Article

Carbon Dynamics of Fruit and Vegetable Wastes and Biodegradable Municipal Waste Compost-Amended Oxisol

Aishatu Mala Musa ^{1,2}, Che Fauziah Ishak ¹, Noraini Md. Jaafar ^{1,*} and Daljit Singh Karam ¹

¹ Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, Serdang 43400, Malaysia; bintumalah@gmail.com (A.M.M.); cfauziah@upm.edu.my (C.F.I.); daljitsingh@upm.edu.my (D.S.K.)

² Department of Soil Science, Modibbo Adama University, Yola 640282, Nigeria

* Correspondence: j_noraini@upm.edu.my

Abstract: Recycling of wastes via composting is advocated as a means to reduce environmental hazards due to the dumping of wastes. Composting also creates a vital source of organic matter that is important in nutrient and soil moisture retention, soil fertility preservation and improving the physical and chemical properties of soils. This study was conducted to evaluate the short-term effects of four compost amendments in an Oxisol on carbon dynamics (carbon dioxide evolution and carbon transformation). The composts were prepared in 3:1 and 1:2 of fruit and vegetable waste (FVW) to biodegradable municipal waste (BMW) with and without indigenous microorganisms (IMO) (3:1 +IMO, 1:2 +IMO, 3:1 –IMO, 1:2 –IMO). Soil incubation studies were carried out for 35 days at three compost application rates of 0, 5 and 10 Mg ha^{−1}, with measurements done including the CO₂ evolution, dehydrogenase enzyme (DHA) assay and compost Fourier transform infrared (FTIR) spectroscopy spectral analysis. At 10 Mg ha^{−1} compost application rate, increased soil respiration rate was obtained at 3:1 +IMO compost, mostly due to increased labile organic matter and higher amount of FVW in the compost mixture, which stimulated soil microorganisms and/or their activities reflected by increased evolution of CO₂ in the process of decomposition of the added composts in the compost-amended soils. The DHA activity increased with compost application rates, and significantly, the highest DHA activity was recorded at 3:1 +IMO compost applied at 10 Mg ha^{−1} soil at 1.38 triphenylformazan (TPF)/g dry soil/24 h. The compost FTIR spectral analysis showed transformations that occurred due to the composting that was carried out. A broadband between 3279–3347 cm wavelength in the FTIR spectroscopy indicated the presence of carboxylic and hydroxyl functional groups because of carbon transformation that occurred in the composts.

Keywords: soil incubation study; soil respiration; carbon transformation; FTIR spectral analysis

Citation: Musa, A.M.; Ishak, C.F.; Jaafar, N.M.; Karam, D.S. Carbon Dynamics of Fruit and Vegetable Wastes and Biodegradable Municipal Waste Compost-Amended Oxisol. *Sustainability* **2021**, *13*, 10869. <https://doi.org/10.3390/su131910869>

Academic Editor: Antoni Sánchez

Received: 11 August 2021

Accepted: 22 September 2021

Published: 30 September 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Carbon stock maintenance in the tropics is challenging due to the high temperature and soil moisture that aggravates decomposition of organic carbon [1]. Compost addition to soil has been reported to increase soil carbon stocks through the addition of labile and recalcitrant soil organic carbon with different turnover rates. Some studies report soil organic matter and soil properties can be improved with the addition of composts to soils [2], because of their gradual mineralization rate. Composts release nutrients gradually over a long period [3], but their rapid decomposition and mineralization may significantly contribute to global warming [4]. Dehydrogenase activity (DHA) is involved in the soil oxidative metabolism, and it can be an indicator of microbial activity in the soil. Soil microbial activity can be increased with increase in labile carbon stock since they are primarily responsible for organic matter degradation and soil nutrient cycling [5]. Enzymes that are involved in intracellular metabolism such as DHA and catalase significantly increased as the amounts of added organic amendments increased from 20–40 Mg ton ha^{−1} [6]. Enzyme assays are vital indicators of soil microbial activity because of their immediate response to any slight

change in soil management practices. Indices on soil mineralization rates and organic matter decomposition can thus be obtained by measuring soil enzymes [7]. Enzymes like dehydrogenase, involved in mineralization of organic carbon, are therefore present at any time because these soil microbes determine soil enzyme synthesis rate [8,9]. Ryals et al. [10] were of the opinion that addition of compost increases the soil carbon and nitrogen store. These differences all originate from the primary substrates used in the composting and the physical location of carbon and nitrogen can also be observed by physical fractionation [11]. Soil organic matter (SOM) availability is mostly a function of a decomposer's access to organic substrates [12] and also by the chemical quality of the material [13,14]. Yu et al. [15] reported that compost and fertilizer application to soils increase the soil organic carbon accumulation mechanisms and compost in addition to increasing macro-aggregation of soils. Chemical characteristics assessment of organic amendments gives an indication of the potential reactivity of such an amendment [16], which aids in revealing the transformation of carbon that occurred with time [10]. Therefore, compost application to agricultural soils can increase plant biomass production, nutrient uptake and soil enzymatic activities [17]. Iovieno et al. [18] concluded from their research that annual compost addition in higher doses improves the activities of soil microorganisms through the provision of a labile soil organic carbon pool. Zhang et al. [19] reported that immediate microbial response observed from the results of their study could possibly be attributed to soil disturbance as a result of the incubation set up and/or the labile materials added. Increased decomposition of soil organic matter can be expected through the action of soil microorganisms that can cause high soil carbon dioxide loss and losses of soil organic carbon. The decomposition of added composts induces nutrient release in soils, and it can be concluded that the carbon dioxide release that occurs as a function of the respiration of soil microorganisms can be used to assess the cycling of nutrients through added composts [20,21]. Soil carbon sequestration can be enhanced through increased maintenance and abundance of carbon pools in soils and composts, reduced soil disturbance, compost addition to the field and leaving crop residues to recycle on the field.

Slow decomposition rates relative to organic matter inputs result in a net gain of carbon, while increased decomposition results in carbon loss through CO₂ efflux. Soil respiration can be defined as the amount of carbon dioxide that is produced by soil microorganisms as a result of their activities. Compost-amended soils may experience increased soil respiration because of change in the microbial community, microbial growth, enhanced microbial activity due to abundance of resources and/or improved soil physical properties due to compost addition that may induce an environment suitable for microbial proliferation [22]. Iovieno et al. [18] concluded from their research that annual compost addition in higher doses improves the activities of soil microorganisms through the provision of a labile soil organic carbon pool. Ryals et al. [23] reported that carbon sequestration due to compost addition occurs through the occlusion of soil organic carbon by soils that protect them from being accessible to soil microorganisms. The transformation of organic matter can be reflected by the presence of organic functional groups. The determination of organic functional groups can be done using Fourier transform infrared spectrophotometer (FTIR) spectroscopy. This involves the use of electromagnetic radiation, whose interaction with substances causes absorption, transmission, reflection, scattering or photoluminescence (PL) of materials, thereby enabling the provision of important information about molecular structure and also the energy transmission level of such a substance [24,25]. FTIR is exceptionally recommended in the characterization of soil organic matter (SOM) as it offers a better understanding of functional groups, soil organic matter structures and molecule sorption to mineral surfaces [26]. Functional groups of organic matter strongly influence soil organic matter properties. Understanding gaps that exist due to compost amendment in Oxisol and the reaction of soil microorganisms to compost qualities and aromatic stability that can make it labile or recalcitrant are important. To elucidate these aspects, short-term compost amendments on organic carbon dynamics and soil respiration in a Munchong series soil (Oxisol) were evaluated.

2. Materials and Methods

2.1. Compost Preparation

A preliminary study was carried out at Flat Seri Serdang and the Serdang wet market Malaysia, respectively, to find out the amount of fruits, vegetables, paper, plant leaves and rice being generated as waste only. The results showed that fruits and vegetables made up 70 and 30 percent of wastes being generated in the market, while 30, 50 and 20 percent were the amount of wastes being generated in the student residential complex sampled. Based on the results of the preliminary survey, composting mixtures of 3:1 and 1:2 of fruit and vegetable waste (FVW) FVW to biodegradable municipal waste (BMW) (FVW: BMW) with and without indigenous microorganisms (IMO) were made to produce composts that were used in the present study. The IMO inoculant was priorly made by chopping and mixing FVW in the ratio 1:3:10, brown sugar: FVW: dechlorinated water. The mixture was mixed and kept in an airtight opaque container and opened daily to release suppressed carbon dioxide. It becomes ready for use after 3–5 days when the pH reads 3.5 and it released a sweet-sour smell [27]. The IMO was used as a source of moisture during the composting process, and 0.5 and 2 litres were added to composting ratios 3:1 and 1:2, respectively. Table 1 presents the ratio and amounts of individual materials used to prepare the composts with and without indigenous microorganisms.

Table 1. Fruit and vegetable wastes and biodegradable municipal waste ratio and weight of materials used in composting (based on fresh weight).

Ratio of FVW: BMW Used in Composting				
		Percentage	Mixture Ratio 3:1	Mixture Ratio 1:2
Fruits	FVW	70	5.25	2.33
Vegetables		30	2.25	1.00
Paper		30	0.75	2.00
Rice	BMW	50	1.25	3.33
Yard wastes		20	0.5	1.33
Total amount (kg)		10 kg	10 kg	

Key: FVW: fruit and vegetable waste, BMW: biodegradable municipal waste.

2.2. Soil Respiration

Composts at varying mixture ratios of 3:1 and 1:2 of FVW: BMW with and without IMO, as detailed in Table 1 and prepared by Musa et al. [27], were taken and applied at the rates of 0, 5 and 10 Mg ha^{−1} to a Munchong series soil (Oxisol). An amount of 100 g of previously sieved Munchong series soil was weighed and placed into a glass jar, distilled water was added to it to reach 60% field capacity and the weight was noted. The soils were allowed to incubate for 10 days. Then, composts 3:1 –IMO@5 Mg ha^{−1}, 3:1 –IMO@10 Mg ha^{−1}, 1:2 –IMO@5 Mg ha^{−1}, 1:2 –IMO@10 Mg ha^{−1}, 3:1 +IMO@5 Mg ha^{−1}, 3:1 +IMO@10 Mg ha^{−1}, 1:2 +IMO@5 Mg ha^{−1}, 1:2 +IMO@10 Mg ha^{−1} and a control (soil only) were applied, and water was maintained at field capacity by regularly weighing the glass jar and making up for any water loss with the application of distilled water. Then, 20 mL of 1N NaOH inside a plastic vial was carefully placed inside the glass jar, and the glass jar was then closed tightly. After 24 h, the jar was opened and the plastic vial was taken out and titrated with 0.1 N HCl, while another vial with 20 mL 1N NaOH was again put into the glass jar after leaving the glass jar open for approximately 1 h, according to [28]. The duration of the experiment was 35 days.

2.3. Enzyme Assay

Dehydrogenase enzyme activity (DHA) of soil respiration soil studies activity at the stop of the experiment was determined following the method proposed by Casida [29] using 2-3-5-Triphenyl tetrazolium chloride (TTC) reduction technique. One gram of moist soil was put into test tube and 0.1 g CaCO₃ and 1 mL 1% TTC solution was all added to it. It was closed with a stopper and was shaken. It was then put into an incubator for 24 h

incubation at 30 °C. The mixture was filtered and extracted with concentrated methanol, and the volume was made up to 50 mL by methanol. To determine the dehydrogenase activity, the optical density of the filtrate was read at 485 nm on a spectrophotometer, using concentrated methanol as blank. Dehydrogenase activity per gram of dry soil was expressed as milligram formazan per gram of dry soil.

2.4. Soil Organic Matter Physical Fractionation Using Sodium Iodide and Micro-Aggregate Separation Using Sieves

Soil physical fractionation for free light fraction (FLF), heavy fraction (HF) and soil micro-aggregate analysis were carried out using some compost-amended soils at 10 Mg ha⁻¹ compost application rates and a control only. The experiment was designed using a CRD with 3 replications. Soil samples were taken and physically fractionated for soil organic matter fractions. Density fractionation using sodium iodide (NaI), as described by [30,31], was employed. An amount of 15 g of previously sieved soil was taken and put into a centrifuge tube, and 50 mL of sodium iodide (NaI) of 1.7 g/cm³ density was added to the tube containing soil, which was then mounted onto a shaker for 30 min and subsequently centrifuged for 10 min at 8000 rpm. The tubes were opened, and the free light fraction (FLF) soil organic matter was siphoned unto a fiber glass filter paper without disturbing the soil; then, 50 mL of 0.01 M CaCl₂ and 50 mL of deionized water were added from the sides of the Buchner funnel to rinse out the funnel. To the soil material remaining at the bottom of the centrifuge tube which is also referred to as the heavy fraction (HF), 50 mL deionized water was added. It was then put to shake in a shaker for 30 min. It was then centrifuged and filtered using a fiber glass filter paper and rinsed with 50 mL deionized water. To recycle, all using NaI only were collected in a 1-L beaker and the density was measured using a hydrometer, then approximately 20 g of activated charcoal and 15 g of NaI powder were added to it and allowed to swirl vigorously on a stirrer for at least 30 min. The contents were then filtered using a Whatman filter paper. The density was then measured again (1.7 g cm³) and it was able to be subsequently used. Both filter papers were then subsequently dried, weighed and analyzed for carbon using loss on ignition [31]. To the soil remaining in the centrifuge tube after the determination of FLF and HF of soil organic matter, physical soil particle size fractionation according to [31] was carried out. Briefly, water was added to the soil remaining in the centrifuge bottle after free light fraction (FLF) and heavy fraction (HF) siphoning, and the soil was dispersed and shaken. It was then filtered using three sieves stacked one upon the other carefully. The sieve sizes were 2000–250, <250–53 and <53–25 µm, respectively. The soils were gently washed with short blasts of water and subsequently dried and weighed.

2.5. Fourier Transform Infrared Spectroscopy (FTIR) of Compost

In this experiment, 4 composts (3:1 –IMO, 3:1 +IMO, 1:2 –IMO and 1:2 +IMO) and the compost-amended soils were taken and analyzed for carbon transformation through functional groups using FTIR Perkins Elmer 1725X FTIR spectrophotometer GX MODEL USA. Fourier transform infrared spectrophotometer (FTIR) spectra of composts and compost-amended soils were obtained from the range of 400 to 4000 cm on the machine at the chemistry department, Faculty of Science, Universiti Putra Malaysia. All samples for the analysis were sieved, and approximately 2.4 mg of the samples was collected and mixed with 100 mg of KBr and compressed to make a pellet [32]. The FTIR spectra of the samples were recorded, and the spectral result was transcribed using Origin Pro 2020 to fit the Gaussian–Lorentzian curve fit of the different samples.

2.6. Statistical Analysis

The experiments were set up in a complete randomized design (CRD) with three replications. Analysis of variance (ANOVA) mean comparison was performed using Tukey's test (SAS version 9.2), while FTIR spectra were analyzed using Origin Pro 2020 to fit the curves.

3. Results and Discussion

3.1. Soil Respiration

Figure 1 is the result of the soil respiration experiment that was conducted for 35 days. The highest soil respiration value of 550.08 kg CO₂ was observed at the addition of 10 Mg ha⁻¹ compost 3:1 +IMO, while the least soil respiration value of 337.28 kg CO₂ was recorded in treatment to which no compost was added (control) on day 1 of measurement. Soil respiration can be defined as the amount of carbon dioxide that is produced by soil microorganisms because of their activities. Compost-amended soils may experience increased soil respiration because of change in the microbial community, microbial growth, enhanced microbial activity due to abundance of resources and/or improved soil physical properties due to compost addition that may induce an environment suitable for microbial proliferation [22]. The result shows an initial increase in respiration rate and then a gradual decrease with time. The result is in agreement with Auffret et al. [33] who reported that soil respiration usually declines with time, which could be attributed to a reduction in decomposable soil organic carbon pool, and this has been confirmed by the results of the composts FTIR analysis whereby -COOH, -OH, -NH₂ and/or -NH [34] developed with time in the composts used. Abdelhafez et al. [35] reported an increase in soil respiration rates of soils amended with organic composts, and it was attributed to higher biological activities through increased microbial exhalation and/or carbon dioxide release due to compost decomposition, which can be confirmed by the FTIR results of composts 3:1 +IMO which transformed more carbon in relation to the other composts. When municipal solid waste (MSW) compost was added at the rates of 6.5 and 26 kg m² to soils in Spain, higher soil respiration than control was observed, and they concluded that continuous addition was favorable to soils [36]. Soil respiration from compost-amended pots were higher than control pots, and it increased with increase in compost application rates [37]. As carbon mineralization is reduced in compost-amended soils, enhanced soil nutrient retention and increased carbon sequestration can be expected [38]. Differences in measurement and definition of the terms carbon quality in soil organic matter gave rise to contradictory results that are inconsistent in some studies. Craine and Gelderman [39] reported that respiration sensitivity increases with time. Conen et al. [40] reported no relationship between soil respiration and incubation time. Sierra [41] reported that respiration sensitivity decreases with the carbon quality of the substrate. Soil organic matter decomposition in the soil is governed by microbial community (structure and biomass) and soil properties which can both influence microbial respiration rates because of their influence on soil microbial activity [42]. The results of the present work are in line with [33,41], who both reported that soil respiration decreases with decrease in labile soil organic matter due to reduction in decomposable soil organic carbon pool and quality of SOM. Teutscheroova et al. [43] were of the opinion that sustainable agriculture can today only be achieved through continuous incorporation of composts to soils.

Figure 2 is the result of the cumulative soil respiration experiment that was conducted for 35 days in the present experiment. Cumulative soil respiration of the compost-amended soils was significantly ($p \leq 0.05$) higher than the control treatment throughout the duration of the experiment. Cumulative soil respiration was highest in soil amended with compost 3:1 +IMO@10 Mg ha⁻¹. Cumulative CO₂-C released during the 28-day incubation period increased with time and increasing rates of compost application were reported [44]. Compost addition increased the rate of cumulative soil respiration throughout the experiment in relation to the control, to which no compost was added, and this can be attributed to the fact that in the compost-amended soils, there was abundance of SOM which microbes can act upon that will lead to the evolution of more CO₂ as they degrade these compounds.

Figure 1. Soil respiration during incubation studies TRT1: control, TRT2: 3:1 IMO@5 Mg ha^{−1}, TRT3: 3:1 −IMO@10 Mg ha^{−1}, TRT4: 1:2 −IMO@5 Mg ha^{−1}, TRT5: 1:2 −IMO@10 Mg ha^{−1}, TRT6: 3:1 +IMO@5 Mg ha^{−1}, TRT7: 3:1 +IMO@10 Mg ha^{−1}, TRT8: 1:2 +IMO@5 Mg ha^{−1}, TRT9: 1:2 +IMO@10 Mg ha^{−1}. Key: TRT – treatment, +IMO—indigenous microorganisms, −IMO—without indigenous microorganisms.

3.2. Dehydrogenase Enzyme Assay

Dehydrogenase activity (DHA) at the end of the soil respiration experiment of 35 days is presented below in Figure 3. The result shows that the dehydrogenase activities of the soil to the application of the different composts at different application rates were significantly different ($p \leq 0.05$). Soil microbial activity is usually induced by the abundance of moisture and labile nutrients that are available for mineralization. The dehydrogenase enzyme is involved in the mineralization of various organic matter and in microbial oxidative activities (soil respiration). Dehydrogenase activity is involved in the soil oxidative metabolism, and as such, it is an indicator of microbial activity in the soil. Enzyme assays are vital indicators of soil microbial activity because of their immediate response to any slight change in soil management practices. Indices on soil mineralization rates and organic matter decomposition can thus be obtained by measuring soil enzymes [7]. The dehydrogenase activity was significantly different in 3:1 +IMO@10 Mg ha^{−1} at 1.38 mg TPF/g dry soil/24 h which was the highest; however, it was not significantly different from compost 3:1 −IMO at 10 Mg ha^{−1}, 1:2 −IMO at 10 Mg ha^{−1}, 3:1 +IMO at 5 Mg ha^{−1} and 1:2 +IMO at 10 Mg ha^{−1} with values of 1.17, 0.93, 1.05 mg TPF/g dry soil/24 h, respectively. Compost 3:1 −IMO at 5 Mg ha^{−1}, 1:2 −IMO at 5 Mg ha^{−1} and control are significantly different from 3:1 +IMO at 10 Mg ha^{−1}. Compost 3:1 +IMO at 10 Mg ha^{−1} was highest with DHA of 1.38 TPF/g dry soil/24 h, while Trt 1, 3 and 9 had values of 0.66, 0.54 and 0.43 mg TPF/g dry soil/24 h, respectively, which were the lowest. It may probably be assumed that because the dehydrogenase activity was not measured at the peak/maximum of the soil respiration experiment, this may be the reason for the low DHA activity recorded because at that time, only the recalcitrant carbon was mostly present for decomposition. The labile nutrient elements had most probably been exhausted by the soil microbes at the start of the incubation experiment, hence the initial high soil respiration. Addition of the composts at different application rates had significant effects on the soil microbiological properties

because it affected dehydrogenase activity at the application rates used. The results of this experiment are in accordance with the results obtained by some researchers that the application of composts had a significant effect on enzymatic activity of soil microorganisms and that higher organic matter content led to the higher dehydrogenase content [45,46]. Compost application to soils induces biological activity of decomposer microorganisms due to increase in decomposable substrates since they use carbon for energy and tissue assimilation. This effect of compost on biological activity is attributed to an increase in substrate availability to decomposer microorganisms since they use organic carbon for energy through respiration or for assimilation into their tissues. Mohammadi [47] also reported increased microbial and enzymatic activity due to application of organic manure and composts to soils. Better conditions for microorganisms and microbial activity are positive beyond the productive function of soil as they will increase biodiversity and influence the biogeochemical cycles that are dependent on organic matter decomposition [46,48]. Heavy metals from composts can inhibit dehydrogenase enzyme activity [6]; however, the compost heavy metals from the present composts used have been reported to be low beyond detection limits [27]. Dehydrogenase activity was reported to be higher at lower compost application rate of 20 Mg ha^{-1} than 80 Mg ha^{-1} , and it was attributed to the toxic effect of heavy metals at the higher compost application rate and the heavy metal content of the composts used [49].

Figure 2. Cumulative soil respiration during incubation studies TRT1: control, TRT2: 3:1 +IMO@5 Mg ha^{-1} , TRT3: 3:1 -IMO@10 Mg ha^{-1} , TRT4: 1:2 -IMO@5 Mg ha^{-1} , TRT5: 1:2 -IMO@10 Mg ha^{-1} , TRT6 3:1 +IMO@5 Mg ha^{-1} , TRT7: 3:1 +IMO@10 Mg ha^{-1} , TRT8: 1:2 +IMO@5 Mg ha^{-1} , TRT9: 1:2 +IMO@10 Mg ha^{-1} ; +IMO—indigenous microorganisms, -IMO—without indigenous microorganisms.

3.3. Soil Organic Matter Fractionation

3.3.1. Free Light Fraction and Heavy Fractions of Soil Organic Matter

Figure 4 shows the free light fraction (FLF) and heavy fraction (HF) soils after density fractionation using NaI according to [30,31]. Table 2 shows the physical fractionation of free

light fraction (FLF) and heavy fraction (HF) of soil organic matter in soils amended with compost at 10 Mg ha^{-1} . The carbon fractions of the light fractions among treatments are not significantly different ($p > 0.05$). This is also true for the heavy carbon fraction. Different forms of organic matter act uniquely on soil quality and to changes in soil management [50] because the different fractions show differing degree of biochemical activities and rate of microbial degradation of added composts. A study by [10] reported that the addition of organic matter positively affected the carbon content of the free light fractions (FLF) and heavy fractions (HF), including the nutrient contents in the topsoil.

Figure 3. Dehydrogenase assay of soil respiration samples Means with similar small letter were not significantly different ($p > 0.05$) according to Tukey's HSD (Honest Significant Difference) TRT1: control, TRT2: 3:1 +IMO@5 Mg ha^{-1} , TRT3: 3:1 −IMO@10 Mg ha^{-1} , TRT4: 1:2 −IMO@5 Mg ha^{-1} , TRT5: 1:2 −IMO@10 Mg ha^{-1} , TRT6 3:1 +IMO@5 Mg ha^{-1} , TRT7: 3:1 +IMO@10 Mg ha^{-1} , TRT8: 1:2 +IMO@5 Mg ha^{-1} , TRT9: 1:2 +IMO@10 Mg ha^{-1} ; +IMO—indigenous microorganisms, −IMO—without indigenous microorganisms.

Figure 4. Free light fraction (FLF) and heavy fraction (HF) soils after density fractionation using NaI [30,31].

Table 2. Free light fraction (FLF) carbon and heavy fraction (HF) carbon fraction of soils at 60 days after incubation.

Treatment	Free Light Fraction Carbon (g/kg Soil)	Heavy Fraction Carbon (g/kg Soil)
3:1 +IMO@10 Mg ha ⁻¹	160.65 ^a ± 16.02	74.04 ^a ± 6.72
3:1 −IMO@10 Mg ha ⁻¹	195.63 ^a ± 9.97	160.23 ^a ± 4.46
1:2 +IMO@10 Mg ha ⁻¹	142.7 ^a ± 6.14	66.4 ^a ± 8.75
1:2 −IMO@10 Mg ha ⁻¹	152.91 ^a ± 2.69	95.43 ^a ± 16.73
CONTROL	133.01 ^a ± 4.58	68.47 ^a ± 1.34

Note All values (mean ± standard error) are averages of three replicated trials. Note that in each column, same means with the same letter are not significantly different at a probability level of 0.05.

3.3.2. Free Light Fraction (FLF) and Heavy Fractions (HF) of Soil Fractionated Using NaI

Song et al. [30] reported that FLF is the immediate reserve of nutrients for soil microorganisms, has a rapid turnover rate and is sensitive to moisture and temperature changes while HF carbon has a slow turnover rate and is not very sensitive. Organic matter amendments increase carbon pools of soil [51]. The results showed the application of the different composts at the rate of 10 Mg ha⁻¹ increased the amount of soil organic carbon in relation to the control. The FLF fractions closely resemble plant material and is the particulate organic matter free-floating in the soil matrix. It is usually the fraction with the fastest turnover time and is generally the most easily accessible to decomposer soil microorganisms and their extra-cellular enzymes. The HF consists of a pool of carbon and nitrogen which are physically protected in soil aggregates and are thus less accessible to decomposers and usually stay longer than the FLF. Application of composts to soils has been reported to increase soil organic matter accumulation in soils and also influence a higher level of soil carbon and nitrogen mineralization [52,53]. Soil carbon turnover depends upon organic inputs and decomposition rate of the soil organic matter applied. Light fraction correlates with nitrogen mineralization rate possibly because it is the fraction that soil microorganisms act upon due to the presence of labile organic matter. Alvarez and Alvarez [54] also reported that the FLF is important in soil respiration because it is a pool between the materials undergoing mineralization and the recalcitrant soil organic matter pool, while the HF is the bed for carbon storage because of the abundance of recalcitrant carbon pools. The application of the composts at 10 Mg ha⁻¹ for composts without added IMO released more FLF carbon, possibly due to fewer microorganisms to degrade the added composts because the FLF is the less stable plant-like portion that has a higher concentration of carbon in relation to the HF that is more stable with less carbon concentration [55].

3.3.3. Soil Physical Fractionation Aggregate Formation

Soil physical fractionation results using different sieve sizes are presented in Table 3. From the table, it can be observed that the physical fractions of the soils were different for each treatment. Physical fractionation of soil organic matter aided in the identification of size distribution, which was important in identifying the physical pools of soil organic matter [55]. Control soils had a low amount of the coarse sand fraction in relation to the other soils with compost addition. Some of the literature has reported that SOC stabilization mechanism (resistance to decomposition) within soil organic matter can be assumed to be dependent upon physical, chemical and biochemical stabilization. Biochemical stabilization of SOM occurs when complex structure is developed by SOM due to its recalcitrance. Physical stabilization normally relates to soil organic matter occlusion within soil aggregates that can cause inaccessibility of soil organic matter to decomposition by soil microorganisms. Meanwhile, chemical stabilization occurs when soil organic matter becomes inaccessible to soil microbes because of their complexation with metal ions or sorption to mineral surface [56–58]. However, in addition, the short incubation period could possibly have been too short to observe aggregate formation because of the compost addition.

Table 3. Soil aggregation.

Treatment	Size	Weight (g)	%
3:1 –IMO@10 Mg ha ^{−1}	250 µm	2.79	18.60
	53 µm	1.75	11.67
	25 µm	0.56	3.73
3:1 +IMO@10 Mg ha ^{−1}	250 µm	2.44	16.27
	53 µm	1.72	11.47
	25 µm	0.44	2.93
1:2 –IMO@10 Mg ha ^{−1}	250 µm	2.74	18.27
	53 µm	1.59	10.60
	25 µm	0.25	1.67
1:2 +IMO@10 Mg ha ^{−1}	250 µm	2.47	16.47
	53 µm	1.64	10.93
	25 µm	0.35	2.33
CONTROL	250 µm	2.15	14.33
	53 µm	2.06	13.73
	25 µm	0.38	2.53

3.4. Compost FTIR Interpretation Using Origin Pro 2020

Figure 5 shows the FTIR spectral image of the four composts (A: 1:2 +IMO, B: 3:1 +IMO, C: 1:2 –IMO, D: 3:1 –IMO) used in the experiments. From the spectral image of the composts, it can be observed that the transformation of the carbon in the composts had occurred with specific regions where the spectral peaks are similar to each compost. The FTIR spectroscopy results revealed enrichment in aromatic structures and a degradation of the aliphatic and alcoholic structures indicating stabilization of the final compost [59]. Studying specific bands in FTIR spectroscopy results enables the understanding of the development of functional groups that have occurred as a result of composting and/or decomposition.

Figure 5. Gaussian–Lorentzian fitted curve FTIR of four composts A 1:2 +IMO, B 3:1 +IMO, C 1:2 –IMO, D 3:1 –IMO.

3.5. Composts' Gaussian–Lorentzian Fitted Curves

To fully understand the spectral peak difference formed by the individual composts, the obtained FTIR spectral carbon transformation data were deconvolved. Deconvolution is an algorithm process that enhances data peak or signal. The second derivative spectra

result and the deconvolved result was used in determining the respective number of bands formed by each compost. To achieve the curve fitting, Origin Pro 2020 was used to fit the process as was contained in each individual band/peak that had transformed by the baseline position. Band characteristics usually include wave number, height and/or band width. The Origin Pro 2020 program then iterates the curve fitting process of the bands. As the iteration proceeds, the parameters decrease or increase to show how best the Gaussian–Lorentzian curve will appear to best fit the original spectrum. The following Figures 6–9 each show the deconvolved and second derivative spectra of each of the four composts that were produced with and without IMO.

Figure 6. Gaussian–Lorentzian fitted curve of 1:2 +IMO compost (A).

Figure 7. Gaussian–Lorentzian fitted curve of 3:1 +IMO compost (B).

Figure 8. Gaussian-Lorentzian fitted curve spectra of 1:2 –IMO compost (C).

Figure 9. Gaussian-Lorentzian fitted curve of 3:1 –IMO compost (D).

The broad spectrum of characteristics on the compost spectral around 3200–3400 cm in the composts, which indicates the development of a carboxylic group (-COOH), an alcohol (-OH) and/or an amine and amide (-NH_2 or -NH) stretching of hydroxyls from phenols and alcohols (34), is fully developed in all four composts. In addition, compost 3:1 +IMO has a peak at 2932 cm that makes it have the C-H group that will degrade with time, thus increasing its nutrient release mechanism. Increase in humification during co-composting is brought about by reduction of carbohydrates, cellulose and hemicellulose complexes; thus, it can be used as an index of compost maturity. All four composts at the stop of composting have the aromatic groups that range from 1400–1600 cm that are characteristic of the C=C aromatic hydrocarbon (double bond aromatic carbon) and the 1630 cm C=C aromatic alkenes that range from 1620–1680 cm wavelength. These together with weak chains that form around 1250–1500 usually make up the aromatic esters of the -NH_2 , which are primarily hard to degrade possibly because they are primarily made up of lignin [34].

The functional group that appears on the 1029–1032 cm wavelength range is designated the ether C-Br, including those that fall on the 1000–1300 cm and the 1070–1150 cm wavelength.

Humification increases alkyl C, aromatic C, carboxyl (-COOH), phenolic, hydroxyl (-OH) and carbonyl (-CO) groups [60] in composts. Due to the increased aromatic nature of composts, the co-composting process influences not only the elemental composition of finished composts but also affects the functional groups [61]. Fersi et al. [62] observed that in the FTIR spectra of composts, a decrease in aliphatic and a concomitant increase in -OH of the composts coupled with lignin modification was recorded for all composts irrespective of microbial inoculant application on day 0, 120 or control during composting of lignocellulosic compounds. Decreasing aliphatic to aromatic groups during composting is an indication of compost maturity (32).

Compost made with 3:1 -IMO have peaks located at 3347 and 3274 cm wavelength. The peaks are the -OH that are characteristic of most organic materials. Composts 1:2 -IMO have peaks that developed on 3311 cm and 3267 cm and have been ascribed to the -OH groups. Compost 3:1 +IMO had peaks developed on 3344 cm, 3281 cm and 2932 cm; these peaks corresponds to peaks of -OH, -COOH, -NH₂ and/or the -NHOH groups while compost 1:2 +IMO has peaks developed at 3279 (34). Thus, all four composts used had the broadband that developed between 3200–3600 cm that has the characteristic -OH, -COOH, -NH₂ and/or the -NHOH groups. Composts 3:1 +IMO and 1:2 +IMO both have the bond formed around the area that ranges between 3200–3600 cm that have been described as the H- bonded -OH group vibrations.

The appearance of bands between 3200–3600 cm was due to the association of hydrogen bonding among the hydroxyl groups of the lignin, cellulose and hemicellulose substrates that were used during the composting [63]. The -OH band that appears between 3200–3600 cm in compost 3:1 -IMO was located at 3274 and 3347 cm after deconvolution; in compost 1:2 -IMO, it was at 3267–3311 cm; in compost 3:1 +IMO, it was at 3281–3344 cm; while in compost 1:2 +IMO, it was located at 3279 cm specifically. The slight change in intensity to the right of these composts with respect to a shift in the peaks is an indication of their maturity and increased humification. At 2932 cm in compost 3:1 +IMO is a C-H peak that usually appears between 2850–3000 cm, and this absorption band is assigned the stretching vibrations in compost. These bands may correspond to aliphatic moieties of cellulose and hemicellulose polysaccharide that will degrade with time. All four composts have the aromatic group ranges that are found between 1400–1600 cm and 1620–1680 cm that all belong to the C=C and the C=H aromatic hydrocarbon. At 1029–1032 cm also falls the C-O covalent bond that is characteristically found at 1000–1300 and 1070 to 1150 cm that are esters. It can be observed from the above results that compost functional group development can be attributed to the substrates used in making it. Composts 3:1, irrespective of IMO addition, had more pronounced functional groups located on 3347 cm⁻¹, 3274 cm⁻¹ (3:1 -IMO) and 3344 and 3281 cm⁻¹ (3:1 +IMO) probably due to the ratio of fruit and vegetable wastes in the compost formulation [27] while in addition, compost 3:1 +IMO had an additional functional group located at 2932 cm⁻¹, possibly obtained because of the ratio of FVW used in the composting and the additional microorganism source due to the addition of indigenous microorganisms (IMO).

4. Conclusions

The results of the study showed that application of composts prepared at different ratio of FVW: BMW with IMO, when applied to soils at higher application rate, had significantly stimulated microbial activities and soil organic carbon accumulation which was observed in the soil respiration results. The highest soil respiration value of 550.08 kg CO₂ was observed at the application of compost 3:1 +IMO at 10 Mg ha⁻¹, and they released more CO₂ in relation to control. The cumulative soil respiration results also gave a similar result. The FTIR results revealed that the various ratios of compost formulation influenced the transformation of the composts added and aided the development of functional groups such as the -OH, -CO, -COOH, -NH₂ and -NH, especially with the development of the

wide band around 3000–3600 cm that is characteristic of the -OH and the -COOH groups. Therefore, it can be concluded that composts 3:1 +IMO application at a higher rate of 10 Mg ha⁻¹ resulted in a higher soil respiration (3:1 +IMO@10 Mg ha⁻¹) in relation to an application rate of 5 Mg ha⁻¹ or control. It can be concluded that application of compost 3:1 +IMO@10 Mg ha⁻¹ seems promising in terms of increased microbial respiration, which will be translated to increased carbon transformation because of the high nutrient content in the composts applied.

Author Contributions: Conceptualization, A.M.M. and C.F.I.; Formal Analysis, A.M.M.; Funding Acquisition, C.F.I.; Investigation, A.M.M.; Methodology, A.M.M., D.S.K. and N.M.J.; Project Administration, C.F.I.; Resources, C.F.I.; Supervision, C.F.I., D.S.K. and N.M.J.; Validation, A.M.M., C.F.I., D.S.K. and N.M.J.; Writing—Original Draft, A.M.M.; Writing—Review and Editing, A.M.M., C.F.I., D.S.K. and N.M.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. However, authors would like to acknowledge the publication funding (UPM Journal Publication Fund 9001103) by Universiti Putra Malaysia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data reported in this study is contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Leite, L.F.C.; Iwata, B.F.; Araújo, A.S.F. Soil organic matter pools in a tropical savanna under agroforestry system in northeastern Brazil. *Rev. Árvore* **2014**, *38*, 711–723. [\[CrossRef\]](#)
2. Biederman, L.A.; Harpole, W.S. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy* **2013**, *5*, 202–214. [\[CrossRef\]](#)
3. Burger, M.; Jackson, L. Microbial immobilization of ammonium and nitrate in relation to ammonification and nitrification rates in organic and conventional cropping systems. *Soil Biol. Biochem.* **2003**, *35*, 29–36. [\[CrossRef\]](#)
4. Srivastava, A.; Das, S.; Malhotra, S.; Majumdar, K. SSNM-based rationale of fertilizer use in perennial crops: A review. *Indian J. Agric. Sci.* **2014**, *84*, 3–17.
5. Rodrigues, J.L.M.; Pellizari, V.H.; Mueller, R.; Baek, K.; Jesus, E.C.; Paula, F.S.; Mirza, B.; Hamaoui, G.S., Jr.; Tsai, S.M.; Feigl, B.; et al. Conversion of the Amazon rainforest to agriculture results in biotic homogenization of soil bacterial communities. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 988–993. [\[CrossRef\]](#) [\[PubMed\]](#)
6. García-Gil, J.C.; Plaza, C.; Soler-Rovira, P.; Polo, A. Long-term effects of municipal solid waste compost application on soil enzyme activities and microbial biomass. *Soil Biol. Biochem.* **2000**, *32*, 1907–1913. [\[CrossRef\]](#)
7. Veum, K.S.; Goyne, K.W.; Kremer, R.J.; Miles, R.J.; Sudduth, K. Biological indicators of soil quality and soil organic matter characteristics in an agricultural management continuum. *Biogeochemistry* **2014**, *117*, 81–99. [\[CrossRef\]](#)
8. Miller, M.; Dick, R.P. Thermal stability and activities of soil enzymes as influenced by crop rotations. *Soil Biol. Biochem.* **1995**, *27*, 1161–1166. [\[CrossRef\]](#)
9. Badiane, N.N.Y.; Chotte, J.L.; Patea, E.; Masse, D.; Rouland, C. Use of soil enzyme activities to monitor soil quality in natural and improved fallows in semi-arid tropical regions. *Appl. Soil Ecol.* **2001**, *18*, 229–238. [\[CrossRef\]](#)
10. Ryals, R.; Kaiser, M.; Torn, M.S.; Berhe, A.A.; Silver, W.L. Impacts of organic matter amendments on carbon and nitrogen dynamics in grassland soils. *Soil Biol. Biochem.* **2014**, *68*, 52–61. [\[CrossRef\]](#)
11. Sollins, P.; Homann, P.; Caldwell, B. Stabilization and destabilization of SOM: Mechanisms and controls. *Geoderma* **1996**, *74*, 65–105. [\[CrossRef\]](#)
12. Dungait, J.A.J.; Hopkins, D.W.; Gregory, A.S.; Whitmore, A.P. SOM turnover is governed by accessibility not recalcitrance. *Glob. Chang. Biol.* **2012**, *18*, 1781–1796. [\[CrossRef\]](#)
13. Jastrow, J.D.; Amonette, J.E.; Bailey, V. Mechanisms controlling soil carbon turnover and their potential application for enhancing carbon sequestration. *Clim. Chang.* **2007**, *80*, 5–23. [\[CrossRef\]](#)
14. Conant, R.T.; Ogle, S.M.; Paul, E.A.; Paustian, K. Measuring and monitoring soil organic carbon stocks in agricultural lands for climate mitigation. *Front. Ecol. Environ.* **2011**, *9*, 169–173. [\[CrossRef\]](#)
15. Yu, H.; Ding, W.; Chen, Z.; Zhang, H.; Luo, J.; Bolan, N. Accumulation of organic C components in soil and aggregates. *Sci. Rep.* **2015**, *5*, 13804. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Kögel-Knabner, I.; Guggenberger, G.; Kleber, M.; Kandeler, E.; Kalbitz, K.; Scheu, S.; Eusterhues, K.; Leinweber, P. Organo-mineral associations in temperate soils: Integrating biology, mineralogy, and organic matter chemistry. *J. Plant. Nutr. Soil Sci.* **2008**, *171*, 61–82. [\[CrossRef\]](#)

17. Antonious, G.F.; Turley, E.T.; Hill, R.R.; Snyder, J.C. Effect of municipal refuse and chicken manure applications on kale and collard green yields and quality. In *Fruit and Vegetable Crops Research Report*; Saha, S.K., Snyder, J., Smigell, C., Eds.; University of Kentucky: Lexington, KY, USA, 2013; pp. 37–39.
18. Iovieno, P.; Morra, L.; Leone, A.; Pagano, L.; Alfani, A. Effect of organic and mineral fertilizers on soil respiration and enzyme activities of two Mediterranean horticultural soils. *Biol. Fertil. Soils* **2009**, *45*, 555–561. [\[CrossRef\]](#)
19. Zhang, Y.; Xu, W.; Duan, P.; Cong, Y.; An, T.; Yu, N.; Zou, H.; Dang, X.; An, J.; Fan, Q.; et al. Evaluation and simulation of nitrogen mineralization of paddy soils in Mollisols area of Northeast China under waterlogged incubation. *PLoS ONE* **2017**, *12*, e0171022. [\[CrossRef\]](#)
20. Radicetti, E.; Campiglia, E.; Marucci, A.; Mancinelli, R. How winter cover crops and tillage intensities affect nitrogen availability in eggplant. *Nutr. Cycl. Agroecosyst.* **2017**, *108*, 177–194. [\[CrossRef\]](#)
21. Radicetti, E.; Osipitan, O.A.; Langeroodi, A.R.S.; Marinari, S.; Mancinelli, R. CO₂ Flux and C Balance due to the Replacement of Bare Soil with Agro-Ecological Service Crops in Mediterranean Environment. *Agriculture* **2019**, *9*, 71. [\[CrossRef\]](#)
22. Tejada, M.; Hernandez, M.T.; Garcia, C. Soil restoration using composted plant residues: Effects on soil properties. *Soil Tillage Res.* **2009**, *102*, 109–117. [\[CrossRef\]](#)
23. Ryals, R.; Silver, W.L. Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands. *Ecol. Appl.* **2013**, *23*, 46–59. [\[CrossRef\]](#)
24. Cui, H.; Abu-Siada, A.; Li, S.; Islam, S. Correlation between dissolved gases and oil spectral response. In Proceedings of the 1st International Conference on Electrical Materials and Power Equipment (ICEMPE), Xi'an, China, 14–17 May 2017; pp. 28–32.
25. Bakar, N.A.; Cui, H.; Abu-Siada, A.; Li, S. A review of spectroscopy technology applications in transformer condition monitoring. In Proceedings of the International Conference on Condition Monitoring and Diagnosis (CMD), Xi'an, China, 25–28 September 2016; pp. 372–375.
26. Margenot, A.J.; Calderón, F.J.; Goeyne, K.W.; Mukome, F.N.D.; Parikh, S.J. IR Spectroscopy, soil analysis applications. *Encycl. Spectrosc. Spectrom.* **2016**, 448–454.
27. Musa, A.M.; Ishak, C.F.; Karam, D.S.; Jaafar, N.M. Effects of fruit and vegetable wastes and biodegradable municipalwastes co-mixed composts on nitrogen dynamics in an oxisol. *Agronomy* **2020**, *10*, 1609. [\[CrossRef\]](#)
28. Rawoteea, S.A.; Ackmez, M.; Kumar, S. Co-composting of vegetable wastes and carton: Effect of carton composition and parameter variations. *Bioresour. Technol.* **2017**, *227*, 171–178. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Casida, L.E. Microbial metabolic activity in soil as measured by dehydrogenase determinations. *Appl. Environ. Microbiol.* **1977**, *34*, 630–636. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Song, B.; Niu, S.; Zhang, Z.; Yang, H.; Li, L.; Wan, S. Light and heavy fractions of soil organic matter in response to climate warming and increased precipitation in a temperate steppe. *PLoS ONE* **2012**, *7*, e33217. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Sohi, S.P.; Mahieu, N.; Arah, J.R.M.; Powlson, D.S.; Madari, B.; Gaunt, J.L. A procedure for isolating SOM fractions suitable for modeling. *Sci. Soc. Am. J.* **2001**, *65*, 1121–1128. [\[CrossRef\]](#)
32. Hsu, J.H.; Lo, S.L. Chemical and spectroscopic analysis of organic matter transformations during composting of pig manure. *Environ. Pollut.* **1999**, *104*, 189–196. [\[CrossRef\]](#)
33. Auffret, M.D.; Karhu, K.; Khachane, A.; Dungait, J.A.; Fraser, F.; Hopkins, D.W.; Wookey, P.A.; Singh, B.K.; Freitag, T.E.; Hartley, I.P.; et al. The role of microbial community composition in controlling soil respiration responses to temperature. *PLoS ONE* **2016**, *11*, e0165448. [\[CrossRef\]](#)
34. Varma, V.S.; Das, S.; Sastri, C.V.; Kalamdhad, A.S. Microbial degradation of lignocellulosic fractions during drum composting of mixed organic waste. *Sustain. Environ. Res.* **2017**, *27*, 265–272. [\[CrossRef\]](#)
35. Abdelhafez, A.A.; Abbas, M.H.H.; Attia, T.M.S.; El Bably, W.; Mahrous, S.E. Mineralization of organic carbon and nitrogen in semi-arid soils under organic and inorganic fertilization. *Environ. Technol. Innov.* **2018**, *9*, 243–253. [\[CrossRef\]](#)
36. Bhattacharyya, P.; Pal, R.; Chakraborty, A.; Chakrabarti, K. Microbial biomass and activity in a laterite soil amended with municipal solid waste compost. *J. Agron. Crop. Sci.* **2001**, *187*, 207–211. [\[CrossRef\]](#)
37. Fabrizio, A.; Tambone, F.; Genevini, P. Effect of compost application rate on carbon degradation and retention in soils. *Waste Manag.* **2009**, *29*, 174–179. [\[CrossRef\]](#) [\[PubMed\]](#)
38. Tsai, C.C.; Chang, Y.F. Carbon dynamics and fertility in biochar-amended soils with excessive compost application. *Agronomy* **2019**, *9*, 511. [\[CrossRef\]](#)
39. Craine, J.M.; Gelderman, T.M. Soil moisture controls on temperature sensitivity of soil organic carbon decomposition for a mesic grassland. *Soil Biol. Biochem.* **2011**, *42*, 455–457. [\[CrossRef\]](#)
40. Conen, F.; Leifeld, J.; Seth, B.; Alewell, C. Warming mineralizes young and old soil carbon equally. *Biogeosciences* **2006**, *3*, 515–519. [\[CrossRef\]](#)
41. Sierra, C.A. Temperature sensitivity of organic matter decomposition in the Arrhenius equation: Some theoretical considerations. *Biochemistry* **2012**, *108*, 1–15. [\[CrossRef\]](#)
42. Xu, Z.; Yu, G.; Zhang, X.; Ge, J.; He, N.; Wang, Q.; Wang, D. The variations in soil microbial communities, enzyme activities and their relationships with soil organic matter decomposition along the northern slope of Changbai Mountain. *Appl. Soil Ecol.* **2015**, *86*, 19–29. [\[CrossRef\]](#)
43. Teutscherova, N.; Vazquez, E.; Santana, D.; Navas, M.; Masaguer, A.; Benito, M. Influence of pruning waste compost maturity and biochar on carbon dynamics in acid soil: Incubation study. *Eur. J. Soil Biol.* **2017**, *78*, 66–74. [\[CrossRef\]](#)

44. Pedra, F.; Polo, A.; Ribeiro, A.; Domingues, H. Effects of municipal solid waste compost and sewage sludge on mineralization of soil organic matter. *Soil Biol. Biochem.* **2007**, *39*, 1375–1382. [[CrossRef](#)]
45. Włodarczyk, T.; Stepniewski, W.; Brzezińska, M. Dehydrogenase activity, redox potential, and emissions of carbon dioxide and nitrous oxide from Cambisols under flooding conditions. *Biol. Fertil. Soils* **2002**, *36*, 200–206. [[CrossRef](#)]
46. Diacono, M.; Montemurro, F. Long term effects of organic amendments on soil fertility. A review. *Agron. Sustain. Dev.* **2010**, *30*, 401–422. [[CrossRef](#)]
47. Mohammadi, K.; Heidari, G.; Nezhad, M.T.K.; Ghamari, S.; Sohrabi, Y. Contrasting soil microbial responses to fertilization and tillage systems in canola rhizosphere. *Saudi J. Biol. Sci.* **2012**, *19*, 377–383. [[CrossRef](#)] [[PubMed](#)]
48. Ros, M.; Klammer, S.; Knapp, B.; Alchberger, K.; Insam, H. Long term effects of compost amendment of soil on functional and structural diversity and microbial activity. *Soil Use Manag.* **2006**, *22*, 209–218. [[CrossRef](#)]
49. de Araújo, A.S.F.; de Melo, W.J.; Singh, R.P. Municipal solid waste compost amendment in agricultural soil: Changes in soil microbial biomass. *Rev. Environ. Sci. Bio/Technol.* **2010**, *9*, 41–49. [[CrossRef](#)]
50. Chan, K.Y.; Heenan, D.P.; Oates, A. Soil carbon fractions and relationship to soil quality under different tillage and stubble management. *Soil Tillage Res.* **2002**, *63*, 133–139. [[CrossRef](#)]
51. Cabrera, V.E.; Stavast, L.J.; Baker, T.T.; Wood, M.K.; Cram, D.S.; Flynn, R.P.; Ulery, A.L. Soil and runoff response to dairy manure application on New Mexico rangeland. *Agric. Ecosyst. Environ.* **2009**, *131*, 255–262. [[CrossRef](#)]
52. Xie, H.; Li, J.; Zhu, P.; Peng, C.; Wang, J.; He, H.; Zhang, X. Long-term manure amendments enhance neutral sugar accumulation in bulk soil and particulate organic matter in a Mollisol. *Soil Biol. Biochem.* **2014**, *78*, 45–53. [[CrossRef](#)]
53. Sun, L.; Chang, S.X.; Feng, Y.S.; Dyck, M.F.; Puurveen, D. Nitrogen fertilization and tillage reversal affected water-extractable organic carbon and nitrogen differentially in a Black Chernozem and a Gray Luvisol. *Soil Tillage Res.* **2015**, *146*, 253–260. [[CrossRef](#)]
54. Alvarez, R.; Alvarez, C.R. Soil organic matter pools and their associations with carbon mineralization kinetics. *Soil Sci. Soc. Am. J.* **2000**, *64*, 184–189. [[CrossRef](#)]
55. Tan, Z.; Lal, R.; Owens, L.; Izaurrealde, R.C. Distribution of light and heavy and nitrogen fertilization on soil organic carbon pools under perennial grass pastures in the southeastern USA. *Soil Biol. Biochem.* **2007**, *58*, 42–49.
56. Courtier-Murias, D.; Simpson, A.J.; Marzadori, C.; Baldoni, G.; Ciavatta, C.; Fernández, J.M.; López-de-Sá, E.G.; Plaza, C. Unraveling the long-term stabilization mechanisms of organic materials in soils by physical fractionation and NMR spectroscopy. *Agric. Ecosyst. Environ.* **2013**, *171*, 9–18. [[CrossRef](#)]
57. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176. [[CrossRef](#)]
58. Duddigan, S.; Shaw, L.J.; Alexander, P.D.; Collins, C.D. A comparison of physical soil organic matter fractionation methods for amended soils. *Appl. Environ. Soil Sci.* **2019**, *2019*, 3831241. [[CrossRef](#)]
59. Makni, H.; Ayed, L.; Ben Khedher, M.; Bakhrouf, A. Evaluation of the maturity of organic waste composts. *Waste Manag. Res.* **2010**, *28*, 489–495. [[CrossRef](#)] [[PubMed](#)]
60. Inbar, Y.Y.; Chen, Y.H. Humic substances formed during the composting of organic matter. *Soil Sci. Soc. Am. J.* **1989**, *54*, 1316–1323. [[CrossRef](#)]
61. Sanchez-Monedero, M.A.; Cegarra, J.; Garcia, D.; Roig, A. Chemical and structural evolution of humic acids during organic waste composting. *Biodegradation* **2002**, *13*, 361–371. [[CrossRef](#)]
62. Fersi, M.; Mbarki, K.; Gargouri, K.; Mechichi, T.; Hachicha, R. Assessment of organic matter biodegradation and physico-chemical parameters variation during co-composting of lignocellulosic wastes with *Trametes trogii* inoculation. *Environ. Eng. Res.* **2019**, *24*, 670–679. [[CrossRef](#)]
63. Barnette, A.L.; Lee, C.; Bradley, L.C.; Schreiner, E.P.; Park, Y.B.; Shin, H.; Cosgrove, D.J.; Park, S.; Kim, S.H. Quantification of crystalline cellulose in lignocellulosic biomass using sum frequency generation (SFG) vibration spectroscopy and comparison with other analytical methods. *Carbohydrate. Polymers* **2012**, *89*, 802–809. [[CrossRef](#)]