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# Food-Based Composts Provide More Soil Fertility Benefits Than Cow Manure-Based Composts in Sandy Soils

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**Abstract:** Nutrient concentration and availability vary substantially among composts depending on the materials used and the production process. Composts produced from agricultural operations typically utilize animal wastes such as manures, whereas composts produced in urban areas mainly incorporate food and yard waste. Our objective was to assess how different composts affect nutrient availability and cycling, mostly carbon (C) and nitrogen (N). In a laboratory incubation, we compared three composts derived from cow manure (composted dairy manure solids, vermicompost made from those manure solids, and Black Kow$^{TM}$) and two composts derived from food waste (composted food waste from the UF-IFAS Compost Cooperative and Ecoscraps$^{TM}$). We used two sandy soils from Gainesville, FL: one from an area under perennial grasses and a second heavily-tilled soil lower in organic matter. Incubations were conducted for eight weeks at 24 and 30 °C, i.e., the annual and July mean soil temperature for the area. The composted and vermicomposted cow manure solids had the greatest $CO_2$ emissions relative to the unamended soils. Soil nitrate was highest with composted food waste, whereas all three cow manure-derived composts resulted in lower soil nitrate compared to the unamended soils. This suggests that N was immobilized with cow manure-derived composts, consistent with the high $CO_2$ emissions measured with these amendments. We found similar results for both soils. Our results indicate a greater potential for food-waste compost as a nutrient source than compost derived primarily from cow manure solids, which could be more beneficial to building soil C.

**Keywords:** compost; mineralization; carbon; nitrogen; phosphorus

## 1. Introduction

Intensification of agricultural systems to meet an increasing food demand has detrimental impacts on the environment, including the excessive production of biodegradable wastes and soil degradation [1,2]. Among potential solutions to address both waste management and soil health issues, composting diverts organic wastes from landfills and recycles nutrients into soil amendments that improve soil fertility and health [3]. In addition, composting reduces pathogens, weed seeds, and transport costs associated with the utilization of raw organic wastes [4,5]. Thus, composts can improve the sustainability of agricultural systems by recycling wastes, improving productivity, and preserving soil health.

As most of the nitrogen (N) in composts is in organic forms that are unavailable to crops, this N must be mineralized into ammonium ($NH_4^+$) and nitrate ($NO_3^-$) before crop uptake. Therefore, meeting recommended N input rates requires high application rates, leading to prohibitively high costs and potentially excessive inputs of phosphorus (P), salts, and metals [6]. As a result, composts are typically applied as soil conditioners to improve physical properties, although the use of composts as fertilizer is increasing [7]. Commercial growers may use a blend of compost and inorganic fertilizer to offset high input costs and optimize nutrient applications [8,9], including when using composted cattle manure [10]. In contrast, homeowners and urban farmers may be more prone to using composts as their sole amendment, as composts can be more cost-effective in these conditions [11]. Regardless of the context in which composts are used, determining the mineralization rates and other properties of composts accurately is critical, although this is often difficult due to variability among composts and local edaphic and climatic conditions.

The type of organic wastes used as feedstock is a major source of variability in compost nutrient content [12]. Municipal waste management programs produce composts derived from food and yard wastes, while composts from agricultural waste consist primarily of animal manures and crop residues. As nutrient content varies among feedstocks, composts made from different materials will have different properties and target use. For example, cattle and dairy manures have less N than poultry or hog manures [13], and separated solids from cow manures are further depleted in N due to the removal of soluble N [14]. Furthermore, higher N content in food as opposed to yard wastes suggests that the former would contribute more to soil fertility than the latter [15]. Ultimately, composts with a low nutrient content should have a greater value when used as soil conditioners to improve soil health, including soil organic matter (SOM), than as fertilizers [16].

Compost processing conditions also increase variability among composts, as composting duration, oxygen availability, moisture [17], and additional processing (e.g., vermicomposting, pelletization) affect nutrient content and other properties [18,19]. These conditions vary considerably among operations, although industrial composting facilities reduce this variability with streamlined protocols that produce a more consistent and stable product [14,18]. In contrast, non-industrial composts from smaller facilities or backyard composting may have greater variation among batches, in addition to potentially higher N content due to the shorter composting periods. Given the increased interest in urban agriculture and home gardening, determining whether non-industrial composts have comparable properties as more stable products generated under standardized industrial conditions could encourage more homeowners to adopt composting practices.

Composts also behave differently depending on the soil and climate in which they are used. In general, higher soil temperatures and moisture increase mineralization rates [20] whereas climate and soil properties (e.g., texture, SOM) affect chemical processes such as ammonia volatilization, mineralization and P sorption [21]. Thus, compost application rates must be determined for a specific region and season to utilize nutrient cycling dynamics effectively.

The objective of this study was to compare food-derived and cow manure-derived composts of different origins (industrial and non-industrial) in two Florida soils incubated at temperatures corresponding to mean and maximum soil temperature. Carbon, N and P cycling dynamics were measured in an 8-week laboratory incubation. We hypothesized that higher C:N ratios in composts derived from cow manure solids would reduce N release relative to food-waste composts, regardless of the origin. We also expected greater stability in industrial compost products, resulting in lower C and N mineralization.

## 2. Materials and Methods

### 2.1. Soil and Compost Processing

Surface soil (0–15 cm) was collected from two instructional farms at the University of Florida (UF) in Gainesville, FL, USA. The first soil was a Lake sand (Hyperthermic, coated Typic Quartzipsamments) with relatively high soil C for the area (Table 1). This soil was collected from an area that had been under a mixture of bahiagrass (*Paspalum notatum*) and wildflowers, mainly *Coreopsis* spp., *Gaillardia* spp., and *Phlox* spp., for over 20 years before being converted to cropland a few months before collection.

The second soil was a Millhopper sand (Loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults), which had lower soil C and N than the Lake soil (Table 1). Resin-extractable P values, which measure a soil P pool that is more freely exchangeable [22] and subject to a smaller background P pool than Mehlich III, were similar between the two soils. However, P concentration in the Millhopper soil was twice that of the Lake soil based on Mehlich III assessments. The Millhopper soil has been in cultivation for several decades, is tilled twice per year, drip- and overhead-irrigated, and fertilized on a plot-by-plot basis.

**Table 1.** Soil properties measured at the start of the study: total carbon (TC), total nitrogen (TN), C:N, nitrate nitrogen (N-$NO_3$), ammonium nitrogen (N-$NH_4$), cation exchange capacity (CEC), phosphorus (P), potassium (K), magnesium (Mg), calcium (Ca), and sulfur (S). All measurements were conducted on one sample, using dry soil except those indicated as fresh soil ($\int$).

| Soil | TC (g C kg$^{-1}$) | TN (g N kg$^{-1}$) | C:N | N-$NO_3$ (mg kg$^{-1}$) $\int$ | N-$NH_4$ (mg kg$^{-1}$) $\int$ | Resin P (mg kg$^{-1}$) $\int$ | pH | CEC (meq/100g) | Mehlich III (mg kg$^{-1}$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | P | K | Mg | Ca | S |
| Lake | 11.7 | 1.0 | 12.1 | 5.3 | 2.2 | 100 | 6.6 | 10.2 | 426 | 231 | 141 | 1125 | 9.5 |
| Millhopper | 8.3 | 0.5 | 15.7 | 1.1 | 0.7 | 118 | 7.3 | 17.5 | 835 | 48 | 85 | 3097 | 11 |

Both soils were air-dried and sieved (2 mm) before the experiment. A subsample was analyzed for several properties (Table 1) by an external laboratory using Mehlich III extractions and quantification by ICP for macronutrients and CEC, in addition to pH measured in water (Waters Analytical Laboratories, Camilia, GA, USA). Other properties were determined in the laboratory at UF: resin-extractable P [22], inorganic N using 2 M KCl extraction and colorimetry (see below), and total C (TC) and total N (TN) by combustion. Soil amendments were selected to compare manure- and food-derived compost of different origins. We used composted dairy manure solids consisting of fibrous solids mechanically separated from flushed dairy manure [23], in addition to vermicompost made from the same composted dairy manure solids (Black Star Organic Products, LLC, Newberry, FL, USA). We also used an industrial product derived from cow manure (Black Kow, Oxford, FL, USA). For food-derived compost, we used composted food waste from the University of Florida-Institute of Food and Agricultural Sciences (UF-IFAS) Compost Cooperative and an industrial food-based compost (EcoScraps Organic Compost, Marysville, OH, USA), the latter consisting of a mixture of plant materials, food waste, and processed forest products. Amendments were partially air-dried in paper bags for 24 h, passed through a 6 mm sieve, and stored in polyethylene bags at 4 °C until the experiment started. A subsample of air-dried amendments was analyzed for nutrient content (Table 2) by an external laboratory (Agrolabs, Harrington, DE, USA) using standard methods: pH in water and macronutrients by digestion and quantification with ICP. Another subsample was analyzed for TC and TN by combustion, resin-extractable P, inorganic N with 2 M KCl, and moisture content in the laboratory at UF.

**Table 2.** Properties of raw amendments measured at the start of the study. All measurements were conducted on one sample, using dry amendments except those indicated as fresh amendments ($\int$).

| Amendment | pH | Moisture (%) | TC (mg g$^{-1}$) | TN (mg g$^{-1}$) | C:N | N-$NH_4$ (mg kg$^{-1}$) $\int$ | N-$NO_3$ (mg kg$^{-1}$) $\int$ | Resin P (mg kg$^{-1}$) $\int$ | % P | % K | % Mg | % Ca | % S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Black Kow | 7.5 | 26 | 140 | 8.9 | 15.6 | 130 | 370 | 404 | 0.20 | 0.45 | 0.19 | 2.95 | 0.35 |
| Composted dairy manure solids | 7.3 | 43 | 428 | 18.2 | 23.8 | 350 | 10 | 338 | 0.25 | 0.20 | 0.17 | 1.62 | 0.28 |
| Vermicompost | 6.6 | 38 | 266 | 14.7 | 17.7 | 170 | 250 | 224 | 0.20 | 0.22 | 0.18 | 1.52 | 0.24 |
| Food waste compost | 8.4 | 42 | 271 | 22.5 | 11.8 | 20 | 680 | 1239 | 0.44 | 2.27 | 0.41 | 7.01 | 0.36 |
| Ecoscraps | 7.1 | 32 | 319 | 18.4 | 17.7 | 280 | 160 | 178 | 0.31 | 0.51 | 0.16 | 2.69 | 0.20 |

### 2.2. Laboratory Incubations

Amendments were thoroughly mixed with each soil at a rate of 125,000 kg dry weight ha$^{-1}$ (58 mg g$^{-1}$ soil) and unamended soils were used as negative controls. This input rate is representative of what small-scale producers and home gardeners in Florida would use [24], as they would be more prone to using non-industrial composts than large-scale commercial growers, who would typically rely on industrial composts used at lower input rates. Moisture content was adjusted to 50% water-filled pore space using double-distilled water for all treatments and a subsample was analyzed for initial nutrient measurements in duplicate, which we refer to as "week 0" samples.

For each soil x amendment combination, six replicates consisting of 150 g of material (on a dry weight basis) were packed into polyethylene containers at an approximate bulk density of 1.43 g $cm^{-1}$, which was comparable to what was measured at field sites. Each container was placed into a 1 L mason jar, with a 10 mL vial of double-distilled water to maintain soil moisture during incubations. Mason jars were sealed with air-tight lids. The six replicates from each treatment were incubated at 24 °C (three replicates) and 30 °C (three replicates) for eight weeks. Temperatures represented the mean annual soil temperature (24 °C) and the mean soil temperature of the warmest month (July, 30 °C) for this area, as measured at a depth of 10 cm at the nearby University of Florida's Plant Science Research and Education Unit (Citra, FL, USA).

### 2.3. $CO_2$ Emissions

A vial with 15 mL of 2 M NaOH was also included with each replicate to capture $CO_2$ emissions as a measure of biological activity and C mineralization. The $CO_2$ collected in NaOH base traps was measured weekly for 8 consecutive weeks according to Franzluebbers [25]. Briefly, vials of 2 M NaOH were capped immediately upon opening the mason jars and subsequently placed on a magnetic stir plate with a stir bar. Then, 3 ml of 1.5 M $BaCl_2$ and one drop of phenolphthalein color indicator were added to the vial and allowed to mix thoroughly. While stirring, 1 M HCl was added slowly to the solution until color changed from pink to white/clear. The volume of HCl used was recorded and converted to quantity of $CO_2$-C based on Franzluebbers [25]:

$$\mathrm{CO_2\text{-}C\ (mg/kg\ soil)} = (\mathrm{mL_{[blank]}} - \mathrm{mL_{[sample]}}) \times N \times M/S, \tag{1}$$

where $N$ = normality of acid (1); $M$ = mass conversion from $cmol_c$ to g C (6000); $S$ = soil weight (g).

The cumulative amount of C emitted per soil (mg C-$CO_2$ $kg^{-1}$ soil) was computed for each replicate over the 8 weeks of incubation and averaged per treatment. Initial assays were conducted in the Lake soil series with 1 M NaOH, but $CO_2$ concentrations exceeded the capacity of the NaOH traps for the composted dairy manure solids, vermicompost, and food waste compost treatments. Experiments for the Lake soil were repeated, in addition to soil controls, with 2 M NaOH to compensate for replicate losses. Repeated replicates were also assessed for soil nutrients. Any replicates in which a weekly measurement failed were not included in the final mean value (7 total). All subsequent assays with the Millhopper soil series were conducted with 2 M NaOH.

### 2.4. Soil Nutrient Analyses

Extractions were conducted on soils (5 g) and composts (1 g) prior to assay setup to determine their N concentration. Inorganic N was extracted from moist soil (5 g) with 2 M KCl and analyzed for $NH_4^+$ [26] and $NO_3^-$ [27] by colorimetry. Samples were extracted for 30 min on a reciprocal shaker, centrifuged (3500 RPM), and filtered (Fisherbrand Q2 filters). Inorganic N was quantified on moist soil from week 0 samples and each replicate at weeks 1, 2, 3, 4, 6, and 8.

Soil resin-extractable P was measured on week 0 samples and each replicate at week 8 using anion-exchange resins [22]. Briefly, 2.5 g of fresh material (moist soil or partially air-dried amendments) was extracted with one resin strip (charged with $NaHCO_3$) and 35 mL of double-distilled water on a reciprocal shaker for 16 h. Resins were eluted with 0.5 M HCl for 1 h. Extracts were analyzed for P concentration with colorimetry, using the molybdate blue method [22].

Total C and N were determined via combustion on a CN analyzer (Thermo Flash EA) for week 0 samples and each replicate at week 8. A more labile pool of C, permanganate-oxidizable C (POXC), was also quantified at week 0 and 8 [28]. Briefly, 2.5 g of air-dried soil was measured into 50 mL polypropylene centrifuge tubes, and 20 mL of 0.02 mol $L^{-1}$ $KMnO_4$ was added to the tubes. Tubes were shaken for 2 min and incubated in the dark for 10 min. After this incubation, 0.5 mL of the solution was transferred into a clean 50 mL tube, diluted with 49.5 mL of double deionized water, and read by colorimetry at 550 nm.

### *2.5. Data Analyses*

The fraction of total carbon inputs emitted as C-CO$_2$ was calculated as:

$$\frac{\left(\text{cumulative C} - \text{CO}_2\ \text{g}^{-1}\ \text{soil in treatment}\ -\ \text{cumulative C} - \text{CO}_2\ \text{g}^{-1}\ \text{soil in control}\right)}{\left(\text{g TC added to replicate/total g in replicate}\right)} \tag{2}$$

The fraction of total nitrogen inputs released as plant-available N (PAN) was calculated as:

$$\frac{\left[\left(\text{N} - \text{NO}_3 + \text{N} - \text{NH}_4\ \text{g}^{-1}\ \text{soil in treatment}\right) - \left(\text{N} - \text{NO}_3 + \text{N} - \text{NH}_4\ \text{g}^{-1}\ \text{soil in control}\right)\right]}{\left(\text{g TN added to replicate/total g in replicate}\right)} \tag{3}$$

Data for cumulative CO$_2$-C emissions (week 8), NO$_3$ (week 1, 4, and 8), POXC, resin P, TC, TN, C:N, the fraction of added N recovered as PAN, and the fraction of added C recovered as CO$_2$ were analyzed separately for each soil x temperature combination. All data were tested for normality of residuals and homogeneity of variances with Shapiro–Wilks and Levene tests, respectively. Transformations (square root, log (x + 1), rank) were applied if assumptions were not met with raw data; this is indicated in figures and tables. If one-way analysis of variance (ANOVA) assumptions were satisfied, data were analyzed with one ANOVA per soil x temperature combination, with treatment as a fixed factor. Tukey HSD tests were used for means separation. If data or transformed data did not meet ANOVA assumptions, treatments were compared with pairwise Kruskal–Wallis analyses per soil x temperature combination. The main exception to this was a subset of NO$_3$ data that were analyzed with the ANOVA for consistency with other sampling dates, soils and/or temperatures, as indicated in figure captions. All analyses were conducted in SPSS, version 25 [29].

## 3. Results

### *3.1. Carbon*

Amended soils always emitted significantly more CO$_2$ than unamended soils, and the Lake soil emitted more than the Millhopper soil (Figure 1). Composted dairy manure solids emitted the greatest amount of CO$_2$ relative to the control, followed by vermicompost and food waste. The two industrial composts (Black Kow and Ecoscraps) consistently emitted the least CO$_2$ out of all the amendments. Patterns among amendments were consistent across soil and incubation temperature, except for larger CO$_2$ emissions for Millhopper soil amended with Ecoscraps compared to Black Kow, whereas both amendments were similar in the Lake soil.

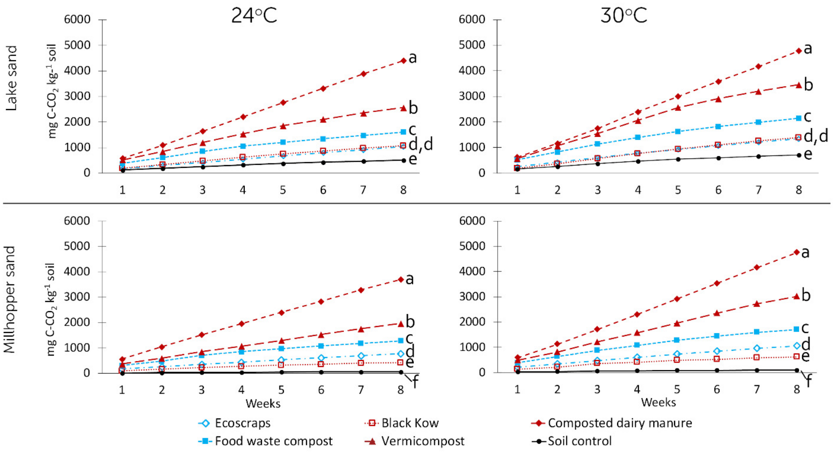

**Figure 1.** Cumulative C-CO$_2$ emissions over an 8 week incubation time. Different letters represent significantly different means based on Tukey's HSD ($\alpha$ = 0.05) on raw data after 8 weeks of incubation (all ANOVAs: F > 863, $p < 0.001$). SEs are all below 45 mg C-CO$_2$ kg$^{-1}$ soil.

The percentage of amendment C inputs released as $CO_2$ was greatest in soil amended with composted dairy manure solids for both soils at 24 °C, whereas composted dairy manure solids and vermicompost emitted the highest percent of C inputs as $CO_2$ for both soils at 30 °C (Table 3). Regardless of temperature, Ecoscraps had the lowest percentage of added C emitted as $CO_2$ in the Lake soil whereas Ecoscraps and Black Kow were the lowest in the Millhopper soil.

**Table 3.** Mean (±standard error) of multiple measurements (one measurement per jar, two to five total jars per treatment) for percentage of TC inputs emitted as C-$CO_2$ and percentage of TN inputs recovered as PAN ($NO_3 + NH_4$). ANOVAs were performed on mean concentrations between treatments. Different letters amongst amendments within each soil x temperature combination represent significant differences based on Tukey's HSD ($\alpha = 0.05$). Data in which residuals had a significant Shapiro–Wilks statistic are indicated (§).

| Soil | Temperature | Amendment | Added C Released as C-$CO_2$ (%) | Added N Recovered as PAN (%) |
|---|---|---|---|---|
| Lake | 24 | Black Kow | 7.3 (±0.4) c | −5.3 (±1.1) d |
| | | Composted dairy manure solids | 16.4 (±0.02) a | −3.4 (±0.1) cd |
| | | Vermicompost | 14.0 (±0.3) b | −1.2 (±0.5) bc |
| | | Ecoscraps | 3.0 (±0.4) d | 1.0 (±0.1) b |
| | | Food waste compost | 7.3 (±0.3) c | 10.8 (±0.6) a |
| | | ANOVA | $F_{4,10} = 207$ | $F_{4,16} = 152$ |
| | 30 | Black Kow | 8.9 (± 0.7) b | −5.5 (±0.7) c |
| | | Composted dairy manure solids | 17.2 (±0.2) a | −4.7 (±0.1) c |
| | | Vermicompost | 18.7 (±0.2) a | −0.3 (±0.05) b |
| | | Ecoscraps | 3.6 (±0.1) c | 0.6 (±0.2) ab |
| | | Food waste compost | 9.6 (±0.2) b | 13.5 (±0.5) a |
| | | ANOVA | $F_{4,6} = 151$ | ‡ $F_{4,16} = 47$ |
| Millhopper | 24 | Black Kow | 4.7 (±0.4) d | −0.3 (±0.1) c |
| | | Composted dairy manure solids | 15.4 (±0.02) a | −1.0 (±0.01) d |
| | | Vermicompost | 13.0 (±0.6) b | −1.4 (±0.02) e |
| | | Ecoscraps | 4.0 (±0.1) d | 1.5 (±0.1) b |
| | | Food waste compost | 8.1 (±0.1) c | 10.7 (±0.5) a |
| | | ANOVA | $F_{4,9} = 255$ | ‡ $F_{4,15} = 68$ § |
| | 30 | Black Kow | 6.6 (±0.4) c | 0.6 (±0.1) b |
| | | Composted dairy manure solids | 19.6 (±0.2) a | −1.0 (±0.03) c |
| | | Vermicompost | 19.9 (±0.3) a | 0.9 (±0.4) b |
| | | Ecoscraps | 5.4 (±0.1) c | 2.1 (±0.1) a |
| | | Food waste compost | 10.7 (±0.1) b | 15.6 (±0.4) a |
| | | ANOVA | $F_{4,10} = 654$ | ‡ $F_{4,10} = 29$ |

‡ Rank-transformed data. § Data had a significant Shapiro–Wilks statistic (i.e., non-normal residuals).

After 8 weeks of incubation, POXC was greater in amended as opposed to unamended soils (Table 4). POXC was highest with composted dairy manure solids and was significantly higher compared to the control soil in all cases. In contrast, POXC was consistently lowest with Black Kow and food waste compost among amended soils, although differences with other amendments were not always statistically significant. In the Lake soil at 30 °C, POXC was significantly higher with composted dairy manure solids compared to all other amendments.

In the Lake soil, TC was highest in Ecoscraps after 8 weeks of incubation, regardless of temperature, and TC was significantly higher than the control for all amendments at 24 °C. All amendments had higher TC than the control at 30 °C, but the difference was significant only for Ecoscraps, composted dairy manure solids, and food waste compost. In the Millhopper soil, all amended soils were significantly higher in TC than the control at both temperatures, with the highest concentrations observed with composted dairy manure solids.

**Table 4.** Mean (±standard error) of multiple measurements (one measurement per jar, two to five total jars per treatment) for total N and C, resin P and permanganate-oxidizable C (POXC) measured at week 8. ANOVA were performed on mean concentrations between treatments. Different letters amongst amendments within each soil x temperature combination represent significant differences based on Tukey's HSD ($\alpha = 0.05$) or Kruskal–Wallis pairwise comparisons ($p < 0.05$) ($^{\dagger}$).

| Soil | Temperature | Amendments | Total C | Total N | C:N | Resin P | POXC |
|---|---|---|---|---|---|---|---|
| | | | (g kg$^{-1}$) | (g kg$^{-1}$) | | (mg P kg$^{-1}$) | (mg C kg$^{-1}$) |
| Lake | 24 | Black Kow | 19 (±2) c | 1.4 (±0.1) b | 13.9 b | 97 (±3) b | 491 (±3) ab |
| | | Composted Dairy Manure Solids | 29 (±2) ab | 1.9 (±0.1) a | 15.2 ab | 90 (±2) bc | 730 (±30) a |
| | | Vermicompost | 22 (±2) bc | 1.6 (±0.1) ab | 13.7 b | 89 (±2) bc | 586 (±42) ab |
| | | Ecoscraps | 32 (±4) a | 1.9 (±0.2) a | 16.6 a | 88 (±7) bc | 580 (±11) ab |
| | | Food Waste Compost | 24 (±2) abc | 2.0 (±0.1) a | 12 c | 173 (±5) a | 521 (±30) ab |
| | | Soil Control | 10 (±1) d | 0.8 (±0.0) c | 12.1 c | 76 (±2) c | 351 (±3) b |
| | | ANOVA | $F_{5,20} = 264$ | $F_{5,20} = 20$ | $F_{5,20} = 26$ | $F_{5,20} = 97.0$ | $^{\dagger}$ |
| | 30 | Black Kow | 23 (±4) ab | 1.5 (±0.2) bc | 14.8 abc | 89 (±6) b | 501 (±8) c |
| | | Composted Dairy Manure Solids | 30 (±2) a | 2.0 (±0.1) ab | 14.6 ab | 98 (±1) b | 774 (±25) a |
| | | Vermicompost | 25 (±1) ab | 1.9 (±0.1) b | 13.6 abc | 89 (±2) b | 531 (±27) bc |
| | | Ecoscraps | 32 (±3) a | 2.0 (±0.2) b | 16.5 a | 75 (±2) c | 598 (±8) b |
| | | Food Waste Compost | 31 (±3) a | 2.7 (±0.2) a | 11.7 c | 158 (±6) a | 471 (±14) c |
| | | Soil Control | 9 (±0.2) b | 0.7 (±0.02) c | 11.8 bc | 68 (±1) c | 328 (±9) d |
| | | ANOVA | $^{\dagger}$ | ‡ $F_{5,20} = 18$ | $^{\dagger}$ | # $F_{5,20} = 99$ | $F_{5,20} = 65.2$ |
| Millhopper | 24 | Black Kow | 14 (±1) c | 0.9 (±0.04) c | 16.3 ab | 97 (±4) ab | 393 (±6) c |
| | | Composted Dairy Manure Solids | 34 (±2) a | 2.0 (±0.1) a | 16.8 ab | 101 (±4) ab | 692 (±26) a |
| | | Vermicompost | 24 (±0.1) b | 1.5 (±0.05) b | 16.4 ab | 104 (±2) ab | 538 (±20) b |
| | | Ecoscraps | 26 (±3) ab | 1.4 (±0.1) b | 18.5 a | 104 (±2) ab | 653 (±33) a |
| | | Food Waste Compost | 21 (±1) b | 1.8 (±0.1) ab | 12 b | 186 (±9) a | 498 (±19) b |
| | | Soil Control | 8 (±0.3) d | 0.6 (±0) d | 14.5 ab | 84 (±13) b | 338 (±1) c |
| | | ANOVA | # $F_{5,12} = 60$ | # $F_{5,12} = 93$ | $^{\dagger}$ | $^{\dagger}$ | $F_{5,12} = 66$ |
| | 30 | Black Kow | 12 (±1) c | 0.8 (±0.03) d | 15.6 b | 99 (±3) ab | 415 (±2) de |
| | | Composted Dairy Manure Solids | 29 (±1) a | 1.8 (±0.1) ab | 16.3 b | 106 (±1) ab | 721 (±60) a |
| | | Vermicompost | 20 (±0.4) b | 1.3 (±0.03) c | 15.4 b | 102 (±3) ab | 550 (±9) bc |
| | | Ecoscraps | 27 (±0.3) a | 1.5 (±0.04) bc | 17.6 a | 95 (±1) ab | 691 (±41) ab |
| | | Food Waste Compost | 23 (±2) ab | 1.9 (±0.2) a | 12.1 d | 178 (±12) a | 464 (±25) cd |
| | | Soil Control | 8 (±1) d | 0.6 (±0.04) d | 14.2 c | 91 (±1) b | 334 (±3) e |
| | | ANOVA | # $F_{5,12} = 100$ | $F_{5,12} = 52$ | $F_{5,12} = 70$ | $^{\dagger}$ | # $F_{5,12} = 38$ |

# Log-transformed data. ‡ Rank-transformed data. $^{\dagger}$ Kruskal–Wallis pairwise comparisons.

### *3.2. Nitrogen*

Ammonium concentrations were typically low (<5 mg $N\text{-}NH_4^+$ kg$^{-1}$), except for the Lake soil amended with composted dairy manure solids at 30 °C, where ammonium concentrations peaked to 10 mg kg$^{-1}$ at weeks 1 and 4 (Supplementary information, Table S1). However, as these high $N\text{-}NH_4^+$ values did not coincide with high soil pH values (soil pH was always lower than 7.3 for this treatment—Supplementary Materials information, Table S2), volatilization losses were unlikely.

Nitrate concentrations increased with food-based composts relative to the control, with a lower increase for Ecoscraps than the food waste compost (Figure 2). However, data transformations required to meet ANOVA conditions resulted in a marginal difference between the two food-based composts in the Millhopper soil at 24 °C ($p = 0.08$) and no significant difference at 30 °C ($p = 0.17$). Nitrate concentration decreased initially during the incubation with all manure-based products compared to the unamended soils, although this was affected by soil and temperature. In the Lake soil, nitrate increased with Black Kow and vermicompost after week 4 (30 °C) or week 6 (24 °C). In the Millhopper soil, nitrate concentration was similar between Black Kow and the unamended control, while nitrate was not detected with vermicompost until week 8 at 30 °C. Nitrate concentration with composted dairy manure solids was low throughout the incubations, regardless of soil and temperature.

Soil TN was significantly greater in the food waste compost than the unamended control in all cases (Table 4). Food waste compost generally had the highest TN among amended soils, except in the Millhopper soil at 24 °C, for which composted dairy manure solids had the highest TN although the difference with food waste compost was not significant. In both soils at both temperatures, all amendments increased TN significantly compared to the control, with the exception of Black Kow in both soils at 30 °C.

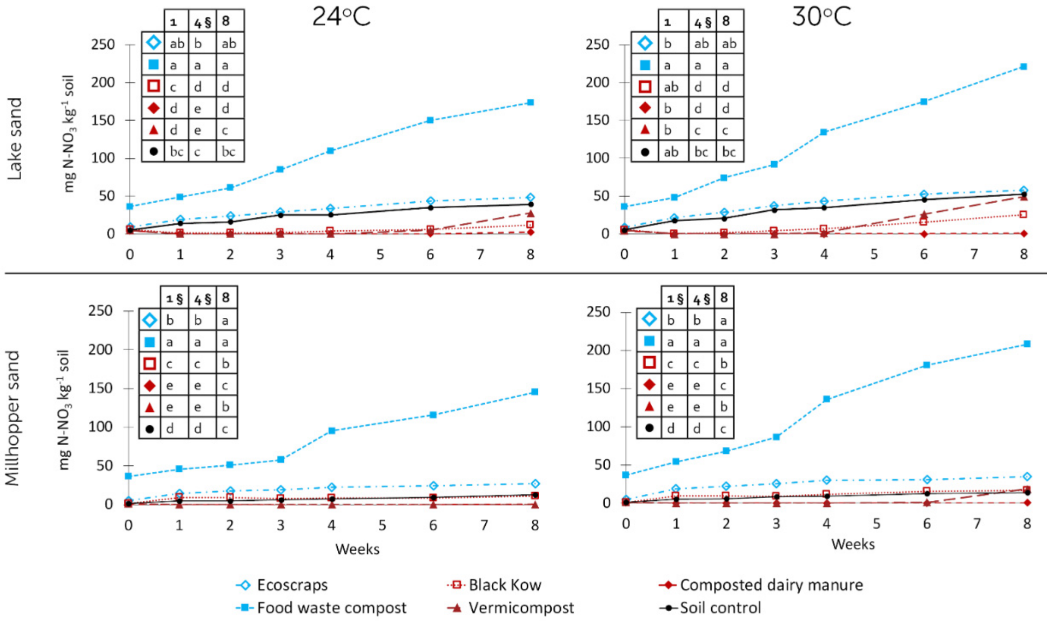

**Figure 2.** Mean N-$NO_3$ $kg^{-1}$ soil measured at weeks 0, 1, 2, 3, 4, 6, and 8 (SEs were always <8.1). In-chart tables show different letters representing significantly different means based on Tukey's HSD ($\alpha = 0.05$) following ANOVAs performed on rank-transformed data (all ANOVAs: $F > 46$, $p$ values $< 0.001$). Data in which residuals had a significant Shapiro–Wilks statistic are indicated (§).

After eight weeks of incubation, soil C:N ratios were lowest with food waste compost among the five amendments for all cases. Food waste compost was the only amendment with a soil C:N ratio lower than the unamended control, although that difference was statistically significant only for the Millhopper soil at 30 °C. Ecoscraps had the highest soil C:N ratio in all cases, although differences with other amendments and the unamended control were not always significant. Ecoscraps was always significantly higher than food waste compost.

Nitrogen inputs recovered as plant-available nitrogen (PAN) were highest in the food waste compost for all soils and temperatures, although the 7- to 23-fold difference between the two food-based composts was only significant at 24 °C, for both soils (Table 3). At 30 °C, differences among food waste compost, Ecoscraps and vermicompost were marginally significant ($p = 0.08$) in the Lake soil whereas the difference between Ecoscraps and food waste compost was not significant ($p = 0.17$) in the Millhopper soil. In contrast, the three cow manure-based composts had a negative PAN recovery value, indicative of N immobilization, except for the very small net N recovery for the Millhopper soil amended with Black Kow and vermicompost at 30 °C.

### 3.3. Phosphorus

Soils amended with food waste compost had significantly higher resin-extractable P relative to the control for all soils and temperatures, and significantly higher resin P than other amendments in the Lake soil at both temperatures (Table 4). Other amendments increased resin P to a lesser extent relative to unamended controls, with significant increases in the Lake soil with Black Kow at 24 °C and all cow manure-based composts at 30 °C (Table 4).

## 4. Discussion

### 4.1. The Effects of Feedstock and Composting Process

All composts increased $CO_2$ emissions relative to the unamended soil, indicating an increase in metabolic activity of soil microorganisms. In general, cow manure-based composts emitted more $CO_2$ than food-based composts, except for Black Know, which had lower $CO_2$ emissions relative to the food waste compost (all cases) and Ecoscraps (only in the Millhopper soil). This contrasts with the larger $CO_2$ emissions reported for municipal vs. manure composts by Castán et al. [16], although their municipal compost was a mixture of food and yard wastes. All three cow manure-based composts released less nitrate than the food-based composts, and less of the total N in the cow manure-based composts was recovered as PAN, consistent with Franklin et al. [30]. Resin-extractable P was highest with food waste compost, but comparable among other amendments, consistent with Gagnon and Simard [31] reporting relatively small changes in soil available P after inputs of stabilized composts.

Among cow manure composts, composted dairy manure solids emitted the most $CO_2$ whereas emissions for vermicompost were lower in all soil/temperature combinations, consistent with Gale et al. [14] that found higher $CO_2$ emissions for less-composted dairy and poultry manures. Additionally, high POXC concentrations were detected with the composted dairy manure solids, indicating a larger pool of active carbon. Reduced $CO_2$ emissions and POXC concentration in the soils amended with vermicompost compared to soils amended with composted dairy manure solids support previous work showing the stabilization effect of vermicomposting [18,32].

Soil nitrate was low with composted dairy manure solids in any soil/temperature combination, while nitrate in vermicompost was only detected after 4–6 weeks depending on temperature. This is consistent with Flavel and Murphy [18], who measured no N mineralization with composted manures as opposed to modest N mineralization with vermicompost made from a mixture of poultry, bovine, and pig manures. The reduction of soil nitrate measured with manure-based composts could be due to denitrification or immobilization, as leaching is prevented in this incubation setup. As we measured high $CO_2$ emissions and high POXC, this suggests immobilization was the primary cause of nitrate disappearance. However, as we did not measure $N_2O$ or $N_2$ emissions, we cannot exclude that denitrification was an important driver of nitrate disappearance in this study.

In contrast, food-based composts released more N (soil inorganic N and percentage of added N recovered as PAN) and emitted less $CO_2$ than cow manure-based composts (except for Black Kow). In addition, the non-industrial food waste compost had the highest concentrations of resin P. This confirms the greater fertilizer value of food-based composts compared to cow manure-based composts, as food waste is high in N and P, e.g., 3% N and 0.41% P in Graunke and Wilkie [33], whereas screened manure solids are high in fiber and low in nutrients [23]. Despite these properties, other manure solid products may provide more fertility than the ones tested in this study, such as solid fraction pig slurry compost pellets that can provide similar N availability as mineral fertilizers [19].

The two industrial composts had the lowest $CO_2$ emissions of all composts tested, consistent with the greater stability of these composts relative to non-industrial composts made from similar feedstock. However, when comparing the food waste composts, less TN was recovered as PAN in the industrial compost than the non-industrial food waste compost (Table 3), which could be due to the addition of wood residues in the Ecoscraps product, similar to yard waste municipal composts that release little PAN [14,16]. Alternatively, this may be due to N losses occurring during longer composting and/or storage periods for industrial products, especially if piles were not protected from rainfall [34]. Furthermore, the industrial cow manure-based compost (Black Kow) likely immobilized N in the Lake soil whereas it had little effect on the other soil, consistent with the lower impact on soil N of industrial as opposed to non-industrial manure products reported by Gagnon and Simard [31]. Ultimately, this is most likely driven by the greater maturity of industrial products, confirming the importance of compost maturity on the resulting effects for soil C and nutrient cycling [14,18].

### *4.2. Effects of Soil and Temperature*

Although statistical comparisons were not made between soils and temperature of a given amendment in this study, comparisons of trends are still informative. The Lake soil was enriched in total C, POXC and N (total and PAN) relative to the Millhopper soil, and this likely impacted how the different composts affected C and N cycling. Emissions of $CO_2$ and TC concentrations were generally highest in the Lake soil, although POXC was not. We observed greater N immobilization with composted dairy manure solids and Black Kow in the Lake soil, with similar results between soils for other amendments. The greater N release of composts in more fertile soils is consistent with Chae and Tabatabai [21], although the greater immobilization observed in more fertile soils is not. This could be due to the greater microbial activity in the Lake soil, as illustrated by greater $CO_2$ emissions in the unamended control, increasing N immobilization during this relatively short incubation study. Overall, compost mineralization trends between the two soils were similar, although the magnitude differed. As we focused on high input rates that are representative of small-scale producers and home gardeners, results could differ with lower application rates that better represent the practices used by large-scale commercial growers.

In general, the higher temperature (30 °C) increased mineralization rates for C and N, including a quicker recovery of PAN with cow manure-based composts after the initial immobilization phase. This expected increase in microbial metabolic rates at higher temperature is consistent with what Maltais-Landry et al. [35] found with different manures. However, similar to soil properties, incubation temperature did not affect trends among composts. Overall, this confirms the importance of climate as a key factor mediating the effects of compost additions on soil C and N cycling.

### *4.3. Implications*

We found a higher N value in food-derived composts relative to cow manure-derived composts, consistent with previous work showing high C:N and slow mineralization of dairy manure solids compared to other amendments, including other manures such as poultry manures [14]. This supports the use of cow manure-derived composts as soil conditioners (e.g., to restore SOM in degraded soils), as high C:N amendments that could prevent N leaching via immobilization [36], or as amendments releasing N slowly in systems with a relatively constant N demand (e.g., turfgrass). If cow manure-based composts are intended for fertilizer use, our data indicate they could benefit from co-composting with food waste or other wastes that add PAN more rapidly (e.g., poultry manures). Alternatively, applying cow manure-based composts with other amendments that release PAN more rapidly after application [16] or mineral fertilizers [10] could also improve their contribution to soil fertility. Processing composted dairy manure solids through vermicomposting could also increase nutrient value, as vermicompost had a shorter N immobilization period, lower $CO_2$ emissions and a larger PAN recovery, consistent with Flavel and Murphy [18]. Thus, vermicomposting of composted dairy manure solids should be considered when conditions are favorable (e.g., time, space and labor available) to additional processing.

Our data suggest that non-industrial composts have comparable, and potentially superior, nutrient content relative to industrial products. Encouraging homeowners and municipalities to compost food and lawn wastes would produce a valuable product for small-scale producers and home gardeners while also diverting organic waste from the landfill. Blending these feedstocks with other sources to adjust fertility would allow optimizing the end product to fit different applications.

## 5. Conclusions

Food-derived composts provided more N benefits than cow manure-derived composts, which often reduced PAN during our 8 week incubation, most likely via microbial immobilization. We found similar effects between industrial and non-industrial composts produced with the same feedstock, and few differences in trends among soils and incubation temperatures for a given compost. Overall, cow manure-derived composts would be most suited as soil conditioners or in systems where N immobilization is desirable; co-applying them with amendments or fertilizers rich in PAN may improve their contribution to soil fertility. In contrast, food-derived composts have a greater nutrient value and could be used as a primary nutrient source, highlighting the benefits of encouraging municipalities and homeowners to divert organic wastes from landfills and produce high-quality soil amendments.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2077-0472/10/3/69/s1, Table S1: Soil N-$NH_4^+$ concentrations (mg N $kg^{-1}$) during the incubation study. Table S2: Soil pH during the incubation study.

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## References

1. Lal, R. Soils and sustainable agriculture. A review. *Agron. Sustain. Dev.* **2008**, *28*, 57–64. [CrossRef]
2. Eckelman, M.J.; Ashton, W.; Arakaki, Y.; Hanaki, K.; Nagashima, S.; Malone-Lee, L.C. Island waste management systems: Statistics, challenges, and opportunities for applied industrial ecology. *J. Ind. Ecol.* **2014**, *18*, 306–317. [CrossRef]
3. Martínez-Blanco, J.; Lazcano, C.; Christensen, T.H.; Muñoz, P.; Rieradevall, J.; Møller, J.; Antón, A.; Boldrin, A. Compost benefits for agriculture evaluated by life cycle assessment. A review. *Agron. Sustain. Dev.* **2013**, *33*, 721–732. [CrossRef]
4. Larney, F.J.; Blackshaw, R.E. Weed seed viability in composted beef cattle feedlot manure. *J. Environ. Qual.* **2003**, *32*, 1105–1113. [CrossRef]
5. Wiese, A.F.; Sweeten, J.M.; Bean, B.W.; Salisbury, C.D.; Chenault, E.W. High temperature composting of cattle feedlot manure kills weed seed. *Appl. Eng. Agric.* **1998**, *14*, 377–380. [CrossRef]
6. Ozores-Hampton, M.; Stansly, P.A.; Salame, T.P. Soil chemical, physical, and biological properties of a sandy soil subjected to long-term organic amendments. *J. Sustain. Agric.* **2011**, *35*, 243–259. [CrossRef]
7. Hargreaves, J.C.; Adl, M.S.; Warman, P.R. A review of the use of composted municipal solid waste in agriculture. *Agric. Ecosyst. Environ.* **2008**, *123*, 1–14. [CrossRef]
8. Sikora, L.J.; Szmidt, R.A.K. Nitrogen sources, mineralization rates, and nitrogen nutrition benefits to plants from composts. In *Compost Utilization in Horticultural Cropping Systems*; Stoffella, P.J., Kahn, B.A., Eds.; CRC Press: Boca Raton, FL, USA, 2001; pp. 287–305.
9. Sikora, L.J.; Enkiri, N.K. Efficiency of compost-fertilizer blends compared with fertilizer alone. *Soil Sci.* **2000**, *165*, 444–451. [CrossRef]
10. Gil, M.V.; Carballo, M.T.; Calvo, L.F. Fertilization of maize with compost from cattle manure supplemented with additional mineral nutrients. *WASTE Manag.* **2008**, *28*, 1432–1440. [CrossRef]
11. Weindorf, D.C.; Muir, J.P.; Landeros-Sánchez, C. Organic Compost and Manufactured Fertilizers: Economics and Ecology. In *Integrating Agriculture, Conservation and Ecotourism: Examples from the Field*; Campbell, W.B., Lopez Ortiz, S., Eds.; Springer Netherlands: Dordrecht, The Netherlands, 2011; pp. 27–53, ISBN 978-94-007-1309-3.
12. Faverial, J.; Boval, M.; Sierra, J.; Sauvant, D. End-product quality of composts produced under tropical and temperate climates using different raw materials: A meta-analysis. *J. Environ. Manag.* **2016**, *183*, 909–916. [CrossRef]
13. Wilkinson, S.R. Plant Nutrient and Economic Value of Animal Manures. *J. Anim. Sci.* **1979**, *48*, 121–133. [CrossRef]
14. Gale, E.S.; Sullivan, D.M.; Cogger, C.G.; Bary, A.I.; Hemphill, D.D.; Myhre, E.A. Estimating plant-available nitrogen release from manures, composts, and specialty products. *J. Environ. Qual.* **2006**, *35*, 2321–2332. [CrossRef]
15. Komilis, D.P.; Ham, R.K. Carbon dioxide and ammonia emissions during composting of mixed paper, yard waste and food waste. *Waste Manag.* **2006**, *26*, 62–70. [CrossRef]
16. Castán, E.; Satti, P.; González-Polo, M.; Iglesias, M.C.; Mazzarino, M.J. Managing the value of composts as organic amendments and fertilizers in sandy soils. *Agric. Ecosyst. Environ.* **2016**, *224*, 29–38. [CrossRef]

17. Hao, X.Y.; Chang, C.; Larney, F.J.; Travis, G.R. Greenhouse gas emissions during cattle feedlot manure composting. *J. Environ. Qual.* **2001**, *30*, 376–386. [CrossRef]
18. Flavel, T.C.; Murphy, D.V. Carbon and nitrogen mineralization rates after application of organic amendments to soil. *J. Environ. Qual.* **2006**, *35*, 183–193. [CrossRef]
19. Pampuro, N.; Bertora, C.; Sacco, D.; Dinuccio, E.; Grignani, C.; Balsari, P.; Cavallo, E.; Bernal, M.P. Fertilizer value and greenhouse gas emissions from solid fraction pig slurry compost pellets. *J. Agric. Sci.* **2017**, *155*, 1646–1658. [CrossRef]
20. Haynes, R.J. Chapter 2. The decomposition process: Mineralization, immobilization, humus formation, and degradation. In *Mineral Nitrogen in the Plant-Soil System*; Academic Press: Cambridge, MA, USA, 1986; pp. 52–109.
21. Chae, Y.M.; Tabatabai, M.A. Mineralization of Nitrogen In Soils Amended With Organic Wastes. *J. Environ. Qual.* **1986**, *15*, 193–198. [CrossRef]
22. Tiessen, H.; Moir, J. Characterization of Available P by Sequential Extraction. In *Soil Sampling and Methods of Analysis*; Carter, M., Gregorich, E., Eds.; CRC Press: Boca Raton, FL, USA, 2007; pp. 293–306.
23. Wilkie, A.C.; Castro, H.F.; Cubinski, K.R.; Owens, J.M.; Yan, S.C. Fixed-film anaerobic digestion of flushed dairy manure after primary treatment: Wastewater production and characterisation. *Biosyst. Eng.* **2004**, *89*, 457–471. [CrossRef]
24. Brown, S.P. *Compost Tips for the Home Gardener*; Electron. ENH1065; University of Florida, Institute of Food and Agricultural Sciences: Gainesville, FL, USA, 2017; Available online: https://edis.ifas.ufl.edu/ep323 (accessed on 9 March 2019).
25. Franzluebbers, A.J. Should Soil Testing Services Measure Soil Biological Activity? *Agric. Environ. Lett.* **2016**, *1*, 1–5. [CrossRef]
26. Weatherburn, M.W. Phenol-Hypochlorite Reaction for Determination of Ammonia. *Anal. Chem.* **1967**, *39*, 971–974. [CrossRef]
27. Doane, T.A.; Horwáth, W.R. Spectrophotometric Determination of Nitrate with a Single Reagent. *Anal. Lett.* **2003**, *36*, 2713–2722. [CrossRef]
28. Weil, R.R.; Islam, K.R.; Stine, M.A.; Gruver, J.B.; Samson-Liebig, S.E. Estimating active carbon for soil quality assessment: A simplified method for laboratory and field use. *Am. J. Altern. Agric.* **2003**, *18*, 3–17.
29. *IBM SPSS*, version 25; IBM: Armonk, NY, USA, 2017.
30. Franklin, D.; Bender-Özenç, D.; Özenç, N.; Cabrera, M. Nitrogen mineralization and phosphorus release from composts and soil conditioners found in the southeastern United States. *Soil Sci. Soc. Am. J.* **2015**, *79*, 1386–1395. [CrossRef]
31. Gagnon, B.; Simard, R.R. Nitrogen and phosphorus release from on-farm and industrial composts. *Can. J. Soil Sci.* **1999**, *79*, 481–489. [CrossRef]
32. Singh, R.P.; Singh, P.; Araujo, A.S.F.; Hakimi Ibrahim, M.; Sulaiman, O. Management of urban solid waste: Vermicomposting a sustainable option. *Resour. Conserv. Recycl.* **2011**, *55*, 719–729. [CrossRef]
33. Graunke, R.E.; Wilkie, A.C. Examining the mechanisms of short-term solubilization of ground food waste for high-rate anaerobic digestion. *Int. Biodeterior. Biodegrad.* **2014**, *86*, 327–333. [CrossRef]
34. Maltais-Landry, G.; Neufeld, K.; Poon, D.; Grant, N.; Nesic, Z.; Smukler, S. Protection from wintertime rainfall reduces nutrient losses and greenhouse gas emissions during the decomposition of poultry and horse manure-based amendments. *J. Air Waste Manag. Assoc.* **2018**, *68*, 377–388. [CrossRef]
35. Maltais-Landry, G.; Bertoni, N.; Valley, W.; Grant, N.; Nesic, Z.; Smukler, S.M. Greater Impacts of Incubation Temperature and Moisture on Carbon and Nitrogen Cycling in Poultry Relative to Horse Manure-based Soil Amendments. *J. Environ. Qual.* **2018**, *921*, 914–921. [CrossRef]
36. Congreves, K.A.; Van Eerd, L.L. Nitrogen cycling and management in intensive horticultural systems. *Nutr. Cycl. Agroecosyst.* **2015**, *102*, 299–318. [CrossRef]