agronomy

Article

Municipal Waste Degradation by Vermicomposting Using a Combination of *Eisenia fetida* and *Lumbricus rubellus* Species

Hira Khalid [1], Amir Ikhlaq [2], Usman Pervaiz [1], Young-Min Wie [3], Eui-Jong Lee [4] and Kang-Hoon Lee [5,*]

[1] Faculty of Engineering, Lahore Leads University, Lahore 54000, Pakistan; usman.dpk2@gmail.com (U.P.)
[2] Institute of Environmental Engineering and Research, University of Engineering and Technology, Lahore 47050, Pakistan
[3] Department of Materials Engineering, Kyonggi University, Suwon 16227, Gyeonggi-do, Republic of Korea
[4] Department of Environmental Engineering, Daegu University, 201 Daegudae-ro, Jillyang, Gyeongsan-si 38453, Gyeongsangbuk-do, Republic of Korea
[5] Department of Energy and Environmental Engineering, The Catholic University of Korea, 43 Jibong-ro, Bucheon-si 14662, Gyeonggi-do, Republic of Korea
* Correspondence: diasyong@catholic.ac.kr

Abstract: Earthworms have been commonly used for solid waste management by employing the process of vermicomposting. In this study, we used two different types of earthworm for vermicomposting and analyzed their efficacy for plant production in comparison to chemical fertilizer. The worms used for vermicomposting included *Eisenia fetida* (EF) and *Lumbricus rubellus* (LR), and we studied compost efficiency for the harvesting of spinach and turnips. The parameters we used to evaluate the performance of the produced compost on crops were variations in sprouting time, harvesting time, plant height, and plant yield. For the production of compost, the waste was collected and degraded in an environment where various parameters, including pH, moisture content, temperature, carbon, and nitrogen, were measured regularly throughout the experiment. The compost obtained from these three setups was used as a fertilizer to grow spinach and turnip. Compost efficiency was compared based on plant yield, plant height, sprouting, and harvesting time. In the case of turnip, the combination worm compost yielded 38% and 58% more than the compost obtained using EF and LR, respectively. For spinach, the EF–LR combined compost gave similar results, 17.4% and 37.9% more yield than the above two worms individually. The study's results showed that the compost obtained by the combination of worms is more promising than the compost obtained from a single species and applied as fertilizer. Moreover, the comparative evaluation by statistical analysis confirmed that growing spinach by combined compost would be a better option compared to growing turnip, due to higher significant difference in outcome parameters.

Keywords: solid waste management; vermicomposting; worm; compost

Citation: Khalid, H.; Ikhlaq, A.; Pervaiz, U.; Wie, Y.-M.; Lee, E.-J.; Lee, K.-H. Municipal Waste Degradation by Vermicomposting Using a Combination of *Eisenia fetida* and *Lumbricus rubellus* Species. *Agronomy* **2023**, *13*, 1370. https://doi.org/10.3390/agronomy13051370

Academic Editors: Xuguang Xing, Ankit Garg and Long Zhao

Received: 20 April 2023
Revised: 2 May 2023
Accepted: 10 May 2023
Published: 12 May 2023

1. Introduction

Solid waste management is considered a major issue in South Asian nations. While some environmental conservation strategies have been formulated, they are only enforced in cities, whereas open dumping is the method of disposal in rural areas [1]. There are various stages of solid waste management: primary collection, secondary collection, and final disposal at landfill sites [2]. Solid waste dumping sites pose serious environmental problems to the air, soil, surface water, and groundwater. Landfill leachate contains thousands of complex chemicals, such as heavy metals, and becomes part of groundwater after infiltration [3,4]. Poor and inadequate solid waste management is one of the main reasons for environmental degradation [5,6]. Moreover, with time, waste quantity is going to increase due to changing life patterns and increasing populations. The impact of waste on the ecosystem largely depends on its composition and disposition practices [7]. If properly and wisely handled, municipal solid waste (MSW) can be a valuable source of biomass, recycled materials, electricity, and revenue.

There are many opportunities for converting MSW to electricity, including a wide variety of waste sources, conversion technologies, facilities, and end-user applications [8]. Sustainable management of municipal solid waste can mitigate major social and environmental concerns [9]. Developed countries have moved to more sophisticated techniques, such as composting and waste to energy [10], which can deliver many opportunities for revenue [11]. Vermicomposting of MSW before land application is a sustainable waste management option [12] and has been adopted by approximately 106 countries. Vermicomposting is one of the most valuable ecological endeavors and can help us acquire useful end products [13,14]. These methodologies are not only helpful in shifting chemical agriculture to organic agriculture but also in improving soil structure and maintaining its natural fertility. This can be beneficial for a developing country that may be extremely dependent on agriculture.

Composting, in essence, is a normal cycle of decomposition of organic material under regulated conditions, under which microorganisms may grow or be inserted into a stable complex shape [15]. Composting uses different organisms that may be widely used for solid waste degradation and management [5]. About 30–60% of solid wastes are generally of organic nature [16]. Humans, livestock, and agriculture collectively generate approximately 39 billion metric tons of organic waste worldwide yearly [11]. Reclaimable organic waste, if processed properly, can be converted into useful products for agriculture [16]. Conversion of organic matter into valuable compost is possible by earthworms.

Vermicomposting is the mechanism by which different earthworms and microbial species break down organic waste [17,18]. Moreover, it is considered to be an advanced biotechnology discipline of vermiculture that leads towards sustainable, cost-effective waste management [19]. Vermicompost (also known as worm compost) is a high-grade and nutrient-rich fertilizer [20,21]. Vermicomposting boosts the macro- and micronutrients in the soil with the addition of useful microbial species to the soil, and the literature shows that vermicompost is more promising for the growth of basil plants than urea [22–24]. In the Himalayas, a low-cost technique of vermicomposting was analyzed for bio-conversion of nasty weed-flora [25]. A higher soil pH with higher available nutrient concentrations increases the total microbial population under organic management of plants with the use of vermicompost [26]. A similar study was conducted to obtain vermicompost from vegetable waste with wheat straw and cow dung [16]. Another study was conducted in which both lab-scale and field-scale experiments were carried out to determine vermicomposting's effectiveness regarding *E. coli* reduction [27]. Soobhany et al. [22] conducted a comparative study for the assessment of maturity index differences in compost and vermicompost acquired from MSW. Interestingly, vermicomposting degraded solid waste more efficiently than aerobic composting [22].

While chemical fertilizers have been considered the most significant contributor in increasing world agricultural productivity, there are many negative effects of chemical fertilizers on the soil and the climate that restrict their use in sustainable agricultural systems [28,29]. The persistent use of chemical fertilization affects the soil's characteristics: it is responsible for the degradation of soil fertility and contributes to heavy metal accumulation in plant tissues [29–32]. Recent studies suggested that vermicompost may become a possible solution to the problem of artificial conventional fertilizers [33]. Another study investigated the application of vermicompost derived solely from weeds to assess its impact on the germination and early growth of several plant species [34]. Yet another study was undertaken for the comparative assessment of some heavy metals for composting and vermicomposting [35]. One study observed that vermicompost used for growing green gram, chickpeas, and field peas has increased germination percentages and yield [36]. Thus, those researchers concluded that vermicomposting might be used for the safe disposal of biodegradable organic waste and could provide additional income for landless farmers in rural agriculture [36]. From the literature, it can be found that vermicompost has been established as a cost-effective bio-fertilizer and can be used for the growth of some vegetables. Most studies have focused on using a single type of worm for vermicomposting, and less focus has been given to the combined application of different worms for compost production.

In the current investigation, *Eisenia fetida* (EF) and *Lumbricus rubellus* (LR) were used as a combination in the same bin to biodegrade kitchen waste and to assess the effect of the obtained compost on selected vegetables. Vermicomposting was studied in three types of setup for the degradation of solid waste: fruit scraps, paper waste, and yard clippings. The waste degradation was studied in controlled conditions (pH, moisture content, C:N, and temperature). The compost obtained from these three setups was tested as a fertilizer for growing spinach and turnips. Compost efficiency was compared based on plant yield, plant height, sprouting, and harvesting time.

2. Materials and Methods

2.1. Collection of Waste

Composting requires the presence of two types of materials: nitrogenous and carbonaceous. The proportion of nitrogenous or carbonaceous material depends on the quality of the required compost. A carbonaceous/nitrogenous (C/N) ratio of 30 can be an optimized ratio for vermicomposting [37]. Kitchen waste, collected from cafeterias and consisting of vegetable and fruit peelings that were rich in nitrogen, was combined with a portion of garden waste and shredded paper waste to make up the carbon content. Before vermicomposting, the collected samples were partially decomposed by keeping them in shade for almost 2 weeks. Furthermore, the initial C/N ratio of 30 was controlled by blending the optimum amount of cow dung (248 g) and additional saw dust and garden waste (12 g) with the partially decomposed waste. Worms were collected from the rear of a facility of the University of Engineering and Technology, Lahore. Two types of worms, i.e., *Eisenia fetida* (EF) and *Lumbricus rubellus* (LR), and a combination of these two, were used for the study. They were introduced into the bins for the initiation of composting (Figure 1). The volume of the bin was 0.15 m^3, i.e., (height × length × width) (0.75 m × 0.5 m × 0.4 m).

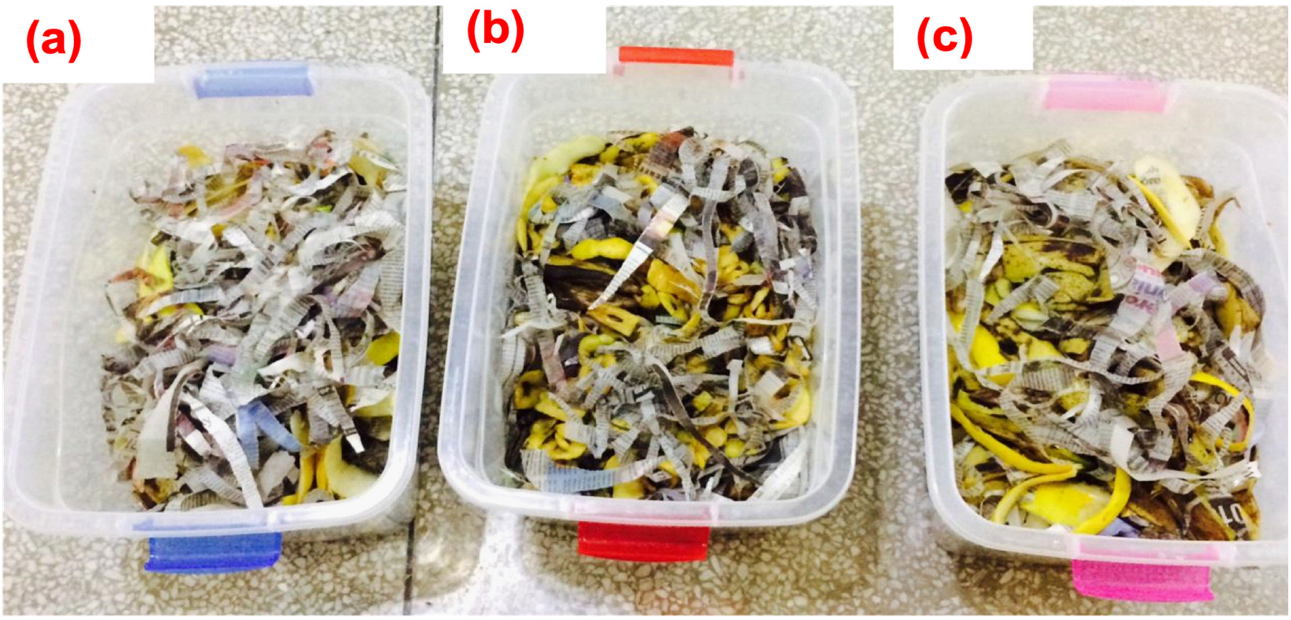

Figure 1. Waste collection bins used for vermicomposting. (**a**): The blue bin contains *Lumbricus rubellus*; (**b**): the red bin contains combined *Eisenia fetida* and *Lumbricus rubellus*; (**c**): the pink bin contains *Eisenia fetida*.

2.2. Initiation of Vermicomposting

Food waste was vermicomposted in beds prepared in plastic bins. Each bed was filled with 1.5 kg of shredded newspaper, 0.5 kg of the substrate (food waste), 0.05 kg of garden waste, and approximately 100 adult earthworms; however, only 76 earthworms remained alive in the first basket. So, a total of 76 earthworms were used for the study in the case of a single type of worm (Figure 1a,c), and in the combined case, 38 *Eisenia fetida* worms and 38 *Lumbricus rubellus* worms were used for uniformity of data (Figure 1b). The worms were introduced into the compost beds to begin the process of vermicomposting (Figure 2). The moisture level of the beds was maintained at about 45–70% [38] during the vermicomposting period by periodically sprinkling them with water through water sprays. The compost was periodically analyzed in the laboratory for moisture content (MC), pH, temperature, organic content (C), C/N, and total Kjeldahl nitrogen (TKN). The containers were supplied with small holes in the top lid to ensure aerobic conditions.

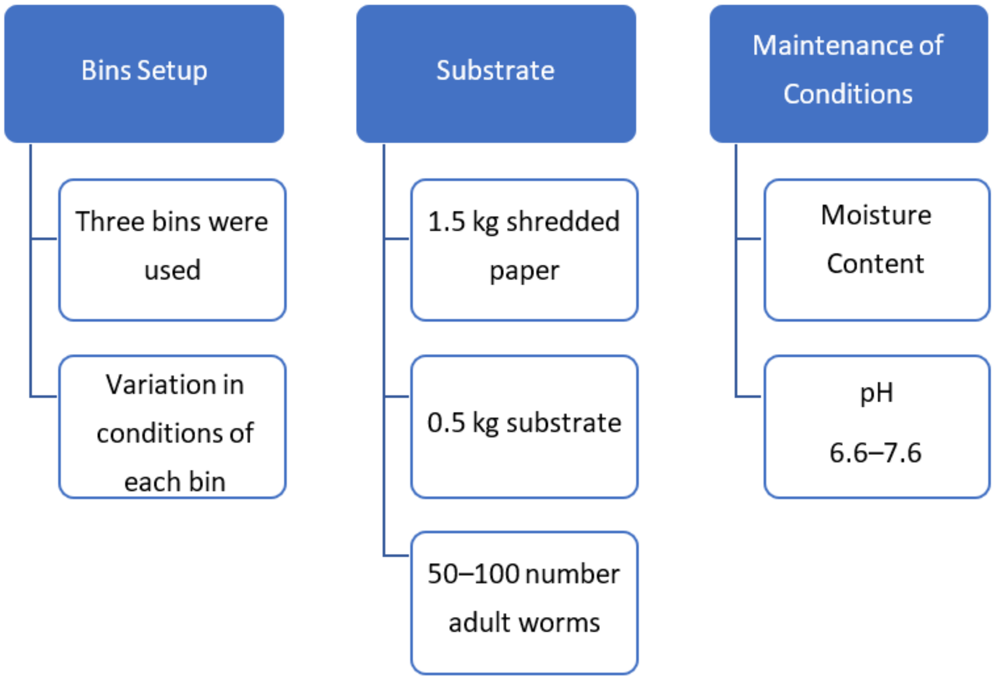

Figure 2. Outlook of experimental methodology used for the vermicomposting.

2.3. Application of Vermicompost in Agricultural Fields

Seedlings that had been transplanted earlier were removed on the 30th day, and the rest were removed at every 15th day after transplanting, keeping the better and healthier plants undisturbed. Weeding was done when necessary to keep the plants free from weeds, for better soil aeration and for the conservation of soil moisture. When the plants were well established, each plant was staked with bamboo sticks to keep the plants erect. Irrigation was done regularly up to the harvest to keep the pots moistened. Vegetables were harvested at the full maturity stage. Moreover, a control variant, i.e., seeding the plants under soil alone, was not tested in this study. We directly applied the compost produced by the vermicomposting into the soil for plant cultivation.

2.4. Sampling of Vegetables

Turnips (*Brassica rapa*) and spinach (*Spinacia oleracea*) were harvested. The collected vegetables were carried in gunny bags, then half of the collected samples were immediately transferred to a storeroom, and the rest were kept in the laboratory for chemical analysis. Proper care was taken while harvesting and handling the collected samples to avoid any mechanical injury. The analysis was replicated three times, and the average of results is reported.

2.5. Methods of Measuring Different Characteristics

2.5.1. Harvesting Time

The variations in *harvesting time* were determined in days and can be calculated by the following equation (Equation (1):

$$\begin{aligned} &Harvesting\ time \\ &\quad = sprouting\ time \\ &\quad + vegetative\ growth/maturity\ time \end{aligned} \tag{1}$$

Sprouting time is the time required by the seeds to sprout and emerge from the soil; it depends on the type of soil and the conditions to which the seeds were exposed. In this study, *sprouting time* in days was also determined to evaluate the difference in role of the different types of worms used in vermicomposting. In addition, the *vegetative growth/maturity time* is the time required by the plants to grow leaves, reach full maturity, and be ready for harvest. In this study, vegetative times were reported in the collective response of the *harvesting time*.

2.5.2. Plant Height

The height of the plants was measured in cm and measured from the ground level to the tip of the longest stem, then the mean value was calculated (the average of three readings was recorded with a standard deviation). The height of the plant was recorded on the 15th, 30th, and 40th day. Lastly, the plant height was recorded at the final harvest.

2.5.3. Yield

After the harvesting of the vegetables, the *total weight* (kg) of each fruit plant was calculated by adding the weight of all the fruit collected from each plant until the final harvest; then, the weight was calculated in kg m^{-2} and converted into t/Ha (Equation (2)).

$$Yield = \frac{total\ weight\ of\ the\ harvested\ plant(\mathrm{kg})}{harvested\ area(\mathrm{m}^2)} \times 10 \tag{2}$$

2.5.4. Characterization of Nutrients in the Soil and the Compost

As macronutrients are a vital requirement for plant growth, the compost obtained by vermicomposting was then characterized on the basis of nutrient concentrations before its application on crops. As a percentage of these nutrients are naturally present in the soil, the same tests were also conducted on the soil where the crops grew. The characteristics of the soil and compost were analyzed by the NCDA and CS methods for waste and compost analysis (total nitrogen, total phosphorous, organic matter (C)). The pH of the samples was analyzed by ASTM D5231-92 (Benchtop pH Meter), and potassium was analyzed using a UV-5200 UV/VIS Spectrophotometer Ultraviolet Visible 172 Spectrophotometer 190–1100 nm wavelength Range 2 nm Bandwidth. The moisture content of the samples was analyzed by the dry oven (101-0A)43 L methodology. The equation used to measure the *MC* of the compost is shown in Equation (3).

$$MC(\%) = \frac{wet\ weight - dry\ weight}{wet\ weight} \times 100 \tag{3}$$

Wet weight is the initial sample weight; i.e., 100 g *dry weight* is the weight of the sample measured after being dried by using the oven at 105 °C for 24 h.

In order to assess the maintained conditions of the three setups, periodic readings were taken for pH, moisture content, C/N ratio, and temperature. In addition, data were collected from the triplicate analysis, and their averages were reported with variation in standard deviation (SD). Furthermore, variations in the characteristics of the vermicomposting on the growth of targeted vegetation were analyzed by statistical analysis (ANOVA, with a 95% confidence level) by using the SPSS program tool.

3. Results and Discussion

3.1. Variation of the Conditions of the Compost under Different Worm Exposures

3.1.1. pH Variation with Time

The pH variation of the compost produced by the different worm conditions is illustrated in Figure 3a. The result shows that the pH value of the EF compost increased from 7.6 ± 0.25 to 7.8 ± 0.26 during the twelve days of experimentation. Moreover, an increasing trend was consistent throughout the study period and recorded as 8.1 ± 0.42 and 9.01 ± 0.43 for the 25th day and the 40th day of analysis, respectively. The increase in pH values was expected due to the decomposition process carried out by the worms, as mentioned elsewhere [39]. Similar trends were observed for the pH variation for the LR and EF–LR compost. The pH values of the LR compost varied from 7.5 ± 0.53 to 8.9 ± 0.61 from the start of the study to 40 days of experimentation. Similarly, for the EF–LR combined compost setup, the pH value on the first day was 7.5 ± 0.22 and on the 40th day, 8.85 ± 0.26, as illustrated in Figure 3a. From these results, it was concluded that the pH of the compost was close to neutral initially, i.e., 7.5 ± 0.22 and increased with time to 8.9 ± 0.61, indicating that the final product can be useful for remediating acidic soils [39]. The comparative study reveals that there was no significant variation in pH for any of the three studied processes as compared to one another after 40 days.

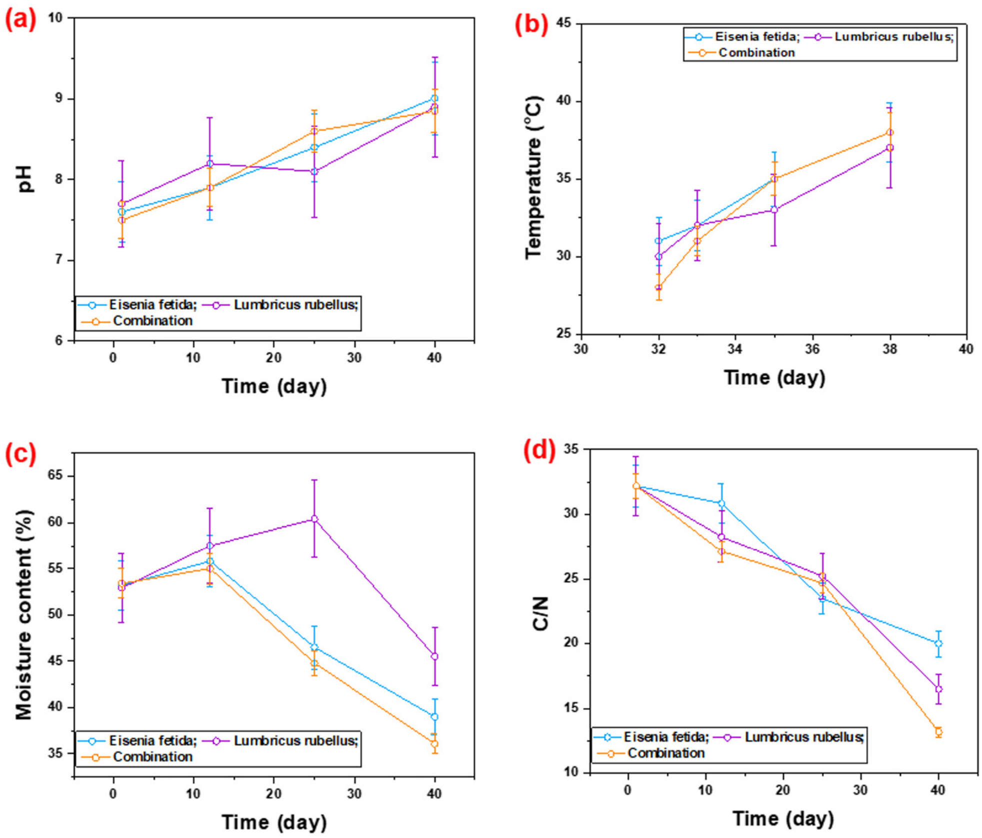

Figure 3. Variation in conditions of the compost during the study period: (**a**): pH variation; (**b**): temperature variation; (**c**): moisture content variation; (**d**): C/N variation (error bar represents the standard deviation (SD)).

3.1.2. Temperature Variation with Time

The temperature variation of the compost with respect to time under different worm conditions is illustrated in Figure 3b. The temperature range was 38 ± 1.23 to 28 ± 0.81 °C for the EF–LR compost. Moreover, the temperature variation of the individual worm compost was from 38 ± 1.90 to 31 ± 1.35 °C and 37 ± 2.4 to 30 ± 2.1 °C for EF and LR, respectively. Thus, the results revealed that the EF–LR combined conditions had a lower temperature as compared to the individual. Moreover, this process needs to be performed during the winter season to avoid the temperature increasing up to a level where the worms may not survive. In the summer, pre-treatment of the substrate can be done to avoid a temperature rise.

3.1.3. Moisture Content (MC)

The moisture content decreased with time in all conditions, as illustrated in Figure 3c. The MC decreased from 60.4 ± 4.22% to 39 ± 1.95%, 45.5 ± 3.18%, and 36.1 ± 1.08% for EF-, LR-, and EF–LR-produced compost, respectively. Moreover, for the EF compost, the setup initially increased from 53.2 ± 2.66% to 55.8 + 1.79% from Day 1 to Day 12, as illustrated in Figure 3c. The value decreased to 46.5 ± 2.13% after 25 days, while after 40 days, it was 39 ± 1.95%. In addition, from the MC results, we concluded that the compost that matured during the 40 days of the experimentation analysis might have reduced microbial activity. As the literature shows, 50 percent MC is the minimum requirement for microbial activity, and less than 50 percent of MC indicates a mature compost [40]. Thus, to overcome the reduction of the MC of the compost after 40 days of vermicomposting, the required quantity of water was provided to maintain the MC at between 45–70%.

3.1.4. Carbon to Nitrogen (C/N) Ratio

Figure 3d shows the carbon to nitrogen (C/N) ratio of the compost produced by EF, LR, and EF–LR. Similar to the MC results, the C/N ratio also decreased with time due to the decomposition reaction and the reduction of carbonous compounds. Moreover, the reduction rate was higher in the EF–LR compost, followed by the LR and EF compost. The C/N ratio of the EF compost decreased to 30.85 ± 1.54, 23.46 ± 1.17, and 20 ± 1 during the 12th, 25th, and 40th day of analysis, respectively. The C/N ratio of the LR compost was 28.26 ± 1.97, 25.21 ± 1.72, and 16.49 ± 1.15, as observed on Days 12, 25, and 40, respectively. Similarly, the C/N ratio of the EF–LR compost decreased to 27.13 ± 0.81, 24.67 ± 0.71, and 13.18 ± 0.40 on the 12th, 25th, and 40th day of analysis. It is important to mention here that the carbon–nitrogen ratio may generally be an indicator of compost maturity and that the C/N ratio should be less than or around 20 for a final compost that represents a good quality of compost [17]. Thus, the EF–LR compost was found to be the best compared to others in terms of C/N. This may be due to the different nature of the worms collectively operating in compost production. During different days, the conditions (pH, moisture content, availability of oxygen, nature of the material, etc.) may change and may affect the performance of the worms and their mortality [41]. However, the combination of two worms with different natures (soil-based and vegetation-based) may positively affect the compost production performance. *Eisenia fetida* was used at the upper part of the basket, while *Lumbricus rubellus* was beneath the upper layer. During the experiments, it was observed that in the combined process, *Eisenia fetida* operated from the surface of organic waste, while *Lumbricus rubellus* went deep into the composting material, and this may be due to their different natures, which helped the overall efficiency of the process compared to a single type of worm.

3.2. Characterization of the Compost

3.2.1. Percentage of Potassium

It can be seen from Figure 4 that in the presence of the single worm species, the percentage of potassium was lower (the EF and LR composts had 6 ± 0.18% and 2.5 ± 0.07%, respectively) as compared to compost produced by the combined worms (EF–LR compost had 8.4 ± 0.20%) in similar kitchen waste and at the same conditions. It is anticipated that this increase in potassium content directly plays a vital role in plant growth when this compost is used as a substitute for conventional fertilizer, since vermicompost promotes nitrogen fixation in soils to enhance their richness. Lastly, the soil had a percentage of 16 ± 0.45% with respect to nitrogen content.

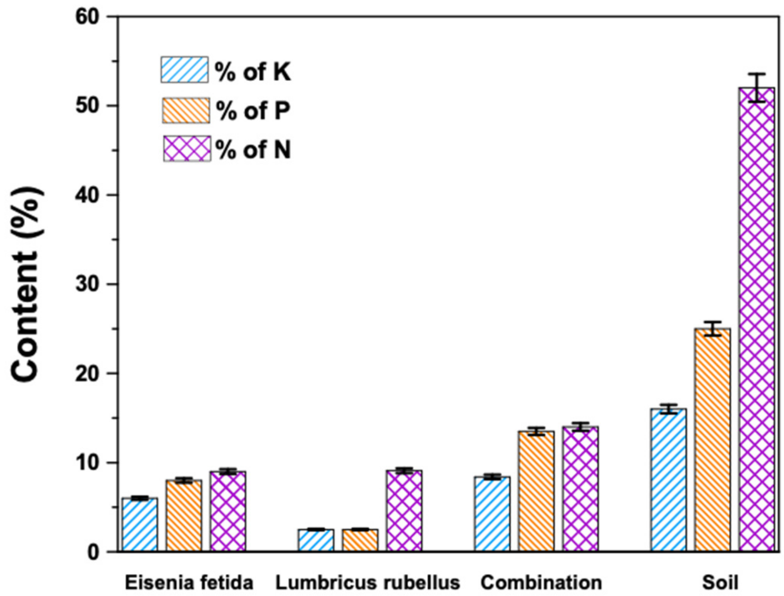

Figure 4. Characterization of compost produced from different worm combinations in term of nitrogen, phosphorous, and potassium (error represents the SD).

3.2.2. Percentage of Phosphorus

Similar to the potassium percentage, the percentage of phosphorus also shows a similar trend. The EF, LR, and EF–LR combined composts had phosphorus concentrations of 8 ± 0.20%, 2.5 ± 0.06%, and 13.5 ± 0.35%, respectively. An increase in the P content of the EF–LR compost resulted in mineralization, which in turn increased soil fertility [42]. The soil already contained 25 ± 0.58% phosphorus, which clearly suggested that two types of worms in a combination works better than individual types alone.

3.2.3. Percentage of Nitrogen

Figure 4 indicates that the nitrogen content was also the highest in the combination process compared to the other two vermicomposting processes, as the nitrogen percentage present in the EF compost was 9 ± 0.23% and 9.1 ± 0.27% in the LR compost. The combination compost of EF–LR had a nitrogen ratio of 14 ± 0.42%. The soil had a nitrogen percentage of 52 ± 1.50%. These results suggested that macronutrients are already present in plenty in fertile soils and in composts. This can also be attributed to nutrient-rich kitchen waste, as it already contains fruits and vegetables that are rich in nutrients [43].

The standard deviation (SD) of the above-mentioned parameters shows that a wider variation is present in nitrogen, followed by phosphorus, while a negligible variation occurred in potassium.

3.3. Evaluation of Compost Efficiency

The mature compost produced from the different combinations of worms was tested on the growth of spinach and turnips as a substitute for conventional fertilizer. For the evaluation of compost efficiency on crops, several parameters were selected. These included sprouting and harvesting times of spinach and turnips, plant height of both crops, and the yield of both crops in comparison to chemical fertilizers.

3.3.1. Sprouting Time

The results shown in Figure 5 give the sprouting time for spinach. In the case of EF and LR, the compost was 4 ± 0.50 days individually, and the EF–LR compost was 3 ± 0.24 days. Similarly, the sprouting time of turnips for EF–LR was also lower (7 ± 0.92 days) compared to the EF and LR composts, which had 9 ± 1.2 and 10 ± 0.92 days of sprouting time, respectively. Vermicompost acts as a bio-oxidative, so it may release compounds that help crop sprouting and growth. Thus, the EF–LR compost was more bio-oxidative in nature, showing a shorter sprouting time for both crops [44]. In general, the statistical analysis of the results shows that variation of the sprouting time of the spinach in all three composts was significantly different, as $p < 0.05$, which shows the difference in sprouting times for spinach. However, no significant difference was observed in the case of the turnip, as $p > 0.05$. It might be due to a non-significant impact of the compost in the sprouting time of the turnip. In addition to that, the overall sprouting time of the combined compost was shorter, and we concluded that seeds exposed to the combined compost could be expected to reach harvest earlier.

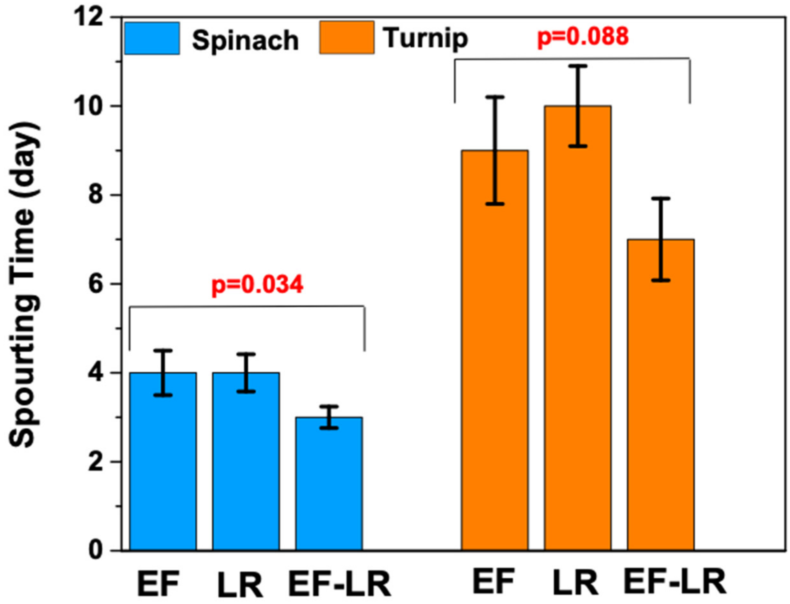

Figure 5. Sprouting time for spinach and turnips for different types of vermicompost (error bar represents the SD) (EF, LR, and EF–LR represent *Eisenia fetida*, *Lumbricus rubellus*, and *Eisenia fetida–Lumbricus rubellus*).

3.3.2. Harvesting Time

Harvesting time was also found to be faster in the case of compost from the combination of worms for both spinach and turnips (Figure 6). The results show that in the case of the EF compost, the harvesting times for spinach and turnips were 29 ± 1.5 and 42 ± 2.2 days, respectively. However, for the LR and EF–LR composts, the harvesting times of spinach and turnips were 31 ± 0.42 and 42 ± 1.9 days, and 27 ± 0.64 and 38 ± 0.92 days, respectively. Generally, compost with good nutrients and optimal chemical composition results in a shorter harvest time for the crop and good plant size [45]. Similar to the sprouting time, statistical analysis of the harvesting time also shows no significant difference for the turnip harvesting under three different composts. Moreover, the spinach shows significantly different results, and we concluded that variation in compost type has significant impact on the harvesting time of spinach. However, in general, EF–LR compost has a shorter harvesting time in both cases. These results show a good correlation between the nutrient levels in the combined process compared to the EF and LR composts alone. Hence, it may be suggested that nutrient-rich compost may help in the reduction of harvesting time [45].

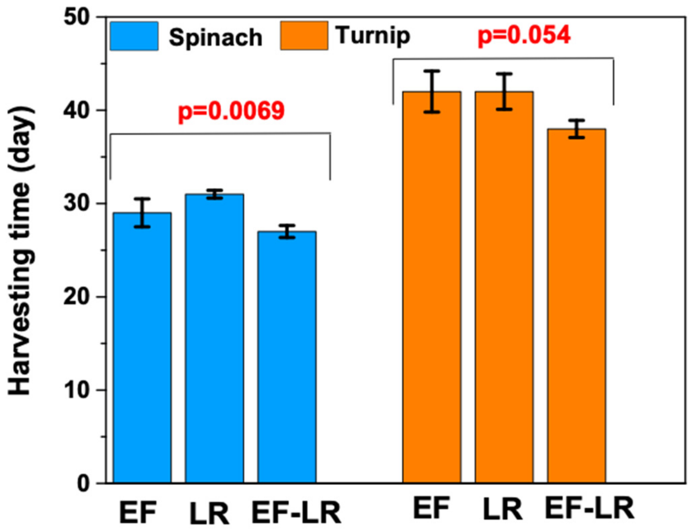

Figure 6. Harvesting time variation of spinach and turnips by vermicompost of different worm combinations (error bar represents the SD) (EF, LR, and EF–LR represent *Eisenia fetida*, *Lumbricus rubellus*, and *Eisenia fetida–Lumbricus rubellus*).

3.3.3. Plant Height

Plant height may be another important indicator to judge the quality of a compost. The results shown in Figure 7 indicate that the EF–LR compost had better results, and the plant height for both spinach and turnips was higher than for the EF and LR composts alone. Figure 7 shows that the heights of the spinach and turnip plants were 4.2 ± 0.1 and 4 ± 0.2 inches in the case of the EF compost, in comparison to the EF–LR-compost-grown plants, which were 4.9 ± 0.24 and 4.4 ± 0.12 inches, respectively. Moreover, the LR-compost-grown plants were shorter compared to the EF–LR-compost-grown plants, as illustrated in Figure 7. The height was 4.4 ± 0.22 inches for the LR compost. Moreover, statistical results also confirmed that for both plants' height, spinach and turnip harvested in the three compost conditions show significant difference ($p < 0.05$). Overall, the combined EF–LR harvested plants have higher plant height compared to the individual harvested plants in both cases. As for genetic structure, plant height is a significant component contributing to plant yield. By using vermicompost, the physical and chemical properties of the soil can be enhanced, which can eventually boost plant height and yield [46].

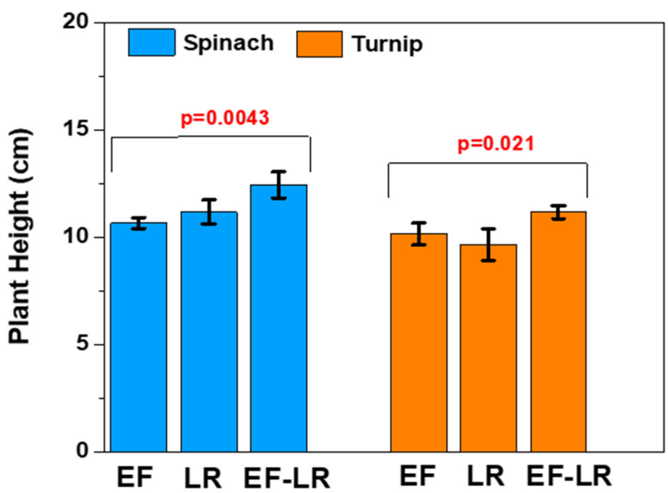

Figure 7. Height variation of spinach and turnip crops grown by vermicompost with different worm combination (error bar represents the SD) (EF, LR, and EF–LR represent *Eisenia fetida*, *Lumbricus rubellus*, and *Eisenia fetida–Lumbricus rubellus*).

3.3.4. Plant Yield

Figure 8 indicates that the yield of turnips in the case of EF compost was 10.95 ± 1.2 t/Ha. The yield of the LR compost was 9.29 ± 0.9 t/Ha. The EF–LR compost yield was 12.86 ± 1.92 t/Ha. In the case of chemical fertilizers, the yield was 11.75 ± 1.5 t/Ha. These results verify that the EF–LR compost used for the turnip plants had a higher yield not only in comparison to the EF and LR composts but also to chemical fertilizer used for crop harvesting. Moreover, statistical analysis results show that the yields of spinach have significantly different outcomes as compared to the turnip in similar exposed conditions. The EF–LR compost has a higher plant yield in the case of spinach and is significantly verified as $p < 0.05$, which shows the difference in results. However, in the case of turnips, the EF–LR compost shows a higher yield, but in comparative evaluation, the difference is not significant, as $p > 0.05$.

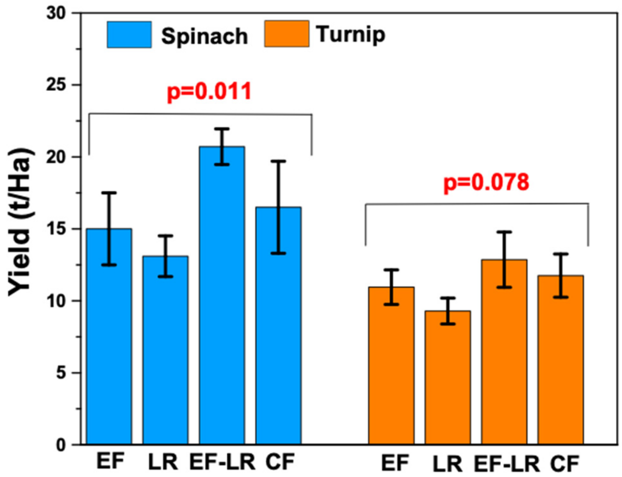

Figure 8. Yield of harvested spinach and turnip plants by vermicomposting of different worm combinations (error bar represents the SD) (EF, LR, EF–LR, and CF represent *Eisenia fetida*, *Lumbricus rubellus*, *Eisenia fetida–Lumbricus rubellus*, and chemical fertilizer).

In general, the outcome yield of both plants would be higher with EF–LR compost in comparison to individual compost and the utilization of chemical fertilizer. This was because by nature, *Eisenia fetida* is epigeic, which means the worms are surface dwellers, and *Lumbricus rubellus* is sometimes anecic and sometimes endogeic in nature, which means the worms live beneath the surface for some span of life and then on the surface for some time [47]. In the case of the EF–LR combined compost, the two species may work independently according to their particular nature. *Eisenia fetida* during the experiment seemed to function on the top surface, while *Lumbricus rubellus* functioned at the bottom of the setup. The setup gave the optimal conditions for both worms to perform efficiently without influencing each other in their specific regions. This likely contributed to the EF–LR compost being the most fertile and rich over the other two composts, subsequently creating the high yield of crops produced by the EF–LR compost [48].

The results obtained for spinach had a similar pattern compared to the turnip yield, as shown in Figure 8. The highest yield was obtained for the EF–LR compost. The yield of spinach was 15.00 ± 2.5 t/Ha in the case of EF compost, and the LR compost had a yield of 13.10 ± 1.42 t/Ha. In the case of EF–LR compost, the yield was 20.71 ± 1.24 t/Ha. The chemical fertilizers showed a yield of 16.5 ± 3.2 t/Ha. *Eisenia fetida* is a worm that is familiar with tropical climates, and in contrast, the *Lumbricus rubellus* is more inclined to temperate climates. The conditions of our setups were closer to tropical, so the former performed better than the latter [49]. Our results confirmed that the EF–LR-based compost yielded 38% and 58%, and 17.4% and 37.9%, higher turnip and spinach production, compared to EF- and LR-based compost, respectively. Moreover, for large-scale application, harvesting of spinach from EF–LR compost would be the better option compared to turnip, as confirmed by the statistical results, which show the significantly different results for plant height, harvesting time, sprouting time, and outcome yield ($p < 0.05$).

4. Conclusions

The goal of the study was to analyze the degradation of solid kitchen waste by three setups of earthworms for composting, in order to find an alternative to chemical fertilizer. *Eisenia fetida*, *Lumbricus rubellus*, and a combination of these two worms were used for the compost formation. The chemical composition of the compost and its impact on the growth of spinach and turnips were evaluated. Through this research, the following conclusions can be drawn.

- The efficiency of the composts was found to be in the following order in terms of utilization as an alternative fertilizer: EF–LR compost > *Eisenia fetida* (EF) compost > *Lumbricus rubellus* (LR) compost. The potassium, phosphorus, and nitrogen ratio of the EF–LR combined compost was (8.4 $\pm$ 0.20%, 13.5 $\pm$ 0.35%, 14 $\pm$ 0.42%), greater than those of the EF compost (6 $\pm$ 0.18%, 8 $\pm$ 0.20%, 9 $\pm$ 0.23%) and the LR compost (2.5%, 2.5%, 9.1%).
- The EF–LR combined compost showed a sprouting time of 7 $\pm$ 0.92 days for turnips and 3 $\pm$ 0.24 days for spinach, which was comparatively shorter than that of the EF compost (9 $\pm$ 1.2 days for turnips and 4 $\pm$ 0.50 days for spinach) and the LR compost (10 $\pm$ 0.92 days for turnips and 4 $\pm$ 0.50 days for spinach). Similarly, a shorter harvesting time was observed for the EF–LR compost (38 $\pm$ 0.92 days for turnips and 27 $\pm$ 0.64 days for spinach), with higher plant height (4.4 $\pm$ 0.12 inches for turnips and 4.9 $\pm$ 0.24 inches for spinach) compared to the other two individually. The individual composts had a harvesting time of 31 $\pm$ 0.42 and 42 $\pm$ 1.9 days, and 29 $\pm$ 1.5 and 42 $\pm$ 2.2 days, for the EF- and LR-based composts for turnips and spinach, respectively, and they had shorter plant heights.
- For turnips, the EF–LR compost yielded 38% and 58%, respectively, more than the compost obtained using EF and LR. For spinach, the EF–LR compost produced similar results, with 17.4% and 37.9% more yield than the other two. The results of our study confirmed that to increase production of crops with resulting lower residual chemical pollutants, compost obtained by the combination of EF and LR worms is more promising for use on a large scale than compost obtained from a single species.
- Statistical analysis also confirmed that for a better option in the comparative production of spinach and turnip growth using the EF–LR compost, our study confirms that spinach growth shows higher variability in the EF–LR compost compared to compost from a single species.

Author Contributions: Conceptualization, H.K.; Validation, A.I., U.P., Y.-M.W. and K.-H.L.; Formal analysis, U.P.; Investigation, H.K.; Resources, A.I., Y.-M.W., E.-J.L. and K.-H.L.; Data curation, A.I. and U.P.; Writing—original draft, H.K.; Writing—review & editing, A.I., E.-J.L. and Y.-M.W.; Visualization, U.P. and Y.-M.W.; Project administration, K.-H.L.; Funding acquisition, K.-H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (2021R1I1A1A01041492).

Data Availability Statement: Not applicable.

Acknowledgments: We are greatly thankful for the support of the management and staff of the Institute of Environmental Engineering and to Research University of Engineering and Technology Lahore for their support.

Conflicts of Interest: There is no conflict of interest among the authors.

References

1. Visvanathan, C.; Adhikari, R.; Ananth, A.P. 3R practices for municipal solid waste management in Asia. *Linnaeus Eco-Tech* **2007**, 11–22. [CrossRef]
2. Khan, A.A.; Ahmed, Z.; Siddiqui, M.A. Issues with solid waste management in South Asian countries: A situational analysis of Pakistan. *J. Environ. Occup. Health* **2012**, *1*, 129–131. [CrossRef]
3. Muhammad, A.M.; Zhonghua, T. Municipal solid waste and its relation with groundwater contamination in Lahore, Pakistan. *Res. J. Appl. Sci. Eng. Technol.* **2014**, *7*, 1551–1560. [CrossRef]
4. Murtaza, G.; Zhonghua, T. Municipal solid waste and its relation with groundwater contamination in Multan, Pakistan. *IJAR* **2017**, *3*, 434–441.
5. Mahar, A.; Malik, R.N.; Qadir, A.; Ahmed, T.; Khan, Z.; Khan, M.A. Review and analysis of current solid waste management situation in urban areas of Pakistan. In Proceedings of the International Conference on Sustainable Solid Waste Management, Anna, India, 5–7 September 2007.
6. Masood, M.; Barlow, C.Y.; Wilson, D.C. An assessment of the current municipal solid waste management system in Lahore, Pakistan. *Waste Manag. Res.* **2014**, *32*, 834–847. [CrossRef] [PubMed]
7. Usman, M.; Barlow, C.Y.; Wilson, D. A case study of groundwater contamination due to open dumping of municipal solid waste in Faisalabad, Pakistan. *Earth Sci. Pak.* **2017**, *1*, 15–16. [CrossRef]
8. Costi, P.; Yasin, H.; Nasir, A.; Mehmood, W. An environmentally sustainable decision model for urban solid waste management. *Waste Manag.* **2004**, *24*, 277–295. [CrossRef]
9. Lim, S.L.; Lee, L.H.; Wu, T.Y. Sustainability of using composting and vermicomposting technologies for organic solid waste biotransformation: Recent overview, greenhouse gases emissions and economic analysis. *J. Clean. Prod.* **2016**, *111*, 262–278. [CrossRef]
10. Berkun, M.; Aras, E.; Nemlioglu, S. Disposal of solid waste in Istanbul and along the Black Sea coast of Turkey. *Waste Manag.* **2005**, *25*, 847–855. [CrossRef]
11. Srivastava, V.; Ismail, S.A.; Singh, P.; Singh, R.P. Urban solid waste management in the developing world with emphasis on India: Challenges and opportunities. *Rev. Environ. Sci. Bio/Technol.* **2015**, *14*, 317–337. [CrossRef]
12. Singh, R.P.; Singh, P.; Araujo, A.S.; Ibrahim, M.H.; Sulaiman, O. Management of urban solid waste: Vermicomposting a sustainable option. *Resour. Conserv. Recycl.* **2011**, *55*, 719–729. [CrossRef]
13. Hoornweg, D.; Thomas, L.; Otten, L. Composting and its applicability in developing countries. *World Bank Work. Pap. Ser.* **1999**, *8*, 1–46.
14. Narkhede, S.D.; Jadhav, R.N.; Khatik, V.A.; Ingle, S.T.; Attarde, S.B. Composting and its applicability in developing countries. *Int. J. Agric. Sci.* **2010**, *6*, 343–349.
15. Ahmad, I. Alternative approaches for solid waste management: A case study in faisalabad pakistan. *Earth Sci. Pak.* **2017**, *1*, 7–9.
16. Suthar, S. Vermicomposting of vegetable-market solid waste using *Eisenia fetida*: Impact of bulking material on earthworm growth and decomposition rate. *Ecol. Eng.* **2009**, *35*, 914–920. [CrossRef]
17. Domínguez, J.; Aira, M.; Kolbe, A.R.; Gómez-Brandón, M.; Pérez-Losada, M. Changes in the composition and function of bacterial communities during vermicomposting may explain beneficial properties of vermicompost. *Sci. Rep.* **2019**, *9*, 1–11. [CrossRef]
18. Das, S.K.; Avasthe, R.; Gopi, R. Vermiwash: Use in organic agriculture for improved crop production. *Pop. Kheti* **2014**, *2*, 45–46.
19. Karmegam, N.; Vijayan, P.; Prakash, M.; Paul, J.A.J. Vermicomposting of paper industry sludge with cowdung and green manure plants using *Eisenia fetida*: A viable option for cleaner and enriched vermicompost production. *J. Clean. Prod.* **2019**, *228*, 718–728. [CrossRef]
20. Ghosh, S.; Goswami, A.J.; Ghosh, G.K.; Pramanik, P. Quantifying the relative role of phytase and phosphatase enzymes in phosphorus mineralization during vermicomposting of fibrous tea factory waste. *Ecol. Eng.* **2018**, *116*, 97–103. [CrossRef]
21. Swati, A.; Hait, S. Fate and bioavailability of heavy metals during vermicomposting of various organic wastes—A review. *Process Saf. Environ. Prot.* **2017**, *109*, 30–45. [CrossRef]
22. Soobhany, N.; Gunasee, S.; Rago, Y.P.; Joyram, H.; Raghoo, P.; Mohee, R.; Garg, V.K. Spectroscopic, thermogravimetric and structural characterization analyses for comparing Municipal Solid Waste composts and vermicomposts stability and maturity. *Bioresour. Technol.* **2017**, *236*, 11–19. [CrossRef] [PubMed]
23. Soobhany, N. Preliminary evaluation of pathogenic bacteria loading on organic Municipal Solid Waste compost and vermicompost. *J. Environ. Manag.* **2018**, *206*, 763–767. [CrossRef] [PubMed]
24. Ramnarain, Y.I.; Ansari, A.A.; Ori, L. Vermicomposting of different organic materials using the epigeic earthworm Eisenia foetida. *Int. J. Recycl. Org. Waste Agric.* **2019**, *8*, 23–36. [CrossRef]
25. Choudhary, A.K.; Suri, V.K. Low-cost vermi-composting technology and its application in bio-conversion of obnoxious weed flora of north-western Himalayas into vermi-compost. *Commun. Soil Sci. Plant Anal.* **2018**, *49*, 1429–1441. [CrossRef]
26. Kochakinezhad, H.; Peyvast, G.A.; Kashi, A.K.; Olfati, J.A.; Asadi, A. A comparison of organic and chemical fertilizers for tomato production. *J. Org. Syst.* **2012**, *7*, 14–25.
27. Cao, W.; Vaddella, V.; Biswas, S.; Perkins, K.; Clay, C.; Wu, T.; Zheng, Y.; Ndegwa, P.; Pandey, P. Assessing the changes in E. coli levels and nutrient dynamics during vermicomposting of food waste under lab and field scale conditions. *Environ. Sci. Pollut. Res.* **2016**, *23*, 23195–23202. [CrossRef]

28. Smil, V. *Enriching the Earth: Fritz Haber, Carl Bosch, and the Transformation of World Food Production*; MIT Press: Cambridge, MA, USA, 2004.
29. Peyvast, G.; Kharazi, P.R.; Tahernia, S.; Nosratierad, Z.; Olfati, J.A. Municipal solid waste compost increased yield and decreased nitrate amount of broccoli. *J. Appl. Hort* **2008**, *10*, 129–131. [CrossRef]
30. Karungi, J.; Ekbom, B.; Kyamanywa, S. Effects of organic versus conventional fertilizers on insect pests, natural enemies and yield of Phaseolus vulgaris. *Agric. Ecosyst. Environ.* **2006**, *115*, 51–55. [CrossRef]
31. Drinkwater, L.; Letourneau, D.K.; Workneh, F.A.H.C.; Van Bruggen, A.H.C.; Shennan, C. Fundamental differences between conventional and organic tomato agroecosystems in California. *Ecol. Appl.* **1995**, *5*, 1098–1112. [CrossRef]
32. Vodounnou, D.; Kpogue, D.N.S.; Tossavi, C.E.; Mennsah, G.A.; Fiogbe, E.D. Effect of animal waste and vegetable compost on production and growth of earthworm (*Eisenia fetida*) during vermiculture. *Int. J. Recycl. Org. Waste Agric.* **2016**, *5*, 87–92. [CrossRef]
33. Joshi, R.; Singh, J.; Vig, A.P. Vermicompost as an effective organic fertilizer and biocontrol agent: Effect on growth, yield and quality of plants. *Rev. Environ. Sci. Bio/Technol.* **2015**, *14*, 137–159. [CrossRef]
34. Hussain, N.; Abbasi, T.; Abbasi, S. Vermicomposting eliminates the toxicity of Lantana (*Lantana camara*) and turns it into a plant friendly organic fertilizer. *J. Hazard. Mater.* **2015**, *298*, 46–57. [CrossRef] [PubMed]
35. Soobhany, N.; Mohee, R.; Garg, V.K. Comparative assessment of heavy metals content during the composting and vermicomposting of municipal solid waste employing *Eudrilus eugeniae*. *Waste Manag.* **2015**, *39*, 130–145. [CrossRef] [PubMed]
36. Baghel, B.; Sahu, R.; Pandey, D. Vermicomposting an economical enterprise for nutrient and waste management for rural agriculture. *Int. J. Curr. Microbiol. Appl. Sci.* **2018**, *7*, 3754–3758. [CrossRef]
37. Shrimal, S.; Khwairakpam, M. Effect of C/N ratio on vermicomposting of vegetable waste. *Dyn. Soil Dyn. Plant* **2010**, *4*, 123–126.
38. Alidadi, H.; Hosseinzadeh, A.; Najafpoor, A.A.; Esmaili, H.; Zanganeh, J.; Takabi, M.D.; Piranloo, F.G. Waste recycling by vermicomposting: Maturity and quality assessment via dehydrogenase enzyme activity, lignin, water soluble carbon, nitrogen, phosphorous and other indicators. *J. Environ. Manag.* **2016**, *182*, 134–140. [CrossRef]
39. Huang, K.; Li, F.; Wei, Y.; Fu, X.; Chen, X. Effects of earthworms on physicochemical properties and microbial profiles during vermicomposting of fresh fruit and vegetable wastes. *Bioresour. Technol.* **2014**, *170*, 45–52. [CrossRef]
40. Liang, C.; Das, K.; McClendon, R. The influence of temperature and moisture contents regimes on the aerobic microbial activity of a biosolids composting blend. *Bioresour. Technol.* **2003**, *86*, 131–137. [CrossRef]
41. Abrahamsson, S.; Bertoni, F. Compost politics: Experimenting with togetherness in vermicomposting. *Environ. Humanit.* **2014**, *4*, 125–148. [CrossRef]
42. Azarmi, R.; Giglou, M.T.; Taleshmikail, R.D. Influence of vermicompost on soil chemical and physical properties in tomato (*Lycopersicum esculentum*) field. *Afr. J. Biotechnol.* **2008**, *7*.
43. Atiyeh, R.; Edwards, C.; Subler, S.; Metzger, J. Pig manure vermicompost as a component of a horticultural bedding plant medium: Effects on physicochemical properties and plant growth. *Bioresour. Technol.* **2001**, *78*, 11–20. [CrossRef] [PubMed]
44. Cegarra, J.; Paredes, C.; Roig, A.; Bernal, M.; García, D. Use of olive mill wastewater compost for crop production. *Int. Biodeterior. Biodegrad.* **1996**, *38*, 193–203. [CrossRef]
45. Montemurro, F.; Ferri, D.; Tittarelli, F.; Canali, S.; Vitti, C. Anaerobic digestate and on-farm compost application: Effects on lettuce (Lactuca sativa L.) crop production and soil properties. *Compos. Sci. Util.* **2010**, *18*, 184–193. [CrossRef]
46. Sarwar, G.; Schmeisky, H.; Hussain, N.; Muhammad, S.; Ibrahim, M.; Safdar, E. Improvement of soil physical and chemical properties with compost application in rice-wheat cropping system. *Pak. J. Bot.* **2008**, *40*, 275–282.
47. Li, H.; Xiang, D.; Wang, C.; Li, X.; Lou, Y. Effects of epigeic earthworm (*Eisenia fetida*) and arbuscular mycorrhizal fungus (*Glomus intraradices*) on enzyme activities of a sterilized soil–sand mixture and nutrient uptake by maize. *Biol. Fertil. Soils* **2012**, *48*, 879–887. [CrossRef]
48. Eisenhauer, N.; Marhan, S.; Scheu, S. Assessment of anecic behavior in selected earthworm species: Effects on wheat seed burial, seedling establishment, wheat growth and litter incorporation. *Appl. Soil Ecol.* **2008**, *38*, 79–82. [CrossRef]
49. Tripathi, G.; Bhardwaj, P. Decomposition of kitchen waste amended with cow manure using an epigeic species (*Eisenia fetida*) and an anecic species (*Lampito mauritii*). *Bioresour. Technol.* **2004**, *92*, 215–218. [CrossRef]