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Vermicompost and Vermicompost Leachate Application in Strawberry Production: Impact on Yield and Fruit Quality

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Abstract: Recycling organic waste is most important for preserving natural resources. The research objective was to quantify the effect of the application of vermicompost and vermicompost leachate on the yield and quality of strawberries and compare it with a standard fertilization program with mineral fertilizers during a 3-year production cycle. Five fertilization treatments were studied: control—without fertilizer (Ø); vermicompost (V); vermicompost + foliar application of vermicompost leachate (VL); vermicompost leachate through fertigation and foliar application (L); and mineral NPK fertilizers (NPK). The application of V positively affected strawberry yield only in the first year. In all three years of fruiting, the highest yield was measured for NPK treatment. In the first year, fertilization had no effect on fruit quality, while in the second and third years, the application of leachate led to a significantly higher concentration of total soluble solids, total anthocyanins, antioxidant activity of the fruit, and a lower concentration of total acid. Strawberries are grown for a two- or three-year production cycle, so the application of V and VL cannot maintain the yield level as was with the application of mineral NPK fertilizers. The quality of strawberry fruit, however, can be improved significantly.

Keywords: fertilizers; mineral composition; antioxidant activity

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1. Introduction

Vermicomposting represents an ecologically acceptable technology for converting organic waste into nutritious compost [1]. Vermicompost contains high concentrations of nutrients in available forms that plants absorb readily [2]. At the same time, vermicompost application can be an effective means of improving soil fertility due to the positive impact on microbiological activity and soil physical properties [3]. So far, vermicompost application has shown a positive effect on the growth of various plant species such as tomato [4], pepper [5], corn [6], strawberries [7], chickpeas [8], and many others. In addition to the solid phase, as the final product, the vermicomposting process produces leachate which can be used as a liquid fertilizer because it contains a certain amount of nutrients [9,10]. Besides necessary nutrients, vermicompost leachates also aid in the development of plants because they contain substances that control plant growth, such as humic acids, auxins (0.55–0.77 pmol mL^{-1}), gibberellins (552–656 pg mL^{-1}), and cytokinins (30–340 fmol mL^{-1}) [11,12], which control a variety of processes related to plant growth and yield, including the absorption of macro- and micronutrients. Additionally, according to several authors, the application of vermicompost improves the fruit's nutritional qualities [6,13,14]. Other studies support the positive effects of the application of vermicompost leachates on the increased resistance to salt stress of white stonecrop (*Sedum album*) and pomegranate (*Punica granatum*) seedlings [15,16] as well as the increased growth of Chinese cabbage (*Brassica pekinensis*) and tomato (*Lycopersicon esculentum*) [10,17].

The strawberry (*Fragaria ananassa* Dush.) is a hugely popular and economically important fruit species in many countries, including Serbia. In 2020, the value of strawberry output globally was USD 14 billion [18]. The strawberry is a cosmopolitan plant that can be grown on different soil types and altitudes. All over the world, the area under strawberry cultivation has increased significantly in the last decade, mainly due to the increased demand [19]. Strawberry fruits are a great source of nutrients, and several bioactive substances that may be beneficial to human health. Strawberry fruits may contain antioxidant, anticancer, anti-inflammatory, and antineurodegenerative biological activities because of their high polyphenol content, particularly anthocyanins [20]. These properties of strawberry fruits can be greatly influenced by agronomical practices, especially fertilization [21].

The objective of this research was to compare and quantify the impact of vermicompost and vermicompost leachate application on the yield and quality of strawberries concerning the mineral NPK fertilization during a 3-year production cycle.

2. Materials and Methods

2.1. Experimental Site

The field experiment was conducted during 2009–2012 at a location near Novi Sad, Serbia: (45°20′24.44″ N, 19°50′22.32″ E). The experiment was conducted on clay loam soil classified as Phaeozem (the dominant soil type in northern Serbia). The soil was slightly alkaline (7.92 pH in H_2O) with a low content of calcium carbonate (0.83%) and organic matter (2.05%). The content of available phosphorus was low (24.9 mg kg^{-1} P), while the content of available potassium was at an optimal level (179 mg kg^{-1} K). The concentrations of the available form of microelements were as follows: 2.06 mg kg^{-1} DTPA-Fe; 18.56 mg kg^{-1} DTPA-Mn; 0.89 mg kg^{-1} DTPA-Cu; 1.26 mg kg^{-1} DTPA-Zn.

The experimental plot was equipped with a drip irrigation system with water from an artesian well. Irrigation was carried out every year from April to September when the irrigation system was automatically switched on to keep the soil moisture tension within the range of 15 to 25 kPa. A tensiometer was used to monitor soil moisture 15 cm below the surface in the space between two strawberry plants. The chemical properties of irrigation water were as follows: dry residue 431 mg L^{-1}; pH 7.31; EC 0.71 dS m^{-1}; HCO_3^- 6.83 meq L^{-1}; Cl^- 3.46 meq L^{-1}; SO_4^{-2} 2.03 meq L^{-1}; Ca^{2+} 2.11 meq L^{-1}; Mg^{2+} 3.02 meq L^{-1}; Na^+ 3.98 meq L^{-1}; K^+ 0.07 meq L^{-1}; Fe 1.1 mg L^{-1}; Mn 0.11 mg L^{-1}; Cu < 0.01 mg L^{-1}; Zn 0.026 mg L^{-1}.

The average air temperature and precipitation data in the study years were obtained from on-site meteorological stations and are presented in Figure 1.

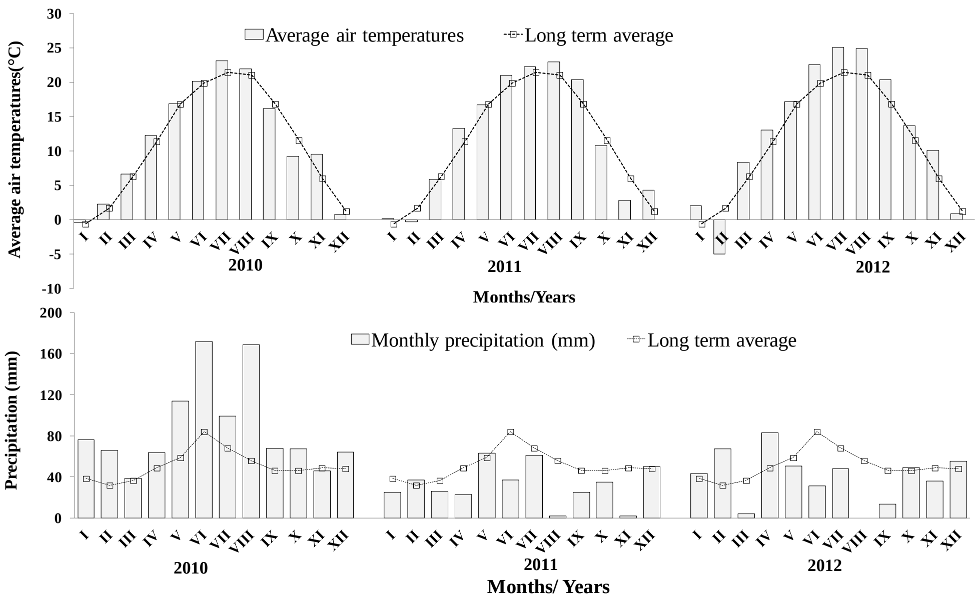

Figure 1. Average air temperature and total monthly precipitation for hydrological years (2010–2012).

2.2. Experiment Design

The experiment included five treatments arranged as completely randomized block designs in four replications. Each individual trial plot consisted of 10 strawberry plants of the June-bearing cultivar Senga Sengana, and the experiment consisted of a total of 20 plots. The experiment was set up on a plot where mineral fertilizers had not been applied for the past 3 years, and the crop that preceded the planting of strawberries was winter wheat. After the wheat harvest in mid-July 2009, the harvest residues were removed from the plot, and the soil was plowed and prepared for planting strawberry seedlings.

A week before strawberry planting, raised beds 15 cm high and 80 cm wide were formed with two drip irrigation hoses with a dropper capacity of 2 dm^{-3} h^{-1}. After that, 50 μm thick and 1.3 m wide black polyethylene perforated foil (10 plants per m^2) was stretched over the raised beds. Strawberry planting was performed manually on 23 July 2009. During the entire period of the experiment, fungicides were applied every year to prevent the most prevalent strawberry diseases: common leaf spot (*Mycosphaerella fragariae*) and fruit rot (*Botrytis cinerea*).

The experiment consisted of five fertilization treatments:

1. Control treatment—no fertilization (Ø).
2. Preplant application of vermicompost in the amount which adds 170 kg N ha^{-1} (V) to the soil.
3. Preplant application of vermicompost (170 kg N ha^{-1}) and foliar application of vermicompost leachate during vegetation (four times during April–May and three times in 15-day intervals during July–August (seven sprays per year in total) (VL)).
4. Foliar application and fertigation with vermicompost leachate (four times during April–May and three times in 15-day intervals during July–August (seven sprays per year in total) (L)).
5. Standard fertilization with mineral fertilizers (NPK). A total of 60 kg N ha^{-1}, 30 kg P_2O_5 ha^{-1}, and 80 kg K_2O ha^{-1} were applied each year as ammonium nitrate, superphosphate, and potassium nitrate, respectively.

In treatments 2 and 3 (V and VL), the vermicompost was incorporated into the surface soil layer (0–30 cm) 1 week before strawberry planting (23 July 2009). At the same time, in treatment 5 (NPK treatment), 300 kg ha^{-1} of compound mineral fertilizer 8:16:24 and 100 kg of ammonium nitrate were applied. Additionally, in this treatment, as a standard fertilization practice, mineral NPK fertilizers were applied through a drip irrigation system once a week from April to mid-September in all three growing seasons. The total applied amounts of nitrogen, phosphorus, and potassium through different fertilization treatments, as well as the time and method of fertilizer application, are shown in Table 1.

Table 1. Total amounts of nitrogen, phosphorus, and potassium applied through different fertilization treatments, time, and method of fertilizer application.

Fertilization Treatments	Time and Method of Fertilizer Application								
	Before Planting (Year 2009) (Plowed)			During Vegetation (Years 2009–12) (Fertigation)			During Vegetation (Years 2009–12) (Foliar Application)		
	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Ø	-	-	-	-	-	-	-	-	-
V	170	251	110	-	-	-	-	-	-
V + L	170	251	110	-	-	-	2.5	4.47	6.3
L	-	-	-	25	44.5	63	2.5	4.47	6.3
NPK	60	80	120	70	40	80	-	-	-

Ø, control; V, vermicompost; V + L, vermicompost + leachate; L, leachate; NPK, mineral fertilizer.

The application of mineral fertilizers was carried out under the same conditions during the growing season when vermicompost leachate was applied, with two-thirds of the total amount of fertilizer applied in the first half of the growing season (before the strawberry blossoms), while the rest was applied in the second half of the growing season during August and September each year.

The vermicompost leachate used in this research was collected on the same farm where the vermicompost was produced. The required amount of vermicompost leachate used during the growing season was collected every year in the spring. Every year before application, the samples of vermicompost leachate were analyzed, and the average values of the chemical composition of three samples (for three years of application) are shown in Table 2. During the growing season, vermicompost leachate was stored in a refrigerator at a temperature of 4 °C.

Table 2. Chemical properties of organic fertilizers.

Chemical Properties	Organic Fertilizers	
	Vermicompost	Vermicompost Leachate
Bulk density (g cm^{-3})	-	1.05
Dry mater (g kg^{-1})	754	12.6 ± 0.64
pH	7.56	7.21 ± 0.11
Total N (g kg^{-1})	19.9	0.357 ± 0.05
NO_3-N (mg kg^{-1})	450	306.2 ± 47.2
NH_4-N (mg kg^{-1})	86.1	50.5 ± 11.15
Organic C (g kg^{-1})	274	17.5 ± 1.94
C/N ratio	13.8	49.2 ± 2.30
Total P (g kg^{-1})	13.2	0.28 ± 0.06
Water soluble P (mg kg^{-1})	621	0.028 ± 0.0006
Total K (g kg^{-1})	10.5	0.75 ± 0.14
Water soluble K (mg kg^{-1})	798	0.075 ± 0.22
Total Ca (g kg^{-1})	18.6	0.102 ± 0.02
Total Mg (g kg^{-1})	6.50	0.074 ± 0.015
Fe (mg kg^{-1})	1054	96 ± 13.05
Mn (mg kg^{-1})	171	1.35 ± 0.91
Cu (mg kg^{-1})	8.90	2.5 ± 0.86
Zn (mg kg^{-1})	45.2	3.0 ± 0.90

For fertigation, aqueous vermicompost extracts were prepared by diluting vermicompost leachate with tap water at a ratio of 1:2 (vol/vol). Before application, the solution was filtered through filter paper and applied at the rate of 2 L m^{-2}. Foliar application of vermicompost leachate at the rate of 0.1 L m^{-2} (filtered undiluted solution) was performed with a hand sprayer in all three growing seasons. Fertigation with vermicompost leachate was performed at the same time as the foliar application. Prior to the application of vermicompost leachate, all the plots were irrigated for an hour before the leachate application. The chemical compositions of applied vermicompost and vermicompost leachate are presented in Table 2.

2.3. Measurements and Analytical Determination

The soil pH value was measured in a soil/water suspension (1:2.5 ratio, respectively) with a Metrel MA 3657 pH meter. The calcium carbonate ($CaCO_3$) content in the soil was measured using a Scheibler calcimeter, a volumetric method. Soil organic matter (organic C) was analyzed by a CHNS analyzer (Elementar Vario EL, GmbH, Hanau, Germany).

Available-form phosphorus and potassium in the soil were analyzed after extraction with an AL solution (0.1 mol L^{-1} ammonium lactate and mol L^{-1} acetic acid, pH 3.75) at a soil-to-solution ratio of 1:20 (w/v) [22]. The concentration of available phosphorus was measured spectrophotometrically, while the concentration of K was measured by flame photometric technique. Plant-available fractions of Fe, Mn, Cu, and Zn in the soil samples were measured after extraction with DTPA-TEA buffer (0.005 mol L^{-1} DTPA + 0.01 mol L^{-1} $CaCl_2$ + 0.1 mol L^{-1} TEA)) by an atomic absorption spectrometer (Shimadzu 6300, Kyoto, Japan). The dry matter content in vermicompost was determined using the gravimetric method by drying to a constant weight at 70 °C for 24 h.

Ground samples of vermicompost were analyzed for total C and N using an automated CHNS analyzer (Elementar Vario EL, GmbH, Hanau, Germany).

The contents of K, Fe, Mn, Cu, and Zn in vermicompost and vermicompost leachate were analyzed by the wet digestion method (mixture of HNO_3:$HClO_4$), while the concentrations of these elements in the solution were determined by the method of atomic absorption spectrophotometry (AAS, Shimadzu 6300). The concentration of P in vermicompost and leachate was measured by the spectrophotometric molybdovanadate method after wet digestion with hydrochloric acid [23]. Mineral N in the vermicompost was extracted by 2 mol L^{-1} KCl (1:4, soil-to-solution ratio, weight basis) and determined by steam distillation [24].

The strawberry yield was calculated by taking into account all harvested fruits. In order to determine the average weight of the fruit, 30 strawberry fruits were randomly selected from each repetition at the peak of the harvest period and weighed separately. The quality parameters of strawberry fruit were determined from the same samples taken for average weight.

The TMS-PRO texture analyzer (Food Technology Corporation—Sterling, VA, USA) with a 5 mm diameter stainless steel probe was used for determining the strawberry fruit firmness. The firmness of the fruit represents the mean value of the resistance force of strawberry fruit from the equatorial side and is measured in newtons (N).

Strawberry fruit color was measured using the Konica Minolta CR-400 three-filter colorimeter (Mississauga, ON, Canada). The measured color values of strawberry fruit are based on the CIE $L^*a^*b^*$ color system (Commission Internationale de l'Éclairage or International Commission on Illumination, CIE), where value L^* represents the luminance (illumination, lightness), and a^* and b^* represent the color. Based on the obtained readings for the values of a^* and b^*, value C was calculated, which represents the chromaticity or purity of the color, as well as the angle h°, which defines the intensity of the red color (0° = purple red, 90° = yellow, 180° = bluish-green, 270° = blue) [25].

Fruit slices, obtained from 30 whole berries in 4 replicates, were homogenized in a blender and used to determine total soluble solids (TSS) and titratable acidity (TA).

The concentration of TSS (expressed in Brix°) in the fresh mass of strawberry fruit was measured by direct reading using a hand-held refractometer (Hunan Xiangxin instruments, Changsha, China), whereas TA was measured on filtered strawberry juice by the titration method with 0.1 M NaOH (the equivalence point was at pH 8.1). The volume of NaOH solution used for titration was multiplied by the correction factor (0.64), and the results were expressed as percentages.

The concentration of total anthocyanins in the fresh fruits of strawberries was determined by the pH differential method with two buffer systems as buffer solutions: potassium chloride, pH 1 (0.025 mol L^{-1}), and sodium acetate, pH 4.5 (0.4 mol L^{-1}) [26]. The anthocyanin content in the fresh strawberry fruit mass was expressed in mg of pelargonidin-3-glucoside equivalents per 100 g of fresh strawberry fruit. In the same samples, the antioxidant activity of strawberry fruit was determined by the FRAP method (ferric reducing antioxidant power) [27]. The total antioxidative capacity of strawberry fruit was expressed in FRAP units, wherein one FRAP unit is equivalent to 100 µM Fe^{2+}.

To determine the mineral composition, thirty whole berries randomly selected from each replicate were mixed thoroughly and then dried at 80 °C for 72 h to the constant weight in a forced air oven. After that, the mineral composition was determined by the method of wet digestion with nitric acid (HNO_3) in a microwave oven at a temperature of 200 °C and a pressure of 170 psi, while the concentrations of K, Ca, Mg, Fe, Mn, Cu, and Zn in the obtained solution were measured by atomic absorption spectrophotometry (Shimadzu 6300).

2.4. Statistics

All data obtained by measurements in the field experiment were subjected to analysis of variance (ANOVA), and the significance of differences between treatment means was assessed using Tukey's test (probability level, $p < 0.05$). The statistical analyses were performed using the STATISTICA 9.0 software (StatSoft Inc., Tulsa, OK, USA).

3. Results

3.1. Strawberry Yield

The preplant application of vermicompost (treatments V and V + L) and standard fertilization with mineral fertilizers (NPK) had a positive effect on the total yield of strawberries in the first year of fruiting (Figure 2). In these treatments, the strawberry yield ranged between 902 and 947 g plant^{-1} and was significantly higher than the yield achieved on the control (737 g plant^{-1}) and L treatment (751 g plant^{-1}) (Figure 2). However, in the second and third years of fruiting, a significantly higher strawberry yield compared to control was recorded only in the NPK treatment, whereas the residual effects of vermicompost application (V and V + L treatments) were not detected in the second and third fruiting years of strawberries (Figure 2). In the first fruiting year, the number of flowers per strawberry plant on the V, V + L, and NPK treatments was significantly higher compared to control. On the other hand, in the second and third year of fruiting, only the plants in the NPK treatment had a significantly higher number of flowers compared to the control and other fertilization treatments. In all three fruiting years, the average fruit weight did not differ significantly between treatments (Figure 2).

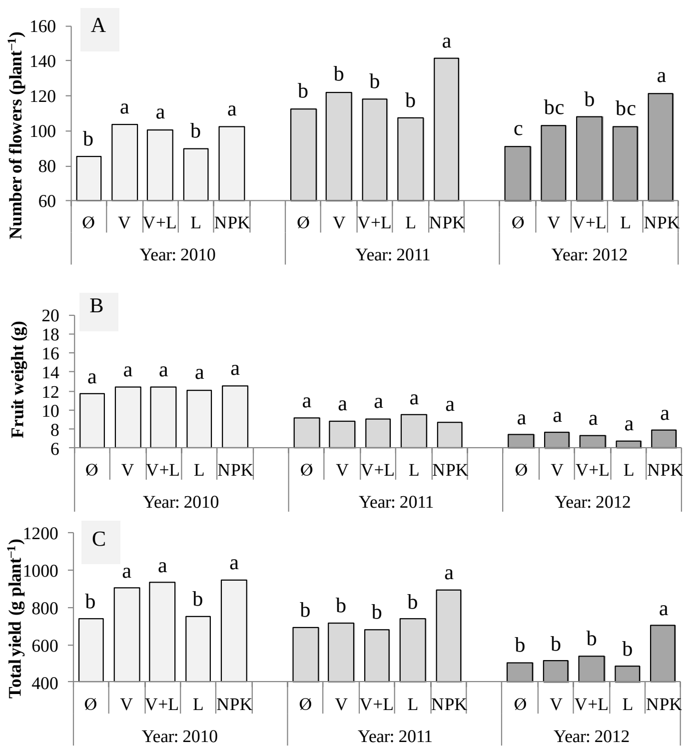

Figure 2. The total number of flowers (**A**), average strawberry fruit weight (**B**), and total yield of strawberries (**C**). Ø, control; V, vermicompost; V + L, vermicompost + leachate; L, leachate; NPK, mineral fertilizer. Different letters denote a significant difference at $p < 0.05$ for each year separately.

3.2. Mineral Composition of Strawberry Fruit

The mineral composition of strawberry fruit over three years of fruiting is shown in Table 3. In the first year of fruiting, in all four fertilization treatments, the concentration of K in strawberry fruit was significantly higher compared to control. In the second and third years of fruiting, a higher concentration of K compared to control was measured only in treatments L and NPK. On the other hand, the application of vermicompost and leachate did not lead to a significant increase in the concentration of the other elements. In contrast, standard fertilization with NPK fertilizers led to increased concentrations of K, Fe, Mn, Cu, and Zn in strawberry fruit in all three years of fruiting.

Table 3. Mineral composition of strawberry fruit.

Fertilization	K g kg^{-1}	Ca g kg^{-1}	Mg g kg^{-1}	Fe mg kg^{-1}	Mn mg kg^{-1}	Cu mg kg^{-1}	Zn mg kg^{-1}
2010 (First Fruiting Year)							
Ø [1]	1.11 c	125 a	102 a	3.98 b	3.72 b	0.39 a	0.80 c
V	1.26 b	120 a	102 a	5.13 ab	3.99 b	0.38 a	0.83 bc
V + L	1.27 b	117 a	96 a	5.75 ab	3.79 b	0.37 a	0.95 b
L	1.42 a	119 a	105 a	4.47 ab	3.95 b	0.38 a	0.74 c
NPK	1.37 ab	114 a	112 a	6.99 a	4.98 a	0.42 a	1.19 a
2011 (Second Fruiting Year)							
Ø	1.32 c	149 a	125 a	6.60 b	5.82 b	0.70 b	1.21 b
V	1.34 bc	152 a	130 a	6.17 b	6.22 b	0.79 b	1.23 b
V + L	1.36 b	155 a	126 a	5.44 b	6.35 b	0.65 bc	1.21 b
L	1.60 a	135 a	129 a	6.35 b	6.06 b	0.52 c	1.25 b
NPK	1.53 ab	146 a	137 a	10.5 a	9.08 a	0.94 a	1.35 a
2012 (Third Fruiting Year)							
Ø	1.56 b	171 a	148 ab	3.61 b	3.37 b	0.34 b	0.57 b
V	1.59 b	155 a	136 b	3.44 b	3.45 b	0.22 c	0.74 b
V + L	1.42 b	157 a	133 b	3.27 b	2.27 c	0.28 bc	0.75 b
L	1.92 a	154 a	143 ab	3.32 b	3.33 b	0.31 bc	0.66 b
NPK	1.86 a	152 a	157 a	6.90 a	5.25 a	0.51 a	1.02 a

Ø, control; V, vermicompost; V + L, vermicompost + leachate; L, leachate; NPK, mineral fertilizer. Different letters denote a significant difference at $p < 0.05$ for each year separately.

3.3. Strawberry Color and Mechanical Properties

Fertilization treatments had a significant effect on fruit color parameters in all three years of fruiting (Table 4). In the first 2 years of fruiting, the lowest values of h° were measured in treatment V. In addition to a more intense color, strawberry fruits in this treatment were characterized by lower chromaticity (lower C values) compared to NPK treatment and control. The application of NPK fertilizers had the opposite effect from the application of leachate. Strawberry fruits in this treatment were characterized by lighter (higher L values) and more chromatic colors (higher C values) but less redness (higher h° values) compared to treatment L. The application of vermicompost (V and V + L treatments) did not significantly affect the color of the strawberry fruit (Table 4).

Figure 3 shows the parameters of strawberry fruit quality depending on the fertilization treatment during the three years of fruiting. The application of vermicompost leachate led to a higher TSS concentration and a higher TSS/TA ratio compared to control. Additionally, leachate application led to a significantly higher concentration of anthocyanins and antioxidant activity of the fruit (FRAP) not only in the control but also in the NPK treatment. On the other hand, the lowest firmness of strawberry fruit in all three years was measured on the treatment where vermicompost leachate was applied (L treatment). Strawberry fruit quality parameters in treatment V, in all three years of fruiting, did not differ significantly compared to the control treatment without fertilization.

Table 4. Strawberry fruit color parameters (L, lightness; C, chromaticity; h°, intensity of red color).

	2010		
Fertilization	L	C	h°
Ø	29.6 a	35.5 a	27.7 ab
V	29.5 a	32.3 ab	29.4 ab
V + L	30.6 a	34.8 a	29.2 ab
L	28.9 a	30.9 b	26.8 b
NPK	30.7 a	35.4 a	29.9 a
	2011		
	L	C	h°
Ø	30.4 a	29.0 a	29.8 ab
V	29.7 ab	27.9 ab	32.8 a
V + L	30.6 a	28.4 a	31.0 ab
L	28.6 b	25.3 b	29.7 b
NPK	31.2 a	30.0 a	33.1 a
	2012		
	L	C	h°
Ø	33.3 ab	38.2 b	33.5 b
V	33.4 ab	37.1 bc	33.6 b
V + L	31.9 b	35.0 cd	34.5 b
L	32.3 b	33.4 d	33.7 b
NPK	34.7 a	41.5 a	37.3 a

Ø, control; V, vermicompost; V + L, vermicompost + leachate; L, leachate; NPK, mineral fertilizer. Different letters denote a significant difference at $p < 0.05$ for each year separately.

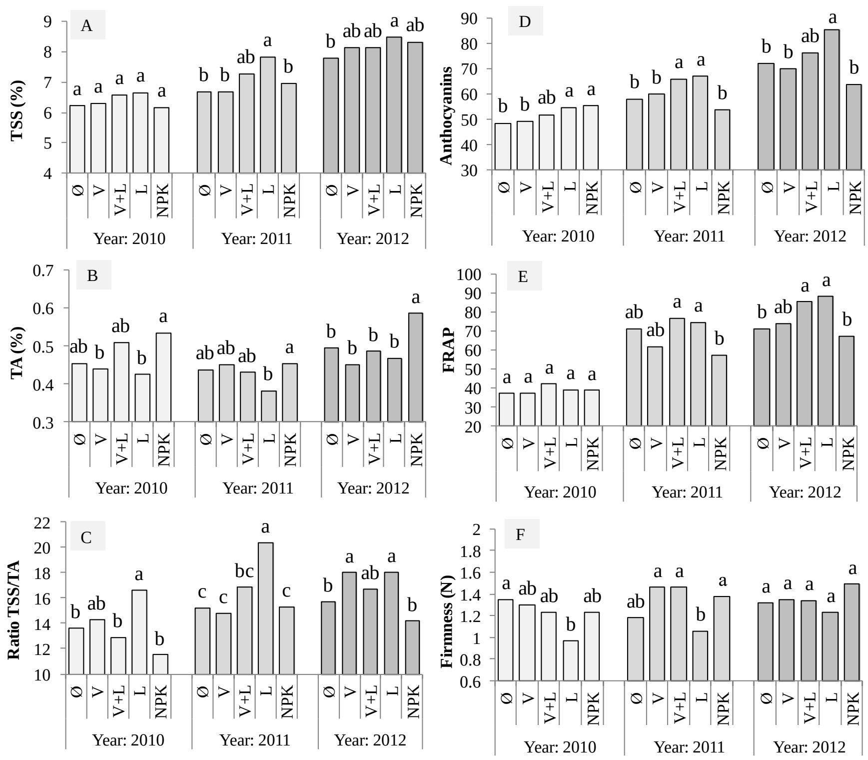

Figure 3. The concentration of total soluble solids (TSS) (**A**), total acids (TA) (**B**) and the ratio between TSS and TA (**C**), anthocyanins (mg cyanidin-3-glucoside/100 g of fruit) (**D**), antioxidant activity (FRAP units) (**E**), and the firmness of strawberry fruit (**F**). Ø, control; V, vermicompost; V + L, vermicompost + leachate; L, leachate; NPK, mineral fertilizer. Different letters denote a significant difference at $p < 0.05$ for each year separately.

4. Discussion

The treatments where vermicompost was applied at the time of planting (treatments V and V + L) and the treatment with a standard fertilization program with NPK fertilizers led to a significant increase in strawberry yield in the first year of fruiting. In these treatments, the yield of strawberries ranged between 813 and 829 g plant^{-1}, respectively, and was significantly higher than the control (693 g plant^{-1}) and the treatment where vermicompost leachate was applied (705 g plant^{-1}) (Figure 2). Such results are in agreement with the previous research by [25,28], who also reported the positive effect of the preplant application of vermicompost on strawberry yield. However, in the second and third years of fruiting, a significantly higher strawberry yield compared to control was observed only in the NPK treatment, while the residual effects of vermicompost application were not registered in the second and third years of fruiting (Figure 2).

In our study, vermicompost was applied prior to strawberry planting. Due to favorable conditions for mineralization (favorable temperatures for mineralization during August), most of the nitrogen from vermicompost likely became available to the strawberry plants in the year of application. In this case, the release of nutrients and primarily nitrogen from the vermicompost coincided with the period of flower differentiation. It is possible that the plants formed a higher reserve of N, leading to more flowers per plant in the first year of fruiting (Figure 2), which in turn led to an increase in yield due to a higher number of fruits per strawberry plant [29,30].

The application of vermicompost leachate in our study did not increase strawberry yield, which is in contrast to the studies of [31,32], who reported the positive effect of foliar application (seven times during vegetation) of compost extract on strawberry yield. The reason for the absence of a positive influence of vermicompost leachate on the yield of strawberries in our study may be the relatively high fertility of the soil on which the experiment was conducted, and the relatively low nitrogen content in vermicompost leachate (Table 2).

The application of vermicompost significantly increased the concentration of K and Zn in strawberry fruit only in the first year of fruiting, while the fertigation and foliar application of vermicompost leachate (L treatment) significantly increased the concentration of K compared to control during all three years of fruiting.

On the other hand, in the NPK treatment, where fertilization was performed during all three years of fruiting, the concentrations of K, Fe, Mn, and Zn in strawberry fruit were significantly higher compared to control. These results are consistent with the research of [33,34], who also reported the positive influence of fertilization with macroelements, primarily nitrogen, on the uptake of microelements.

The concentration of TSS in strawberry fruit, in all three years of fruiting, had values that ranged from 6.01% to 8.47%. In the first year, no significant differences were registered between treatments regarding TSS concentration in strawberry fruit, despite a significant difference in yield between treatments. In the first year of fruiting, significantly more precipitation was measured not only compared to the second and third years of fruiting but also compared to the long-term average (Figure 1). Heavy precipitation, combined with cloudy weather, may be the reason why the concentration of TSS in strawberry fruit did not differ significantly between treatments. Ref. [35] also reported the enormous influence of weather conditions during strawberry harvest on the concentration of TSS and the chemical composition of strawberry fruit in general. In the second and third years of fruiting, the highest TSS concentration was measured on treatment L, which led to a significantly higher TSS/TA ratio compared to other treatments.

The authors of [31] also reported a higher TSS concentration and lower TA values in strawberry fruit compared to the control treatment due to the application of vermicompost leachate. According to [36], the foliar application of a vermicompost extract led to an increase or decrease in fruit firmness depending on the tomato variety, while in all varieties, it led to a decrease in the concentration of ascorbic acid. On the other hand, the highest TA was measured in the fruits on NPK treatment. The increased acidity of strawberry fruit may be a consequence of the higher amount of N applied on this treatment (compared to other treatments), which could lead to higher fruit acidity and a lower TSS/TA ratio [21,37].

The highest anthocyanin concentration and antioxidant activity of the fruit (FRAP values) were measured on the treatment where vermicompost leachate was applied. The vermicompost leachate used in our study had a relatively high K concentration (Table 2), which may have affected the anthocyanin concentration in strawberry fruit [38]. Additionally, vermicompost leachate contains phytohormones [11,12], which could have a significant role in increasing the concentration of anthocyanins in strawberry fruit, especially gibberellic acid [39].

The higher concentration of anthocyanins due to the application of vermicompost leachate resulted in a change in the color of strawberry fruit [40], so the fruits had a more intense red color (lower values of h°) and a darker and less chromatic color compared to the treatment with NPK fertilizers, and in some years, compared to the control as well.

Additionally, the higher concentrations of TSS and anthocyanins and the darker fruit color all indicate a higher degree of fruit maturity, which explains why the fruits had the lowest fruit firmness after the application of vermicompost leachate [41].

The influence of fertilization treatment on certain parameters of strawberry quality differed between the years of fruiting, which indicates the existence of interactions between external factors (temperature, precipitation, etc.) and applied fertilizers [37].

5. Conclusions

The results showed that the preplant application of vermicompost applied in a relatively small dose (equivalent to 170 kg N/ha) had a positive effect on the yield, which in the first year of fruiting was comparable to the yield obtained in the treatment with the standard application of NPK fertilizers. On the other hand, in the second and third years of fruiting, the yield on this treatment was at the level of the control treatment (without fertilization) and significantly lower compared to the treatment with standard fertilization with NPK fertilizers.

The application of vermicompost leachate by fertigation and foliar application did not affect strawberry yield but had a positive effect on strawberry fruit quality parameters such as total soluble solids, total anthocyanins, and antioxidant activity of strawberry fruit. If strawberries are grown for 2 or 3 years in the same place, the preplant application of vermicompost and vermicompost leachate application during vegetation cannot maintain the yield level as with the application of mineral NPK fertilizers, but the quality of strawberry fruit can be improved significantly.

Recycling of organic wastes is becoming increasingly important as the need to protect natural resources grows, and vermicomposting as a technology can certainly make a significant contribution. Further research should provide answers to the economic aspects of the application of vermicompost and vermicompost leachate in strawberry production as well as answers to the eventual contamination of strawberry fruit with harmful substances that can be found in organic fertilizers.

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