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# Valorization of Quality of Vermicomposts and Composts Using Various Parameters

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**Abstract:** Due to the increasing biomass of biowaste it is necessary to manage it rationally. This work presents comparisons and valorization of vermicomposts (VCs) and composts (Cs) prepared from various biowastes generated in households and private gardens, in terms of their practical use. The tested VCs and Cs were subjected to chemical analyses to assess the amounts of macro- (N, P, K, S, Mg, Ca, Na) and micronutrients (Fe, Zn, Mn, Cu, Ni), as well as contents of organic matter (OM), total organic carbon (TOC), humic compounds (HS) and labile and water extractable organic carbon (LC, WEOC). Moreover, humification indexes (HR, HI, DP) were determined. The amounts of macro- and micronutrients, OM, TOC, LC, WEOC were greater for vermicomposts. Regardless of these differences, both vermicomposts and composts were characterized by considerable amounts of organic matter ranging from 325 to 631 $g\cdot kg^{-1}$ and TOC amounting from 82 to 270 $g\cdot kg^{-1}$. Moreover, the tested organic fertilizers were characterized by high contents of N (7–21.5 $g\cdot kg^{-1}$), K (3.7–24.4 $g\cdot kg^{-1}$), Ca (12.2–44.0 $g\cdot kg^{-1}$), Fe (133.1–333.8 $mg\cdot kg^{-1}$) and Mn (71.5–113.8 $mg\cdot kg^{-1}$). The analyzed VCs and Cs did not exceed the permissible amounts of heavy metals (Cr, Pb) and contained a comparable amount and quality of humus compounds. The level of $C_{HS}$ ranged from 29.6 to 41 $g\cdot kg^{-1}$ for vermicomposts, and from 19.8 to 51.8 $g\cdot kg^{-1}$ for composts. The humification indexes indicate that VCs and Cs were well–matured despite different composting conditions. The HI values for VCs ranged from 8.3% to 10% and for Cs amounted from 12.2% to 16.8%. Similarly, the HR values were higher for composts (24.3–33%) in comparison to VCs (15.2–20.1%). Vermicomposting and composting of biowaste is economically and environmentally justified. Fertilizers obtained in the composting process are a valuable source of organic material and nutrients essential for plants and can be safely used in private gardens.

**Keywords:** agriculture; biowastes; heavy metals; humic compounds; humification indexes; macro- and micronutrients



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## 1. Introduction

Biowastes are a group of municipal wastes, whose mass has recently increased significantly. The prevailing pandemic situation following the COVID-19 outbreak favors such a trend, which was confirmed by numerous authors [1–3]. According to the cited authors, the mass of generated biowastes has increased by 20%, while even a 1.5-fold increase in the mass was noted in some areas. The reasons include primarily the increased consumption and the shopping panic accompanying the imposed lockdown and the resulting fear of problems with the supply of food products. First of all, some products were excessively accumulated, often being perishable food products with a short shelf life, which have not been fully used and constituted a source of food waste, followed by an additional mass of biowaste [2]. Jribi et al. [4] reported that this type of biowaste comprises mainly vegetables, fruit and cereal products, which were either inappropriately stored or were inadequately prepared and had to be disposed of. This mass differing in chemical composition, and hence value, constitutes a valuable material for composting.

Stenmarck et al. [5] reported that 8% of the world's food waste production is destined for home composting, which is about 7.4 kg per capita, per year. However, the group of biowastes also includes biodegradable waste from the maintenance of green areas in cities and private gardens. According to various sources [5–7], biowaste accounts for 30–50% of the total mass of generated municipal wastes. In most countries biowaste is collected selectively, although it is not a rule [8]. Nevertheless, these wastes need to be properly managed in order to reduce their possible negative impact on the environment. Biowaste composting is a popular and cheap solution, in line with the circular economy concept. This process is carried out commercially by appropriate installations; however, as emphasized by Vazquez and Soto [9], home composting complements biodegradable waste management. Moreover, as shown by the local community survey conducted by Jakubus and Michalak-Oparowska [10], home composting of biowaste is gaining popularity and is generally considered acceptable. Vazquez and Soto [9] indicated that recycling of 50% of generated biodegradable waste in domestic composters decreases waste treatment and transportation costs from 34% up to 50%, while simultaneously reducing greenhouse gas emissions by 40% compared to standard landfilling.

Currently, vermitechnology is gaining interest as a method of sustainable and proper biowaste utilization [11–14]. Singh et al. [13] stated that vermicomposting is a technique of biowaste management with the effective support of earthworms. Numerous authors [13,15,16] emphasize the many advantages of vermicompost and its use for agriculture and horticulture. Vermicomposts improve soil health, microbial activity, limit diseases caused by soil-borne pathogenic organisms, as well as stimulate plant growth by changing the physical, chemical and biological properties of the soil. Similar advantages come from the use of traditionally prepared composts [17,18]. However, differences in the quality of the prepared vermicomposts and composts should be considered. This could result from the different biowastes used and the different conditions of the applied process. The standard assessment of organic fertilizer quality is based on the amount of organic matter and N, P and K contents, in view of the fertilizing function of these substances. However, apart from these parameters, it is also reasonable to assess the amount of micronutrients, the content of heavy metals, as well as the quantity and quality of humus compounds. Since organic fertilizers such as vermicomposts and composts are characterized by a considerable amount of organic matter and carbon is present in various combinations, it is important to analyze this aspect in detail. The knowledge on the stability of the carbon compounds in organic matter of vermicomposts and composts is significant from the point of view of their influence on soil fertility [17]. In relation to this, the special role of fulvic and humic acids, as well as labile and water extractable carbon, must be indicated due to their different susceptibilities to solubility and biochemical and microbiological transformations [19,20]. The literature on the evaluation of vermicomposts or composts ignores this aspect, instead focusing on the general characteristics of these organic fertilizers.

In view of the above, the purpose of this study was to present a detailed assessment of vermicomposts and composts in terms of their abundance in macro- and micronutrients and the quantity and quality of humic compounds. Additionally, the amounts of selected heavy metals, as well as easily mineralizable organic carbon forms, were evaluated. Obtained results will facilitate comprehensive valorization of vermicomposts and composts in terms of their quality and compare their practical usability.

## 2. Materials and Methods

### *2.1. Composting Procedure and Raw Materials*

The aim of the research was achieved on the basis of six different organic material samples (vermicomposts and composts) prepared from selectively collected biowastes. The authors of the study had neither access to raw materials nor influence on the quantity, quality and frequency of deposited wastes for vermicomposting and composting processes. The vermicomposts (VCs) and composts (Cs) were not commercially produced, but only constituted a method of rational management of biomass generated in the household and garden. The following wastes were used for their preparation: food and kitchen wastes from households (VC 1–3); biowastes from the garden: yard trimmings such as plant residues and mowed grass clippings (C4, 6); mixed food and kitchen wastes from households and biowastes from the garden (C5). According to the list of waste referred to Article 7 of Directive 2008/98/EC [21], used wastes belong to the same group of municipal wastes, code 20.

Vermicomposts 1, 2 and 3 were prepared by the vermicomposting process in vermicomposters (Vermitutt Worm Bin). Due to the fact that there are no official recommendations as to the preferred composter and there is a large range of these devices on sale, the operation of the one given in this paper was approximated. The vermicomposter is divided into four partitions (boxes), stacked one above another, with a volume of 15 L each. This design allows for a continuous addition of biowaste and gradual removal of the compost without the need of mixing. A mixture of apple pomace with earthworms (*Eisenia fetida)* was used as an initial input material for the vermicomposting process. The biowaste for the vermicomposter was delivered with a varying frequency and in different amounts, which depended on the activity of the household. Individual boxes were filled within six months. The leachate of composted biowastes was collected in the lowest part of vermicomposter and subsequently it was discharged via a drain valve. The vermicomposting process was carried out at room temperature (±23 °C) and with constant moisture of the mass (±60%).

Composts 4, 5 and 6 were prepared by the aerobic method as a fertilizer for their home gardens by private homeowners. The composting process was carried out in home composters made of thermoplastic. The temperature of the composting process depended on the weather conditions, while the moisture of the composted mass was kept at a similar level (±60%). The organic material (bigger particles were chopped into smaller ones, maximum size of 15–40 mm) was successively collected in containers without any mixing of the bulk volume. This contributed to lesser oxygenation of the mixture inside the composter compared to its top layer. Under such conditions the organic waste mixture was kept for a year. After this time, the whole mass was mixed to homogenize it and then transferred to dark plastic bags to complete the maturation stage.

The vermicompost samples were collected from individual boxes of the vermicomposter and the bulk samples represented approximately 80–100% of the total box volume. The compost samples were collected from the bags after their contents had been mixed. The samples of organic materials were dried at 105 °C for a period of 12 h. The dried samples were ground into a fine powder and stored in plastic bags at a temperature of 4 °C.

### 2.2. Chemical Analysis of the Compost

The chemical analyses were conducted on dried samples. The reaction (pH) and electrolytic conductivity (EC) of the tested materials were determined in an aqueous solution at a ratio of 1:10. Total organic carbon (TOC), nitrogen (N) and sulfur (S) contents in VCs and Cs were assayed using a Vario Max CNS elemental analyzer. On the basis of TOC and N total amounts the C:N ratio was calculated following equation: C:N = $\frac{TOC}{Ntot}$. The loss-on-ignition method was used to determine organic matter (OM) of vermicomposts and composts. For this purpose samples were subjected to dry combustion for 6 h at a temperature of 550 °C. The ash of VCs and Cs after combustion was used to determine the total amounts of macro- and micronutrients as well as heavy metals. Thus the ash was dissolved in 5 mL of 6 mol·$dm^3$ HCl and diluted to a constant volume with distilled water. In the obtained extracts K, Ca, Mg and Na assessment was performed using atomic absorption spectrophotometry, while total phosphorus (P) content was measured colorimetrically by the vanadium–molybdenum method [22]. The determinations of microelements and heavy metals were performed in the same solutions that were used to determine macronutrients. The micronutrients (Fe, Mn, Zn, Cu, Ni) and heavy metals (Pb, Cr) were evaluated using atomic absorption spectrophotometry with a Varian Spectra AA 220 FS apparatus.

Humus fractionation of VCs and Cs was performed according to the method proposed by Kononova and Bielczikova, in which humic substances (HS) were determined in a mixture of 0.1 mol·dm$^{-3}$ $Na_4P_2O_7$ + 0.1 mol·dm$^{-3}$ NaOH solution [23]. The fulvic acid fraction (FA) was separated after precipitation of humic acids at pH 1.5 (HA). Carbon in the obtained fractions ($C_{HS}$ and $C_{FA}$) was oxidized by 0.1 mol·dm$^{-3}$ $KMnO_4$ in the $H_2SO_4$ medium. Humic acid carbon ($C_{HA}$) was calculated by subtracting $C_{FA}$ from $C_{HS}$. Optical density ($Q_{4/6}$) of the humic substances was determined at 465 nm and 665 nm. Additionally, the samples were used to analyze labile and water extractable organic carbon. The labile carbon (LC) was assessed by $KMnO_4$ oxidation [24], while water extractable organic carbon (WEOC) was determined according to the method presented by Ghani et al. [25] with the final determination of organic carbon by wet combustion [26].

Additionally, three popular indexes, i.e., the humification ratio (HR), humification index (HI) and the degree of polymerisation (DP), were used in this study. The humification indexes were calculated using the following equations [27]:

$$\text{HR}\ (\%) = \frac{CHS}{TOC} \cdot 100 \quad (1)$$

$$\text{HI}\ (\%) = \frac{CHA}{TOC} \cdot 100 \quad (2)$$

$$\text{DP} = \frac{CHA}{CFA} \quad (3)$$

### *2.3. Statistical Analysis*

The data presented in the paper are means of three replications. The data were compiled applying one–way ANOVA. Each of the sixteen parameters was tested independently using the F-test at the significance level $\alpha$ = 0.95. The null hypothesis assumption was that the mean values of the examined parameter are equal for each of the analyzed vermicomposts and composts against the alternative hypothesis that not all the means are equal. As a result of the rejection of the null hypothesis the least significant differences were calculated using the Tukey test at the significance level $\alpha$= 0.05. Tukey's analysis was performed to distinguish homogeneous groups among the analyzed vermicomposts and composts. In addition, Person's correlation coefficients were calculated for the analyzed parameters. Moreover, for pairs $(x, y)$ of correlated parameters estimates of simple regressions of the form can be determined (regression model): $y = \beta_0 + \beta_1 x$, where the regression parameter $\beta_1$ shall be interpreted as follows: if parameter $x$ increases by one unit, parameter $y$ increases (decreases) by $\beta_1$ units. The data were analyzed using the STATOBL software working in the Windows environment.

## 3. Results and Discussion

The basic assumption of biowaste composting is the possibility of reusing organic matter and nutrients contained in it. This approach to the production of biomass is consistent with the concept of circular economy and it is the most rational method of biowaste management [8,18,28]. Considering the final use of compost or vermicompost for agricultural or horticultural purposes, their quality is of greater importance, including the abundance of organic matter and the essential nutrients. Additionally, selected physicochemical properties of organic materials, such as reaction and electrolytic conductivity, are also significant. Reaction is a key factor in determining the transformation of organic compounds and the availability of nutrients for plants. Therefore, it is also important to analyze this parameter in the vermicomposts and composts. In the tested VCs 1–3 the pH values ranged from 7.9 to 8.4, while in Cs 4–6 from 6.5 to 7.2 (Table 1). Regardless of the biowaste composting method, the EC values were comparable to the level of 3.1 to 3.7 mS·cm$^{-1}$ (Table 1). Singh et al. [13] gave similar ranges of pH and EC values for various vermicomposts. Moreover, these authors citing Wong et al. [29] reported that VCs with an EC below 4 mS·cm$^{-1}$ is appropriate to be used as fertilizer for plant growth. Sciubba et al. [30] presented similar values of pH and EC for various composts, while Ibrahim et al. [31] reported higher EC values.

**Table 1.** The values of pH and EC of analyzed vermicomposts and composts.

| Parameter | VC1 | VC2 | VC3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|
| pH | 7.9 | 8.4 | 8.3 | 7.2 | 6.8 | 6.5 |
| EC (mS·cm$^{-1}$) | 3.5 | 3.6 | 3.7 | 3.3 | 3.7 | 3.1 |

In Poland, VCs and Cs dedicated to agricultural use have to meet specific threshold amounts of N, P, K, organic matter and heavy metals [32]. According to the above-mentioned Regulation, the content of OM must be at least 30% d.m., the amount of potassium ($K_2O$) and phosphorus ($P_2O_5$) should be more than 0.2% d.m., while the total N value should be min. 0.3% d.m. The limit value of organic matter at 31.5% for composts was indicated by Vazquez and Soto [9].

Comparing the above-mentioned threshold values of OM with those obtained in this study, only C5 failed to meet the requirement for OM because for this compost a 150 g·kg$^{-1}$ of OM was recorded. For VCs 1–3 the organic matter contents were considerably higher and amounted from 456 to 631 g·kg$^{-1}$, while C4 and C6 contained 325 and 407 g·kg$^{-1}$, respectively (Figure 1). Consequently, the vermicomposts were characterized by higher TOC contents ranging from 150 to 270 g·kg$^{-1}$ than composts 4–6 (82 to 163 g·kg$^{-1}$) (Figure 1). Similar TOC contents for VC were reported by Singh et al. [13] and Ramnarain et al. [33]. For composts, Jakubus [17], Sciubba et al. [30] and Ibrahim et al. [31] found comparable amounts of TOC to those presented in this study. Significantly higher amounts (2- to 3-fold greater) of OM and TOC were indicated by Yu et al. [34] for compost, but in this case the analyzed compost was prepared on the basis of cow manure, which may explain such a difference.

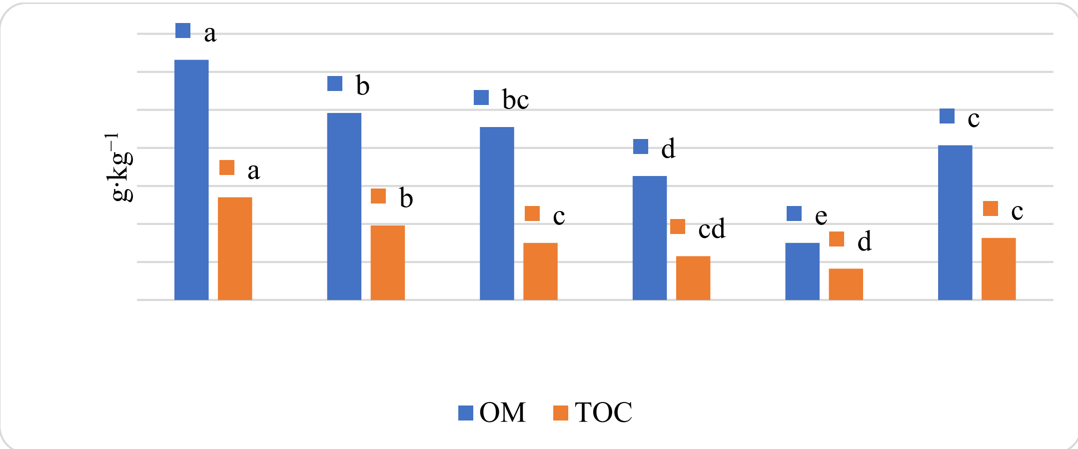


**Figure 1.** Contents of organic matter (OM) and total organic carbon (TOC) in analyzed vermicomposts and composts (the same lowercase letters indicate homogeneous groups of VCs and Cs).

Compost introduced into the soil first of all provides a significant amount of organic matter; however, it needs to be remembered that not only the amount but also the quality of the applied organic matter is very important. Therefore, apart from the basic determination of the OM and TOC contents, it is necessary to analyze the quantity and quality of humic compounds and easily mineralized carbon compounds. Especially the latter compounds directly affect the rate and direction of changes of native and introduced carbon in the soil, creating soil fertility. The changes of water extractable organic compounds can reflect the transformation degree of organic matter and the stability of materials during the composting process [34]. The authors [24,29,34,35] emphasized the importance of WEOC transformations. They considered WEOC as a component of the labile and the most active fraction of organic waste. It is a sensitive measure of subtle changes in organic matter, and it could directly reflect the organic matter transformation process. Consequently, the composition of WEOC was suggested as a better indicator of stability for the OM. In view of the above, the analyzed VCs and Cs were characterized in the terms of labile carbon and water extracted organic carbon. Again, vermicomposts were characterized by a higher content of easily mineralized carbon compounds (LC and WEOC) than composts. As shown by the data in Figure 2, the amounts of LC ranged from 0.94 to 1.02 g·kg$^{-1}$ and WEOC from 6.08 to 7.32 g·kg$^{-1}$ for VC 1–3, while for Cs 4–6 it was from 0.23 to 0.58 g·kg$^{-1}$ LC and from 1.9 to 4.43 g·kg$^{-1}$ for WEOC. On this basis it can be assumed that after introducing VCs into the soil, they will accelerate the mineralization processes, becoming a source of both easily activated nutrients for plants and a source of energy for microorganisms.

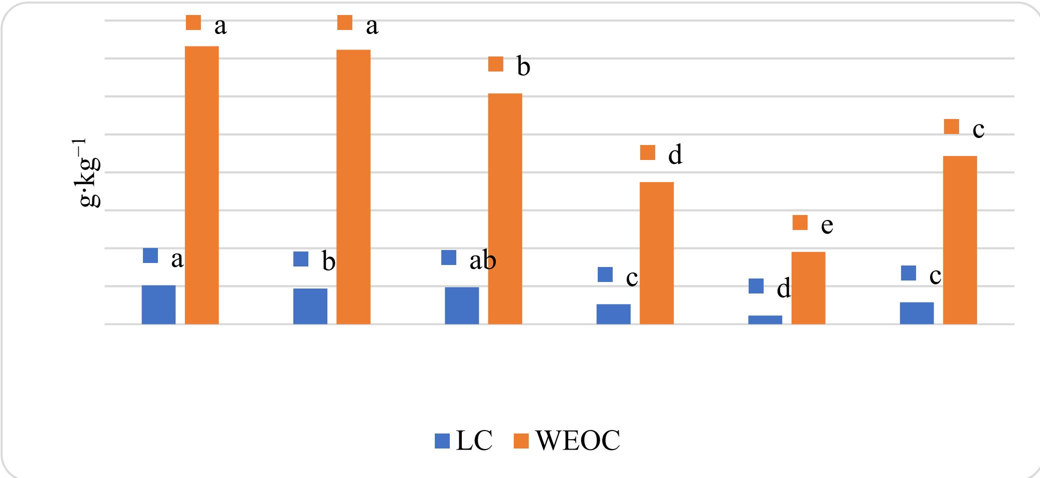


**Figure 2.** Contents of labile carbon (LC) and water extractable organic carbon (WEOC) in analyzed vermicomposts and composts (the same lowercase letters indicate homogeneous groups of VCs and Cs).

A detailed quality analysis of VCs and Cs should also include the humic compounds strongly determining chemical properties of organic fertilizers. Humic substances are the result of the humification process of organic compounds, which may proceed at different rates depending on the environmental conditions. Humic substances mainly consist of fulvic and humic acids, wherein HAs have a more complex structure than FAs. Fulvic acids are compounds weakly polymerized and relatively readily undergoing chemical and microbiological changes, which results in their considerable solubility and mobility. In turn, HAs are generally recognized as being non-degradable or sparsely degradable compounds with a strongly polymerized structure [34,36]. Generally immature composts contain a high FA content and a relatively low HA content, while HA dominates in mature composts [36].

In the present study, the vermicomposting and composting process differed significantly in terms of the prevailing conditions (outdoor, indoor, addition of earthworms vs. no such addition, various biowastes, duration of the process). However, regardless of the above, the tested materials had comparable quantitative levels of humic substances. The amount of $C_{HS}$ ranged from 29.6 to 41 g·kg$^{-1}$ for the vermicomposts, and from 19.8 to 51.8 g·kg$^{-1}$ for the composts (Figure 3). The amounts of $C_{FA}$ and $C_{HA}$ for the individual organic materials were comparable, without being significantly different. The $C_{FAs}$ amounts of VCs 1–3 ranged from 15.2 to 19.8 g·kg$^{-1}$, and for Cs 4–6 it was from 9.9 to 26.6 g·kg$^{-1}$. On the other hand, the $C_{HAs}$ ranged from 14.4 to 22.4 g·kg$^{-1}$ and from 9.9 to 25.2 g·kg$^{-1}$ for VCs 1–3 and Cs 4–6, respectively (Figure 3).

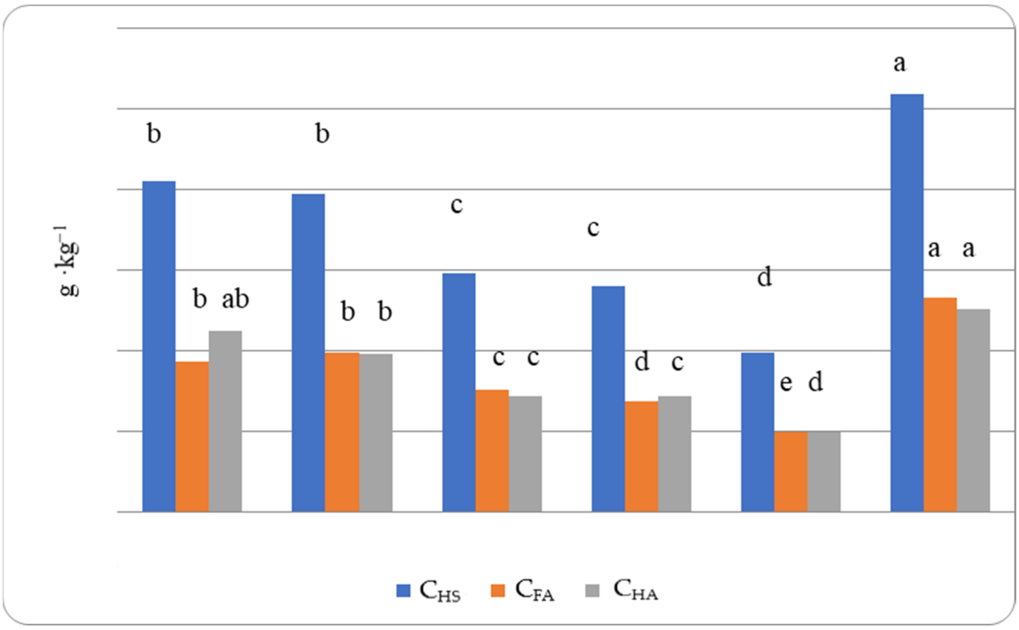


**Figure 3.** Contents of humic substance ($C_{HS}$), fulvic acids ($C_{FA}$) and humic acids ($C_{HA}$) in analyzed vermicomposts and composts (the same lowercase letters indicate homogeneous groups of VCs and Cs).

When assessing the quality of the vermicomposts and composts the evaluation of their stability and maturity is also essential. This is an extremely important element of composting because an unstable and immature organic material may have adverse effects on plant growth and the environment. First of all, the presence of volatile chemicals, such as organic acids toxic for plants, must be underlined. Additionally, an incompletely matured compost with a higher C:N ratio can lead to a biological block of nitrogen, also known as "nitrogen starvation" [37]. There is also disagreement among various authors in relation to the specific limit value of C:N. According to Chen et al. [38], Gomez-Brandon et al. [39] and Singh et al. [40] the C:N ratio for the finished compost should range from 10:1 to 15:1. Similar conclusions in their own research were shown by Vazquez and Soto [9], who proved that C:N for mature composts should be 9–16:1. However, Antil et al. [41] stated that the C:N ratio in composts should range from 15:1 up to 20:1. Additionally, Asquer et al. [42] indicated that the C:N ratio needs to be lower than 20:1. Taking into consideration a broad range of the C:N ratio at 9–20:1 as the criterion, only the analyzed VC3 failed to meet this threshold (Table 2). Jakubus [17] and Sciubba et al. [30] indicated similar values of the C:N ratio in composts, while Ibrahim et al. [31] showed a higher value (18:1) of the discussed parameter. For vermicomposts, Balachandar et al. [43] indicated higher values of C:N (16.56–17.55) than those in the presented study.

**Table 2.** The C:N ratio and humification indexes obtained for analyzed vermicomposts and composts.

| Compost | HI (%) | HR (%) | DP ($C_{HA}$:$C_{FA}$ Ratio) | $Q_{4/6}$ | C:N |
|---|---|---|---|---|---|
| VC1 | 8.3 | 15.2 | 1.2 | 8.1 | 17:1 |
| VC2 | 10.0 | 20.1 | 1.0 | 8.1 | 9:1 |
| VC3 | 9.6 | 19.7 | 1.0 | 7.7 | 8:1 |
| C4 | 16.8 | 33.0 | 1.0 | 6.6 | 9:1 |
| C5 | 12.2 | 24.3 | 1.0 | 7.2 | 12:1 |
| C6 | 15.5 | 31.8 | 1.0 | 7.1 | 9:1 |

Vermicomposts and composts produced from similar raw organic materials should be assessed by various humification indexes, especially when their maturity is considered. According to Li et al. [36], the humified fraction of OM is the most important and responsible for fertility functions. Thus, evaluation of the humification degree is an agronomic criterion for compost quality. In practice, HR, HI and DP are generally accepted and helpful in compost maturity evaluation. Table 2 contains values of the other parameters enabling the assessment of VCs and Cs in terms of their maturity. It is assumed that mature composts should have an HI value above 30% [44]. For such a criterion being adopted here, none of the analyzed organic fertilizers reached this value because, as indicated in Table 2, HI values ranged from 8.3% (VC1) to 16.8% (C4). For vermicompost No. 1 and compost No. 4 the lowest (15.2%) and the highest (33.0%) HR values were determined (Table 2). However, there is no limit HR value specified in the literature, which could be helpful in assessing compost maturity. Nevertheless, results presented by various authors showed similar values of HR and HI for composts [17,42,45] and they are comparable with those given in this study. The polymerization degree (PD) expressed as the $C_{HA}$:$C_{FA}$ ratio is widely used to describe the relative speed of the HA and FA transformation, as well as the maturity of the compost. Azim et al. [37], on the basis of a literature review, stated that the correct threshold value of PD needs to be greater than one and simultaneously, according to Alavarenga et al. [46], not higher than 2.5. Taking into account this threshold it may be assumed that all the analyzed VCs and Cs were well-matured because the values obtained for them ranged from 1.0 to 1.2 (Table 2).

The $Q_{4/6}$ ratio is negatively related to the aromatic polycondensation degree and molecular weight of humic substances. High $Q_{4/6}$ values imply the presence of low molecular weight aromatic molecules, which in contrast to $Q_{4/6}$ low values indicate high contents of large molecular weight molecules, such as humic-like compounds, usually present in well-matured organic materials [46]. In the present study, the analyzed vermicomposts and composts also showed comparable values of optical density expressed as $Q_{4/6}$, which range from 6.6 (C4) to 8.1 (VC1 and 2) (Table 2). Similar values of the discussed parameter were showed by Lv et al. [19]. In turn, Ozdemir et al. [28] reported the value range of optical density from 3.23 to 8.8 to be adequate for compost maturation. Based on this statement, the VCs and Cs analyzed in this study were well maturated.

When assessing the macronutrient abundance of the vermicomposts and composts it should be emphasized that their amounts in the vermicomposts are significantly greater than in the composts. Moreover, the amounts of macronutrients generally did not differ significantly between the VCs and Cs (Table 3). As previously mentioned, according to Polish law, VCs and Cs must meet specific requirements for NPK content. As results from the data in Table 3, the amounts of N ranged from 7 to 17.6 $g \cdot kg^{-1}$ for C4–6 and from 16.1 to 21.5 $g \cdot kg^{-1}$ for VCs, which significantly exceeds the minimum limit specified in the above-mentioned documents. Similar N amounts in vermicomposts were indicated by Singh et al. [13] and Ramnarain et al. [33]. Additionally, a similar range of N values in composts can be found in the literature data [17,31,37]. Higher N amounts were shown by Sciubba et al. [30] and Yu et al. [34].

**Table 3.** Macronutrient total amounts in analyzed vermicomposts and composts ($g \cdot kg^{-1}$).

| Macronutrient | VC1 | VC2 | VC3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|
| N | 16.1 c | 21.5 a | 18.4 b | 10.0 d | 7.00 e | 17.6 bc |
| P | 4.1 c | 6.0 a | 5.8 a | 1.2 d | 5.9 b | 4.8 b |
| K | 18.0 b | 24.4 a | 17.2 b | 4.5 c | 3.7 c | 5.5 c |
| S | 4.60 a | 4.6 a | 3.5 b | 2.7 c | 1.4 d | 2.9 c |
| Ca | 20.6 c | 34.1 b | 44.0 a | 13.4 d | 12.2 d | 12.3 d |
| Mg | 4.1 c | 8.7 b | 13.5 a | 1.7 d | 1.4 d | 1.6 d |
| Na | 1.6 b | 2.1 a | 1.5 b | 0.9 c | 1.4 b | 0.9 c |

The same lowercase letters indicate homogeneous groups of VCs and Cs.

In comparison to the Regulation of the Minister of Agriculture and Rural Development [32], the obtained amounts of P and K (Table 3) were considerably higher, especially for VCs. The contents of P and K in VCs 1–3 ranged from 4.1 to 5.8 $g \cdot kg^{-1}$ and from

17.2 to 24.4 g·kg$^{-1}$, respectively. Cs 4–6 presented lower amounts amounting from 1.2 up to 5.9 g·kg$^{-1}$ of P and from 3.7 to 5.5 g·kg$^{-1}$ for K. Singh et al. [13] for vermicomposts, which showed significantly higher (4–5 times) amounts of P and comparable K. On the other hand, the composts tested by Jakubus [17] had a lower quantitative level of P and a higher levels of K.

Considerably higher contents of P and K in composts were reported by Sciubba et al. [30], Ibrahim et al. [31] and Yu et al. [34]. For plant development, other macronutrients such as S, Ca, Mg and Na are also important, but they are not subject to routine and mandatory verification and are often ignored in scientific research when valorizing VCs and Cs. Jakubus [17], when analyzing the fertilization quality of various composts, found a similar level of Mg and definitely lower contents of Ca, Na and S compared to the data obtained in this study. Particular attention in this context needs to be paid to 8-fold higher amounts of sulfur given by the cited author (Table 3).

Vermicomposts and composts, apart from macronutrients, are also rich in micronutrients. Micronutrients are taken up in smaller amounts than the previously characterized macronutrients; however, they play important functions in most physiological and biochemical processes [47]. Generally, vermicomposts contained higher amounts of Ni, Cu and Fe and lower levels of Zn and Mn in relation to the contents specified in the composts (Table 4). Regardless of the above, the amounts of micronutrients found in the vermicomposts in this study were significantly lower than those reported by Ramnarain et al. [33]. Compared to the values given in this study, Jakubus [17], Ibrahim et al. [31] and Rodrigues et al. [48] indicated greater amounts of micronutrients in the composts prepared on the basis of various biowastes. When valorizing the quality of vermicomposts or composts, we must take into account the fact that they may be loaded with heavy metals. The group of heavy metals includes many elements, which are both micronutrients necessary for plants, such as Cu, Zn, Mn, Ni, and toxic ones, such as Pb or Cr. Taking into account the negative impact of heavy metals on the soil environment and their easy incorporation into the food chain, vermicomposts and composts must meet the criteria for the content of heavy metals. According to the Regulation of the Minister of Agriculture and Rural Development on 18 June 2008 [32], vermicompost or compost cannot exceed, among other things, 100 mg·kg$^{-1}$ Cr, 60 mg·kg$^{-1}$ Ni and 140 mg·kg$^{-1}$ Pb. The EU guidelines [49] in this regard are more restrictive because the amount of Ni in composts cannot be higher than 20 mg·kg$^{-1}$, Pb higher than 45 mg·kg$^{-1}$, and Cr greater than 70 mg·kg$^{-1}$ d.m. Contents of these metals in the analyzed vermicomposts and composts showed that all of them meet the national and European standards, since the amounts of Ni, Pb and Cr were significantly lower (Table 4, Figure 4) in relation to the above-mentioned threshold values. The studies of Balachandar et al. [43] also indicated the amount of heavy metals in vermicomposts to be significantly below the permissible limits. Nevertheless, it should be noted that vermicomposts were generally characterized by higher amounts of Cr and Pb compared to those specified in the composts (Figure 4). For VCs 1–3, the Cr contents ranged from 8.8 to 19.2 mg·kg$^{-1}$ and for Pb from 4.9 to 12.1 mg·kg$^{-1}$. On the other hand, for Cs 4–6, the Cr amounts were significantly lower and ranged from 3.4 to 6.5 mg·kg$^{-1}$. Lead levels in composts vary significantly from 4.0 to 20.5 mg·kg$^{-1}$ (Figure 4). Jakubus [17], Ibrahim et al. [31] and Rodrigues et al. [48] gave significantly higher amounts of Cr, Pb and Ni for composts.

**Table 4.** Micronutrient total amounts in analyzed vermicomposts and composts (mg·kg$^{-1}$).

| Micronutrient | VC1 | VC2 | VC3 | C4 | C5 | C6 |
|---|---|---|---|---|---|---|
| Cu | 13.3 bc | 18.4 a | 16.4 ab | 9.4 cd | 9.6 cd | 8.1 d |
| Zn | 3.0 d | 5.4 b | 4.3 c | 8.8 a | 6.1 b | 4.3 c |
| Mn | 71.5 c | 102.5 ab | 85.1 bc | 93.1 b | 113.8 a | 99.5 ab |
| Ni | 4.0 bc | 6.4 a | 5.3 ab | 5.8 ab | 3.0 c | 2.9 c |
| Fe | 188.5 c | 333.8 a | 273.8 b | 214.3 c | 198.6 c | 133.1 d |

The same lowercase letters indicate homogeneous groups of VCs and Cs.

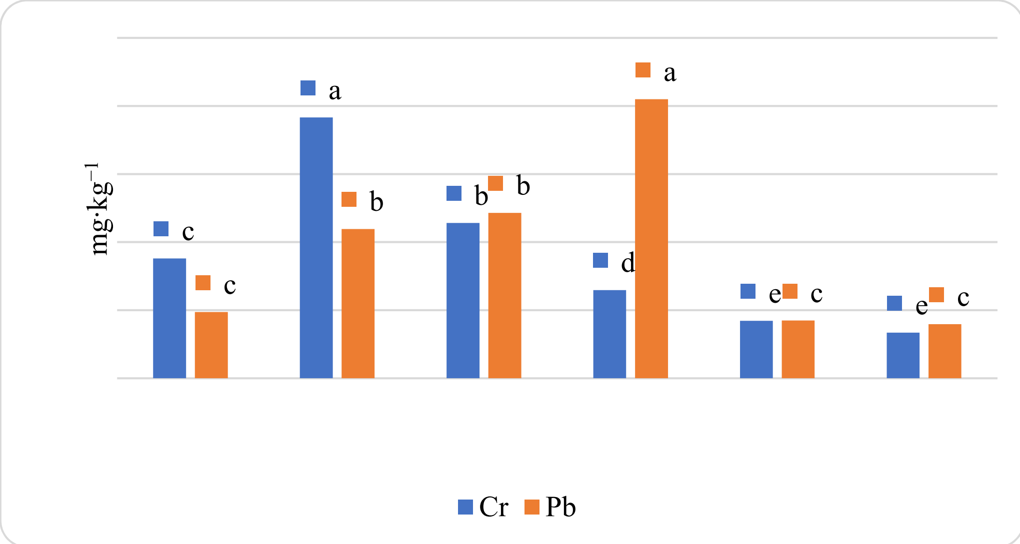


**Figure 4.** Heavy metal total contents (Cr, Pb) in analyzed vermicomposts and composts (the same lowercase letters indicate homogeneous groups of VCs and Cs).

The chemical composition of organic additives is important especially when they are used as fertilizers. In this case the potential transformations of organic compounds (organic matter, carbon, nitrogen, sulfur and phosphorus compounds) introduced into the soil with composts or vermicomposts are also important. Apart from the value of particular parameters, it is very interesting to see how these parameters interact with each other. Such mutual relationships can be evaluated based on the correlations between the analyzed parameters, an aspect which was also assessed in this study (see Supplementary Material, Tables S1 and S2). However, their correlations may be the same and fail to explain the interrelationships or state whether if the value of one of them increases, the other increases or decreases proportionally. Such information can be obtained from the linear regression model.

Regardless of the analyzed vermicomposts or composts, a strong influence of the organic matter and WEOC on other parameters was noted. In vermicomposts, the amount of OM positively influenced the content of TOC, $C_{SH}$, LC and WEOC, which was particularly noticeable in the case of TOC and $C_{SH}$. Together with an increase in OM by 1 g·kg$^{-1}$ the average amount of TOC or $C_{SH}$ can increase by 0.63 and 0.05 g·kg$^{-1}$ in vermicomposts, respectively (Figure 5). The increasing content of OM at the same time can strongly decrease the amount of P, Mg and Ca. The increment of OM by 1 g·kg$^{-1}$ can cause a reduction in the content of the above-mentioned nutrients by 0.12 (Ca), 0.05 (Mg) and by 0.02 (P) g·kg$^{-1}$ (Figure 6). The negative although slightly weaker interactions were noted between the amount of OM and metal contents: Zn, Ni, Cu, Fe and Pb (Table S1). In vermicomposts, an effect of WEOC content on the amounts of TOC, $C_{SH}$ and S was also found. According to the linear regression presented in Figure 7, at an WEOC increase by 1 g·kg$^{-1}$ TOC increased by 67.61 g·kg$^{-1}$, $C_{SH}$ by 8.02 g·kg$^{-1}$ and S by 0.84 g·kg$^{-1}$, respectively.

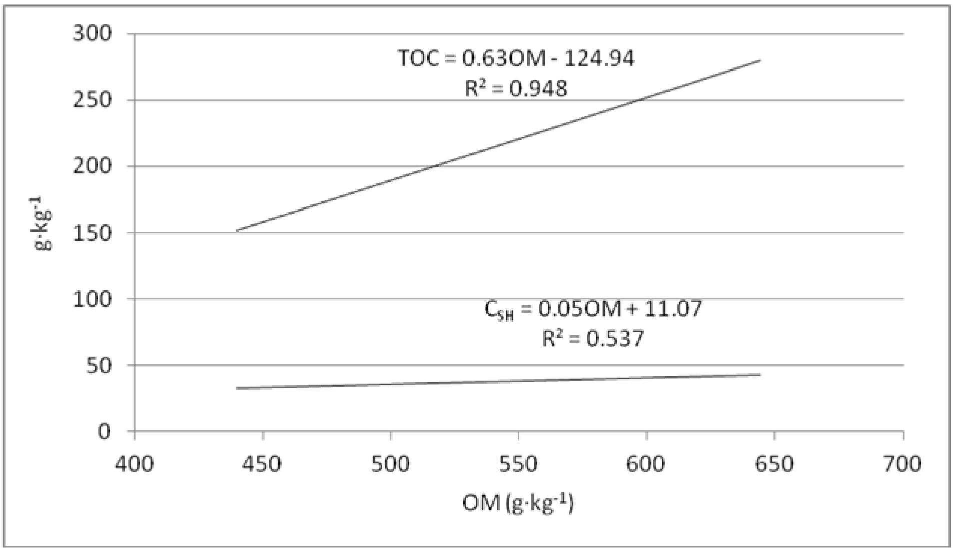


**Figure 5.** Linear regression for organic matter (OM) and humic substance ($C_{SH}$) and total organic carbon (TOC) in vermicomposts.

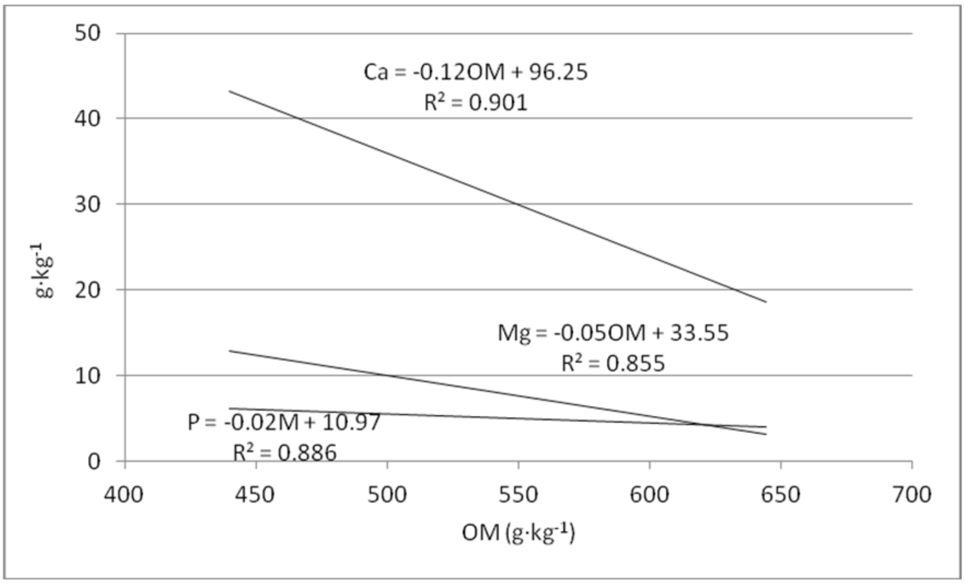


**Figure 6.** Linear regression for organic matter (OM) and Ca, P and Mg in vermicomposts.

On the other hand, in composts, the gain of OM by 1 g·kg$^{-1}$ was accompanied with an average TOC increment by 0.33 g·kg$^{-1}$, $C_{SH}$ by 0.12 g·kg$^{-1}$ and the N by 0.04 g·kg$^{-1}$ (Figure 8). The effect of OM on the amount of WEOC, LC or S was positive, although less marked (Table S2). The amounts of WEOC also influenced selected compost parameters and their dependences were directly proportional. An increase in WEOC by 1 g·kg$^{-1}$ caused an increase in OM by 86.52 g·kg$^{-1}$, TOC by 25.0 g·kg$^{-1}$ and $C_{SH}$ by 10.79 g·kg$^{-1}$, respectively (Figure 9). Moreover, together with an increment of WEOC by 1 g·kg$^{-1}$, the gain in the amount of LC by 0.142 g·kg$^{-1}$, S by 0.65 g·kg$^{-1}$ and N by 3.55 g·kg$^{-1}$ was observed (Figure 10).

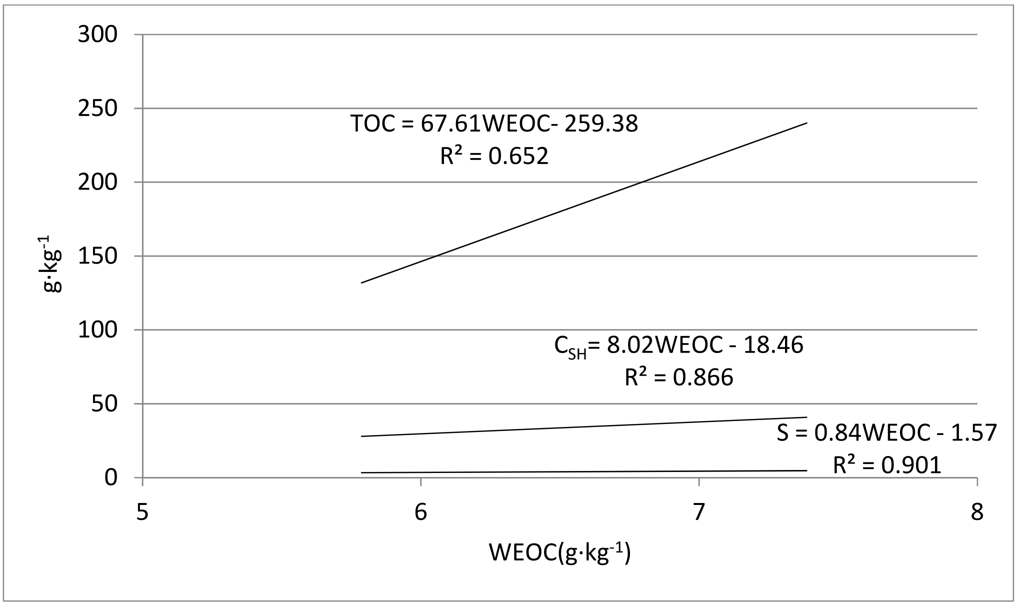


**Figure 7.** Linear regression for water extractable organic carbon (WEOC) and humic substance ($C_{SH}$), total organic carbon (TOC) and S in vermicomposts.

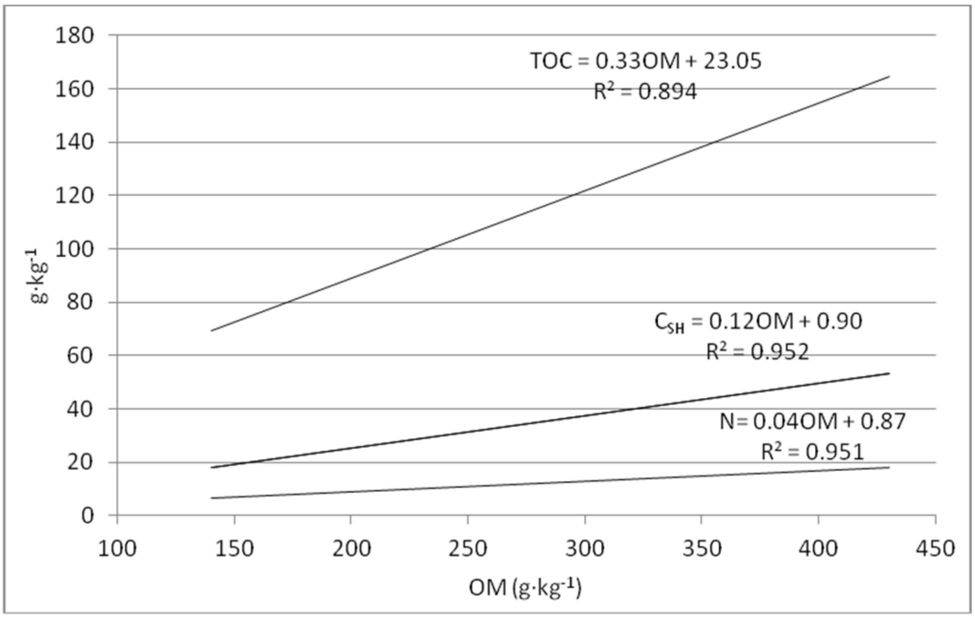


**Figure 8.** Linear regression for organic matter (OM) and humic substances ($C_{SH}$), N and total organic carbon (TOC) in composts.

The relationships shown above emphasize the essential importance of both organic matter and water extractable organic carbon in shaping the quality of the vermicomposts and composts. A strong influence was observed with regard to total organic carbon, humic substance, labile carbon, as well as the nutrients integrally bound to the organic matter of vermicomposts and composts, i.e., nitrogen and sulfur. Taking into account the fact that the above-mentioned C compounds are more or less susceptible to decomposition, it can theoretically be assumed that they may play an important role in the transformation of VCs and Cs in the soil. Obviously, to verify the above assumption experimental studies need to be conducted. On the one hand, the rapid degradation of easily mineralizable C compounds (LC, WEOC) can contribute to enhancing the microbial activity of the soil as well as releasing N and S from easily mineralizable combinations. On the other hand, the introduction of organic matter from VC or C to the soil will increase the amount of humic substances—persistent C compounds that determine the improvement of sorption and buffer the properties of the soil.

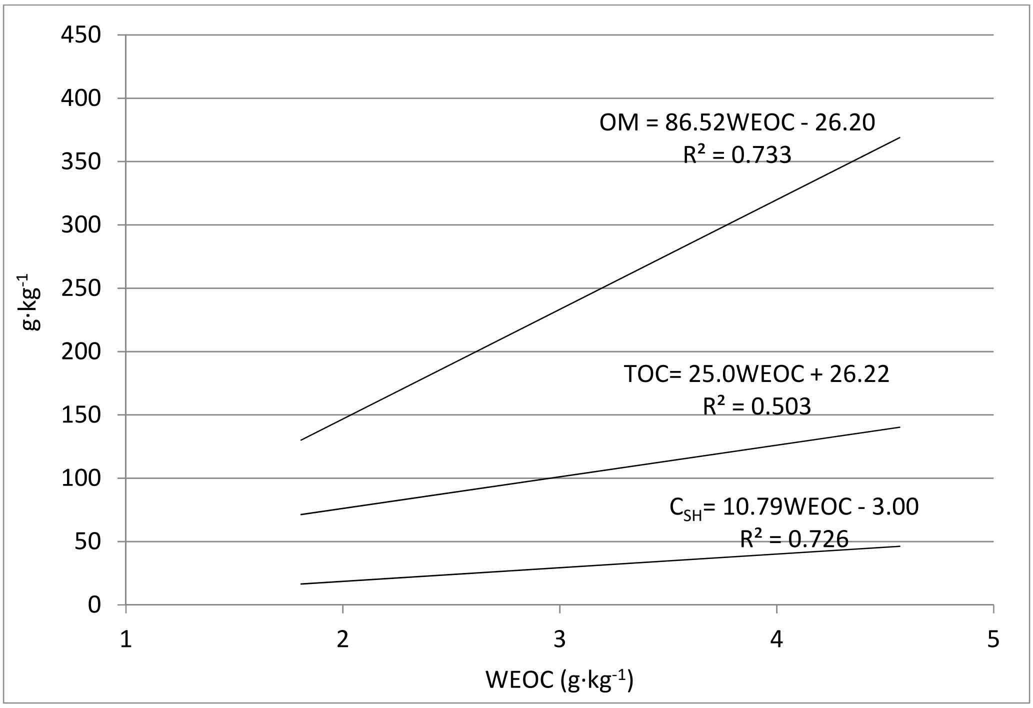


**Figure 9.** Linear regression for water extractable organic carbon (WEOC) and humic substance ($C_{SH}$), total organic carbon (TOC) and organic matter (OM) in composts.

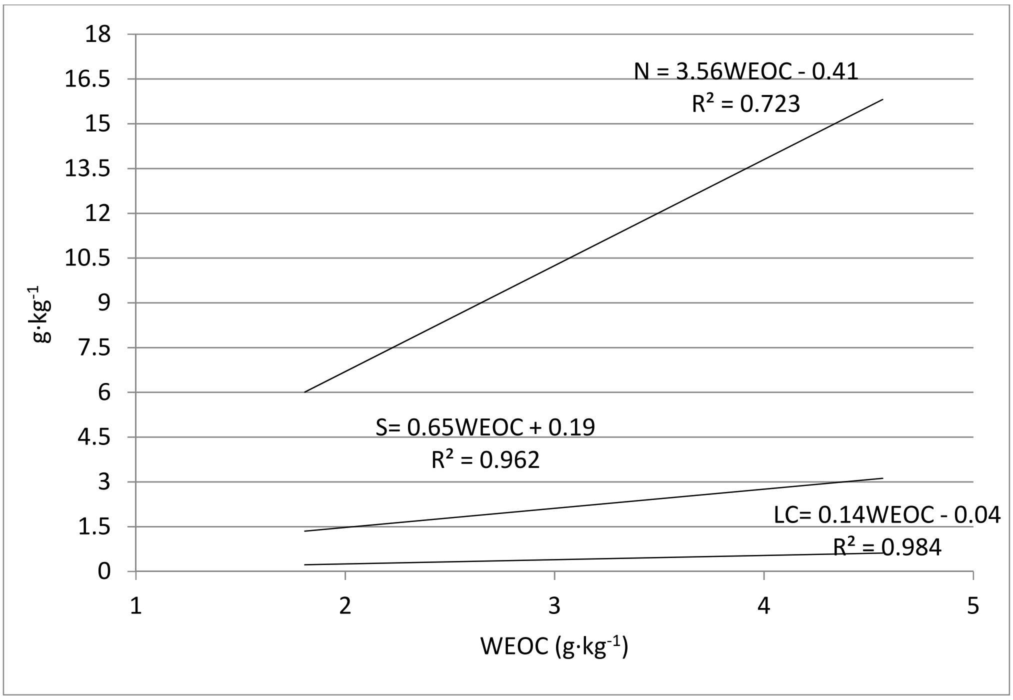


**Figure 10.** Linear regression for water extractable organic carbon (WEOC) and labile carbon (LC), N and S in composts.

## 4. Conclusions

On the basis of the obtained results it can be concluded that both the vermicomposts and composts were of good quality, serving as a valuable source of organic matter and nutrients for plants and thus they can be used for private gardening purposes. The fact that the content of heavy metals in the VCs and Cs did not exceed the permissible standards, high safety of their soil application should be underlined. Compared to the composts, vermicomposts were more abundant in macro- and micronutrients. For them, higher amounts of organic matter, TOC, LC and WEOC were also recorded. In view of the above, vermicomposts seem to be better fertilizers than traditionally prepared composts. In this context, not only the amount of introduced nutrients essential for plants should be emphasized, but also the load of easily mineralized carbon compounds (LC and WEOC). However, despite the differences resulting from the biowaste used, as well as specificity of the process, the tested vermicomposts and composts did not vary in terms of the quantity and quality of humus compounds described by the DP, $Q_{4/6}$ values or the amount of $C_{HA}$ and $C_{FA}$. Regardless of the humification indexes (HR, HI, DP) indicating a satisfactory maturity of the tested materials, the high $Q_{4/6}$ values underlined low optical density and poorly polymerized humic compounds in the analyzed organic fertilizers.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture12020293/s1, Table S1: Correlation coefficients matrix for vermicomposts; Table S2: Correlation coefficients matrix for composts

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