibrium solution of sample CLW as a function of pH. b) Proton affinity distributions in the DOM of the equilibrium solution of compost samples of different origin as a function of pH.

Figure 5. Charge curves of the HS-like of sample CLW as a function of pH. Symbols represent experimental data obtained from potentiometric titrations and lines represent fits with equation 6.

Figure 6. Charge curves of the a) FA-like and b) HA-like extracted at different stages of the composting process of sample CUW. Symbols represent experimental data from potentiometric titrations and lines represent fits with equation 6.

874 **Table captions**

875

876 **Table 1.** Chemical composition of the compost samples. Percentages in parentheses are
877 calculated based on the total content.

878 **Table 2.** Chemical characterization of the equilibrium solutions.

879 **Table 3.** Chemical characterization and extraction yield of the HS-like obtained with the
880 extraction protocol of the IHSS.

881 **Table 4:** Acid-base parameters of the dissolved organic matter in the equilibrium
882 solutions from compost samples of different feedstock and different composting stages.
883 Errors associated to the fitting are also shown.

884 **Table 5.** Intrinsic acid-base parameters of the HS-like extracted from the compost. Errors
885 associated to the fitting are also shown.

886 **Table 6.** Variation of the soil properties and the parameters obtained in the germination
887 assays following the application of compost as a soil amendment.

888

889

Table 1.

		%C	%C _{oxi}	%N	C/N	%S	P-total (mg/Kg)	P-Olsen (mg/Kg)	Ca (mg/Kg)	Mg (mg/Kg)	Na (mg/Kg)	K (mg/Kg)	CEC cmol(+)/Kg
Compost	CLW	22.8	17.8 (77.8%)	1.8	12.8	0.7	13505	3452 (25.6%)	78040	18230	11410	30187	149.7
	CUW	34.0	29.3 (86.1%)	2.7	12.6	0.2	5002	279 (5.6%)	77470	3739	4830	12237	167.0
	CDDW	23.3	18.8 (81.0%)	2.3	10.3	0.2	2513	251 (10.0%)	16100	3621	618.1	7597	95.3
	CSS	31.3	30.9 (98.6%)	3.6	8.6	1.1	21021	508 (2.4%)	19880	5200	2150	4269	51.5
Vermicompost	CVA	29.7	27.5 (92.4%)	2.4	12.5	0.4	5512	1386 (25.1%)	13100	4516	2807	10247	136.7
	CVDW	43.9	33.1 (75.4%)	5.2	8.5	0.4	4152	297 (7.2%)	9632	4430	1089	14577	98.8
Maturation	UW0	40.4	38.6 (95.4%)	2.5	15.9	0.2	3129	295 (9.4%)	25670	2520	4300	10063	127.6
	CUW15	38.9	36.9 (95.0%)	2.8	13.8	0.3	3950	255 (9.0%)	28420	2637	4531	8878	96.3
	CUW30	35.2	34.8 (98.9%)	2.7	12.9	0.3	4717	474 (10.0%)	43100	3451	5190	10737	108.7

%C_{oxi}: percentage of oxidizable carbon

Table 2.

		DOC (mg/L)	%C	NH ₄ ⁺ (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	PO ₄ ³⁻ (mg/L)	pH	EC (μS/cm)
Compost	CLW	861	9.7	21.2	22.5	38.9	552.0	1363.6	124.1	8.5	6020
	CUW	548	3.7	7.8	28.0	8.8	175.4	349.2	29.5	7.7	2840
	CDDW	115	1.2	4.6	28.6	12.3	17.3	149.5	45.2	6.9	883
	CSS	698	4.5	159.1	95.7	55.8	21.1	55.0	29.0	7.6	3850
Vermicompost	CVA	111	0.8	14.1	80.7	66.1	114.2	431.0	241.4	6.7	3280
	CVDW	717	4.3	11.1	17.8	15.1	26.7	333.2	70.3	6.3	1370
Maturation	UW0	1187	6.2	10.8	197.0	62.3	207.9	349.9	110.2	6.4	3870
	CUW15	429	2.3	13.2	133.1	37.4	194.3	322.0	80.4	6.8	3030
	CUW30	430	2.5	10.1	64.1	24.9	225.6	533.1	60.0	7.9	3300

DOC: dissolved organic carbon. %C: oxidizable C released to the solution. EC: electrical conductivity.

Table 3

		Fulvic Acid-like								Humic Acid-like							
		Yield (g/kg)	%C	%N	%H	%O	C/N	O/C	H/C	Yield (g/kg)	%C	%N	%H	%O	C/N	O/C	H/C
Compost	CLW	7.0	35.4	3.4	3.4	56.1	12.3	1.2	1.1	34.9	55.2	6.0	5.7	33.4	11.4	0.4	1.2
	CUW	3.3	40.8	4.4	6.0	47.8	10.9	0.9	1.8	21.1	54.5	6.7	6.1	31.7	9.4	0.4	1.3
	CDDW	4.2	38.4	2.6	3.1	55.5	17.1	1.1	1.0	19.0	50.6	4.9	4.5	39.5	12.0	0.6	1.1
	CSS	4.8	40.9	6.1	5.8	45.0	7.9	0.8	1.7	23.8	58.5	5.8	8.3	25.5	11.8	0.3	1.7
Vermicompost	CVA	2.3	49.7	3.7	5.4	40.1	15.6	0.6	1.3	33.4	53.5	3.7	5.5	36.2	16.8	0.5	1.2
	CVDW	4.7	39.8	3.2	3.6	52.9	14.5	1.0	1.1	26.4	52.7	6.1	4.6	36.1	10.0	0.5	1.1
Maturation	UW0	2.2	52.2	6.2	6.2	34.6	9.9	0.5	1.4	33.1	59.8	5.4	8.0	26.1	12.8	0.3	1.6
	CUW15	2.7	52.3	5.2	6.1	35.7	11.8	0.5	1.4	19.8	54.4	5.4	6.9	32.4	11.7	0.4	1.5
	CUW30	2.4	50.3	4.3	5.7	38.8	13.8	0.6	1.3	21.9	54.6	5.6	5.7	33.1	11.3	0.5	1.3

Table 4

	CLW		CUW		CDDW		CSS		CVA		CVDW		UW0		CUW15		CUW30	
log K₁	3.67	0.02	3.69	0.03	3.06	0.03	4.24	0.02	3.27	0.07	3.45	0.02	4.50	< 0.01	3.99	0.05	3.57	0.07
(*)M ₁	0.09	< 0.01	0.06	< 0.01	0.06	< 0.01	0.18	< 0.01	0.04	< 0.01	0.08	< 0.01	0.42	< 0.01	0.05	< 0.01	0.03	< 0.01
log K₂	6.56	< 0.01	6.51	0.01	6.42	0.01	6.27	0.01	6.55	0.01	6.65	0.01	6.05	0.01	6.54	0.01	6.65	0.01
(*)M ₂	0.43	< 0.01	0.18	< 0.01	0.10	< 0.01	0.25	< 0.01	0.08	< 0.01	0.33	< 0.01	0.16	< 0.01	0.24	< 0.01	0.25	< 0.01
log K₃	10.25	< 0.01	10.11	0.01	10.17	0.01	9.65	< 0.01	10.00	0.01	10.33	0.01	9.73	0.01	10.06	0.01	10.08	0.01
(*)M ₃	0.45	< 0.01	0.19	< 0.01	0.10	< 0.01	0.74	0.01	0.10	< 0.01	0.21	< 0.01	0.27	< 0.01	0.22	< 0.01	0.21	< 0.01
(*)Q ₀	-0.48	< 0.01	-0.23	< 0.01	-0.14	< 0.01	-0.40	< 0.01	-0.10	< 0.01	-0.36	< 0.01	-0.52	< 0.01	-0.26	< 0.01	-0.26	< 0.01
<i>R</i> ²	<i>0.9997</i>		<i>0.9997</i>		<i>0.9999</i>		<i>0.9998</i>		<i>0.9996</i>		<i>0.9993</i>		<i>0.9998</i>		<i>0.9994</i>		<i>0.9991</i>	
<i>RMSE</i>	<i>0.0055</i>		<i>0.0024</i>		<i>0.0009</i>		<i>0.0062</i>		<i>0.0013</i>		<i>0.0052</i>		<i>0.0035</i>		<i>0.0041</i>		<i>0.0050</i>	
(*)M _T	0.96		0.44		0.25		1.17		0.22		0.62		0.85		0.52		0.50	

(*) Parameters in mmol/g_{compost}. M_T corresponds to the total abundance of acid positions

Table 5

	b	log K₁	M₁(mmol/g_{SH})	m₁	log K₂	M₂(mmol/g_{SH})	m₂	R²	RMSE	M_T(mmol/g_{SH})
FA CLW	0.57	2.72 ± 0.02	3.02 ± 0.02	0.44 ± 0.02	8.31 ± 0.02	1.56 ± 0.02	0.43 ± 0.02	0.9997	0.0154	4.58
FA CUW	0.63	2.93 ± 0.01	3.49 ± 0.08	0.60 ± 0.01	7.76 ± 0.16	1.62 ± 0.23	0.34 ± 0.05	0.9998	0.0142	5.11
FA CDDW	0.66	2.76 ± 0.01	3.46 ± 0.07	0.54 ± 0.01	7.58 ± 0.08	1.51 ± 0.16	0.30 ± 0.03	0.9999	0.0073	4.96
FA CSS	0.65	3.38 ± 0.04	4.77 ± 0.16	0.45 ± 0.01	8.07 ± 0.17	2.81 ± 0.49	0.39 ± 0.06	0.9998	0.0260	7.57
FACVA	0.60	3.31 ± 0.01	3.01 ± 0.15	0.88 ± 0.03	7.42 ± 0.14	2.61 ± 0.39	0.32 ± 0.05	0.9996	0.0270	5.63
FA CVDW	0.63	2.63 ± 0.01	3.89 ± 0.04	0.54 ± 0.01	8.03 ± 0.06	1.72 ± 0.11	0.40 ± 0.03	0.9997	0.0190	5.61
<i>Average FA^a</i>	<i>0.62 ± 0.03</i>	<i>2.96 ± 0.32</i>	<i>3.61 ± 0.60</i>	<i>0.58 ± 0.15</i>	<i>7.86 ± 0.33</i>	<i>1.97 ± 0.53</i>	<i>0.36 ± 0.05</i>			<i>5.58 ± 0.97</i>
HA CLW	0.47	3.64 ± 0.02	2.64 ± 0.03	0.39 ± 0.01	8.43 ± 0.10	1.31 ± 0.13	0.57 ± 0.05	0.9999	0.0070	3.95
HA CUW	0.46	3.41 ± 0.04	2.80 ± 0.19	0.60 ± 0.03	7.88 ± 0.22	1.94 ± 0.48	0.33 ± 0.08	0.9994	0.0272	4.74
HA CDDW	0.48	3.15 ± 0.04	2.93 ± 0.11	0.47 ± 0.01	7.96 ± 0.22	1.49 ± 0.31	0.36 ± 0.07	0.9998	0.0132	4.42
HA CSS	0.43	3.78 ± 0.07	2.60 ± 0.07	0.30 ± 0.01	8.46 ± 0.21	1.11 ± 0.24	0.55 ± 0.09	0.9999	0.0081	3.70
HACVA	0.45	3.46 ± 0.03	2.47 ± 0.03	0.44 ± 0.01	8.37 ± 0.11	1.09 ± 0.13	0.57 ± 0.06	0.9998	0.0124	3.56
HA CVDW	0.44	3.47 ± 0.02	2.43 ± 0.04	0.60 ± 0.01	8.15 ± 0.19	1.32 ± 0.20	0.50 ± 0.07	0.9998	0.0138	3.75
<i>Average HA^a</i>	<i>0.46 ± 0.02</i>	<i>3.49 ± 0.21</i>	<i>2.62 ± 0.19</i>	<i>0.47 ± 0.11</i>	<i>8.21 ± 0.25</i>	<i>1.38 ± 0.29</i>	<i>0.48 ± 0.10</i>			<i>4.00 ± 0.44</i>
^a Calculated average value for the model parameters of HS-like extracts										
	b	log K₁	M₁(mmol/g_{SH})	m₁	log K₂	M₂(mmol/g_{SH})	m₂	R²	RMSE	M_T(mmol/g_{SH})
FA CUW15	0.74	3.53 ± 0.01	3.38 ± 0.09	0.87 ± 0.02	8.00 ± 0.27	1.62 ± 0.33	0.35 ± 0.08	0.9995	0.0260	5.00
FA CUW30	0.68	3.15 ± 0.01	3.45 ± 0.03	0.71 ± 0.01	7.96 ± 0.07	1.69 ± 0.09	0.34 ± 0.02	1.0000	0.0060	5.14
HA CUW15	0.50	4.15 ± 0.02	2.15 ± 0.08	0.69 ± 0.02	8.14 ± 0.21	1.42 ± 0.28	0.41 ± 0.08	0.9998	0.0132	3.57
HA CUW30	0.48	3.93 ± 0.03	2.50 ± 0.09	0.59 ± 0.01	8.12 ± 0.28	1.37 ± 0.34	0.41 ± 0.09	0.9998	0.0133	3.88

Table 6

	pH	%C	%N	P-total (mg/kg)	P-Olsen (mg/kg)	CEC (cmol ₊ /kg)	Root length (cm)	NRE	RSG(%)	RRG(%)	GI(%)
<i>Ch2 (Control)</i>	4.53	0.66	n.d.	258.0	4.6	1.27	4.32	0.0	100.0	100.0	100.0
<i>Ch2 + 2%CLW</i>	7.13	0.96	0.05	509.8	53.6	12.3	6.39	0.48	100.0	147.7	147.7
<i>Ch2 + 5%CLW</i>	7.77	1.59	0.09	640.4	105.7	27.1	6.62*	0.53*	109.4	153.1*	167.5*
<i>Ch2 + 10%CLW</i>	8.19*	1.90	0.13	846.6	365.0*	37.3*	6.56	0.52	103.8	151.8	157.5
<i>Ch2 + 2%CUW</i>	6.63	1.06	0.02	347.4	3.8	4.4	5.75	0.34	113.2	134.1	151.8
<i>Ch2 + 5%CUW</i>	7.59	1.38	0.06	429.5	9.9	13.2	5.80	0.47	105.7	147.4	155.8
<i>Ch2 + 10%CUW</i>	7.77	3.28	0.32	603.5	22.0	20.0	6.37	0.33	107.5	133.0	143.0
<i>Ch2 + 2%CSS</i>	5.34	1.29	n.d.	704.5	28.1	2.8	3.97	-0.08	103.8	91.9	95.4
<i>Ch2 + 5%CSS</i>	5.98	2.59	0.53	1338.2	42.5	6.7	5.01	0.16	103.8	115.8	120.2
<i>Ch2 + 10%CSS</i>	6.15	3.47*	0.39*	1956.2*	101.6	10.8	5.08	0.17	113.2*	117.5	133.0
<i>Ch2 + 2%CVA</i>	6.63	0.98	n.d.	478.8	29.6	6.2	5.97	0.38	100.0	138.0	138.0
<i>Ch2 + 5%CVA</i>	7.59	1.36	0.06	733.6	39.9	11.5	6.24	0.44	107.5	144.4	155.3
<i>Ch2 + 10%CVA</i>	7.77	2.04	0.16	1128.3	78.4	23.4	6.47	0.50	100.0	149.6	149.6
<i>Ch2 + 2%CDDW</i>	7.21	0.93	0.06	534.7	48.1	12.1	6.55	0.52	103.8	151.5	157.2
<i>Ch2 + 5%CDDW</i>	7.49	1.56	0.48	760.1	69.2	16.1	6.14	0.42	111.3	141.9	158.0
<i>Ch2 + 10%CDDW</i>	7.79	2.29	0.27	1002.4	206.6	22.3	6.26	0.45	110.4	144.7	159.7

n.d. – non detected *Indicates the case with the higher increase in the corresponding parameter after the amendment application. CEC: cation exchange capacity. NRE: normalized residual elongation index. RSG: relative seed germination index. RRG: relative radicle growth index. GI: germination index

Figure 1

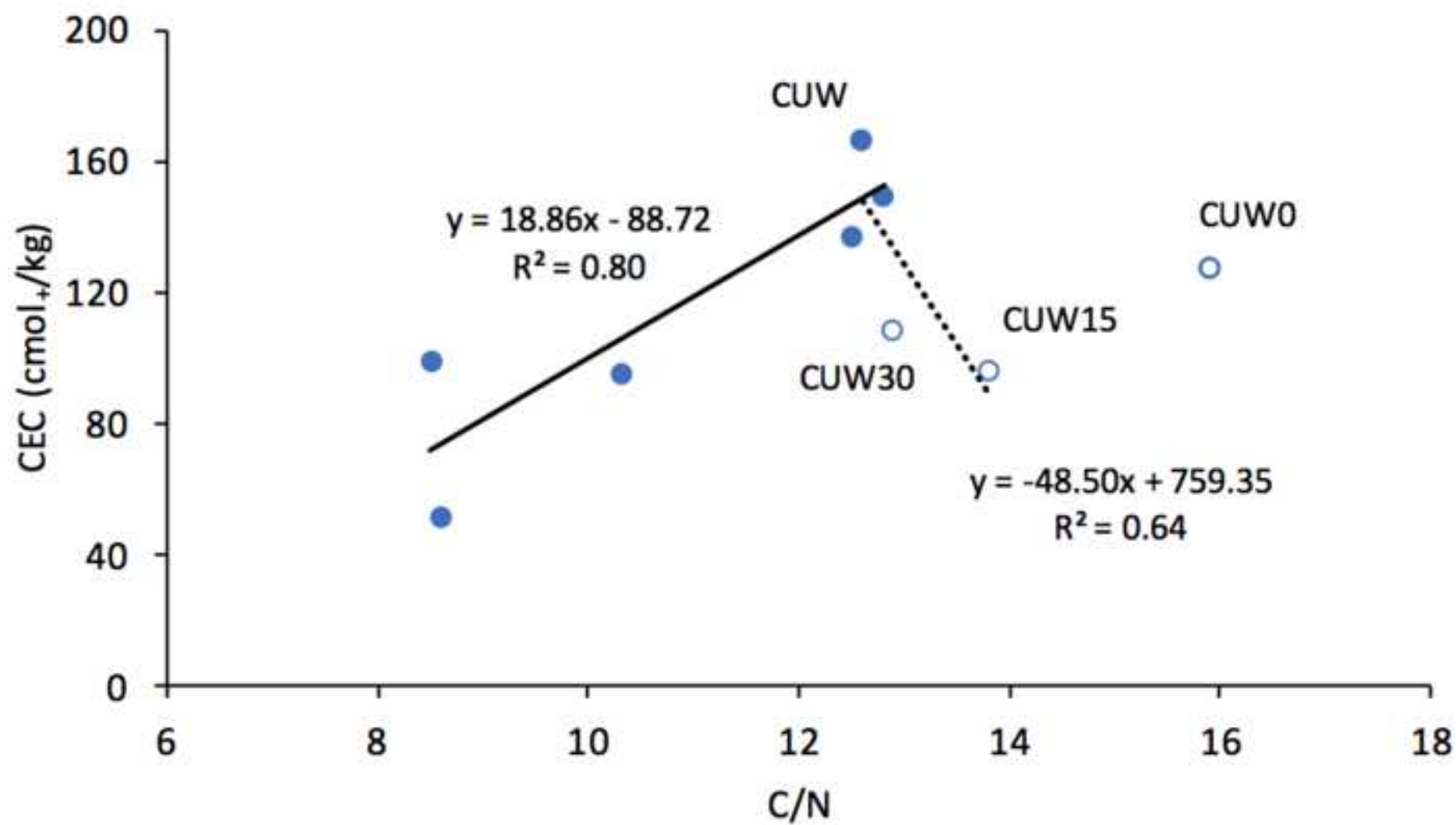
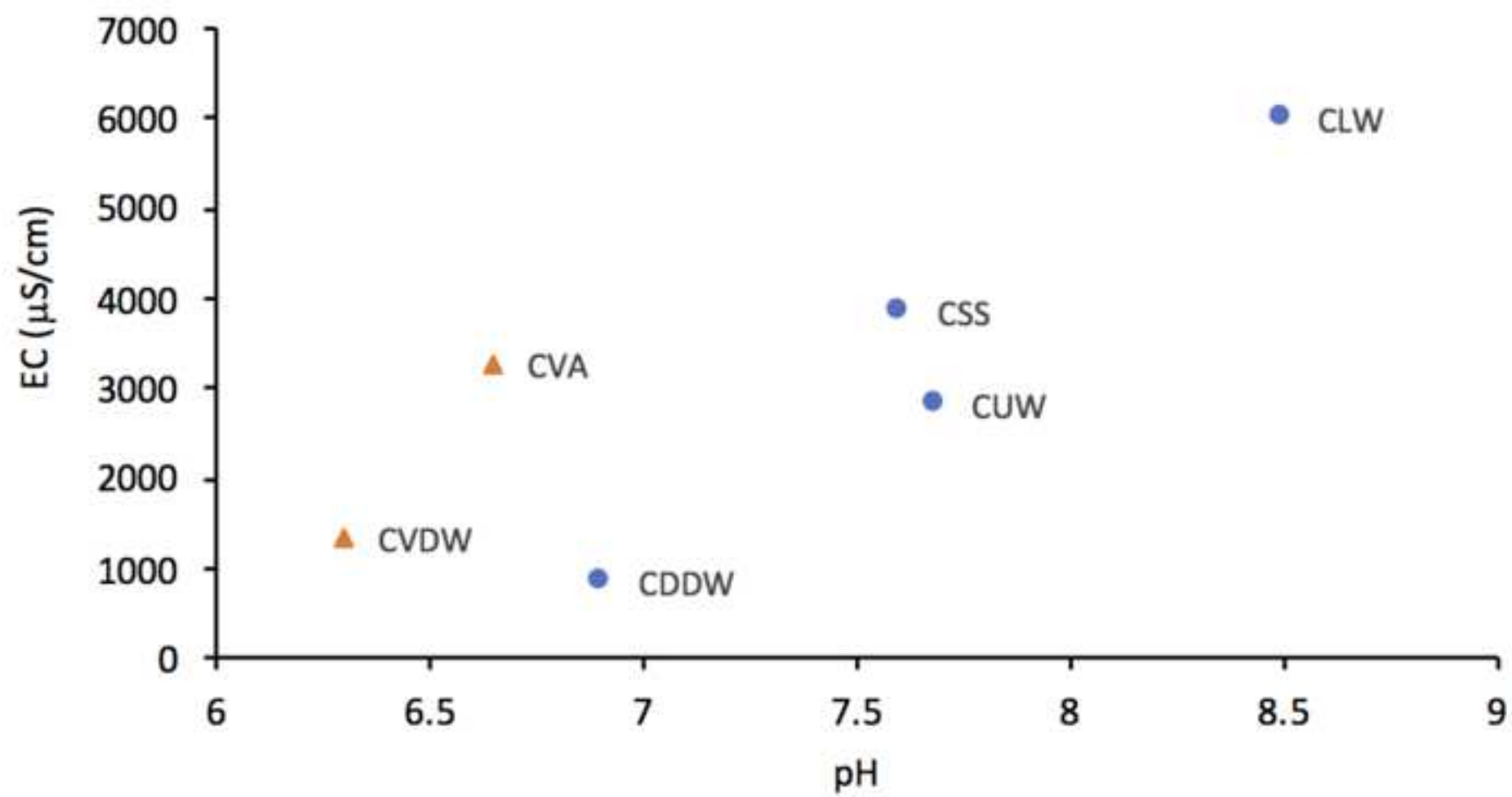
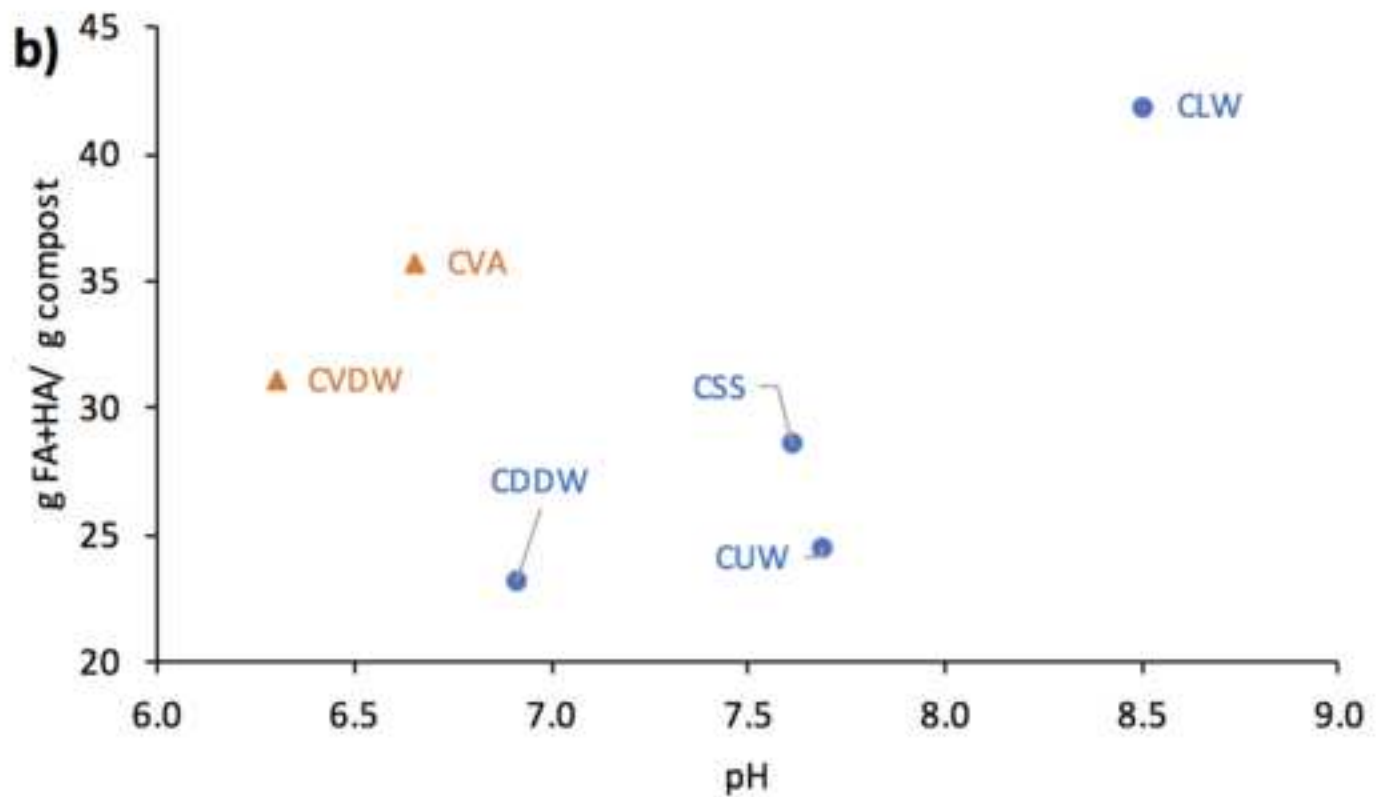
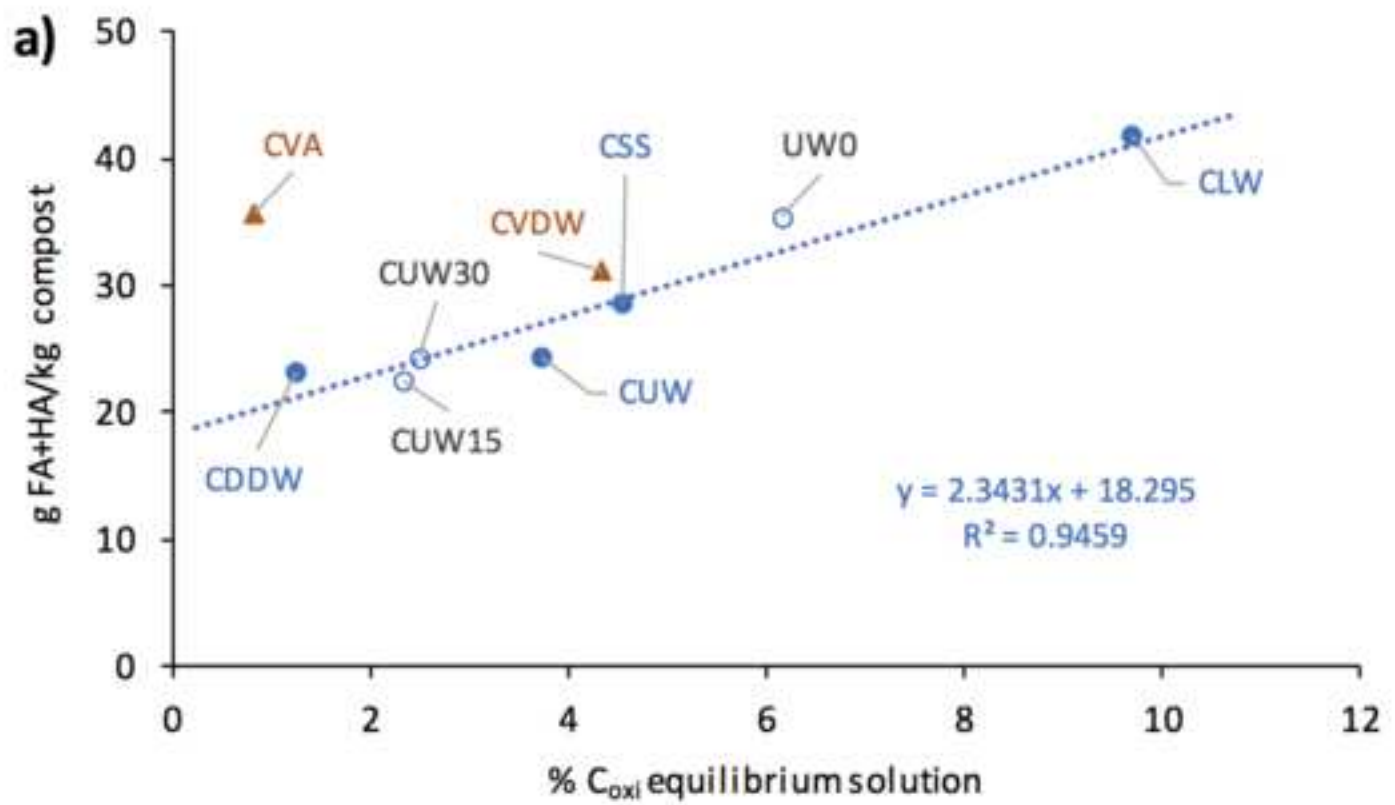


Figure 2

[Click here to access/download;Figure;Figure 2.tiff](#) 





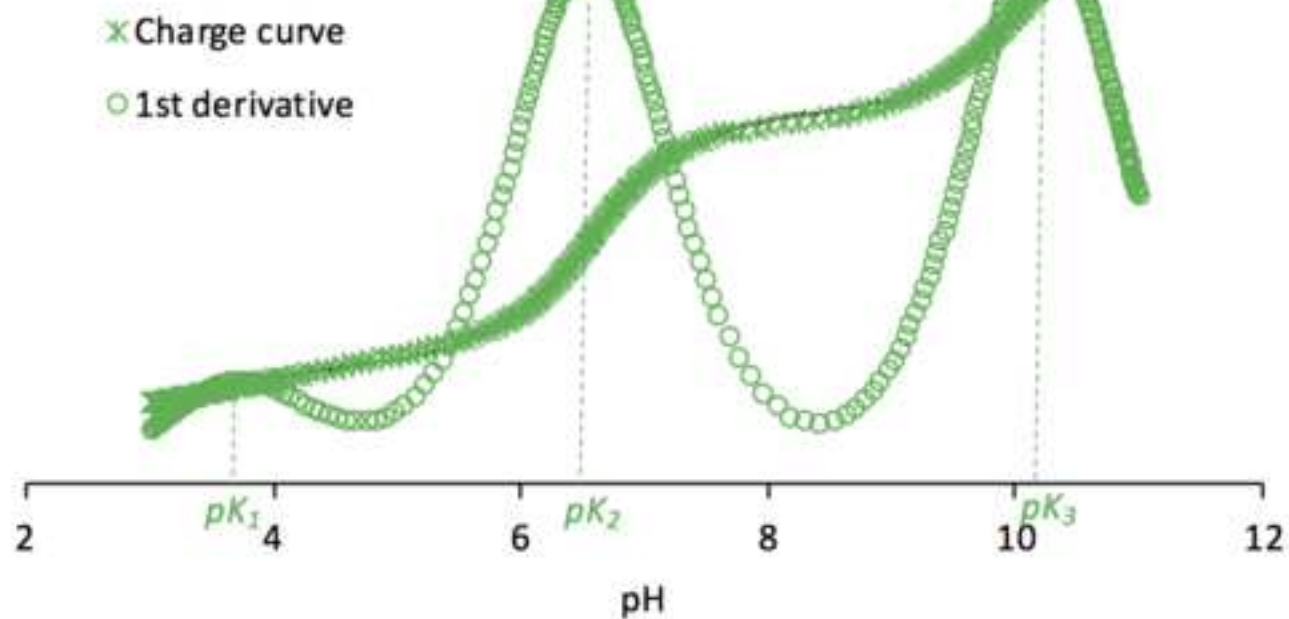
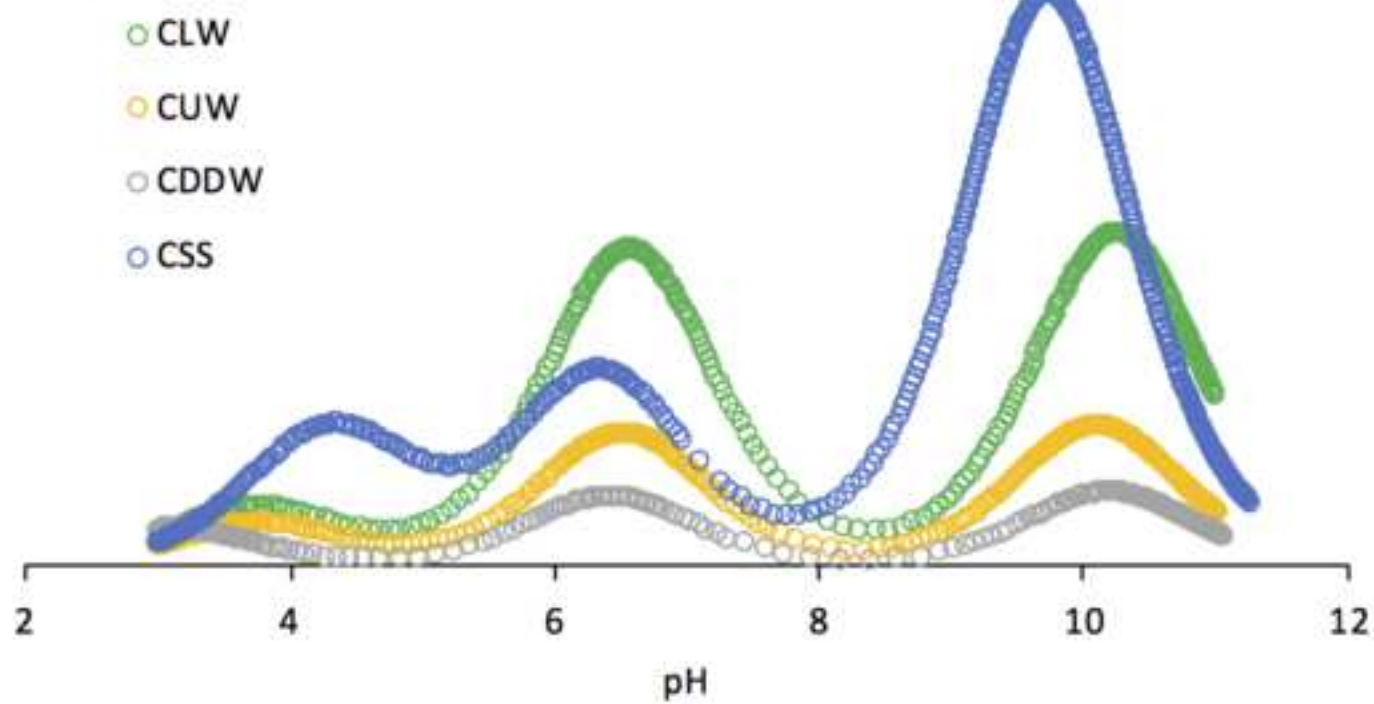
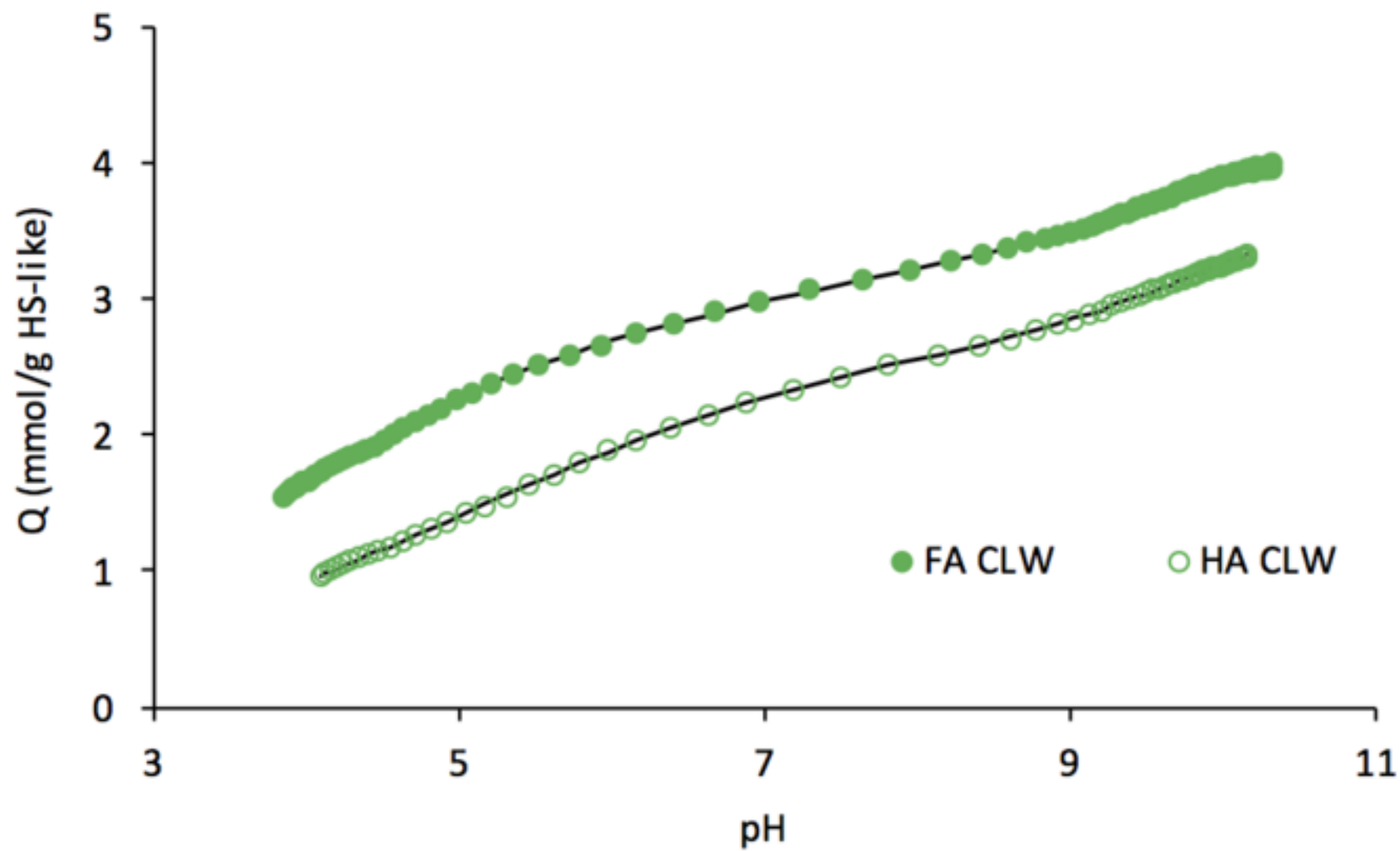
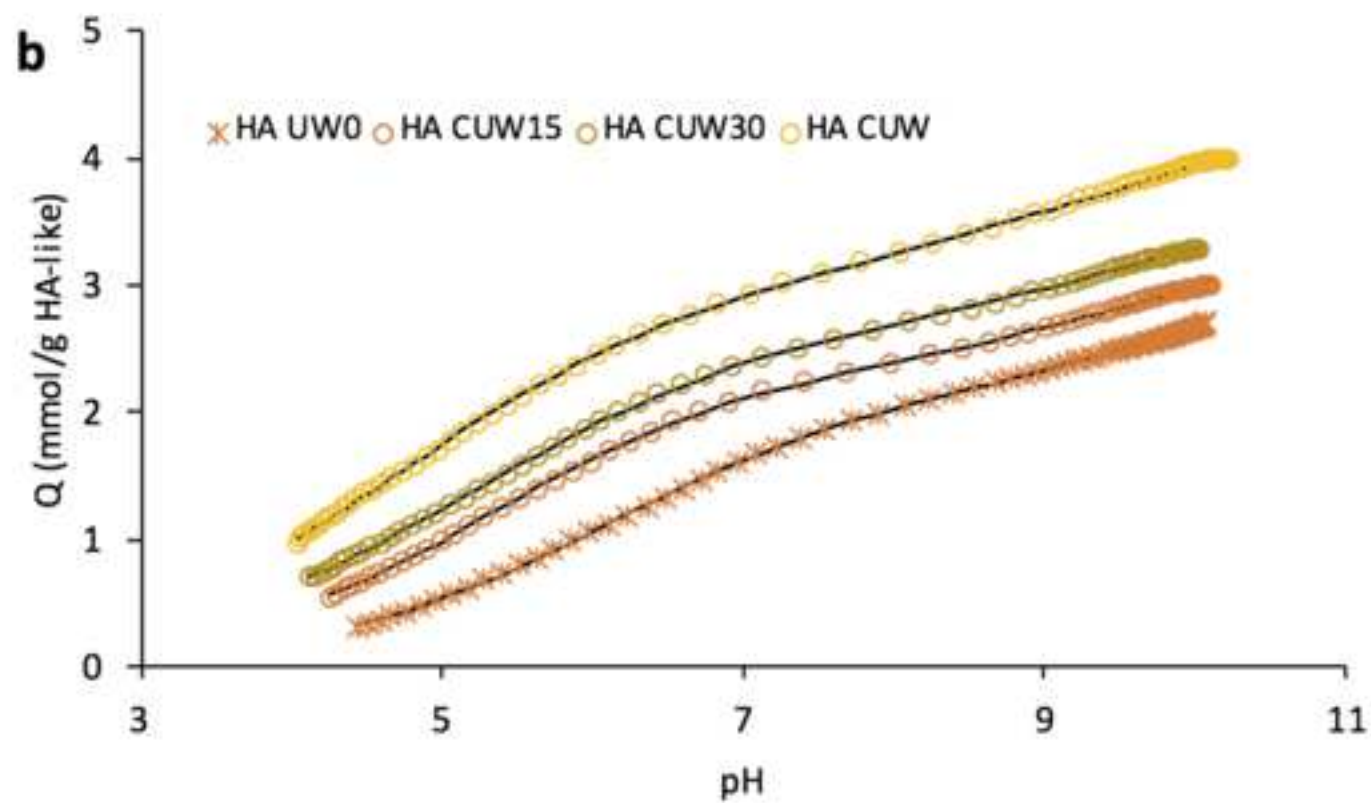
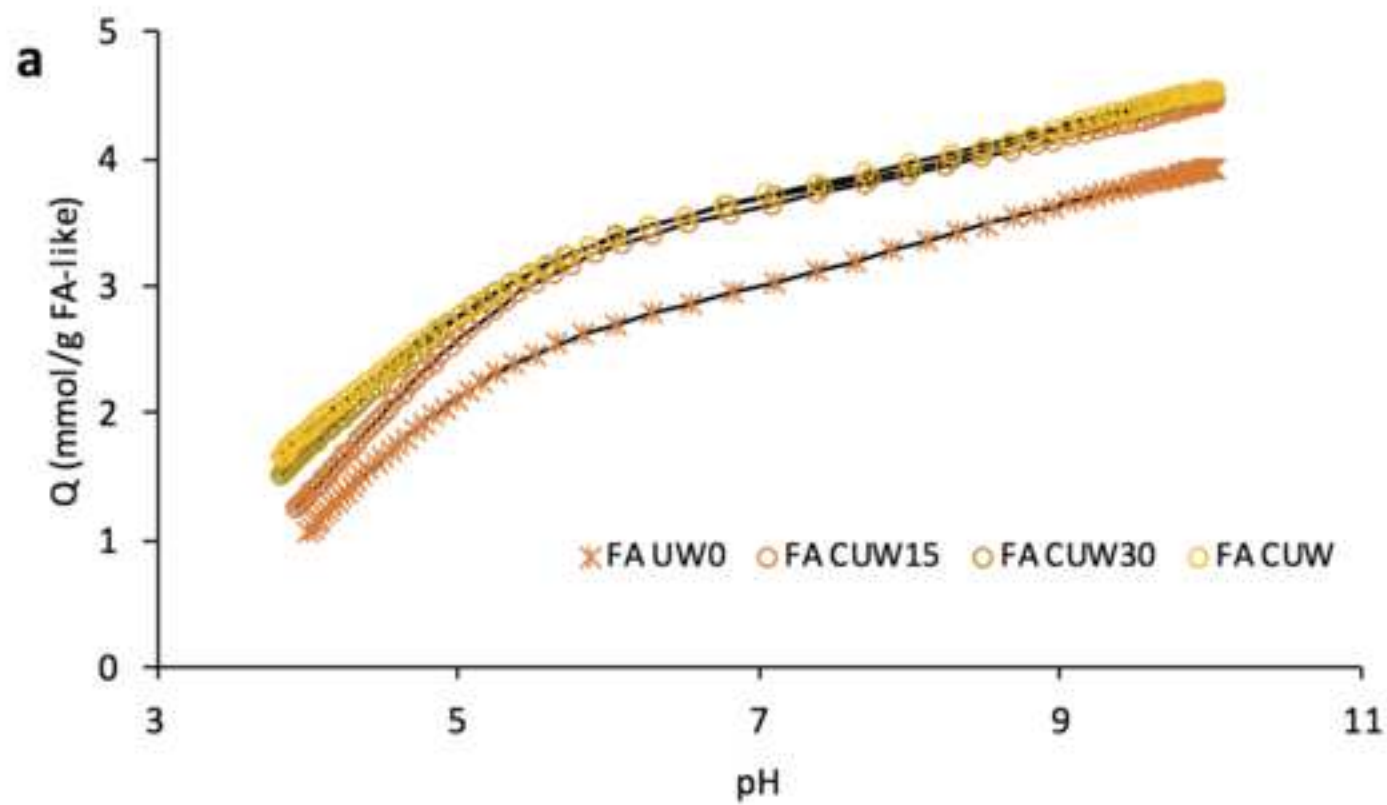
a**b**

Figure 5





SUPPORTING INFORMATION

Factors That Affect Physicochemical and Acid-Base Properties of Compost and its Potential Use as a Soil Amendment

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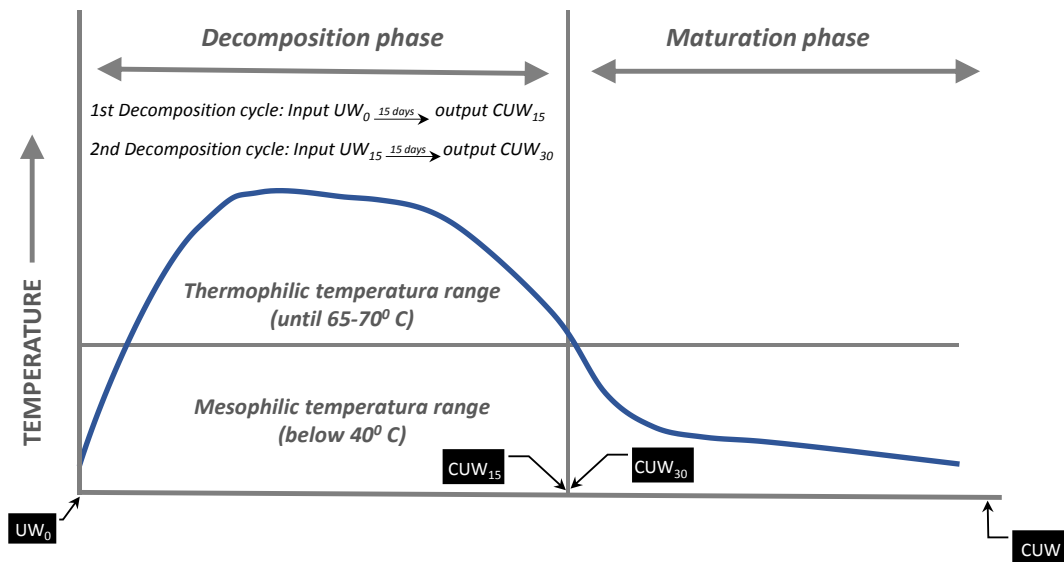


Figure S1. Sketch of the composting in a tunnel-system process with two 15-day decomposition cycles prior to the maturation stage.

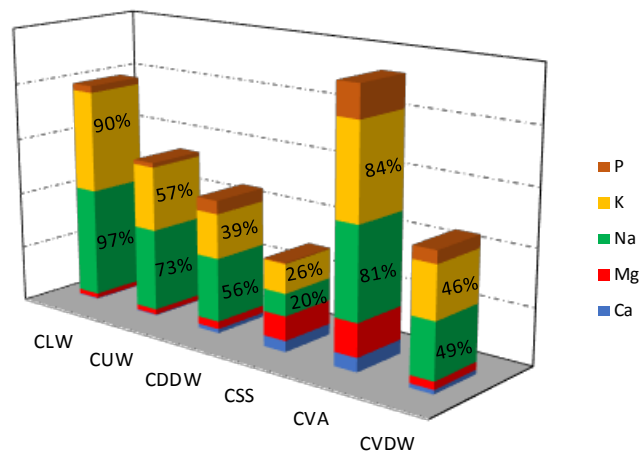


Figure S2. Percentage of major components in the compost that are released to the equilibrium solution.

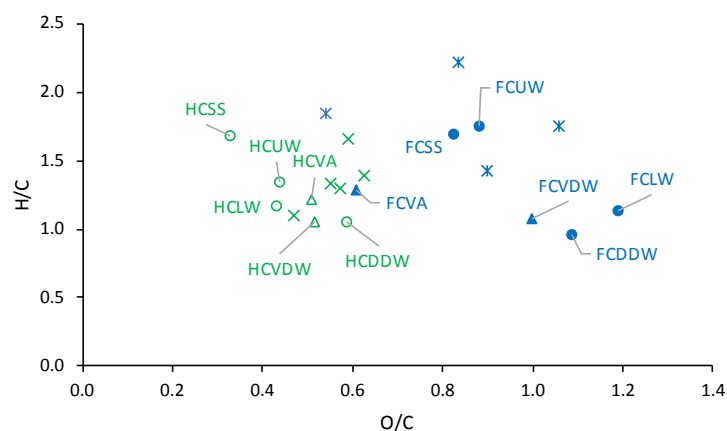


Figure S3. Van Krevelen diagram. Empty and filled symbols correspond to the HA-like and FA-like extracts, respectively, of the present study; crosses and asterisks correspond to HA and FA, respectively, from the literature data (taken from: Amir et al., *Process Biochem* 40 (2005), 1693-1700; Amir et al., *J. Hazard. Mater.* 177 (2010), 524-529; Baddi et al., *Bioresour. Technol.* 93 (2004), 285-290; Hanc et al., *Waste Manage.* 99 (2019) 1-11; Huang et al., *Bioresour. Technol.* 97 (2006), 1834-1842; Jouraiphy et al., *Bioresour. Technol.* 99 (2008), 1066-1072; Liu et al., *Waste Manage.* 103 (2020), 342-351).

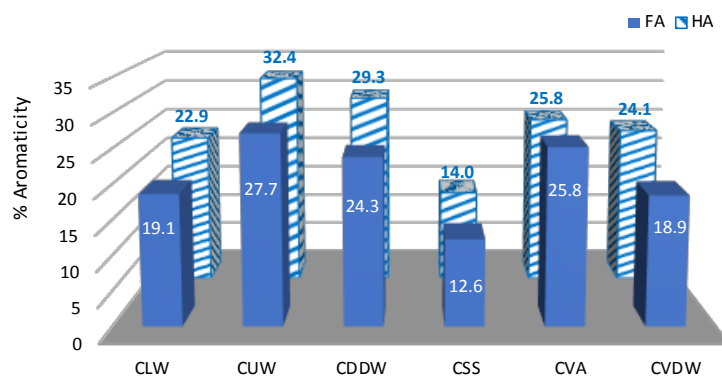


Figure S4. Aromaticity percent for the FA-like and HA-like extracts.

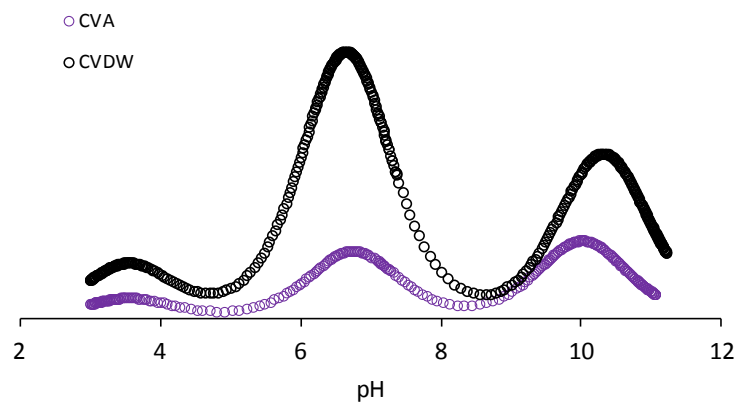


Figure S5. Proton affinity distributions obtained for the DOM of the equilibrium solution from vermicompost samples.

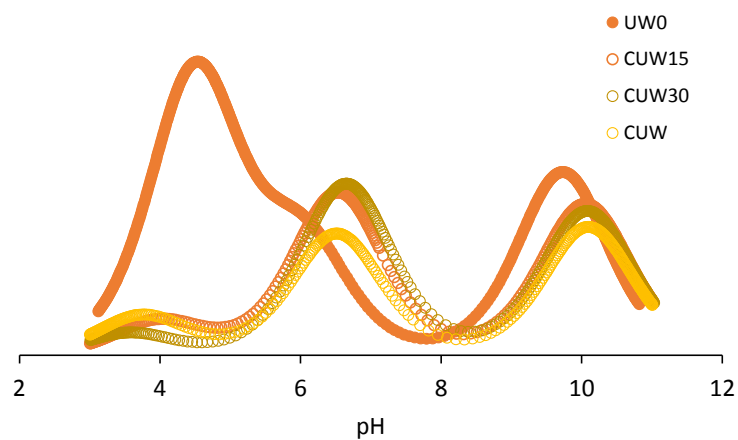


Figure S6. Proton affinity distributions obtained for the DOM of the equilibrium solution during different stages of the composting process of sample CUW.

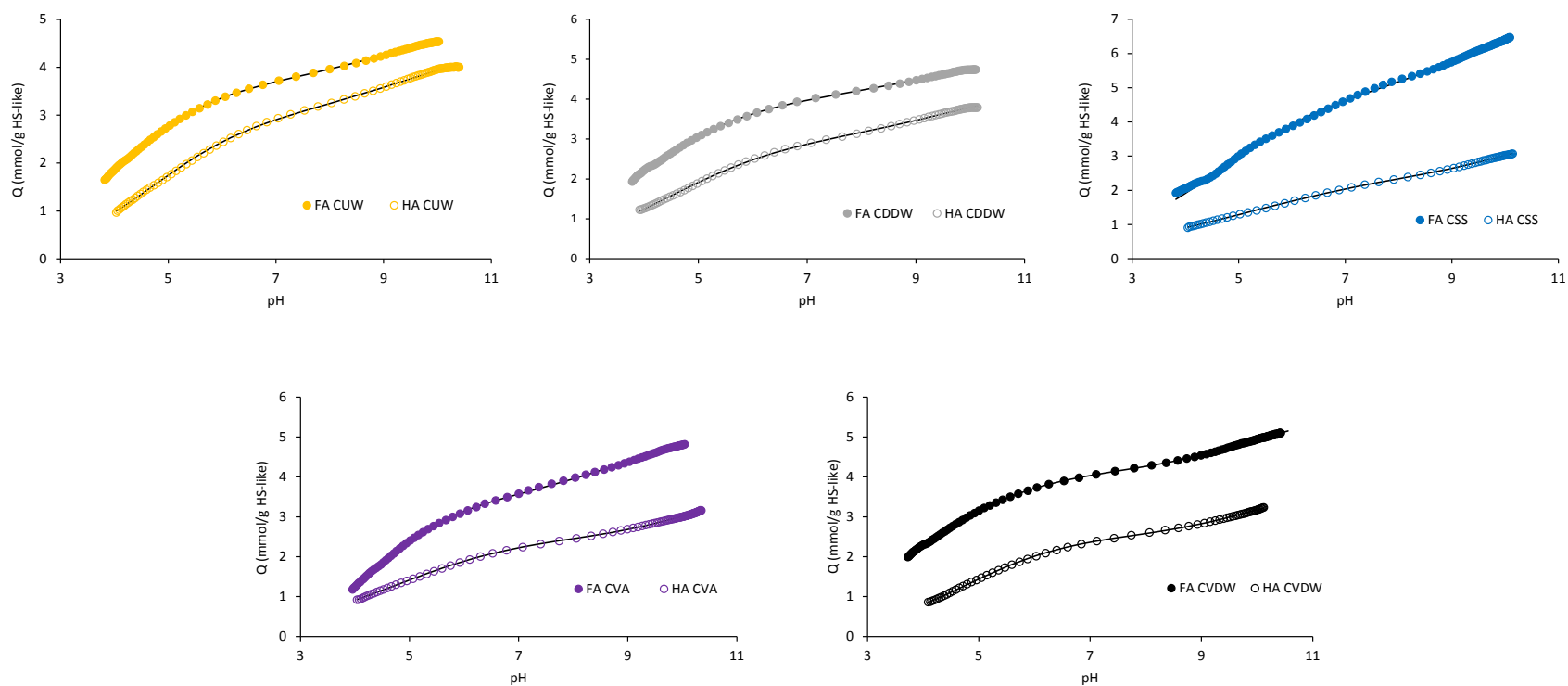


Figure S7. Charge curves for the HS-like extracts from compost of different origin.

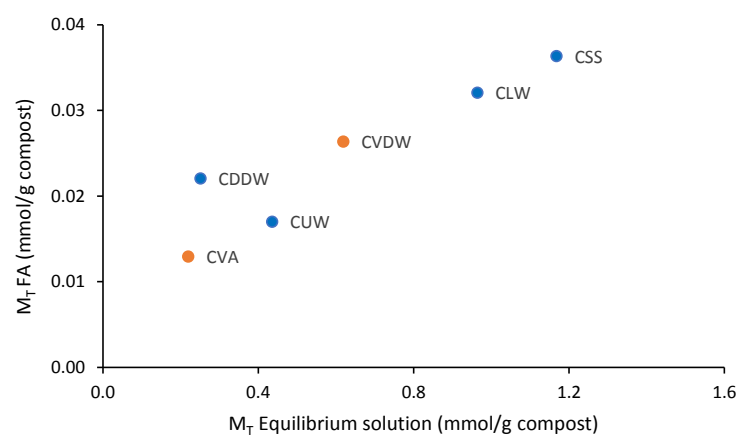


Figure S8. Relationship between the abundance of acid sites of the DOM in the equilibrium solution and in the FA-like of the compost and vermicompost samples.

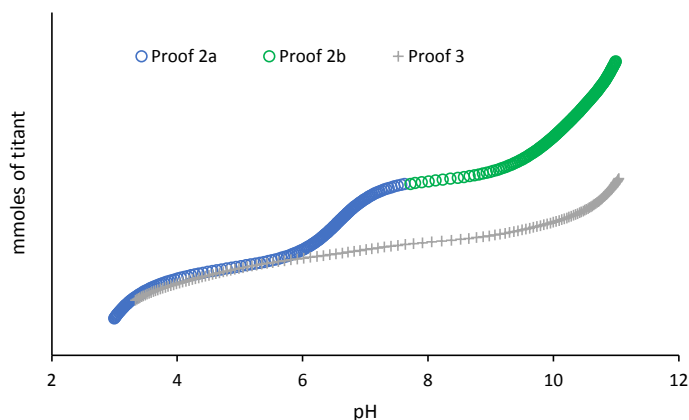


Figure S9. Comparison of the titration curves of the equilibrium solutions (test 2a, aliquot titrated with acid and test 2b, aliquot titrated with base) and the curves obtained after acidification and subsequent titration with base (test 3).

In order to understand the difference in the charge behaviour of the DOM in the equilibrium solutions and the HS-like fractions, it is important to analyze the results of different tests carried out to optimize the methodology of the acid-base titrations of the equilibrium solutions. Test 1 consisted of a similar method to that described by Sciubba et al. (2015) (Environ. Sci. Pollut. Res. 22, 13393-13403). In this test, a certain volume of strong acid (HCl) was added to yield pH values close to 3 and the solution was then titrated with KOH to pH values close to 11. Test 2 consisted of titrating an aliquot of the equilibrium solution with HCl (2a) and another aliquot with KOH (2b). For test 3, an aliquot of the equilibrium solution was titrated with HCl until pH 3 and then immediately titrated with KOH to pH 11. In test 4, an aliquot of the equilibrium solution was titrated with NaOH to pH 11 and then with HCl back to pH 3. The results of the experiments carried out after acidifying the sample prior to titration against a base (tests 1 and 3) are almost identical, but very different from the tests carried out without acidifying the samples (tests 2 and 4). For this reason, only the results of tests 2 and 3 are shown in Figure S9. The charge curve obtained after acidifying the sample had a much gentler slope, with a large decrease in the inflection point corresponding to the second site. This may explain the different acid-base behaviour of the DOM in the equilibrium solutions and the HS-like extracts, as the extraction procedure for the latter is based on the different solubility of the fractions with varying pH.

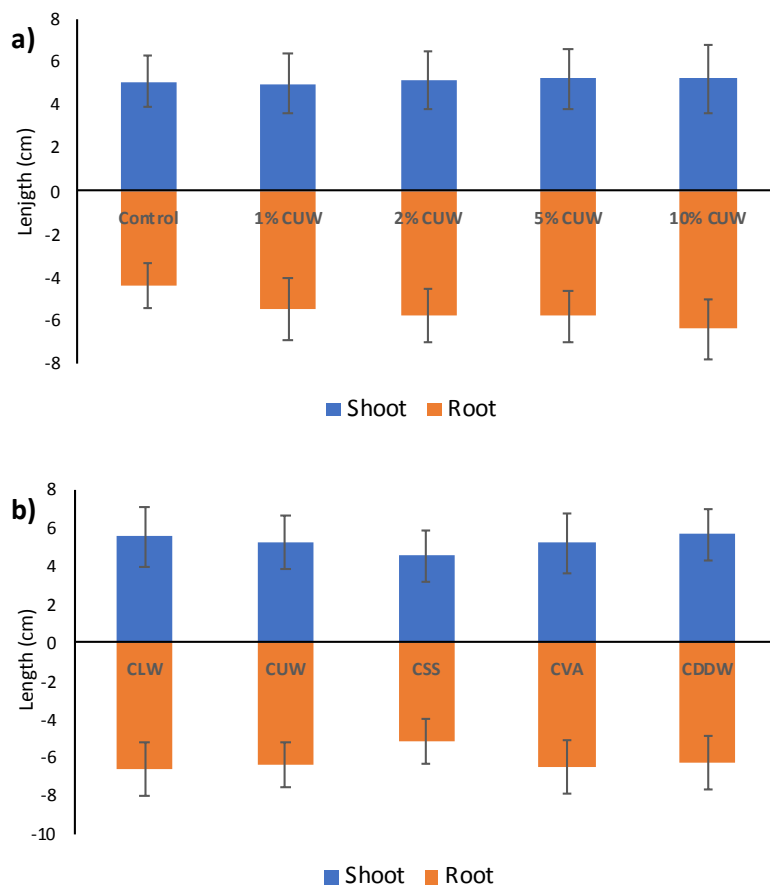


Figure S10. a) Effect of the content of CUW in the amended soils on the shoot and root growth of *Lolium perenne*. b) Variation of the shoot and root growth of *Lolium perenne* as a function of the compost sample applied in the amendment.

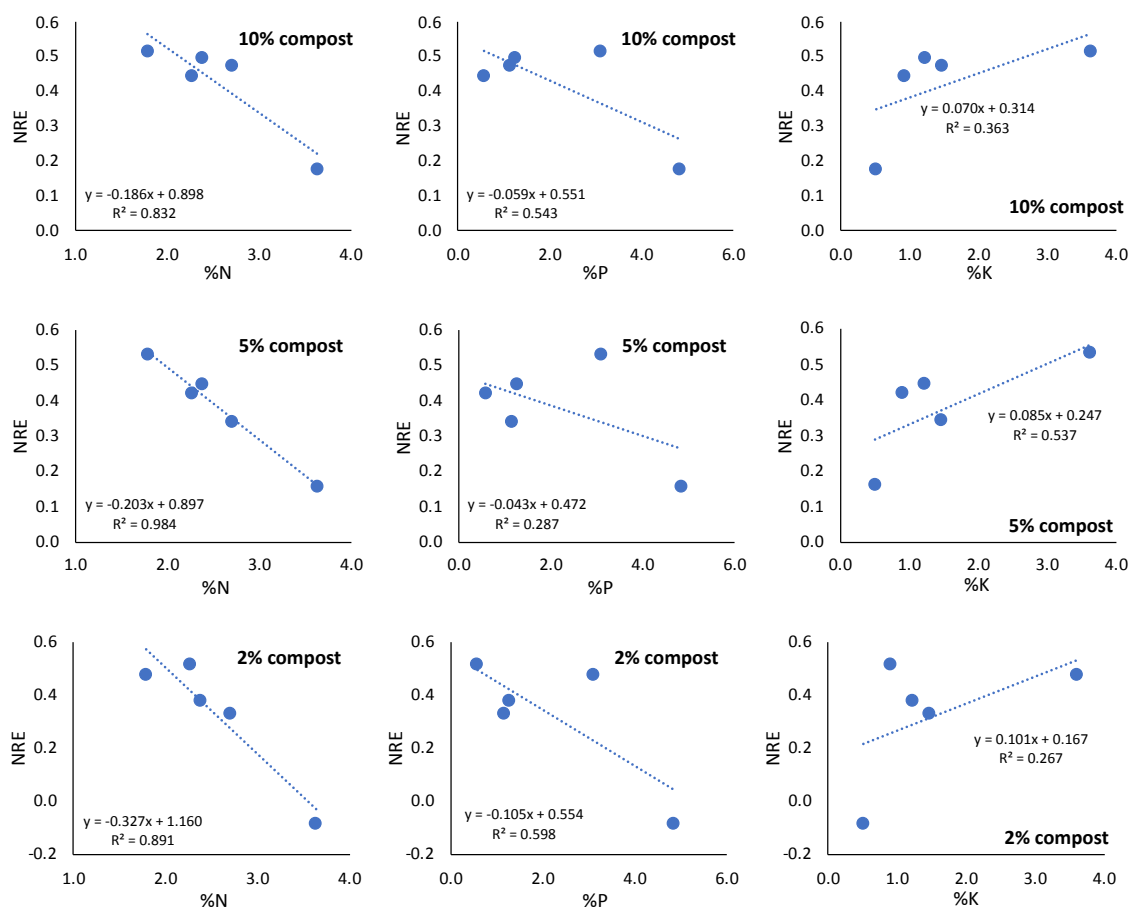


Figura S11. Correlation between the NRE for *Lolium perenne* in each amended soil and the %N, %K (as K_2O) and %P (as P_2O_5) of the corresponding compost

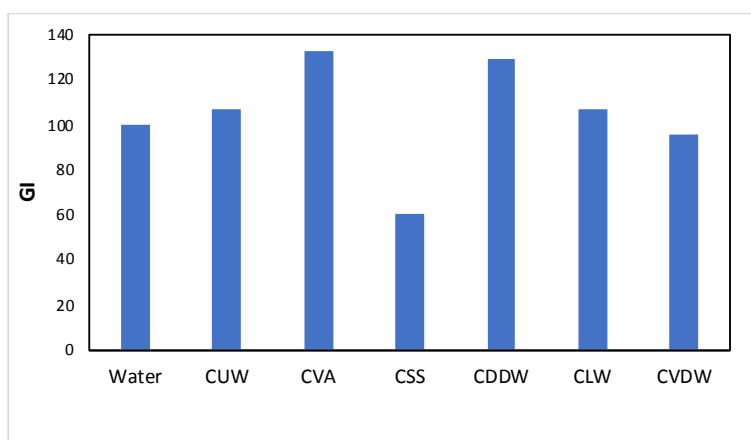


Figura S12. Variation of the Germination Index for the water extracts of the compost samples.

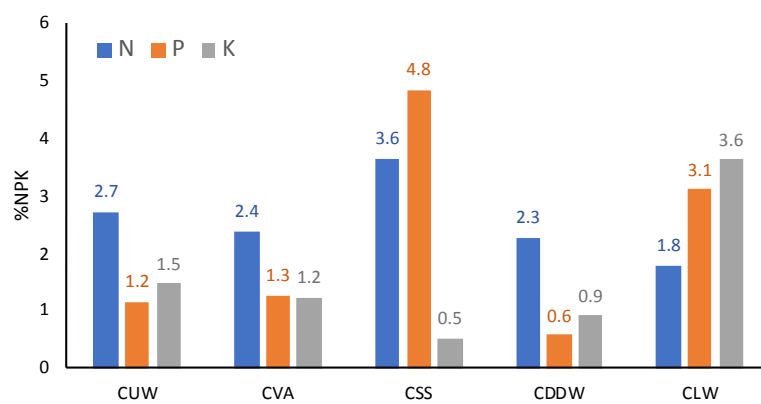


Figura S13. NPK values for the compost samples.

Table S1. Codes and description of the samples

	Samples code	Samples description
Compost	CLW (Compost Livestock Waste)	Commercial product obtained by a pile composting system from manure and other animal waste effluents
	CUW (Compost Urban Waste)	Commercial product obtained by a tunnel composting system from urban waste material combined with green and forestry waste
	DCDW (Domestic Compost of Domestic Waste)	Product obtained in individual composters from domestic food waste combined with green waste
	CSS (Compost Sewage Sludge)	Product obtained by a pile composting system from sewage sludge combined with forestry waste
Vermicompost	VCA (Vermicompost Algae)	Vermicompost obtained from manure (60%) and seaweed
	VCDW (Vermicompost of Domestic Waste)	Vermicompost obtained in individual composters from domestic food waste combined with green waste
Maturation	UW0 (Urban Waste)	Sample taken at the beginning of the composting process. consisting of a mixture of residues from urban waste. green and forestry waste, properly separated at source (see Figure S1)
	CUW15 (Compost Urban Waste 15 days)	Sample taken at the end of the first composting cycle (see Figure S1)
	CUW30 (Compost Urban Waste 30 days)	Sample taken at the end of the second cycle and before maturation stage (see Figure S1)

Table S2. Pearson's correlation between different characteristics of the compost studied

a) Feedstock

	%C	%Coxi	%N	C/N	%S	P-total	P-Olsen	CEC	Fe	Al	Yield HS
%C	1	0.895*	0.910*	-0.502	-0.090	-0.192	-0.532	-0.140	-0.369	-0.465	-0.199
%Coxi		1	0.798	-0.485	0.145	0.071	-0.591	-0.268	-0.077	-0.235	-0.258
%N			1	-0.802	0.122	-0.023	-0.550	-0.497	-0.085	-0.166	-0.222
C/N				1	-0.357	-0.220	0.573	0.897*	-0.449	-0.418	0.376
%S					1	0.973**	0.305	-0.562	0.672	0.504	0.373
P-Total						1	0.331	-0.446	0.707	0.551	0.314
P-Olsen							1	0.421	-0.171	-0.206	0.901*
CEC								1	-0.743	-0.700	0.294
Fe									1	0.970**	-0.298
Al										1	-0.401
Yield HS											1

*Correlation is significant at the 0.05 level. **Correlation is significant at the 0.01 level

b) Maturation

	%C	%Coxi	%N	C/N	%S	P-total	P-Olsen	CEC	Fe	Al
%C	1	0.911	-0.419	0.916	-0.029	-0.979*	-0.403	-0.509	-0.710	-0.813
%Coxi		1	-0.354	0.807	0.271	-0.883	-0.007	-0.751	-0.381	-0.599
%N			1	-0.747	0.688	0.596	-0.024	-0.292	0.598	0.790
C/N				1	-0.349	-0.979*	-0.317	-0.219	-0.806	-0.954*
%S					1	0.184	0.447	-0.838	0.681	0.597
P-Total						1	0.355	0.381	0.766	0.899
P-Olsen							1	-0.262	0.769	0.495
CEC								1	-0.231	-0.063
Fe									1	0.932
Al										1

*Correlation is significant at the 0.05 level. **Correlation is significant at the 0.01 level

Table S3. Total content of metals in the compost samples.

		Fe	Al	As	Cd	Co	Cr	Cu	Mn	Ni	Pb	Zn
		(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)	(mg/Kg)
Compost	CLW	6463	8256	8.8	<0.1	2.8	28.8	177.7	345.2	12	4.2	1047
	CUW	4022	5705	6.3	2.9	2.5	11.7	37.1	126.2	8.1	19.1	116.8
	CDDW	13000	19920	3.8	<0.1	3.2	19.4	65.2	184.9	9.8	36.3	145.3
	CSS	23110	24720	8.2	<0.1	4.8	76.9	252.3	254.8	38.3	64.9	629.8
Vermicompost	CVA	3468	3109	3.3	<0.1	<0.2	4.9	47.5	436.1	5.1	3.6	153.5
	CVDW	878	1276	<1.0	<0.1	<0.2	26.2	51.8	71.5	6.0	89.0	43.7
Maturation	UW0	3312	4608	3.3	<0.1	<0.2	11.6	25.5	113.4	13.3	15.0	94.4
	CUW15	3970	5552	2.6	<0.1	<0.2	18.7	31.8	109.2	10.1	16.8	104.9
	CUW30	4798	6012	3.8	<0.1	<0.2	11.6	35.1	137.2	11.2	81.6	118.5

Table S4. Concentration of metals in the equilibrium solution of the compost samples

		Fe (mg/L)	Al (mg/L)	As (µg/L)	Cd (µg/L)	Co (mg/L)	Cr (mg/L)	Cu (mg/L)	Mn (mg/L)	Ni (mg/L)	Pb (mg/L)	Zn (mg/L)
Compost	CLW	7.00	0.19	57	<1	0.017	0.030	1.40	0.157	0.078	0.01	2.94
	CUW	1.09	0.29	54	1	<0.002	0.004	0.11	0.031	0.007	0.02	0.28
	CDDW	0.05	0.04	23	<1	<0.002	<0.004	0.02	0.003	<0.003	<0.01	0.03
	CSS	19.25	0.32	42	<1	<0.002	0.007	0.21	0.328	0.179	<0.01	0.54
Vermicompost	CVA	0.01	0.01	23	<1	<0.002	<0.004	0.03	0.48	<0.003	0.01	0.06
	CVDW	0.23	0.06	13	<1	<0.002	0.012	0.09	0.02	0.004	0.03	0.06
Maturation	UW0	1.22	0.10	42	<1	<0.002	<0.004	0.01	0.294	0.030	<0.01	0.02
	CUW15	0.93	0.14	36	<1	<0.002	0.004	0.03	0.060	0.012	<0.01	0.08
	CUW30	1.23	0.17	56	<1	<0.002	0.006	0.10	0.002	0.013	0.02	0.19

Table S5. Information derived from the UV-Visible spectroscopy for the DOM of the equilibrium solution of the compost simples.

	Compost				Vermicompost		Maturation		
	CLW	CUW	CDDW	CSS	CVA	CVDW	UW0	CUW15	CUW30
$\epsilon_{280} (L/(molC\ cm))$	266.9	279.5	402.3	146.0	306.3	291.0	75.5	166.2	237.0
% Aromaticity	20.1	20.7	26.9	14.0	22.1	21.3	10.5	15.0	18.6
Molecular mass	1555.0	1605.2	2095.2	1072.3	1712.1	1651.1	791.1	1153.0	1435.8

Table S6. Acid-base parameters of the HS-like extracts obtained by fitting equation 6 to the experimental data. Errors associated to the parameters are included.

	CLW				CUW				CDDW				CSS			
	FA		HA		FA		HA		FA		HA		FA		HA	
log K₁	3.84	<i>0.03</i>	4.92	<i>0.04</i>	3.99	<i>0.02</i>	4.70	<i>0.06</i>	3.82	<i>0.03</i>	4.44	<i>0.06</i>	4.57	<i>0.05</i>	5.17	<i>0.08</i>
M ₁ (mmol/g _{SH})	3.11	<i>0.05</i>	2.74	<i>0.03</i>	3.65	<i>0.05</i>	2.92	<i>0.18</i>	4.01	<i>0.09</i>	3.05	<i>0.10</i>	5.00	<i>0.13</i>	2.71	<i>0.06</i>
m ₁	0.36	<i>0.01</i>	0.32	<i><0.01</i>	0.47	<i>0.01</i>	0.46	<i>0.02</i>	0.41	<i>0.01</i>	0.38	<i>0.01</i>	0.37	<i>0.01</i>	0.25	<i>0.01</i>
log K₂	9.84	<i>0.12</i>	10.06	<i>0.13</i>	9.38	<i>0.15</i>	9.65	<i>0.24</i>	9.48	<i>0.29</i>	9.72	<i>0.28</i>	9.70	<i>0.18</i>	10.11	<i>0.22</i>
M ₂ (mmol/g _{SH})	1.47	<i>0.16</i>	1.20	<i>0.15</i>	1.46	<i>0.17</i>	1.82	<i>0.47</i>	1.24	<i>0.29</i>	1.37	<i>0.33</i>	2.57	<i>0.41</i>	0.99	<i>0.22</i>
m ₂	0.42	<i>0.04</i>	0.57	<i>0.05</i>	0.35	<i>0.04</i>	0.32	<i>0.08</i>	0.35	<i>0.08</i>	0.38	<i>0.08</i>	0.40	<i>0.06</i>	0.56	<i>0.09</i>
R ²	<i>0.9997</i>		<i>0.999</i>		<i>0.9999</i>		<i>0.9996</i>		<i>0.9998</i>		<i>0.9998</i>		<i>0.9998</i>		<i>0.9999</i>	
RMSE	<i>0.0144</i>		<i>0.0075</i>		<i>0.0094</i>		<i>0.0231</i>		<i>0.0150</i>		<i>0.0150</i>		<i>0.0231</i>		<i>0.0077</i>	
M_T (mmol/g _{SH})	4.58		3.95		5.11		4.74		5.25		4.42		7.57		3.70	

	CVA				CVDW			
	FA		HA		FA		HA	
log K₁	4.36	<i>0.01</i>	4.75	<i>0.03</i>	3.81	<i>0.01</i>	4.76	<i>0.02</i>
M ₁ (mmol/g _{SH})	3.20	<i>0.09</i>	2.57	<i>0.03</i>	4.19	<i>0.02</i>	2.56	<i>0.02</i>
m ₁	0.60	<i>0.01</i>	0.35	<i>0.01</i>	0.40	<i><0.01</i>	0.45	<i>0.01</i>
log K₂	9.06	<i>0.10</i>	10.04	<i>0.11</i>	9.87	<i>0.04</i>	9.91	<i>0.15</i>
M ₂ (mmol/g _{SH})	2.42	<i>0.23</i>	0.99	<i>0.11</i>	1.42	<i>0.05</i>	1.20	<i>0.14</i>
m ₂	0.31	<i>0.03</i>	0.58	<i>0.06</i>	0.48	<i>0.02</i>	0.52	<i>0.05</i>
R ²	<i>0.9999</i>		<i>0.9998</i>		<i>0.9999</i>		<i>0.9999</i>	
RMSE	<i>0.0140</i>		<i>0.0104</i>		<i>0.0088</i>		<i>0.0085</i>	
M_T (mmol/g _{SH})	5.63		3.56		5.61		3.75	

	UW0				CUW15				CUW30			
	FA		HA		FA		HA		FA		HA	
log K₁	4.24	<0.01	6.09	0.04	4.31	<0.01	5.30	0.03	4.11	<0.01	5.19	0.04
M ₁ (mmol/g _{SH})	2.36	0.09	2.20	0.05	3.39	0.03	2.34	0.05	3.63	0.02	2.71	0.07
m ₁	0.77	0.02	0.46	0.01	0.65	0.01	0.49	0.01	0.53	0.00	0.43	0.01
log K₂	8.38	0.05	10.17	0.32	9.11	0.08	9.86	0.23	9.52	0.07	9.93	0.36
M ₂ (mmol/g _{SH})	2.15	0.17	1.10	0.31	1.62	0.10	1.23	0.23	1.51	0.07	1.17	0.33
m ₂	0.26	0.02	0.52	0.10	0.31	0.02	0.45	0.07	0.37	0.02	0.44	0.10
<i>R</i> ²	0.9999		0.9999		1.0000		0.9999		1.0000		0.9999	
<i>RMSE</i>	0.0077		0.0089		0.0060		0.0106		0.0044		0.0118	
M_T (mmol/g _{SH})	4.51		3.30		5.00		3.57		5.14		3.88	

Tabla S7. Intrinsic acid-base parameters of the NICA-Donnan model for HS and HS-like extracts.

Code ^a	b	log K ₁	M ₁ ^c	m ₁	log K ₂	M ₂ ^c	m ₂	M _T ^c	Reference
Average FA ^b	0.62	2.96	3.61 (64.7%)	0.58	7.86	1.97 (35.3%)	0.36	5.58	This work
Generic FA	0.57	2.34	5.88 (76.0%)	0.38	8.60	1.86 (24.0%)	0.53	7.74	Milne et al. (2005) ^d
C118-FA	0.62	2.55	4.68 (65.0%)	0.55	6.96	2.52 (35.0%)	0.20	7.20	Plaza et al. (2005) ^d
CS-FA	0.69	3.29	4.97 (72.8%)	0.62	8.51	1.86 (27.2%)	0.61	6.83	Fernández et al. (2007) ^d
Compost FA	0.75	2.74	6.02 (89.5%)	0.50	7.00	0.71 (10.5%)	0.91	6.73	van Zomeren et al. (2009) ^d
Average HA ^b	0.46	3.49	2.6 (65.5%)	0.47	8.21	1.38 (34.5%)	0.48	4.00	This work
Generic HA	0.49	2.93	3.15 (55.3%)	0.50	8.00	2.55 (44.7%)	0.26	5.70	Milne et al. (2005) ^d
C118-HA	0.46	2.80	3.63 (66.0%)	0.43	7.15	1.87 (34.0%)	0.20	5.50	Plaza et al. (2005) ^d
CS-HA	0.61	3.43	2.67 (61.7%)	0.66	8.05	1.66 (38.3%)	0.43	4.33	Fernández et al. (2007) ^d
Compost HA	0.75	4.29	2.43 (69.0%)	0.53	7.38	0.93 (31.0%)	0.79	3.36	van Zomeren et al. (2009) ^d
MSWC HA	0.60	3.33	2.57 (55.3%)	0.65	8.50	2.08 (44.7%)	0.48	4.65	Pedra et al. (2008) ^d

^aThe code used in this table is the same that appears in the original paper

^bAverage FA or HA refers to average values obtained for the HS-like from the different compost samples used in the present paper

^cThe abundance of carboxylic, phenolic and total acid groups is expressed in mmol/g_{HS}

^dMilne et al. (Environ. Sci. Technol., 2001, 35, 2049-2059); Plaza et al. (Environ. Sci. Technol., 2005, 39, 7141-7146); Fernández et al. (Chemosphere, 2007, 69, 630-635); van Zomeren et al. (Environ. Sci. Technol., 2009, 43, 1393-1399); Pedra et al. (Bioresour. Technol., 2008, 99, 2141-2147)

Tabla S8. Effect of compost application on the exchangeable cations of the amended soil

	Ca (cmol(+)/kg)	Mg (cmol(+)/kg)	Na (cmol(+)/kg)	K (cmol(+)/kg)	CEC (cmol(+)/kg)
<i>Ch2 (Control)</i>	0.45	0.71	0.01	0.45	1.27
<i>Ch2 + 2%CLW</i>	6.82	2.18	1.44	1.84	12.3
<i>Ch2 + 5%CLW</i>	10.87	4.73	4.96	6.49	27.1
<i>Ch2 + 10%CLW</i>	12.34	8.01*	6.40*	10.53*	37.3*
<i>Ch2 + 2%CUW</i>	3.15	0.00	0.46	0.76	4.4
<i>Ch2 + 5%CUW</i>	9.83	1.34	0.99	1.01	13.2
<i>Ch2 + 10%CUW</i>	13.41*	1.89	2.10	2.58	20.0
<i>Ch2 + 2%CSS</i>	1.45	0.99	0.20	0.19	2.8
<i>Ch2 + 5%CSS</i>	3.92	1.78	0.64	0.39	6.7
<i>Ch2 + 10%CSS</i>	6.40	2.58	1.24	0.60	10.8
<i>Ch2 + 2%CVA</i>	3.69	1.83	0.63	0.00	6.2
<i>Ch2 + 5%CVA</i>	5.78	2.73	1.16	1.87	11.5
<i>Ch2 + 10%CVA</i>	9.07	5.80	3.08	5.43	23.4
<i>Ch2 + 2%CDDW</i>	8.65	1.62	0.45	1.39	12.1
<i>Ch2 + 5%CDDW</i>	9.58	2.63	0.84	3.09	16.1
<i>Ch2 + 10%CDDW</i>	11.03	4.37	1.44	5.49	22.3

*Indicates the case with the higher increase in the corresponding parameter after the amendment application

CRedit authorship contribution statement

Rocío López: Conceptualization, methodology, investigation, formal analysis, data curation, writing – original draft.

Juan Antelo: Methodology, investigation, data curation, writing – review & editing.

Ana Catarina Silva: Methodology, investigation, data curation, writing – review & editing.

Fátima Bento: Conceptualization, funding acquisition, resources, validation, writing – review & editing.

Sarah Fiol: Methodology, funding acquisition, resources, project administration, writing – review & editing.