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The Effect of Vermicompost and Earthworms (*Eisenia fetida*) Application on Phytomass and Macroelement Concentration and Tetanic Ratio in Carrot

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Abstract: This experiment evaluated the effects of various vermicompost amounts (0%, 10%, 20%, 25%, and 50%) of the total weight of the mixture of soil and vermicompost) and red worms (0, 10, and 20 individuals/pot) on carrot phytomass and macroelements concentration when applied to soil. Increasing the quantity of vermicompost (Vc) raised the weight of carrot roots and leaves. When we increased the dose of Vc, differences in phytomass growth were diminished gradually. Fifty percent of Vc in the soil did not have a negative impact on the formation of carrot roots and leaves. Vc increased the water content in roots and decreased it in leaves. Earthworms (EWs) in soil increased the weight of both carrot roots and leaves. The positive impact of EW on roots and leaves was higher when the vermicompost content in the soil was lower. EWs showed positive effects on the potassium concentration in whole carrot phytomass. Both EWs and Vc increased the value of the tetanic ratio in the carrot roots, which lowers their quality. EWs showed positive effects on the potassium concentration in whole carrot phytomass. Relationships found between K × Ca and Mg × S were antagonistic. Positive dependencies were detected between the carrot root yield and N, P, K concentration in both leaves and roots.

Keywords: red worms; vermicompost; roots; leaves; tetanic ratio; synergism

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1. Introduction

Carrot (*Daucus carota* L.) is mainly grown in temperate climates. It is a very valuable component of human food because it is an important source of vitamins and antioxidants, a significant source of carbohydrates and minerals and it has a high nutritional value. Its consumption plays a role in prevention of several diseases [1]. It has an anticancerogenic effect and a positive effect on the liver, it reduces the occurrence of cardiovascular diseases, and it increases the immunity of humans [2]. Despite the positive effects of the consumption of fresh and fermented carrots and other vegetables on the public health, the area designated for growing vegetables in Slovakia is only around 6000 hectares.

Mineral and organic fertilizers are used for growing carrot in Slovakia. Slovak farmers have a general shortage of farmyard manure. The availability of composts is greater, but the trust of Slovak farmers in composts, with the exception of vermicompost, is low. Increased confidence in vermicomposts is related to the fact that a vermicompost is a place for life and reproduction of the earthworms. Vermicompost full of earthworms and cocoons indicates its biological suitability for agricultural purposes [3]. Approximately 20–25% of the yield of field crops grown in Central Europe is a result of fertilization. This number is around

30% for garden crops. It is clear that plant nutrition is an important intensifying factor of crop production. According to the United Nations [4], it is estimated that in 2030 there will be 8.5 billion people on our planet. Global population is forecasted to be up to 9.7 billion in 2050, and up to 11.2 billion in 2100. This increased population will require more water, food, mineral resources, and living space, which will place an increasing pressure on the environment. For this reason, it is necessary to research various solutions to increase food production while avoiding further deterioration of the environment. A possible solution is the biowaste recycling for the production of high-value organic amendments and their use in plant cultivation. However, it should be taken into consideration that the impact of organic fertilizers (including composts) on the environment, vegetative growth of plants and crop quality is not always positive, but it can be neutral or even negative [5–10] because it depends on several factors such as environmental and soil conditions, parameters of organic fertilizers, the rate and date of their supply, application technique, species of cultivated plants, and other parameters [5–12]. In addition to increased content of some heavy metals in plants [13], another possible consequence of incorrect use of organic amendments is the increased content of nitrates (NO_3^-) in groundwater [14], as well as in plants [15]. Increased release of ammonia (NH_3) into the air [16] and contamination of plants with microorganisms that are harmful to either humans or plants [17] have also been observed. Further, after their usage, inappropriate nutrient ratios in plants were recorded, which in some cases endangered the human health [18]. From the point of view of human and animal nutrition, the K:(Ca + Mg) ratio, called the tetanic ratio, is important in consumed plant parts [19–21]. The tetanic ratio indicates sufficient or insufficient calcium (Ca) and magnesium (Mg) intake, and its value should be $\leq$2.2.

Processing of organic amendments by composting before their application to the soil significantly improves their parameters [18], reduces the risk of microbiological contamination of cultivated vegetables with bacteria of the genus *Salmonella* or *Escherichia coli* [13,22], and creates more time for their use in crop production. The application of quality composts including vermicomposts as subtype, as well as other organic amendments, usually has a positive effect on the whole range of soil parameters [13,18,23]. Vermicomposts positively affect water regime in the soil, pH, soil sorption capacity [24–27], and soil air regime [28]. Vermicomposts further increase soil aggregate stability [29] and water infiltration into the soil [30–32] and reduce soil bulk density [33] and number of bacteria of the genus *Azotobacter chroococcum* in the soil [18]. Vermicomposts also supply macro- and microelements, growth stimulators [34], they increase the bioavailability of nutrients in the soil, which consequently increases the nutrient content in plants [27]. Vermicompost retains nutrients for a long time, and contrary to conventional composts, it delivers the required amount of macro- and micronutrients to plants in a shorter time [35]. However, vermicomposts also increase the bioavailability of heavy metals together with macro- and microelements, so their application may cause some environmental concerns [33].

The well-known positive impact of composts on the aforementioned soil parameters often results in their positive impact on the quantitative and qualitative parameters of cultivated field and garden crops, fruit trees, and shrubs [36–39]. Based on a meta-analysis, Blouin et al. [40] found that vermicompost increases commercial yield by around 26%. The amount of yield increase after the use of vermicomposts depends on the quality of the soil to which the vermicompost is applied, its parameters, the application rate, the date of use, the type of cultivated plant, etc. In the experiment of Kováčik et al. [41], increasing the vermicompost content in the soil substrate to above 20% caused a reduction in formation. In contrast, Blouin et al. [40] reported that in most plants, the positive effect of vermicompost on plant growth reached a maximum when 30% to 50% of the soil volume was vermicompost. Several scientific papers reported that after the application of vermicompost, contents of phenols, flavonoids, total antioxidants, carotenes, lycopene, crude fiber, carbohydrates, inulin, calcium, magnesium, phosphorus, iron, zinc, and other parameters increased in root, leaf, and fruit vegetables [8,9,42–44]. After adding vermicompost, pineapple leaves had nitrogen (N), phosphorous (P), potassium (K), Ca, Mg, and sulphus

(S) concentrations that were higher than or equal to the leaves of plants fertilized with chemical fertilizers [45]. In plant species *Aglaonema* (Chinese evergreen), *Dracaena marginata* and *Spathiphyllum wallisii* [46], but also in *Petunia hybrida* L. [47], increasing the levels of vermicompost in the growing medium increased the N, P, K, Ca, and Mg concentrations. Similarly, in savory plants (*Satureja hortensis* L.), vermicompost significantly increased N and P concentration [48]. Significant accumulation of N, P, K, Ca, and Mg in the root and shoot system with the application of humic acids derived from vermicompost correlated with nutrient uptake by plants in the study by Baldotto et al. [49]. Protein and fat contents increased in cereal grains after vermicompost application [50]. The total content of oils, essential oils, bioactive substances, vitamin C, and other substances in spicy and medicinal plants also increased [51–53]. The fruits of plants fertilized with vermicompost had better taste [54], and their color was more attractive [55] or stronger [56]. The use of compost in plant cultivation reduced the incidence of diseases in plants. The rate of reduction of the incidence of a particular disease depends on the composted components [53]. The conclusions of Alidadi et al. [57] showed that the application of vermicompost reduced the number of health and environmental problems. The enhancement of the positive effects of vermicomposts on phytomass formation and several quality parameters of cultivated plants occurs when they are applied together with mineral fertilizers, growth stimulants, nitrogen bacteria, mycorrhotic fungi, soil improvers, etc. [58–61].

The presence of earthworms in soil is one of the indicators of the quality of the soil environment [62,63]. Earthworms have a positive effect on the stability of soil aggregates, soil porosity, water infiltration [30–32], and the quantity and quality of humic substances in the soil [64,65]. They increase the content of available nutrients [24,66,67] and soil pH [68,69] and affect the abundance of soil biota, especially bacteria and fungi [70]. Dependent on a number of factors, they can increase, decrease, or have no effect on the amount of N leached, the amount of N released into the air, and the amount of soil erosion [71–74]. They often serve as a means of reducing the toxic effects of heavy metals and various chemicals found in soils [65,75]. Earthworms with a positive effect on several physical, chemical, and biological soil parameters [76,77] usually also have a positive effect on cultivated plants. The degree of positive effect depends significantly on weather conditions [78]. In the experiments of Ratsiatosika et al. [79] soil inoculation with earthworms increased rice yields by up to 45%. Based on the findings of meta-analyses, van Groenigen et al. [80] found that the presence of earthworms in the ecosystem increased plant yields by an average of 25%, above-ground phytomass production by 23%, and roots mass by 20%. A positive correlation between the number of earthworms and crop production is not consistently observed; it is not systematic [81]. Several authors [82–86] presented better health and better-quality parameters of plants (higher content of macro- and microelements and amino acids, and higher antioxidant activity) grown on soils inoculated with the earthworms. In addition to the positive effects of earthworms on crop height and quality, their negative or neutral effects, or a combination of positive and negative effects, have been reported [87–89]. One of the reasons, for this contrasting results is the different growing season of cultivated plants, because plants with longer growing times cope with the undesirable attack of root hairs by earthworms better. Further, plants with a longer growing season make better use of positive impact of earthworms on several soil parameters [3,41]. It is known that the roots of some plants may act as an attractant to earthworms, [90]; conversely, the roots of other plants may have negative allelopathic effects on earthworms [91].

It is clear from the presented findings that despite the existence of a considerable amount of information on the effects of vermicomposts and earthworms on plants, it is not yet known how many earthworms of a particular species are beneficial and how many of them are harmful for growing specific plants. Moreover, the response of carrots to graded doses of vermicompost is not known, and there is no information on the effect of earthworms and vermicompost on the K: (Ca + Mg) ratio in parts of plants intended for animal feed or human nutrition.

For these reasons, the aim of this study is to find answers to these questions: How (1.) increasing the proportion of vermicompost and (2.) the presence and absence or different abundance of red worm (*Eisenia fetida*) in the soil affects the weight of carrot roots and leaves and the concentration of macroelements in them.

2. Materials and Methods

2.1. Experimental Design and Field Management

Pot experiment was performed in the vegetation cage in the area of the Slovak University of Agriculture in Nitra (48°18′ N, 18°05′ E) in 2017 and 2018 (running every year for 137 days). In this experiment, the impact of (1.) the quantity of vermicompost in soil and (2.) the impact of the number of earthworms (*Eisenia fetida*) on the weight of carrot roots and leaves and concentration of macroelements in them were studied.

The total number of treatments (tr.) was 13 (Table 1). Soil (tr. 1) and a mixture of soil and vermicompost (tr. 2 to tr. 13) were weighed into cylinder-shaped containers 0.35 m high and 0.35 m in diameter. Treatment 1 was a control treatment (soil without vermicompost). Treatments 2–5 examined the impact of increasing the quantity of vermicompost in the growing medium, which was prepared by mixing different portions of soil and vermicompost. Treatments 6–13 studied the effect of the number of earthworms (red worms) added to the prepared growing media (tested in treatments 1–5).

Table 1. Overview of the treatments and individual amounts of used soil, vermicompost, and earthworms in the pot experiment.

Treatment		**Componet**			**Ratio**	**Proportion of Vc**
No.	**Designation**	**So (kg pot^{-1})**	**Vc (kg pot^{-1})**	**EW_S (Individuals)**	**So:Vc**	**(%) Mass Content**
1	So	20	0	0	-	0
2	$SoVc_{9:1}$	18	2	0	9:1	10
3	$SoVc_{4:1}$	16	4	0	4:1	20
4	$SoVc_{3:1}$	15	5	0	3:1	25
5	$SoVc_{1:1}$	10	10	0	1:1	50
6	$SoVc_{9:1} + EW_{S10}$	18	2	10	9:1	10
7	$SoVc_{9:1} + EW_{S10}$	18	2	20	9:1	10
8	$SoVc_{4:1} + EW_{S10}$	16	4	10	4:1	20
9	$SoVc_{4:1} + EW_{S20}$	16	4	20	4:1	20
10	$SoVc_{3:1} + EW_{S10}$	15	5	10	3:1	25
11	$SoVc_{3:1} + EW_{S20}$	15	5	20	3:1	25
12	$SoVc_{1:1} + EW_{S10}$	10	10	10	1:1	50
13	$SoVc_{1:1} + EW_{S20}$	10	10	20	1:1	50

Notes: No.—number; So—soil; Vc—vermicompost; EWs—earthworms.

The pots contained 20 kg of soil (Haplic Luvisol) in treatment 1 and 20 kg of the mixture consisting of soil and applied vermicompost in treatments 2–5. In treatment 2, the media was prepared by mixing 18 kg of soil (So) with 2 kg of vermicompost (Vc), representing the ratio So:Vc = 9:1, (10% proportion of Vc—mass content). In treatment 3, the mixture consisted of 16 kg of soil and 4 kg of vermicompost, constituting the ratio of So:Vc = 4:1 (20% proportion of Vc). In treatment 4, the mixture consisted of 15 kg of soil and 5 kg of vermicompost, giving the ratio of So:Vc = 3:1 (25% proportion of Vc). In treatment 5, the mixture consisted of 10 kg of soil and 10 kg of vermicompost, with the ratio of So:Vc = 1:1 (50% proportion of Vc). The same soil was used in all 13 treatments (Haplic Luvisol). This Haplic Luvisol was obtained from the field located in Párovské Háje village (near Nitra), in particular from A-horizon (0.0–0.25 m). The basic agrochemical parameters of the used soil (So) and vermicompost (Vc) are indicated in Table 2.

Table 2. Parameters of soil and vermicompost used in the experiment (100% dry matter).

Subs.	**N_{in}**	**P**	**K**	**Ca**	**Mg**	**S**	**N_t**	**C_{ox}**	**C:N**	**EC**	**pH**
	mg kg^{-1}						**%**			**mS cm^{-1}**	
So	9.20	17.80	173	3100	452	4.40	0.07	0.90	11.88	0.12	6.35
Vc	310.1	3085	8763	5135	3252	2068	2.97	19.89	5.53	4.98	7.33

Notes: Subs.—substrate component; N_{in}—inorganic nitrogen; P—phosphorus; K—potassium; Ca—calcium; Mg—magnesium; S—Sulphur; N_t—total nitrogen, C_{ox}—total organic carbon; EC—electrical conductivity; So—soil; Vc—vermicompost.

In treatments 6–13, the same growing medium was used as in treatments 2–5 but red worms of the same size (5.0 ± 0.2 cm) were added, which were also supplied by the company VermiVital, Ltd. Treatments 6 and 7 contained the same substrate as treatment 2. Similarly, treatments 8 and 9 contained the same substrate as treatment 3. Similarly, treatments 10 and 11 contained the same substrate as treatment 4, and the substrate of treatments 12 and 13 was identical to the substrate of treatment 5. The treatments with even numbers 6, 8, 10, and 12 had 10 individuals of red worms, and treatments with odd numbers 7, 9, 11, and 13 had 20 individuals of red worms.

The vermicompost used in the experiments was produced and supplied by the company VermiVital Ltd. (Záhorce, Slovakia). If the mentioned vermicompost (310 mg kg^{-1} N_{in}) was used in the field conditions of Slovakia (bulk density 1.2 g cm^{-3} in soils intended for the cultivation of root vegetables) at the same amount as in treatment 5 (50% share in the layer up to 0.2 m of soil), then it would supply 744 kg ha^{-1} of inorganic N, which is a very high dose of N. With a 10% share of vermicompost, 149 kg ha^{-1} N is added to the soil.

Before inserting the soil substrates into pots, the plastic net was placed at the bottom of all pots to prevent the earthworms (EWs) escaping. The pots with weighted substrates were placed on the saucers, which were able to capture 1000 mL of the leaked soil solution during the period of precipitation. The leaked solution was returned to the pots.

The experiment was established according to the method of random arrangement of pots in four repetitions (each repetition consisted of 4 pots, where one pot was one repetition). The model crop was carrot (*Daucus carota* L. ssp. *sativus*) cultivar Nantes 3 (company Osiva Moravia, Olomouc, Czechia). In both years, the sowing day was 16 March. Subsequently, the experiment was irrigated to 75% of field water capacity. In the following 70 days, all pots were irrigated with the same amount of water containing a minimal quantity of nutrients (N-2.15, P-0.19, K-0.46, Ca-2.44, Mg-0.42, and S 2.62 mg L^{-1}). During the last 67 days of the experiment, treatments 2 to 13 were irrigated with a higher amount of water because plants in these treatments evaporated more water as a result of a significantly larger leaf area. The field water capacity was checked in the months of April to May in three- to four-day intervals. In the month of June in one- to three-day intervals and in the month of July during sunny and warm days it was checked daily. The control was carried out by weighing the pots. Missing moisture was made up by adding water to the original weight of the pot (the weight of each pot was determined before the start of the experiment after adding all the components, including water, to the desired soil moisture). Twenty days after the emergence of plants, they were thinned to ensure the same number per pot (50 plants per pot). In both years, the harvest of carrots was carried out on 31 July (137 days after sowing). Pots with plants were shaded on days of intense radiation.

2.2. Analysis of Soil and Vermicompost

The following analytical methods were used for determining the agrochemical parameters of the soil and vermicompost used. Ammonium ($N\text{-}NH_4^+$) was measured with the Nessler's colorimetric method; $N\text{-}NO_3^-$ by colorimetric method with phenol–2.4 disulphonic acid, where the extract from soil was achieved by using the water solution of

1% K_2SO_4. Inorganic nitrogen (N_{in}) was calculated as a sum of N-NH_4^+ + N-NO_3^- (N_{in} = N–NH_4^+ + N–NO_3^-). Both N–NH_4^+ and N–NO_3^- were determined in a fresh soil sample.

The contents of available P, K, Ca, and Mg were determined in the dry soil sample by the Mehlich 3 extraction procedure [92]. The content of P was determined by the colorimetric method, K by flame photometry, Ca and Mg by atomic absorption spectrophotometry, S spectrophotometrically (in the leachate of ammonium acetate), total nitrogen (N_t) by distillation after the mineralization with strong H_2SO_4 [93], total organic carbon (C_{ox}) after the oxidation according to Tyurin [94], EC by analysis of specific electrical conductivity, and pH (in a solution of 1.0 mol L^{-1} KCl, soil to solution ratio 1:2.5) potentiometrically.

2.3. Yield Evaluation

All carrot plants were picked up manually (roots with leaves) from the soil substrate. Ten average individuals were selected to evaluate the weight of the roots and leaves. Dry matter and concentration of macroelements were measured in the same 10 individuals. Prior to weighing the phytomass, carrot roots were washed with drinking water to remove the residuals of soil substrate. Subsequently, the rest of water was removed with filter paper. The roots were separated from the leaves with a knife, and their fresh weights were determined. After homogenization (via ceramic grater and a knife), the dry matter and concentration of macroelements (N, P, K, Ca, Mg, and S) were detected in roots and leaves.

2.4. Determination of Dry Matter and Nutrient Concentration in Carrot Phytomass

The quantity of dry matter in carrot roots and leaves was determined by gravimetric analysis in aluminum crucibles at a temperature of 105 °C.

Before determination of macroelements concentration in tissue of carrot roots and leaves, it was necessary to dry the homogenized plant material (grated roots and cut leaves) in a properly ventilated room at a temperature of 22 °C. The dried roots and leaves were ground with a laboratory grinder. The prepared samples were used for determination of N, P, K, Ca, Mg, and S concentration in the above-ground and underground carrot phytomass.

Nitrogen was determined by distillation using the Kjeldahl method after mineralization in the medium of concentrated H_2SO_4 [95]. Phosphorus was determined spectrophotometrically (as phosphomolybdenum blue), potassium and calcium by flame photometry, and magnesium by atomic absorption spectrophotometry after mineralization in the medium of mixture HNO_3 and $HClO_4$ (2:1, v/v) [96]. Sulphur was determined nephelometrically after mineralization in the mixture of HNO_3 and $HClO_4$ (3:2, v/v).

2.5. Statistical Analysis

The acquired results were processed with one-way analysis of variance (ANOVA) and by the Pearson correlation coefficient (r). The differences between the treatments were evaluated by the Tukey test at the significance level of α = 0.05. The Pearson correlation coefficient (r) was processed at significance levels of α = 0.05 and α = 0.01. Averages from two years of trials were used in the statistical analysis. The statistical program Statgraphics, version 5.0 was used.

3. Results and Discussion

3.1. Weight of Roots and Leaves

Depending on the available nutrient reserves in the soil and the application rate of nutrients, plant fertilization results either in the growth or decline of phytomass formation, and the changes can be both dynamic and gradual. High nutrient rates cause a decrease in phytomass formation [97,98], so a rational fertilization policy increases yield while being economical and ecological at the same time [18]. With the increasing quantity of vermicompost in the soil substrate (0%, 10%, 20%, 25%, and 50%), the weight of carrot roots and leaves increased too (Tables 3 and 4). The percentage of growth between treatments 1 and 2, 2 and 3, 4 and 5, and 5 and 6 had a diminishing tendency. The weight growth in roots achieved

137%, 35%, 10%, and 9%, and in leaves achieved 120%, 14%, 3%, and 2%, respectively. These findings confirm both that the dynamics of increasing yields slow down with increasing doses of nitrogen [99] and that with the growth of application doses of fertilizers containing nitrogen, the increase in yield is not linear, but has the character of a curve (parabola).

Table 3. Impact of vermicompost and earthworms on the weight of fresh carrot roots.

Treatment No.	Treatment Designation	g/10 Plants	%				
1	So	163.51 [a]	100				
2	$SoVc_{9:1}$	387.54 [b]	237.01	100			
3	$SoVc_{4:1}$	523.61 [e]	320.23	135.11	100		
4	$SoVc_{3:1}$	578.07 [h]	353.54	149.16	110.40	100	
5	$SoVc_{1:1}$	632.09 [j]	386.58	163.10	120.72	109.35	100
6	$SoVc_{9:1} + EWs_{10}$	428.25 [c]	261.91	110.50	81.79	74.08	67.75
7	$SoVc_{9:1} + EWs_{20}$	463.31 [d]	289.47	119.55	88.48	80.15	73.30
8	$SoVc_{4:1} + EWs_{10}$	554.18 [f]	338.93	143.00	105.84	95.87	87.67
9	$SoVc_{4:1} + EWs_{20}$	561.99 [g]	343.70	145.01	107.33	97.22	88.91
10	$SoVc_{3:1} + EWs_{10}$	600.84 [i]	367.46	155.04	114.75	103.94	95.06
11	$SoVc_{3:1} + EWs_{20}$	606.04 [i]	370.64	156.38	115.74	104.84	95.88
12	$SoVc_{1:1} + EWs_{10}$	642.71 [k]	393.07	165.84	122.75	111.18	101.68
13	$SoVc_{1:1} + EWs_{20}$	649.33 [l]	397.12	167.55	124.01	112.33	102.73
$HSD_{0.05}$		6.603	-	-	-	-	-
1–13		522.42	-	-	-	-	-
2–5		530.33	100.00	-	-	-	-
6–13		563.33	106.22	-	-	-	-
6, 8, 10, 12		556.50	104.93	100.00	-	-	-
7, 9, 11, 13		570.17	107.51	102.46	-	-	-

Notes: No.—number; So—soil; Vc—vermicompost; EWs—earthworms; $HSD_{0.05}$—honestly significant difference at the level α = 0.05; different letter behind a numerical value corresponds to the statistically significant difference at the level 95.0%.

Table 4. Impact of vermicompost and earthworms on the weight of fresh carrot leaves.

Treatment No.	Treatment Designation	g/10 Plants	%					R/L
1	So	57.26 [a]	100					2.86
2	$SoVc_{9:1}$	126.06 [b]	220.15	100				3.07
3	$SoVc_{4:1}$	143.13 [c]	249.97	113.54	100			3.66
4	$SoVc_{3:1}$	146.86 [cd]	256.48	116.50	102.61	100		3.94
5	$SoVc_{1:1}$	149.78 [cd]	261.58	118.82	104.65	101.99	100	4.22
6	$SoVc_{9:1} + EWs_{10}$	130.79 [b]	228.41	103.75	91.38	89.06	87.32	3.27
7	$SoVc_{9:1} + EWs_{20}$	142.89 [c]	249.55	113.35	99.83	97.30	95.40	3.24
8	$SoVc_{4:1} + EWs_{10}$	146.84 [cd]	256.44	116.48	102.59	99.99	98.04	3.77
9	$SoVc_{4:1} + EWs_{20}$	148.55 [cd]	259.43	117.84	103.79	101.15	99.18	3.78
10	$SoVc_{3:1} + EWs_{10}$	149.64 [cd]	261.33	118.71	104.55	101.89	99.91	4.02
11	$SoVc_{3:1} + EWs_{20}$	150.84 [d]	263.43	119.66	105.39	102.71	100.71	4.02
12	$SoVc_{1:1} + EWs_{10}$	152.60 [d]	266.50	121.05	106.62	103.91	101.88	4.21
13	$SoVc_{1:1} + EWs_{20}$	154.00 [d]	268.95	122.16	107.59	104.86	102.82	4.22
$HSD_{0.05}$		7.368	-	-	-	-	-	-
1–13		138.40	-	-	-	-	-	-
2–5		141.46	100.00	-	-	-	-	-
6–13		147.02	103.93	-	-	-	-	-
6, 8, 10, 12		144.97	102.48	100.00	-	-	-	-
7, 9, 11, 13		149.07	105.38	102.83	-	-	-	-

Notes: No.—number; So—soil; Vc—vermicompost; EWs—earthworms; R—roots; L—leaves; $HSD_{0.05}$—honestly significant difference at the level α = 0.05; different letter behind a numerical value corresponds to the statistically significant difference at the level 95.0%.

Surprisingly, the high portion (50%) of Vc in soil substrate (tr. 5) (which is equal to the application of 744 kg N ha^{-1} in inorganic form in field conditions) did not have a depressive impact on the formation of carrot roots and leaves. This is in contrast with findings of other authors, who observed that increasing the Vc content above 40% [100] and 20% [41] caused a decrease in phytomass formation of the cultivated crop in their experiments.

The data in Table 4 show that, along with the increased portion of Vc in soil substrate, the numerical value of roots/leaves weight ratio increased, which indicates that Vc increased the weight of roots more than the weight of leaves. More intensive growth of carrot roots than leaves as a result of Vc application is a positive finding because roots are more important from a commercial perspective. The change of ratio of the growth rate between roots and leaves is caused predominantly by the changes in lighting and nutrition intensity for plants [101].

The evaluation of fertilizer rates, whether they are high, sufficient, or low, is highly dependent on the cultivated crops. Different plants usually react differently to the same doses of fertilization substances under the same cultivation conditions. This was affirmed by comparing our data in Table 3 with the findings of Kováčik et al. [102]. The data presented in Table 3 indicate that carrot root weight in the treatment with 50% proportion of Vc increased by 9% when compared to the treatment with 25% of Vc. But in the experiment of Kováčik et al. [102], when growing radish under the same soil and weather conditions as in our experiment, the weight of radish roots (depending on the date of harvest) decreased by 30.68% and 34.47%, respectively.

Up to a 137% increase in carrot root yield between unfertilized treatment 1 and treatment 2 (Table 3) demonstrates that it is highly reasonable to use vermicompost with a fertilizer containing nitrogen in the soils where content of N_{in} is low (Table 2).

The comparison of average weight of the roots and leaves cultivated in the treatments with and without EWs (tr. 6–13 vs. tr. 2–5) confirms that the earthworms increased root weight by 6.22% (Table 3) and leaf weight by 3.93% (Table 4). Observed impact of EWs on carrot phytomass weight is in correspondence with the findings of Doan et al. [87] and Elmer [89], who recorded statistically insignificant (but also significantly positive and negative) plant reactions to the presence of earthworms in the growing media. The opposite finding in the cultivation of radish under the conditions that were identical to the conditions of our experiment was recorded by Kováčik et al. [41], who found that earthworms had a negative effect on the formation of above-ground and underground radish phytomass throughout the experiment. According to authors, this happened because earthworms attacked the root hairs. Further, Brown et al. [90] stated that the roots are one of the main food sources for earthworms and may well act as an attractant to them. The observed different effect of earthworms on the weight of carrot and radish roots was caused by the different length of growing season of these crops. The longer vegetation period of the carrot allowed the root system to regenerate after the initial attack on the root hairs by the earthworms, and due to the positive effect of the earthworms on the physical and chemical parameters of the soil, more intensive carrot growth was observed.

The highest positive effect of EWs on carrot phytomass was monitored in treatments with the lowest quantity of Vc (just 10%) in the soil substrate. On the contrary, the smallest increases of root and leaf weight were recorded in the treatments where earthworms were put into the soil substrate with the highest quantity of Vc (50%). So, the positive impact of EWs on root and leaf weight increased in correlation with the decreasing organic matter (less vermicompost) in the soil. According to Kováčik et al. [41], the influence of earthworms on the weight of roots and leaves decreased as the content of organic matter in soil increased and as the soil bulk density decreased.

Ten individual earthworms per pot with the soil substrates containing 10%, 20%, 25%, and 50% Vc increased the root weight by 10.50%, 5.84%, 3.94%, and 1.68% (Table 3) and leaf weight (Table 4) by 3.75%, 2.59%, 1.89%, and 1.88% (tr. 6 vs. tr. 2; tr. 8 vs. tr. 3; tr. 10 vs. tr. 4; tr. 12 vs. tr. 5), respectively. Twenty individual EWs per pot enhanced the root weight by 19.55%, 7.33%, 4.82%, and 2.73% (Table 3) and leaf weight (Table 4) by 13.35%, 3.79%, 2.71%, and 2.82% (tr. 7 vs. tr. 2; tr. 9 vs. tr. 3, tr. 11 vs. tr. 4; tr. 13 vs. tr. 5), respectively. The average difference between the root and leaf weights caused by the different number of earthworms (20 and 10 individuals/pot) in the soil substrate (tr. 7, 9, 11, 13 vs. tr. 6, 8, 10, 12) achieved 2.46% (roots) and 2.83% (leaves) in the presence of a higher number of EWs (Tables 3 and 4). As a result of different numbers of EWs, the differences in root weights were statistically significant between the pairs of treatments in three out of four cases (tr. 6 vs. 7, 8 vs. 9, 10 vs. 11, 12 vs. 13), despite the small numerical (percentual) increases. On the contrary, the differences in leaf weights between the treatments with 10 and 20 individuals of EWs were insignificant in three out of four cases.

3.2. Dry Matter Content

With the increase in water content in a plant body, the content of dry matter falls proportionally. Dry matter percentage in carrot roots decreased (Table 5) in correlation with the increasing portion of Vc in the soil substrates (0%, 10%, 20%, 25%, and 50%). The decrease in dry matter content (followed by increasing water content) was related to a significantly high quantity of available nitrogen and other nutrients in the vermicompost used (Table 1), leading to a consequently better intake of these nutrients for plant growth [13], showing the ability of organic fertilizers to improve soil water economy [24,103]. The highest content of dry matter, and thus the lowest content of water in carrot roots was detected in the control (unfertilized) treatment. Consumers of fresh vegetables usually prefer the vegetables with as high a water content as possible [18]. The average content of dry matter in carrot roots for all treatments was 17.01%, which corresponds with data presented by Sharma et al. [104].

Table 5. Impact of vermicompost and earthworms on the dry matter percentage in carrot roots and leaves.

Treatment		Roots			Leaves			R/L	
No.	**Designation**	**%**	**Rel. %**		**%**	**Rel. %**			
1	So	18.25 ^{f}	100.00	100.00	12.22 ^{a}	100.00	100.00	1.49	1.49
2	SoVc$_{9:1}$	17.48 ^{de}	95.78		12.22 ^{a}	100.00		1.43	
3	SoVc$_{4:1}$	16.94 ^{bc}	92.82	92.05	12.45 ^{ab}	101.88	107.53	1.36	1.29
4	SoVc$_{3:1}$	16.65 ^{b}	91.23		13.08 ^{abc}	107.04		1.27	
5	SoVc$_{1:1}$	16.13 ^{a}	88.38		14.81 $_{d}$	121.19		1.09	
6	SoVc$_{9:1}$ + EWs$_{10}$	17.65 ^{e}	96.71		12.45 ^{ab}	101.88		1.42	
7	SoVc$_{9:1}$ + EWs$_{20}$	17.74 ^{e}	97.21		12.67 ^{abc}	103.68		1.40	
8	SoVc$_{4:1}$ + EWs$_{10}$	16.93 ^{bc}	92.77		13.22 ^{abc}	108.18		1.28	
9	SoVc$_{4:1}$ + EWs$_{20}$	17.19 ^{cd}	94.19	92.93	13.32 ^{abc}	109.00	111.39	1.29	1.25
10	SoVc$_{3:1}$ + EWs$_{10}$	16.70 ^{b}	91.51		13.61 ^{bc}	111.37		1.23	
11	SoVc$_{3:1}$ + EWs$_{20}$	16.84 ^{bc}	92.27		13.64 ^{c}	111.62		1.23	
12	SoVc$_{1:1}$ + EWs$_{10}$	16.13 ^{a}	88.38		14.96 ^{d}	122.42		1.08	
13	SoVc$_{1:1}$ + EWs$_{20}$	16.50 ^{ab}	90.41		15.03 ^{d}	123.00		1.10	
	HSD$_{0.05}$	0.44			1.161				
	1–13	17.01			13.36				
	2–5	16.80			13.14				
	6–13	16.96			13.61				
	6, 8, 10, 12	16.85			13.56				
	7, 9, 11, 13	17.07			13.67				

Notes: No.—number; So—soil; Vc—vermicompost; EWs—earthworms; R—roots; L—leaves; HSD$_{0.05}$—honestly significant difference at the level α = 0.05; different letter behind a numerical value corresponds to a statistically significant difference at the level 95.0%.

The impact of vermicompost on the dry matter content in the roots was stronger than in the leaves, and in the opposite direction. The dry matter content in roots decreased considerably as the Vc in the substrates increased; in the leaves, it mostly increased insignificantly. Increased nitrogen supply in growing vegetables is often reflected in the enhanced growth of phytomass weight, owing to higher nutrient intake and water use than in the growth of dry matter weight [18]. Vermicompost had the opposite effect on the root dry matter when compared to leaf dry matter. Due to this, the ratio between root dry matter and leaf dry matter decreased as the quantity of Vc in the soil substrate increased (Table 5). In the treatment without Vc, the portion of dry matter of root weight was 1.49 times higher than the portion of dry matter of leaf weight. In the treatment with 50% of Vc, this ratio was only 1.09.

The earthworms in the soil substrate (tr. 6 and 7 vs. tr. 2, tr. 8 and 9 vs. tr. 3, tr. 10 and 11 vs. tr. 4, tr. 12 and 13 vs. tr. 5) did not influence the content of dry matter in roots or leaves significantly. It was detected that the earthworms increased the content of dry matter slightly in both above-ground and underground carrot phytomass. In the treatments with 20 EWs per pot, a slightly higher quantity of dry matter was observed than in the treatments with 10 EWs per pot. The differences in water amount between the treatments with 10 and 20 individuals per pot in the soil substrate were not significant. Despite the positive impact of EWs on root and leaf weight in fresh carrot (Tables 3 and 4) the water content did not increase. This provides evidence for the increase in weight of above-ground and underground carrot organs being a result of enhanced formation of plant tissues and not of increased water intake. In many cases, supplying vegetables with fertilizers containing nitrogen results in the formation of a higher yield via increased water content in roots, bulbs, fruits, and leaves [18].

3.3. Macroelement Concentration and Tetanic Ratio

The concentration of nutrients in plants is highly determined by fertilization. The concentration of N, P, and K in carrot roots and leaves rose with the increasing quantities of Vc in the soil substrates (Tables 6 and 7), i.e., with the increasing contents of given nutrients in the substrates.

Table 6. Impact of vermicompost and earthworms on the concentration of macroelements and tetanic ratio in carrot roots (dry matter).

Treatment		N	P	K	Ca	Mg	S	K:(Ca + Mg)
No.	Designation	mg kg^{-1}						
1	So	5560 ^{a}	1975 ^{a}	24,200 ^{a}	2400 ^{g}	1866 ^{a}	2010 ^{h}	5.67
2	$SoVc_{9:1}$	8299 ^{b}	3629 ^{b}	30,089 ^{b}	2329 ^{g}	1989 ^{ab}	1848 ^{g}	6.97
3	$SoVc_{4:1}$	8414 ^{b}	3674 ^{b}	30,289 ^{b}	1985 ^{def}	2043 ^{ab}	1774 ^{fg}	7.52
4	$SoVc_{3:1}$	9569 ^{c}	3865 ^{b}	31,552 ^{de}	1753 ^{bcd}	2133 ^{b}	1767 ^{efg}	8.12
5	$SoVc_{1:1}$	10,310 ^{d}	4461 ^{c}	33,064 ^{g}	1567 ^{abc}	2184 ^{b}	1758 ^{efg}	8.81
6	$SoVc_{9:1} + EWs_{10}$	8382 ^{b}	3799 ^{b}	31,717 ^{de}	2205 ^{fg}	2048 ^{ab}	1716 ^{def}	7.46
7	$SoVc_{9:1} + EWs_{20}$	8404 ^{b}	3830 ^{b}	32,318 ^{f}	2114 ^{efg}	2054 ^{ab}	1676 ^{cde}	7.75
8	$SoVc_{4:1} + EWs_{10}$	8502 ^{b}	3719 ^{b}	30,801 ^{c}	1844 ^{cde}	2087 ^{ab}	1658 ^{cd}	7.84
9	$SoVc_{4:1} + EWs_{20}$	8527 ^{b}	3739 ^{b}	31,287 ^{cd}	1742 ^{bcd}	2102 ^{ab}	1618 ^{c}	8.14
10	$SoVc_{3:1} + EWs_{10}$	9612 ^{c}	3888 ^{b}	31,675 ^{de}	1700 ^{abcd}	2130 ^{b}	1645 ^{cd}	8.27
11	$SoVc_{3:1} + EWs_{20}$	9736 ^{c}	3902 ^{b}	31,898 ^{ef}	1688 ^{abcd}	2126 ^{b}	1602 ^{bc}	8.36
12	$SoVc_{1:1} + EWs_{10}$	10,346 ^{d}	4502 ^{c}	33,286 ^{gh}	1484 ^{ab}	2179 ^{b}	1521 ^{ab}	9.09
13	$SoVc_{1:1} + EWs_{20}$	10,363 ^{d}	4577 ^{c}	33,632 ^{h}	1410 ^{a}	2169 ^{b}	1485 ^{a}	9.40
$HSD_{0.05}$		408.31	325.43	492.39	306.58	236.05	95.61	-
1–13		8925	3812	31,216	1863	2085	1698	7.91
2–5		9148	3907	31,249	1909	2087	1787	7.82
6–13		9234	3995	32,077	1773	2112	1615	8.26
6, 8, 10, 12		9211	3977	31,870	1808	2111	1635	8.13
7, 9, 11, 13		9258	4012	32,284	1739	2113	1595	8.38

Notes: No.—number; So—soil; Vc—vermicompost; EWs—earthworms; K:(Ca + Mg)—tetanic ratio; $HSD_{0.05}$—honestly significant difference at the level α = 0.05; different letter behind a numerical value corresponds to the statistically significant difference at the level 95.0%.

Table 7. Impact of vermicompost and earthworms on the concentration of macroelements and tetanic ratio in carrot leaves (dry matter).

Treatment		N	P	K	Ca	Mg	S	K:(Ca + Mg)
No.	Designation	mg kg^{-1}						
1	So	14,240 ^{a}	1688 ^{a}	34,600 ^{a}	24,000 ^{e}	8184 ^{g}	3270 ^{a}	1.08
2	$SoVc_{9:1}$	15,080 ^{b}	1938 ^{b}	39,300 ^{b}	20,200 ^{d}	6716 ^{cd}	4200 ^{b}	1.46
3	$SoVc_{4:1}$	15,640 ^{c}	1963 ^{b}	44,200 ^{e}	18,450 ^{c}	6686 ^{c}	4400 ^{bcd}	1.76
4	$SoVc_{3:1}$	16,760 ^{d}	2180 ^{cde}	51,600 ^{g}	13,900 ^{b}	5534 ^{b}	4500 ^{bcde}	2.66
5	$SoVc_{1:1}$	18,300 ^{e}	2370 ^{e}	62,200 ^{i}	7630 ^{a}	4501 a	5000 ^{g}	5.13
6	$SoVc_{9:1}$ + EWs_{10}	15,100 ^{b}	1970 ^{b}	40,800 ^{c}	19,850 ^{d}	7052 ^{ef}	4300 ^{bc}	1.52
7	$SoVc_{9:1}$ + EWs_{20}	15,110 ^{b}	2010 ^{bc}	41,400 ^{d}	19,850 ^{d}	7206 ^{f}	4420 ^{bcd}	1.53
8	$SoVc_{4:1}$ + EWs_{10}	15,750 ^{c}	2073 ^{bcd}	45,600 ^{f}	18,300 ^{c}	6854 ^{cde}	4635 ^{cdef}	1.81
9	$SoVc_{4:1}$ + EWs_{20}	15,800 ^{c}	2110 ^{bcd}	45,610 ^{f}	18,150 ^{c}	6997 ^{def}	4840 ^{fg}	1.81
10	$SoVc_{3:1}$ + EWs_{10}	16,800 ^{d}	2200 ^{cde}	52,380 ^{h}	13,908 ^{b}	5302 ^{b}	4700 ^{efg}	2.73
11	$SoVc_{3:1}$ + EWs_{20}	16,860 ^{d}	2250 ^{de}	52,574 ^{h}	14,015 ^{b}	5507 ^{b}	4865 ^{fg}	2.69
12	$SoVc_{1:1}$ + EWs_{10}	18,480 ^{e}	2375 ^{e}	62,500 ^{i}	7550 ^{a}	4630 ^{a}	5000 ^{g}	5.13
13	$SoVc_{1:1}$ + EWs_{20}	18,470 ^{e}	2355 ^{e}	62,400 ^{i}	7600 ^{a}	4753 ^{a}	5030 ^{g}	5.05
$HSD_{0.05}$		475.60	206.64	519.72	418.34	306.26	395.16	-
1–13		16,338	2114	48,859	15,646	6148	4551	2.24
2–5		16,445	2113	49,325	15,045	5859	4525	2.36
6–13		16,546	2168	50,408	14,903	6038	4724	2.41
6, 8, 10, 12		16,533	2155	50,344	14,941	5960	4708	2.41
7, 9, 11, 13		16,560	2181	50,496	14,904	6116	4789	2.40

Notes: No.—number; So—soil; Vc—vermicompost; EWs—earthworms; K:(Ca + Mg)—tetanic ratio; $HSD_{0.05}$—honestly significant difference at the level α = 0.05; different letter behind a numerical value corresponds to the statistically significant difference at the level 95.0%.

In plants, nutrient concentrations are significantly influenced by fertilization and variety. According to Assunção et al. [105], the differences in N concentration between varieties of carrot roots were at the level of 30% on average. The differences in the P concentration were at the level of 35%, and the differences in the K concentration were up to the level of 45%. In the leaves, except for phosphorus, the differences in N and K concentrations between varieties were smaller. According to our data (Table 6), the values of N and K concentration in carrot roots were lower compared to the data reported by Assunção et al. [105] and Aquino et al. [106]. P concentrations were comparable. The concentrations of Ca, Mg, and S were higher. In the whole carrot phytomass, the concentration of P and K also increased along with the growing concentration of N. The increase in N, P, and K concentrations in the whole carrot phytomass and the fall of Ca concentrations corresponding to the growing doses of vermicompost (tr. 1–5) are in accordance with the observations of Godlewska and Becher [107], who recorded higher concentrations of K and lower concentrations of Ca in maize plants after the application of organic fertilizers (Tables 6 and 7). In all treatments (Table 8), the recorded antagonism between K and Ca in carrot leaves and roots has already been presented in the work of Jakobsen et al. [108]. The concentration of Mg in carrot roots increased with the growing portion of Vc in the soil substrate, but it decreased in leaves (tr. 1–5). On the contrary, the concentration of S declined in roots and rose in leaves, which underlines the negative correlation between Mg and S (Table 8). However, Aulakh and Malhi [109] claimed that the interactions of nutrients with Mg and S are rare. The monitored drop of S concentration in carrot roots, along with the higher N concentration (or rising P and K concentration), is in accordance with the findings of Kováčik et al. [110] and Rietra et al. [111]. The negative relationship between the N and S concentrations recorded in roots was not detected in leaves. Kowalenko [112] drew attention to the possibility of recording both positive and negative relationships between the N and S concentrations, as well as between other mineral elements in plants.

Table 8. Correlation coefficient (r) expressing the relationships between the concentrations of individual macroelements determined in carrot roots and leaves.

Organ	Nutrient	P	K	Ca	Mg	S	No.
Roots	N	0.891 ++	0.894 ++	−0.729 ++	0.517 ++	−0.693 ++	52
	P	–	0.935 ++	−0.614 ++	0.490 ++	−0.688 ++	
	K		–	−0.629 ++	0.472 ++	−0.766 ++	
	Ca			–	−0.454 ++	0.581 ++	
	Mg				–	−0.299 +	
Leaves	N	0.779 ++	0.976 ++	−0.973 ++	−0.803 ++	0.731 ++	
	P	–	0.821 ++	−0.809 ++	−0.710 ++	0.673 ++	
	K		–	−0.994 ++	−0.829 ++	0.743 ++	
	Ca			–	0.832 ++	−0.725 ++	
	Mg				–	−0.661 ++	

Notes: +—statistically significant ($p < 0.05$); ++—statistically highly significant ($p < 0.01$); No—number of measurements.

Several publications stated that there is a negative dependence between Mg and Ca, and also between Mg and other nutrients, when taken in cationic form [18,113,114]. However, Djabou et al. [115] observed positive dependencies between Mg–Ca and between Mg–K. Similarly, in our experiments, the relationship between Mg and Ca concentrations is negative in roots, but they are positive in leaves. On the contrary, the dependencies between Mg and N, Mg and P, and Mg and K concentrations are positive in roots but negative in leaves (Table 8). The different impact of applied nutrients on the accumulation of other nutrients, depending on the analyzed organ, was recorded by Ortas [116]. The reason for the different findings for the relationships of synergism and antagonism is that these relationships are determined by many factors, including the concentration of nutrients in soil, ionic form of nutrients, soil temperature, growth phase of plants, and weather [18,111,117].

Activity of earthworms in soil increases availability of macro and microelements, including heavy metals [67,81,118–121], which leads to their significantly higher concentration in plants. The results presented in Tables 6 and 7 (tr. 2–5 vs. tr. 6–13) suggest that in the majority of cases, the slightly positive insignificant impact of earthworms was observed on the N, P, K, and Mg concentrations in roots and the N, P, K, Mg, and S concentrations in leaves. The increases in N, P, K and Mg concentrations in roots oscillated around 0.9%, 2.3%, 2.6%, and 1.2%, and in leaves (N, P, K, Mg, and S) they oscillated around 0.6%, 2.6%, 2.2%, 3.1%, and 4.4%. As a result of the activity of earthworms, the Ca concentration declined in roots by 7.1% and in leaves by 0.9%. The S concentration decreased by 9.6% in roots. The presence of EWs in soil substrate contributed to the significant increase in the only element concentration—K in both carrot roots and leaves. The concentration of sulfur decreased considerably in carrot roots but only in the treatments where the earthworms were added to the substrate.

The young green plant parts have a K:(Ca + Mg) ratio that is usually higher than 2.2, often in the range of 3:1 to 7:1. The long-term consumption of such fodder by animals (mainly by cattle) leads to calcium and magnesium deficiencies in their blood, and consequently, in the whole body. The deficiency of Ca and Mg in the mammals causes convulsions, ossifluence, garget, and death. In the past, when animal nutrition in Slovakia was based only on feeding with bulk feeds, animals often suffered from Ca and Mg insufficiency. The symptoms of so-called grass tetany often occurred [122], i.e., hypomagnesemia tetany. Nowadays, production of forage mixtures respects the tetanic ratio K:(Ca + Mg) $\leq$ 2.2:1 [21,123]. In humans, hypomagnesia mainly impairs parathyroid functioning. The parathyroid glands release a hormone that increases the level of calcium in the blood when it is low. Low Mg in the blood causes secondary Ca deficiency (hypocalcaemia), and it can lead to heart failure. When taking into consideration the role of magnesium in the protection of humans against cardiovascular diseases, heart attack, and diabetes [124], optimal concentrations of Mg in vegetables becomes an important question of their quality and of human nutrition and health [125].

The data indicated in Tables 6 and 7 show that the tetanic ratio (TR) values were higher in roots than in leaves. In carrot roots of each treatment, TR values were higher than 2.2 and varied from 5.67 to 9.40, while in leaves they varied from 1.08 to 5.13. In carrot leaves, the TR values were higher than 2.2 only in the treatments where the vermicompost accounted for 25% and 50% of the soil substrate (tr. 4, 5, 10–13). The TR values in carrot roots and leaves increased proportionally with the increasing quantity of Vc in the substrate (tr. 1–5) as a result of the fact that vermicompost contained 50.65 times more K than the used soil but only 1.66 and 7.19 times more Ca and Mg (Table 2). VC in terms of tetanic ratio worsened the quality of carrot roots. This finding proves that the fertilization by fertilizers supplying a significant amount of potassium increases the K:(Ca + Mg) ratio in the above-ground phytomass [126] regardless of the source of potassium, whether it is supplied by mineral or organic fertilizers.

The presence of EWs in growing substrates increased the TR values in roots, and in most cases, also in leaves. The average TR value in carrot roots was 7.82 for treatments without EWs (tr. 2–5) and 8.26 in the treatments with EWs. In leaves, the average TR value for treatments without EWs was 2.36 and 2.41 for treatments with EWs. TR was higher in roots for treatments with 20 individual EWs per pot when compared with the treatments with 10 individuals per pot. A similar impact of EWs numbers (10 and 20 per pot) on TR values was also recorded in carrot leaves. This observation of the effect of vermicompost and earthworms on the tetanic ratio in carrot roots and leaves is a new original finding which is beneficial, especially for vegetarians, who are more at risk of hypomagnesia than the rest of the population.

The ratio of macroelement concentration in carrot leaves and roots (Table 9) demonstrates that, apart from phosphorus, the concentrations of other macroelements (N, K, Ca, Mg, and S) were higher in the leaves than in the roots. Some citizens of Slovakia originating in Asian countries do not throw away the leaves of carrot, unlike the domestic inhabitants. The higher concentration of macroelements in the leaves than in the carrot roots may partly explain this habit. Similarly, more nitrogen and magnesium in the carrot leaves when compared to the roots of two different cultivars (winter and summer) was recorded by Assuncão et al. [105]. Aquino et al. [106] presented partially different findings, which showed that carrot leaves contained less N and K than the roots. Their observations about the allocation of other elements (P, Ca, Mg, and S) in leaves and roots correspond with the data indicated in Table 9. Regarding the different macroelements (N, P, K, Ca, Mg, and S), the quantity of crop yield is most significantly affected by nitrogen [99,127]. This is the reason why some farmers in Slovakia, who want to save money for the fertilizers (purchase and their application), often apply only nitrogen fertilizers because fertilization by K and P does not have the immediate significant positive effect on phytomass formation [128,129]. Concentration of nutrients in plants shows whether the plants are supplied by a particular element sufficiently and if the compensation of nutrition is needed via the application of fertilizers. Since different elements contribute to the phytomass formation in different amounts, farmers mostly monitor the concentration of N in plants during the whole growing season. The data presented in Table 10 affirm the significant positive dependence between the quantity of N in roots and root yield. A highly significant positive dependence was also detected between the K, P, and Mg concentrations in roots and root yield. On the contrary, a highly significant negative correlation was found between the Ca and S concentrations in roots and root yield.

The correlations of nutrition elements in field crops are based mostly on the information about the concentration of nutrients in above-ground rather than underground phytomass; therefore, in our work we also studied the dependence between the nutrient concentration in leaves and the root yield (Table 10). The highly significant positive dependencies were detected between the N, P, K, and S concentrations in leaves and the root yield, and the negative dependencies were found between the Ca and Mg concentrations in leaves and the root yield. The presented data emphasize that to improve carrot nutrition by macroelements, criteria should be developed by evaluating the concentration of macroelements in leaves and roots separately.

Table 9. Ratios of nutrient concentration in leaves and roots (L/R).

Treatment No.	Treatment Designation	N	P	K	Ca	Mg	S
1	S	2.56	0.86	1.43	10.00	4.39	1.63
2	$SVc_{9:1}$	1.82	0.53	1.31	8.67	3.38	2.27
3	$SVc_{4:1}$	1.86	0.53	1.46	9.29	3.27	2.48
4	$SVc_{3:1}$	1.75	0.56	1.64	7.93	2.59	2.55
5	$SVc_{1:1}$	1.77	0.53	1.88	4.87	2.06	2.84
6	$SVc_{9:1}$ + EWs_{10}	1.80	0.52	1.29	9.00	3.35	2.51
7	$SVc_{9:1}$ + EWs_{20}	1.80	0.52	1.28	9.39	3.41	2.64
8	$SVc_{4:1}$ + EWs_{10}	1.85	0.56	1.48	9.92	3.38	2.80
9	$SVc_{4:1}$ + EWs_{20}	1.85	0.56	1.46	10.42	3.52	2.99
10	$SVc_{3:1}$ + EWs_{10}	1.75	0.57	1.65	8.18	2.17	2.86
11	$SVc_{3:1}$ + EWs_{20}	1.73	0.58	1.65	8.30	2.24	3.04
12	$SVc_{1:1}$ + EWs_{10}	1.79	0.53	1.88	5.09	2.43	3.29
13	$SVc_{1:1}$ + EWs_{20}	1.78	0.51	1.86	5.39	2.63	3.39
1–13		1.83	0.55	1.57	0.84	2.96	2.68
2–5		1.80	0.54	1.58	7.88	2.81	2.53
6–13		1.79	0.54	1.57	8.41	2.88	2.93
6, 8, 10, 12		1.79	0.54	1.58	8.26	2.89	2.88
7, 9, 11, 13		1.79	0.54	1.56	8.57	2.94	3.00

Notes: No.—number; So—soil; Vc—vermicompost; EWs—earthworms.

Table 10. Correlation coefficient (r) expressing the relationship between the fresh root biomass and the concentration of macroelements in the carrot roots and leaves.

Dependent Parameter	Independent Parameter		r	No.
Yield of fresh carrot roots	N concentration	in roots	0.925 ++	52
	P concentration		0.864 ++	
	K concentration		0.877 ++	
	Ca concentration		−0.785 ++	
	Mg concentration		0.498 ++	
	S concentration		−0.762 ++	
	N concentration	in leaves	0.819 ++	
	P concentration		0.787 ++	
	K concentration		0.852 ++	
	Ca concentration		−0.830 ++	
	Mg concentration		−0.770 ++	
	S concentration		0.867 ++	

Notes: No.—number of measurements; ++ statistically highly significant (p < 0.01).

4. Conclusions

With the rising quantity of vermicompost in the soil substrate, the weight of carrot roots and leaves also increased. As the dose of Vc in the treatments increased, the differences in phytomass percentage increases got smaller. Surprisingly, the high proportion of Vc in the soil substrate did not have a negative effect on the formation of both carrot roots and leaves. Vc increased the weight of roots more than leaves. The values of TR in carrot roots or leaves increased proportionally with the increasing quantity of Vc in the substrate. Vc increased the water content in the roots.

The highest positive effect of EWs on carrot phytomass was observed in the treatments with the lowest quantity of Vc in the soil substrate. On the contrary, the weakest positive impact of EWs on the weight of roots and leaves was recorded in the treatments with the highest quantity of Vc in the soil substrate. EWs had a positive impact on the K concentration in carrot roots and leaves. EWs increased the numeric TR value in carrot roots more significantly than in leaves.

The concentrations of macroelements (N, K, Ca, Mg, and S) were higher in leaves than in roots. Antagonistic relationships were recorded between K × Ca and Mg × S concentrations. A positive dependence was observed between the carrot root yield and the N, P, and K concentrations in leaves and roots.

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References

1. Kwiatkowski, C.A.; Haliniarz, M.; Kołodziej, B.; Harasim, E.; Tomczyńska-Mleko, M. Content of some chemical components in carrot (*Daucus carota* L.) roots depending on growth stimulators and stubble crops. *J. Elem.* **2015**, *20*, 933–943. [CrossRef]
2. Silva Dias, J.C. Nutritional and Health Benefits of Carrots and Their Seed Extracts. *FooNutr. Sci.* **2014**, *5*, 2147–2156. [CrossRef]
3. Kováčik, P.; Wierzbowska, J.; Smoleń, S.; Polláková, N.; Jabbarov, Z. Weight of Carrot Phytomass and Content of Vitamin C 100 Days after Seeding in Dependence of Vermicompost Quantity and Earthworms (*Eisenia fetida*) in Soil Substrate. *Pol. J. Environ. Stud.* **2022**, *3*, 723–733. [CrossRef]
4. United Nations. *The World Populations Prospects: 2015 Revision. Key Findings and Advance Tables*; Working Paper No. ESA/P/WP.241; United Nations Department of Economic and Social Affairs. Population Division: New York, NY, USA, 2015. Available online: https://www.un.org/en/development/desa/publications/world-population-prospects-2015-revision.html (accessed on 1 June 2022).
5. León, A.P.; Martín, J.P.; Chiesa, A. Vermicompost application and growth patterns of lettuce (*Lactuca sativa* L.). *Agric. Trop. Subtrop.* **2012**, *45*, 134–139. [CrossRef]
6. Zayed, M.S.; Hassanein, M.K.K.; Esa, N.H.; Abdallah, M.M.F. Productivity of pepper crop (*Capsicum annuum* L.) as affected by organic fertilizer, soil solarization, and endomycorrhizae. *Ann. Agric. Sci.* **2013**, *58*, 131–137. [CrossRef]
7. Chakraborty, B.; Kundu, M.; Chattopadhyay, R.N. Organic Farming with Bio-mulching—A New Paradigm for Sustainable Leaf Yield & Quality of Mulberry (*Morus alba* L.) under Rainfed Lateritic Soil Condition. *Agric. Agric. Sci. Procedia* **2016**, *11*, 31–37. [CrossRef]
8. Gholami, H.; Fard, F.R.; Saharkhiz, M.J.; Ghani, A. Yield and physicochemical properties of inulin obtained from Iranian chicory roots under vermicompost and humic acid treatments. *Ind. Crops Prod.* **2018**, *123*, 610–616. [CrossRef]
9. Gholami, H.; Saharkhiz, M.J.; Fard, F.R.; Ghani, A.; Nadaf, F. Humic acid and vermicompost increased bioactive components, antioxidant activity and herb yield of Chicory (*Cichorium intybus* L.). *Biocatal. Agric. Biotechnol.* **2018**, *14*, 286–292. [CrossRef]
10. Najjari, F.; Ghasemi, S. Changes in chemical properties of sawdust and blood powder mixture during vermicomposting and the effects on the growth and chemical composition of cucumber. *Sci. Hortic.* **2018**, *232*, 250–255. [CrossRef]
11. Ali, M.; Griffiths, A.J.; Williams, K.P.; Jones, D.L. Evaluating the growth characteristics of lettuce in vermicompost and green waste compost. *Eur. J. Soil Biol.* **2007**, *43*, S316–S319. [CrossRef]
12. Roba, T.B. Review on: The Effect of Mixing Organic and Inorganic Fertilizer on Productivity and Soil Fertility. *Open Access Libr.* **2018**, *5*, e4618. [CrossRef]
13. Loss, A.; Couto, R.R.; Brunetto, G.; da Veiga, M.; Toselli, M.; Baldi, E. Animal Manure as Fertilizer: Changes in Soil Attributes, Productivity and Food Composition. *Int. J. Res.–Granthaalayah.* **2019**, *7*, 307–331. [CrossRef]

14. Basso, B.; Ritchie, J.T. Impact of compost, manure and inorganic fertilizer on nitrate leaching and yield for a 6-year maize–alfalfa rotation in Michigan. *Agr. Ecosyst. Environ.* **2005**, *108*, 329–341. [CrossRef]
15. Li, S.; Li, J.; Zhang, B.; Li, D.; Li, G.; Li, Y. Effect of different organic fertilizers application on growth and environmental risk of nitrate under a vegetable field. *Sci. Rep.* **2017**, *7*, 17020. [CrossRef] [PubMed]
16. Stelt, B.; Temminghoff, E.J.M.; Vliet, P.C.J.; Riemsdijk, W.H. Volatilization of ammonia from manure as affected by manure additives, temperature and mixing. *Bioresour. Technol.* **2007**, *98*, 3449–3455. [CrossRef]
17. Bhatt, M.K.; Labanya, R.; Joshi, H.C. Influence of long-term chemical fertilizers and organic manures on soil fertility—A review. *Univers. J. Agric. Res.* **2019**, *7*, 177–188. [CrossRef]
18. Kováčik, P.; Ryant, P. *Agrochemistry (Principles and Practice)*, 1st ed.; Slovak University of Agriculture in Nitra: Nitra, Slovakia, 2019; 358p.
19. Mrkvička, J.; Veselá, M. Influence of fertilization rates on species composition, quality and yields of the meadow fodder. *Plant Soil Environ.* **2002**, *48*, 494–498. [CrossRef]
20. Hejduk, S.; Doležal, P. Nutritive value of broad-leaved dock (*Rumex obtusifolius* L.) and its effect on the quality of grass silages. *Czech J. Anim. Sci.* **2004**, *49*, 144–150. [CrossRef]
21. Davydov, S.; Davydova, A.; Schelchkova, M.; Makarevich, R.; Fyodorov-Davydov, D.; Loranty, M.; Boeskorov, G. Essential mineral nutrients of the high-latitude steppe vegetation and the herbivores of mammoth fauna. *Quat. Sci. Rev.* **2020**, *228*, 106073. [CrossRef]
22. Mukherjee, A.; Speh, D.; Dyck, E.; Diez-Gonzalez, F. Preharvest evaluation of coliforms, Escherichia coli, Salmonella, and Escherichia coli O157:H7 in organic and conventional produce grown by Minnesota farmers. *J. Food Prot.* **2004**, *67*, 894–900. [CrossRef]
23. Wang, F.; Wang, X.; Song, N. Biochar and vermicompost improve the soil properties and the yield and quality of cucumber (*Cucumis sativus* L.) grown in plastic shed soil continuously cropped for different years. *Agr. Ecosyst. Environ.* **2021**, *315*, 107425. [CrossRef]
24. Doan, T.T.; Tureaux, H.T.; Rumpel, C.; Janeau, J.L.; Jouquet, P. Impact of compost, vermicompost and biochar on soil fertility, maize yield and soil erosion in Northern Vietnam: A three year mesocosm experiment. *Sci. Total Environ.* **2015**, *514*, 147–154. [CrossRef] [PubMed]
25. Yagi, R.; Ferreira, M.E.; Pessôa da Cruz, M.C.; Barbosa, J.C. Organic matter fractions and soil fertility under the influence of liming, vermicompost and cattle manure. *Sci. Agric.* **2003**, *60*, 549–557. [CrossRef]
26. Fernández-Bayo, J.D.; Nogales, R.; Omero, E.R. Assessment of three vermicomposts as organic amendments used to enhance diuron sorption in soils with low organic carbon content. *Eur. J. Soil Sci.* **2009**, *60*, 935–944. [CrossRef]
27. Mahmoud, E.K.; Ibrahim, M.M. Effect of vermicompost and its mixtures with water treatment residuals on soil chemical properties and barley growth. *J. Soil Sci. Plant Nutr.* **2012**, *12*, 431–440. [CrossRef]
28. Xu, C.; Mou, B. Vermicompost affects soil properties and spinach growth, physiology, and nutritional value. *HortScience* **2016**, *51*, 847–855. [CrossRef]
29. Aksakal, E.L.; Sari, S.; Angin, I. Effects of vermicompost application on soil aggregation and certain physical properties. *Land Degrad. Dev.* **2016**, *27*, 983–995. [CrossRef]
30. Schon, N.L.; Fraser, P.M.; Mackay, A.D.; Dickinson, N. Relationship between earthworm abundance, ecological diversity and soil function in pastures. *Soil Res.* **2021**, *59*, 767–777. [CrossRef]
31. Hallam, J.; Holden, J.; Robinson, D.A.; Hodson, M.E. Effects of winter wheat and endogeic earthworms on soil physical and hydraulic properties. *Geoderma.* **2021**, *400*, 115126. [CrossRef]
32. Ma, L.; Shao, M.; Fan, J.; Wang, J.; Li, Y. Effects of earthworm (*Metaphire guillelmi*) density on soil macropore and soil water content in typical Anthrosol soil. *Agr. Ecosyst. Environ.* **2021**, *311*, 107338. [CrossRef]
33. Goswami, L.; Nath, A.; Sutradhar, S.; Bhattacharya, S.S.; Kalamdhad, A.; Vellingiri, K.; Kim, K.-H. Application of drum compost and vermicompost to improve soil health, growth, and yield parameters for tomato and cabbage plants. *J. Environ. Manag.* **2017**, *200*, 243–252. [CrossRef] [PubMed]
34. Sinha, R.K.; Agarwal, S.; Chauhan, K.; Valani, D. The wonders of earthworms & its vermicompost in farm production: Charles Darwin's 'friends of farmers', with potential to replace destructive chemical fertilizers. *Agric. Sci.* **2010**, *1*, 76–94.
35. Sinha, R.K.; Herat, S.; Valani, D.; Chauhan, K. The Concept of Sustainable Agriculture: An Issue of Food Safety and Security for People, Economic Prosperity for the Farmers and Ecological Security for the Nations. *Am.-Eurasian J. Agric. Environ. Sci.* **2009**, *5*, 1–55.
36. Khan, K.; Pankaj, U.; Verma, S.K.; Gupta, A.K.; Singh, R.P.; Verma, R.K. Bio-inoculants and vermicompost influence on yield, quality of *Andrographis paniculata*, and soil properties. *Ind. Crops Prod.* **2015**, *70*, 404–409. [CrossRef]
37. Durak, A.; Altuntaş, Ö.; Kutsal, İ.K.; Işık, R.; Karaat, F.E. The effects of vermicompost on yield and some growth parameters of lettuce. *Turk. J. Agric. Food Sci. Technol.* **2017**, *5*, 1566–1570. [CrossRef]
38. Negi, Y.K.; Sajwan, P.; Uniyal, S.; Mishra, A.C. Enhancement in yield and nutritive qualities of strawberry fruits by the application of organic manures and biofertilizers. *Sci. Hortic.* **2021**, *283*, 110038. [CrossRef]
39. Paczka, G.; Mazur-Paczka, A.; Garczyńska, M.; Kostecka, J.; Butt, K.R. Garlic (*Allium sativum* L.) cultivation using vermicompost-amended soil as an aspect of sustainable plant production. *Sustainability* **2021**, *13*, 13557. [CrossRef]

40. Blouin, M.; Barrere, J.; Meyer, N.; Lartigue, S.; Barot, S.; Mathieu, J. Vermicompost significantly affects plant growth. A meta-analysis. *Agron. Sustain. Dev.* **2019**, *39*, 34. [CrossRef]
41. Kováčik, P.; Olšovská, K.; Smoleń, S.; Smoleń-Ledwożyw, I. Parameters of radish phytomass (*Raphanus sativus* L.) determined by vermicompost and earthworms (*Eisenia fetida*). *Folia Hortic.* **2021**, *33*, 217–233. [CrossRef]
42. Worthington, V. Nutritional quality of organic versus conventional fruits, vegetables and grains. *J. Altern. Complem. Med.* **2001**, *7*, 161–173. [CrossRef]
43. Gutiérrez-Miceli, F.A.; Santiago-Borraz, J.; Molina, J.A.M.; Nafate, C.C.; Abud-Archila, M.; Llaven, M.A.O.; Rincon-Rosales, R.; Dendooven, L. Vermicompost as a soil supplement to improve growth, yield and fruit quality of tomato (*Lycopersicum esculentum*). *Bioresour. Technol.* **2007**, *98*, 2781–2786. [CrossRef] [PubMed]
44. Demir, Z.; Kiran, S. Effect of vermicompost on macro and micro nutrients of lettuce (*Lactuca sativa* Var. Crispa) under salt stress conditions. *KSU J. Agric. Nat.* **2020**, *23*, 33–43. [CrossRef]
45. Mahmud, M.; Abdullah, R.; Yaacob, J.S. Effect of Vermicompost on Growth, Plant Nutrient Uptake and Bioactivity of Ex Vitro Pineapple (*Ananas comosus* var. MD2). *Agronomy* **2020**, *10*, 1333. [CrossRef]
46. Khomami, A.M.; Haddad, A.; Alipoor, R.; Hojati, S.I. Cow manure and sawdust vermicompost effect on nutrition and growth of ornamental foliage plants. *Cent. Asian J. Environ. Sci. Technol. Innov.* **2021**, *2*, 68–78. [CrossRef]
47. Theunissen, J.; Ndakidemi, P.A.; Laubscher, C.P. Review: Potential of vermicompost produced from plant waste on the growth and nutrient status in vegetable production. *Int. J. Phys. Sci.* **2010**, *5*, 1964–1973. [CrossRef]
48. Esmaielpour, B.; Rahmanian, M.; Khorramdel, S.; Gharavi, H. Effect of Organic Fertilizers on Nutrients Content and Essential Oil Composition of Savory (*Satureja hortensis* L.). *Agritech* **2018**, *38*, 433–441. [CrossRef]
49. Baldotto, L.E.B.; Baldotto, M.A.; Giro, V.B.; Canellas, L.P.; Olivares, F.L.; Bressan-Smith, R. Performance of 'Vitória' pineapple in response to humic acid application during acclimatization. *Rev. Bras. Ciênc. Solo* **2009**, *33*, 979–990. [CrossRef]
50. Joshi, R.; Vig, A.P.; Singh, J. Vermicompost as soil supplement to enhance growth, yield and quality of *Triticum aestivum* L.: A field study. *Int. J. Recyl. Org. Waste Agric.* **2013**, *2*, 16. [CrossRef]
51. Basak, B.B.; Jat, R.S.; Gajbhiye, N.A.; Saha, A.; Manivel, P. Organic nutrient management through manures, microbes and biodynamic preparation improves yield and quality of Kalmegh *(Andrograghis paniculata)* and soil properties. *J. Plant Nutr.* **2020**, *43*, 548–562. [CrossRef]
52. Serri, F.; Souri, M.K.; Rezapanah, M. Growth, biochemical quality and antioxidant capacity of coriander leaves under organic and inorganic fertilization programs. *Chem. Biol. Technol. Agric.* **2021**, *8*, 33. [CrossRef]
53. Eisa, E.-S.E.A.; Meligy, M.M.; Ziedan, E.-S.H.E. Application of composts and potassium sulphate on root rot incidence, morphological growth, yield components, oil content and constitutes of marjoram plants (*Majorana hortensis* L.). *Biocatal. Agric. Biotechnol.* **2022**, *42*, 102334. [CrossRef]
54. Vineet, S. Use of vermicompost in apple orchards in Himachal Pradesh, India. *Agric. Sci.* **2012**, *1*, 17–44.
55. Singh, R.; Sharma, R.R.; Kumar, S.; Gupta, R.K.; Patil, R.T. Vermicompost substitution influences growth, physiological disorders, fruit yield and quality of strawberry (*Fragaria x ananassa* Duch.). *Bioresour. Technol.* **2008**, *99*, 8507–8511. [CrossRef]
56. Abud-Archila, M.; Luján-Hidalgo, M.C.; López-Pérez, J.M.; Ordaz-Rivera, J.; Ruiz-Valdiviezo, V.M.; Oliva-Llaven, M.Á.; Gutiérrez-Miceli, F.A. Growth and fruit chemical characteristics of blackberry (*Rubus fruticosus*) cultivated with vermicompost, *Glomus mosseae* and phosphate rock. *Compost Sci. Util.* **2018**, *26*, 225–231. [CrossRef]
57. Alidadi, H.; Saffari, A.R.; Ketabi, D.; Peiravi, R.; Hosseinzadeh, A. Comparison of vermicompost and cow manure efficiency on the growth and yield of tomato plant. *Health Scope* **2014**, *3*, e14661. [CrossRef]
58. Fallah, M.; Hadi, H.; Amirnia, R.; Hassanzadeh-Ghorttapeh, A.; Zuan, A.; Tan, K.; Sayyed, R.Z. Eco-friendly soil amendments improve growth, antioxidant activities, and root colonization in lingrain (*Linum usitatissimum* L.) under drought conditions. *PLoS ONE* **2021**, *16*, e0261225. [CrossRef]
59. Sharafabad, Z.H.; Abdipour, M.; Hosseinifarahi, M.; Kelidari, A.; Rashidi, L. Integrated humic acid and vermicomposting changes essential oil quantity, and quality in field-grown *Lavandula angustifolia* L. intercropped with *Brassica nigra* L. *Ind. Crops Prod.* **2022**, *178*, 114635. [CrossRef]
60. Hemati, A.; Alikhani, H.A.; Ajdanian, L.; Babaei, M.; Lajayer, B.A.; van Hullebusch, E.D. Effect of different enriched vermicomposts, humic acid extract and indole-3-acetic acid amendments on the growth of *Brassica napus*. *Plants* **2022**, *11*, 227. [CrossRef]
61. Zewide, I.; Singh, S.; Kassa, H. Tuber yield and economics of potato as affected by application of vermicompost, mineral nitrogen and phosphorus in Southwestern Ethiopia. *Agrivita J. Agric. Sci.* **2022**, *44*, 65–73. [CrossRef]
62. Fründ, H.C.; Graefe, U.; Tischer, S. Earthworms as bioindicators of soil quality. In *Biology of Earthworms. Soil Biology*; Karaca, A., Ed.; Springer: Berlin/Heidelberg, Germany, 2011; Volume 24, pp. 261–278.
63. Bartz, M.L.C.; Pasini, A.; Brown, G.G. Earthworms as soil quality indicators in Brazilian no-tillage systems. *Appl. Soil Ecol.* **2013**, *69*, 39–48. [CrossRef]
64. Zhang, J.; Hu, F.; Li, H.; Gao, Q.; Song, X.; Ke, X.; Wang, L. Effects of earthworm activity on humus composition and humic acid characteristics of soil in a maize residue amended rice–wheat rotation agroecosystem. *Appl. Soil Ecol.* **2011**, *51*, 1–8. [CrossRef]
65. Luo, S.; Ren, L.; Wu, W.; Chen, Y.; Li, G.; Zhang, W.; Wei, T.; Liang, Y.-Q.; Zhang, D.; Wang, X.; et al. Impacts of earthworm casts on atrazine catabolism and bacterial community structure in laterite soil. *J. Hazard. Mater.* **2022**, *425*, 127778. [CrossRef]

66. Tripathi, G.; Bhardwaj, P. Comparative studies on biomass production life cycles and composting efficiency of *Eisenia foetida* (Savigny) and *Lampitomauritii* (Kinberg). *Bioresour. Technol.* **2004**, *92*, 275–283. [CrossRef]
67. Garg, P.; Gupta, A.; Satya, S. Vermicomposting of different types of waste using *Eisenia foetida*: A comparative study. *Bioresour. Technol.* **2006**, *97*, 391–395. [CrossRef]
68. García-Montero, L.G.; Valverde-Asenjo, I.; Grande-Ortíz, M.A.; Menta, C.; Hernando, I. Impact of earthworm casts on soil pH and calcium carbonate in black truffle burns. *Agroforest. Syst.* **2013**, *87*, 815–826. [CrossRef]
69. Desie, E.; van Meerbeek, K.; de Wandeler, H.; Bruelheide, H.; Domisch, T.; Jaroszewicz, B.; Joly, F.X.; Vancampenhout, K.; Vesterdal, L.; Muys, B. Positive feedback loop between earthworms, humus form and soil pH reinforces earthworm abundance in European forests. *Funct. Ecol.* **2020**, *34*, 2598–2610. [CrossRef]
70. Gong, X.; Wang, S.; Wang, Z.; Jiang, Y.; Hu, Z.; Zheng, Y.; Chen, X.; Li, H.; Hu, F.; Liu, M.; et al. Earthworms modify soil bacterial and fungal communities through enhancing aggregation and buffering pH. *Geoderma* **2019**, *347*, 59–69. [CrossRef]
71. Blanchart, E.; Albrecht, A.; Brown, G.; Decaens, T.; Duboisset, A.; Lavelle, P.; Mariani, L.; Roose, E. Effects of tropical endogeic earthworms on soil erosion. *Agr. Ecosyst. Environ.* **2004**, *104*, 303–315. [CrossRef]
72. Wu, D.; Liu, M.; Song, X.; Jiao, J.; Li, H.; Hu, F. Earthworm ecosystem service and dis-service in an N-enriched agroecosystem: Increase of plant production leads to no effects on yield-scaled N_2O emissions. *Soil Biol. Biochem.* **2015**, *82*, 1–8. [CrossRef]
73. Ejack, L.; Kernecker, M.L.; Prieto, R.; Chen, C.; Gul, S.; Bradley, R.L.; Whalen, J.K. Earthworms did not increase long-term nitrous oxide fluxes in perennial forage and riparian buffer ecosystems. *Pedobiologia* **2021**, *85–86*, 150727. [CrossRef]
74. Na, L.; Abail, Z.; Whalen, J.K.; Liang, B.; Hu, C.; Hu, R.; Wu, Y. Earthworms increase nitrogen uptake by lettuce and change short-term soil nitrogen dynamics. *Appl. Soil Ecol.* **2022**, *176*, 104488. [CrossRef]
75. Xiao, R.; Ali, A.; Xu, Y.; Abdelrahman, H.; Li, R.; Lin, Y.; Bolan, N.; Shaheen, S.M.; Rinklebe, J.; Zhang, Z. Earthworms as candidates for remediation of potentially toxic elements contaminated soils and mitigating the environmental and human health risks: A review. *Environ. Int.* **2022**, *158*, 106924. [CrossRef] [PubMed]
76. Sharma, S.; Pradhan, K.; Satya, S.; Vasudevan, P. Potentiality of Earthworms for Waste Management and in Other Uses—A Review. *J. Am. Sci.* **2005**, *1*, 4–16.
77. Russell, L.; Farrish, K.; Damoff, G.; Coble, D.; Young, L. Establishment of earthworms on reclaimed lignite mine soils in east Texas. *Appl. Soil Ecol.* **2016**, *104*, 125–130. [CrossRef]
78. Eriksen-Hamel, N.S.; Whalen, J.K. Impacts of earthworms on soil nutrients and plant growth in soybean and maize agroecosystems. *Agric. Ecosyst. Environ.* **2007**, *120*, 442–448. [CrossRef]
79. Ratsiatosika, O.; Razafindrakoto, M.; Razafimbelo, T.; Rabenarivo, M.; Becquer, T.; Bernard, L.; Trap, J.; Blanchart, E. Earthworm inoculation improves upland rice crop yield and other agrosystem services in Madagascar. *Agriculture* **2021**, *11*, 60. [CrossRef]
80. Van Groeningen, J.W.; Lubbers, I.M.; Vos, H.M.J.; Brown, G.G.; de Deyn, G.B.; Groenigen, K.J. Earthworms increase plant production: A meta-analysis. *Sci. Rep.* **2014**, *4*, 6365. [CrossRef]
81. Bertrand, M.; Barot, S.; Blouin, M.; Whalen, J.; de Oliveira, T.; Roger-Estrade, J. Earthworm services for cropping systems. A review. *Agron. Sustain. Dev.* **2015**, *35*, 553–567. [CrossRef]
82. Agarwal, S.; Sharma, J. Agronomic impact of earthworms, cow dung compost, vermicompost and chemical fertilizers on growth and yield of brinjal (*Solanum melongena*). *Int. J. Environ. Eng.* **2014**, *6*, 249–260. [CrossRef]
83. Ros, M.B.H.; Hiemstra, T.; van Groenigen, J.W.; Chareesri, A.; Koopmans, G.F. Exploring the pathways of earthworm-induced phosphorus availability. *Geoderma* **2017**, *303*, 99–109. [CrossRef]
84. Kováčik, P.; Šalamún, P.; Smoleń, S.; Škarpa, P.; Šimanský, V.; Moravčík, L'. Determination of the carrot (*Daucus carota* L.) yields parameters by vermicompost and earthworms (*Eisenia foetida*). *Potravin. Slovak J. Food Sci.* **2018**, *12*, 520–526. [CrossRef]
85. Huo, D.; Yan, K.Q.; Meng, F.H.; Zhang, H.M.; Song, Y.Z.; Hong, Y.C.; Li, L.; Cai, P.M. Improvements in the growth, quality, and yield of wuyi rock tea (*Camellia sinensis*) after breeding earthworms in situ in tea gardens in China. *Appl. Ecol. Environ. Res.* **2021**, *19*, 1491–1503. [CrossRef]
86. Hullot, O.; Lamy, I.; Tiziani, R.; Mimmo, T.; Ciadamidaro, L. The effect of earthworms on plant response in metal contaminated soil focusing on belowground-aboveground relationships. *Environ. Pollut.* **2021**, *274*, 116499. [CrossRef] [PubMed]
87. Doan, T.T.; Ngo, P.T.; Rumpel, C.; Nguyen, B.V. Interactions between compost, vermicompost and earthworms influence plant growth and yield: A one-year greenhouse experiment. *Sci. Hortic.* **2013**, *160*, 148–154. [CrossRef]
88. Nurhidayati, N.; Ali, U.; Murwani, I. Yield and quality of cabbage (*Brassica oleracea* L. var. *capitata*) under organic growing media using vermicompost and earthworm *Pontoscolex corethrurus* inoculation. *Agric. Agric. Sci. Procedia* **2016**, *11*, 5–13. [CrossRef]
89. Elmer, W.H. Effect of leaf mold mulch, biochar, and earthworms on mycorrhozal colonization and yield of asparagus affected by Fusarium crown and root rot. *Plant Dis.* **2016**, *100*, 2507–2512. [CrossRef]
90. Brown, G.G.; Barois, I.; Lavelle, P. Regulation of soil organic matter dynamics and microbial activity in the drilosphere and the role of interactions with other edaphic functional domains. *Eur. J. Soil Biol.* **2000**, *36*, 177–198. [CrossRef]
91. Liu, J.; Xu, G.; Yin, L.; Xu, X.; Armitage, D.W.; Dong, T. Invasive plants exert disproportionately negative allelopathic effects on the growth and physiology of the earthworm *Eisenia fetida*. *Sci. Total Environ.* **2020**, *747*, 141534. [CrossRef]
92. Mehlich, A. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Commun. Soil Sci. Plant Anal.* **1984**, *15*, 1409–1416. [CrossRef]
93. Bremner, J.M. Determination of nitrogen in soil by the Kjeldahl method. *J. Agric. Sci.* **1960**, *55*, 11–33. [CrossRef]

94. Dziadowiec, H.; Gonet, S.S. *A Guide to the Methods for Determination of Soil Organic Matter*; Prace Komisie Naukowej PTG: Warsaw, Poland, 1999; 65p.
95. Cohen, J.B. *Practical Organic Chemistry*; MacMillan and Co.: London, UK, 1910; p. 356.
96. Koppová, A.; Pirkl, J.; Kalina, J. Determination of ash-compounds in plant material by exact expeditive methods. In *Scientific Work of the Research Institute of Plant Production*; ČSAZV: Prague-Ruzyň, Czech Republic, 1955; pp. 119–127.
97. De Souza, Á.H.C.; Rezende, R.; Lorenzoni, M.Z.; de Seron, C.; Hachmann, T.L.; Lozano, C.S. Response of eggplant crop fertigated with doses of nitrogen and potassium. *Rev. Bras. Eng. Agr.* **2017**, *21*, 21–26. [CrossRef]
98. Essel, B.; Abaidoo, R.C.; Opoku, A.; Ewusi-Mensah, N. Economically optimal rate for nutrient application to maize in the semi-deciduous forest zone of Ghana. *J. Soil Sci. Plant Nutr.* **2020**, *20*, 1703–1713. [CrossRef] [PubMed]
99. Mojid, M.A.; Wyseure, G.C.L.; Biswas, S.K. Requirement of nitrogen, phosphorus and potassium fertilizers for wheat cultivation under irrigation by municipal wastewater. *J. Soil Sci. Plant Nutr.* **2012**, *12*, 655–665. [CrossRef]
100. Arancon, N.Q.; Edwards, C.A.; Atiyeh, R.; Metzger, J.D. Effects of vermicomposts produced from food waste on the growth and yields of greenhouse peppers. *Bioresour. Technol.* **2004**, *93*, 139–144. [CrossRef]
101. Suqiura, D.; Tateno, M. Optimal leaf-to-root ratio and leaf nitrogen content determined by light and nitrogen availabilities. *PLoS ONE* **2011**, *6*, e22236. [CrossRef]
102. Kováčik, P.; Šalamún, P.; Smoleń, S.; Renčo, M. Impact of vermicompost as component of growing medium on phytomass formation of radish (*Raphanus sativus* L.). *Agriculture* **2018**, *64*, 106115. [CrossRef]
103. Liu, C.-A.; Li, F.-R.; Zhou, L.-M.; Zhang, R.-H.; Jia, Y.; Lin, S.-L.; Wang, L.-J.; Siddique, K.H.M.; Li, F.-M. Effect of organic manure and fertilizer on soil water and crop yields in newly-built terraces with loess soils in a semi-arid environment. *Agric. Water Manag.* **2013**, *117*, 123–132. [CrossRef]
104. Sharma, K.D.; Karki, S.; Thakur, N.S.; Attri, S. Chemical composition, functional properties and processing of carrot—A review. *J. Food Sci. Technol.* **2012**, *49*, 22–32. [CrossRef]
105. Assunção, N.S.; Clemente, J.M.; de Aquino, L.A.; Dezordi, L.R.; dos Santos, L.P.D. Carrot yield and recovery efficiency of nitrogen, phosphorus and potassium. *Rev. Caatinga* **2016**, *29*, 859–865. [CrossRef]
106. Aquino, R.F.B.A.; Assunção, N.S.; Aquino, L.A.; de Aquino, P.M.; de Oliveira, G.A.; de Carvalho, A.M.X. Nutrient demand by the carrot crop is influenced by the cultivar. *Rev. Bras. Cienc. Solo* **2015**, *39*, 541–552. [CrossRef]
107. Godlewska, A.; Becher, M. The effect of waste materials on the content of some macroelements in test plants. *J. Ecol. Eng.* **2021**, *22*, 167–174. [CrossRef]
108. Jakobsen, S.T. Interaction between plant nutrients: III. Antagonism between potassium, magnesium and calcium. *Acta Agric. Scand. B Soil Plant Sci.* **1993**, *43*, 1–5. [CrossRef]
109. Aulakh, M.S.; Malhi, S.S. Interactions of nitrogen with other nutrients and water: Effect on crop yield and quality, nutrient use efficiency, carbon sequestration, and environmental pollution. *Adv. Agron.* **2005**, *86*, 341–409. [CrossRef]
110. Kováčik, P.; Kozánek, M.; Renčo, M. The effect of substrate produced from pig manure by biodegradation of larvae of house flies on the phytomass of maize (*Zea mays* L.). *Acta Fytotechn. Zootechn.* **2011**, *14*, 62–67.
111. Rietra, R.P.J.J.; Heinen, M.; Dimkpa, C.O.; Bindraban, P.S. Effects of nutrient antagonism and synergism on yield and fertilizer use efficiency. *Commun. Soil Sci. Plant Anal.* **2017**, *48*, 1895–1920. [CrossRef]
112. Kowalenko, C.G. Variations in within-season nitrogen and sulfur interaction effects on forage grass response to combinations of nitrogen, sulfur, and boron applications. *Commun. Soil Sci. Plant Anal.* **2004**, *35*, 759–780. [CrossRef]
113. Ohno, T.; Grunes, D.L. Potassium- magnesium interactions affecting nutrient uptake by wheat forage. *Soil Sci. Soc. Am. J.* **1985**, *49*, 685–690. [CrossRef]
114. Marschner, H. *Mineral Nutrition of Higher Plants*, 2nd ed.; Elsevier Academic Press: San Diego, CA, USA; London, UK, 2005; 889p.
115. Djabou, A.S.M.; Qin, Y.; Thaddee, B.; Figueiredo, P.G.; Feifei, A.; Carvalho, L.J.C.B.; Omokolo, D.N.; Li, K.; Niemenak, N.; Chen, S. Effects of calcium and magnesium fertilization on antioxidant activities during cassava postharvest physiological deterioration. *Crop Sci.* **2018**, *58*, 1385–1392. [CrossRef]
116. Ortas, I. Influence of potassium and magnesium fertilizer application on the yield and nutrient accumulation of maize genotypes under field conditions. *J. Plant Nutr.* **2018**, *41*, 330–339. [CrossRef]
117. Hoopen, F.T.; Cuin, T.A.; Pedas, P.; Hegelund, J.N.; Shabala, S.; Schjoerring, J.K.; Jahn, T.P. Competition between uptake of ammonium and potassium in barley and arabidopsis roots: Molecular mechanisms and physiological consequences. *J. Exp. Bot.* **2010**, *61*, 2303–2315. [CrossRef]
118. Sizmur, T.; Palumbo-Roe, B.; Watts, M.J.; Hodson, M.E. Impact of the earthworm *Lumbricus terrestris* (L.) on As, Cu, Pb and Zn mobility and speciation in contaminated soils. *Environ. Pollut.* **2011**, *159*, 742–748. [CrossRef] [PubMed]
119. Ruiz, E.; Alonso-Azcárate, J.; Rodríguez, L. Lumbricus terrestris L. activity increases the availability of metals and their accumulation in maize and barely. *Environ. Pollut.* **2011**, *159*, 722–728. [CrossRef] [PubMed]
120. Domínguez, J.; Gómez-Brandón, M. The influence of earthworms on nutrient dynamics during the process of vermicomposting. *Waste Manag. Res.* **2013**, *31*, 859–868. [CrossRef]
121. Du, Y.-L.; He, M.-M.; Xu, M.; Yan, Z.; Zhou, Y.-Y.; Guo, G.-L.; Nie, J.; Wang, L.-Q.; Hou, H.; Li, F.-S. Interactive effects between earthworms and maize plants on the accumulation and toxicity of soil cadmium. *Soil Biol. Biochem.* **2014**, *72*, 193–202. [CrossRef]
122. Grunes, D.L.; Welch, R.M. Plant contents of magnesium, calcium and potassium in relation to ruminant nutrition. *J. Anim. Sci.* **1989**, *67*, 3485–3494. [CrossRef]

123. Metson, A.J.; Saunders, W.M.H. Seasonal variations in chemical composition of pasture. *N. Z. J. Agric. Res.* **1978**, *21*, 341–353. [CrossRef]
124. Bo, S.; Pisu, E. Role of dietary magnesium in cardiovascular disease prevention, insulin sensitivity and diabetes. *Curr. Opin. Lipidol.* **2008**, *19*, 50–56. [CrossRef]
125. White, P.; Broadley, M. Biofortification of crops with seven mineral elements often lacking in human diets—Iron, zinc, copper, calcium, magnesium, selenium and iodine. *New Phytol.* **2009**, *182*, 49–84. [CrossRef]
126. Aydin, I.; Uzun, F. Potential decrease of grass tetany risk in rangelands combining N and K fertilization with MgO treatments. *Eur. J. Agron.* **2008**, *29*, 33–37. [CrossRef]
127. Yousaf, M.; Li, J.; Lu, J.; Ren, T.; Cong, R.; Fahad, S.; Li, X. Effects of fertilization on crop production and nutrient-supplying capacity under rice-oilseed rape rotation system. *Sci. Rep.* **2016**, *7*, 1270. [CrossRef]
128. Daoud, B.; Pawelzik, E.; Naumann, M. Different potassium fertilization levels influence water-use efficiency, yield, and fruit quality attributes of cocktail tomato—A comparative study of deficient-to-excessive supply. *Sci. Hortic.* **2020**, *272*, 109562. [CrossRef]
129. Peçanha, D.A.; Freitas, M.S.M.; Vieira, M.E.; Cunha, J.M.; de Jesus, A.C. Phosphorus fertilization affects growth, essential oil yield and quality of true lavender in Brazil. *Ind. Crops Prod.* **2021**, *170*, 113803. [CrossRef]