IMPACT OF STORAGE TIME ON THE COMPOSITION OF A FINISHED COMPOST PRODUCT: A CASE STUDY

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HIGHLIGHTS

- The concentrations of major plant nutrients, key minor plant nutrients, and carbon were measured for finished turkey poult litter compost that had been stored for 29 to 583 days in open windrows at a commercial composting facility.
- It was found that the concentrations of TN, P_2O_5, K_2O, and minor plant nutrients were not significantly correlated with respect to compost age.
- Significant negative correlations were observed for the concentrations of organic matter and carbon resulting in a decrease in C:N.
- Significant decreases in compost pH and increases in bulk density were also observed.

ABSTRACT. *Several studies have provided information concerning the loss of nitrogen, phosphorous, potassium, carbon, and organic matter from manures and plant residues during active composting. However, very little information was found to provide insight into the changes in compost composition as the product ages during curing and storage in uncovered windrows. The objective of this study was to observe changes in compost composition after it was removed from a composting shed and was stored in large un-covered windrows at a compost production site that used turkey poult litter (manure and wood shavings) as the primary ingredient. Compost samples and production records were obtained for 7 windrows and it was determined that the active composting time under the shed (AC) averaged 99 days and the time allowed for curing and storage in the uncovered windrows (CS) ranged from 29 to 583 days. As a result, the total compost age (CA = AC + CS) at the time of sampling ranged from 131 to 674 days. The quantities measured were moisture, pH, bulk density, electrical conductivity (EC), carbon (C). organic matter (OM), total ammoniacal N (TAN = NH_4^+-N + NH_3-N), nitrate-N, organic-N, total-N (TN), P_2O_5, K_2O, Ca, Mg, S, Zn, Cu, Mn, Fe, Na, and Al. The TN content was not found to change significantly while being stored in the outside windrows. However, the TAN content decreased significantly with storage time while nitrate-N and organic-N concentrations increased. The results showed evidence of nitrification of ammonium-N and a build-up of organic-N during storage. Storage time did not significantly impact concentrations of P_2O_5, K_2O, Al, Na, and all minor plant nutrients measured. The pH fell from 8.9 at a compost age of 131 days to a mean of 6.8 by day 363 providing evidence of formation of organic acids during storage. Significant decreases during storage were observed for C, OM, and C:N. The rate of organic matter loss during storage was -0.623 g OM/kg DM/day and carbon was lost at the rate of -0.447 g C/kg DM/day. The electrical conductivity was not correlated with storage time and the mean was 3.80 ± 3.25 mmhos/cm. The bulk density increased significantly during curing and storage (R^2 = 0.693) and was believed to be the result of compression settling.*

Keywords. *Compost, Manure Management, Plant nutrients, Treatment.*

Over the last decade, interest in producing and selling compost made using poultry litter has increased as an alternative to brokerage of litter as a low-cost, fertilizer substitute. Most broiler chicken litter and turkey grow-out litter contain small to modest amounts of organic bedding that yields a litter that has a low C:N, on the order of 9:1 to 12:1, and has been shown to be a valuable source of nitrogen for crop production (Ashworth et al., 2019). However, heavily bedded poultry litter can have a C:N on the order of 20:1 or more and can be a net immobilizer of nitrogen in the soil (Gale et al., 2006; Ashworth et al., 2019). As a result, composting has been suggested as a better alternative to land application for poultry litter with a high C:N values (Chastain et al., 2013).

Commercial turkey production involves two types of barns that correspond to two phases of production. The first phase of production includes brooding of newly hatched turkey chicks and raising them to a mass of 2.3 to 2.7 kg per bird which is called a turkey poult. The poults are then moved to barns on a separate farm where they are grown out to a market size that can range from 7 to 22 kg per bird. Litter

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removed from turkey poult barns contains a large amount of organic bedding relative to the mass of manure since large amounts of wood shavings are used for each flock of turkey chicks. The litter is often removed from the poult barns after each flock as a means of disease control. As a result, turkey poult litter has a lower moisture content, lower fertilizer value, and a C:N on the order of 22:1 (Chastain et al., 2013; Ashworth et al., 2019) which has been shown to reduce crop yields due to immobilization of soil N (Gale et al., 2006). It has also been shown that moving and spreading turkey poult litter costs 47% more than litter from a turkey grow-out barn (Chastain et al., 2013). As a result, composting is often recommended as one of the better alternatives to spreading litter removed from turkey poult barns onto cropland. Results from a composting demonstration project (Chastain et al., 2013) indicated that a very stable compost could be produced using turkey poult litter as the only ingredient in a simple turned windrow system.

Composting is an aerobic microbial process that decomposes organic matter (Rynk et al., 1992; Chardoul et al., 2015; Al-Batina et al., 2016; USCC, 2023). The term active composting is used to describe the first stage in the process when the majority of organic matter decomposition occurs. Active composing is divided into three phases that are defined by the temperature of the composting material. The first phase is an initial mesophilic phase that is characterized by a steady increase in windrow temperature from the ambient temperature to about 50°C and lasts for 7 to 10 days. The second phase, which can last for several weeks, is characterized by thermophilic windrow temperatures (50°C to 70°C) and is the time period when thermophilic microbes consume most of the readily degradable carbon and nitrogen. The third phase is also characterized by mesophilic conditions (10°C to 50°C) and fungi become active in the decomposition process and the windrow temperature will no longer rise after turning and will steadily decrease to just a few degrees above ambient temperature. A compost product is often described as finished when it has been observed that the active composting stage has been completed. The main criterion used is that addition of moisture and oxygen will no longer result in an increase in windrow temperature. The appearance of the product will also no longer resemble the initial materials, will have a dark brown or black color, and will not give off unpleasant odor (Rynk et al., 1992; Chastain et al., 2013; USCC, 2023). The amount of time required for active composting to take place can vary with the materials in the composting recipe and the efficiency of the composting method used (Rynk et al., 1992).

After active composting has been completed, psychrophilic microbes and fungi continue to slowly decompose decay-resistant materials contained in the initial mixture of ingredients until the product is described as stable (Rynk et al., 1992; Chardoul et al., 2015; Al-Batina et al., 2016). This period is often called the curing stage, however, precise criteria to determine when the curing stage has concluded are not well defined. One criterion that has been proposed is measurement of the CO_2 evolution rate, and a product is considered stable when the CO_2 evolution rate of the product is less than 8 mg CO_2-C/g OM/day (AASHTO, 2010).

The modes of nutrient and carbon loss during the active composting stage have been well documented and have been summarized in handbooks and operating manuals since the early 1990s (e.g., Rynk et al., 1992; Chardoul et al., 2015). Previous studies on the changes that occur during active composting have indicated that large amounts of TN and C were lost from the composting material. The primary mode of nitrogen loss was ammonia volatilization and carbon was lost as carbon dioxide (Rynk et al., 1992; Michel et al., 2004; Chastain et al., 2013). Total nitrogen losses ranged from 7% to 60% of the TN depending on the carbon source used, the initial value of C:N, and the efficiency of the process (Rynk et al., 1992; Mahimairaja et al., 1994; Tiquia et al., 2002; Michel et al., 2004; Chastain et al., 2013). Many commercial compost producers use some type of turned windrow system and typical TN and C losses during active composting are on the order of 50% (Rynk, et al., 1992; Chastain et al., 2013).

During the active composting phase, the organic portion of the total nitrogen has been observed to mineralize to ammonium-N (NH_4^+-N) followed by the conversion of NH_4^+-N to NO_3-N by nitrifying bacteria (Mahimairaja et al., 1994; Michel et al., 2004; Chastain et al., 2013). That is, the nitrogen in the composting windrow followed the same steps of the nitrogen cycle that occurs after applying poultry litter to soil (Claassen and Carey, 2007). As the composting process continues, a small amount of the TN may also be lost from the windrow by way of nitrate leaching (Chastain et al., 2013).

In addition to TN loss, reductions in phosphorous and potassium have also been observed during active composting. Phosphorous losses ranged from 14% to 39% and potassium losses were as low as 1% and as high as 42% (Michel et al., 2004; Chastain et al., 2013). Very little information is available concerning the modes of P and K loss from the composting material. It was possible that decomposition of the initial substrates resulted in the mineralization of organic P allowing a portion of the soluble P and K to be washed from windrows exposed to rainfall (Chastain, et al., 2013).

Once a compost product has been allowed to cure, the product is typically stored in the same windrow until the product is bagged for retail sale or is sold in bulk. Only one study was found in the literature that provided information concerning changes in the TN, C, NH_4^+-N, and NO_3-N contents of a compost product during storage (Al-Bataina et al., 2016). They compared the composition of a compost product that had been stored for 0, 28, and 63 days following active composting. They found no evidence of nitrogen loss, and a decrease in carbon content that resulted in a decrease in C:N ratio. The largest chemical changes observed were the decrease in NH_4^+-N and the increase in NO_3-N as would be expected due to nitrification occurring within the windrow. The total volatile solids content (VS) was observed to decrease by 25% over 63 days of storage and the bulk density increased from 119.8 to 202.3 kg/m^3. No information was provided concerning the concentrations of organic-N, P, K, or any important minor plant nutrient such as S, Ca, Mg, or Fe.

One of the problems faced by producers of compost is the accumulation of large windrows of product on the compost yard prior to marketing. The extra storage time increases the total cost to produce the product and can impede the production of new compost if space in the curing and storage area is unavailable. The practical question related to the marketing delays was how much nitrogen, and carbon can be lost from open windrows of finished compost while being stored prior to sale? It was believed that measurable amounts of TN and C would be lost during storage. The processes were expected to be similar to those observed during active composting, but at a reduced rate. There were additional questions concerning the variation in the concentrations of plant nutrients, such as P_2O_5 and K_2O, and compost properties such as electrical conductivity and the bulk density of the product. It was expected that the bulk density would increase with respect to storage time due to compression settling. The objective of this study was to observe the impacts of storage time on the concentrations of major plant nutrients, key minor plant nutrients, organic matter, carbon, and moisture contained in finished compost stored in outside windrows at a small commercial composting facility that used turkey poult litter as the sole ingredient. Changes in the compost pH, electrical conductivity (EC), and dry bulk density with respect to time in storage were also observed.

MATERIALS AND METHODS

A turkey poult producer, located in the central region of South Carolina, began a compost business using a process similar to the one described by Chastain et al. (2013). The only ingredient in the initial compost mix was poult litter that was removed from poult barns onsite or that was obtained from other turkey poult farms in the area. Active composting was carried out in an open-sided, post-frame building with a concrete floor. Moisture was added to the poult litter as the windrow was built in layers and the level of moisture was evaluated using the ball squeeze method (Rynk et al., 1992; Chastain et al., 2013). The windrows were turned using a tractor and loader and compost temperatures were measured with a long-stem thermometer and recorded. Once active composting was complete, as indicated by falling windrow temperatures, the windrow was reformed outside the building in a storage area where it was allowed to cure in open windrows prior to sale. The windrows were 1.5 to 2.0 m tall and about 15 to 20 m long. However, as compost was sold during the study, the length of some of the windrows decreased. The primary market for the compost was bulk sales for garden and landscape use.

During a site visit it was determined that the producer had seven large windrows, made from the same compost recipe. Some of the windrows had been stored for over a year due to delays in marketing. This commercial compost facility was selected to be the site for the case study for the following reasons: (1) the business was producing a compost product from a simple, relatively consistent, mixture of wood shavings and turkey manure, (2) the active composting process and material was similar to a previously published case study (Chastain et al., 2013), (3) the facility had been permitted by the state of South Carolina, USA, and (4) the producer had precise records concerning the amount of time each windrow was in the active composting phase, and the time the windrow had been kept in the storage area. A windrow sampling schedule was carried out to observe the impact of storage time on the concentrations of major plant nutrients, key minor plant nutrients, organic matter, carbon, and moisture contained in the stored compost product. The samples were also analyzed to determine if storage time had an impact on pH, electrical conductivity (EC), and dry bulk density.

CALCULATION OF COMPOST AGE AND WINDROW SAMPLING

The case study was initiated on 30 July 2021. At that time seven large windrows of finished poult litter compost were in the storage area. Detailed production records were provided by the producer that provided the date active composting was initiated, the number of times the windrows were turned, and the date that active composting was complete which was also the date when the finished compost was moved to the curing and storage area. Windrow temperature records were available for the active composting stage but were not included in this study since the objective was to observe changes in the product during curing and storage and not to study the dynamics of the active composting process. In addition, the adequacy of the process had already been evaluated as part of obtaining a permit to operate in South Carolina which included evaluation of windrow temperature history and testing for compost stability of the product. Furthermore, the producer desired to keep much of the permit information confidential since it was not required to meet the objective of the current study.

Compost production records provided the dates required to calculate the following for each of the windrows: the active compost time (*AC*, days) and the curing and storage time (*CS*, days) on the day that the windrows were sampled. The total compost age (*CA*, days) was calculated as:

$$CA = AC + CS \tag{1}$$

The total compost age was used as the time variable in the analysis since it provided the most unambiguous description of the time when the windrows were sampled and reinforced that the study was focused on changes during curing and storage and not during active composting. It was also observed that the seven different windrows were in various stages of curing since the windrows had been in the storage area for 29 to 496 days at the onset of the study.

Samples were collected at 6 to 10 locations down the length of each of the windrows and at various depths in the windrow using a shovel. This provided several samples from each of the locations from the windrow and yielded approximately 36 L of compost that was mixed well in large buckets to yield a mechanically averaged sample that was representative of the compost product contained in the windrow. A large composite sample was obtained from the buckets and was placed in two large sealable plastic bags to yield approximately 6 L of sample per windrow for analysis. The sampling procedure yielded one large representative sample for each of the seven windrows on the first day of sampling (30 July 2021). The windrows were sampled again, 87 days later, on 25 October 2021. The same sampling procedure was repeated and provided an additional seven large samples, one per windrow. On the second day it was found that a large portion of the oldest windrow had been sold between the first and second sampling dates resulting in a much shorter windrow for sampling. It was decided that the study would end since one of the windrows would soon be gone and substantial amounts of the remaining windrows would most likely be sold. The two days of sampling provided 14 observations for regression analysis to determine if total compost age had an impact on the concentrations of major plant nutrients (N, P_2O_5, K_2O) C, OM, as well as pH, EC, moisture content, and bulk density.

COMPOST SAMPLE ANALYSIS

Each of the 14 windrow samples were analyzed to determine the concentrations of total nitrogen (TN), total ammoniacal nitrogen (TAN = ammonium-N + ammonia-N), nitrate-N (NO_3-N), total phosphorous, total potassium, calcium (Ca), magnesium (Mg), sulfur (S), zinc (Zn), copper (Cu), manganese (Mn), iron (Fe), sodium (Na), and aluminum (Al). The total P and total K were reported as P_2O_5 and K_2O to correspond with how commercial fertilizers are formulated and fertilizer recommendations are made. Other characteristics measured included: moisture content (MC), total carbon content (C), organic matter content (OM), pH, electrical conductivity (EC), and dry bulk density.

Standard laboratory procedures were used for all analyses and details are summarized online by the laboratory director of the Agricultural Services Laboratory at Clemson University (ASL, 2022a and 2022b). The concentrations of TN and C were determined from a dried and ground portion of the sample using the Elementar procedure. The ammonium-N concentrations were measured by mixing a representative 2 g sub-sample in a flask containing 20 mL of KCl (2 M) followed by standard digestion and acid titration techniques. This method included the small amount of ammonia-N that was present in the compost sample. As a result, it provided a measurement of the total ammoniacal nitrogen (TAN). The NO_3-N content was determined using the cadmium reduction method for solid manures. The organic-N content (Org-N) was calculated as:

$$\text{Org-N} = \text{TN} - \text{TAN} - \text{NO}_3\text{-N} \qquad (2)$$

All other elements (P, K, Ca, Mg, S, Zn, Cu, Mn, Fe, Al, and Na) were measured using ICP Mass Spectrometry (ASL, 2022b). The moisture content of all replicate samples was determined by drying a sub-sample in an oven maintained at 105°C for 2.5 to 3 h and determining the weight of the dry matter fraction (DMF). The moisture content (%) was calculated as: MC = 100 (1-DMF). The organic matter was determined by burning a dry sample in a 360°C furnace for 2.5 h. The OM was expressed as the percent of the dry matter and was calculated as the difference between the dry weight and the ash weight divided by the dry weight. The pH was measured after mixing a 15 mL sub-sample with 15 mL of deionized water and soaking for 30 min. The pH of the resulting solution was measured using a pH analyzer. The electrical conductivity (EC) was determined by making a 1:5 dilution of the sample with deionized water. After allowing the slurry to equilibrate, an electrical conductivity meter was used to measure the conductivity in mmhos/cm.

The bulk density was measured on a volume basis (ASL, 2022a). Approximately 3 L of compost was spread on a tray and allowed to dry overnight in an oven maintained at 80°C. The next day, five 500 mL samples were measured out and weighed in a calibrated container. The bulk density that was reported was the average of these five samples. The major nutrients, minor plant nutrients, and the bulk density were reported on a dry basis since the moisture content varied from sample to sample.

WEATHER DATA

No weather data were available at the composting site. However, daily weather data taken at the NOAA weather station for central South Carolina were available online (NOAA, 2023). The weather station was located in Columbia, South Carolina which was about 50 miles from the case study site. The published weather data were used to calculate the average ambient temperatures and the cumulative rainfall amounts for the time period when each windrow was stored outside until the first sampling day (30 July 2021). The average temperature and cumulative rainfall between 30 July 2021, and the second sampling day (25 October 2021) was also calculated and was the same for the seven windrows. It should be noted that the average temperatures measured in Columbia, South Carolina, would be expected to be very similar to those that would have been observed at the composting facility. However, due to typical variation in regional rainfall patterns, the rainfall totals measured in Columbia, SC would not be expected to be the same as for the composting facility. At best the rainfall and temperature data were viewed as descriptive of the general climate for the region where the study was conducted. The rainfall and temperature data were not accurate enough to be included in the data analysis. However, the amount of rainfall that fell in the central region of South Carolina did provide some context to compare windrow moisture contents.

STATISTICAL ANALYSIS

Linear correlation analysis was used to determine if the moisture content, pH, EC, bulk density, all forms of nitrogen, P_2O_5, and K_2O were significantly correlated with respect to total compost age (*CA*). An Analysis of Variance for the Regression (ANOVAR) was performed to provide an F-test to determine if the correlation coefficient (r) was significant (Steel and Torrie, 1980). The minimum level of probability that was accepted was $p = 0.05$. If the correlation was significant, regression analysis was used to determine the equation that best fit the data. The statistics that were reported for the significant regression equations were the coefficient of determination (R^2), and the standard error of the y-estimate (SEy) obtained from the ANOVAR. If the correlation was not significant the appropriate means were calculated along with the coefficient of variation (CV = 100 × standard deviation/mean) and the 95% confidence interval (Steel and Torrie, 1980).

Since no chemical or physical process was expected to alter the dry matter concentration of the measured minor nutrients, sodium and aluminum, a simple one-way analysis of variance was performed for each of these elements with each of the windrows serving as a treatment with two replications.

The least-significant difference (LSD) test was performed with a p-value of 0.05 and 7 degrees of freedom (Steel and Torrie, 1980). Only relatively large differences in element concentrations between windrows would be considered significant since the total error degrees of freedom was small.

RESULTS AND DISCUSSION

The seven windrows of composted turkey poult litter were moved to the storage area of the compost facility over a period from 21 March 2020 to 1 July 2021. At the beginning of the study (30 July 2021) it was determined that the time in storage ranged from 29 days for W1 to 496 days for W7 as shown in table 1. The average ambient air temperatures during storage ranged from 17.3°C for W6 to 27.1°C for W1. The cumulative amount of rain that fell in the region while the windrows were stored in the open ranged from about 155 mm for W1 to 1762 mm for W7. During the 87-day period between the first and second days of windrow sampling the average temperature was 24.1°C and an additional 372 mm of rain fell in the region. While the available rainfall data were not collected at the compost facility, they do indicate that more rain fell on the windrows that had been in the storage area for a longer period of time. Therefore, higher than average windrow moisture contents would be expected if a large amount of the rainfall infiltrated windrows while being stored in the open.

Based on the producer's records it was determined that the active composting phase ranged from 82 to 120 days with an average of 98.9 days (table 2). The windrows were turned 6 to 8 times during active composting with an average of 7.3 turns per windrow. On the first day of sampling (30 July 2021), the curing and storage period for the windrows (*CS*) ranged from 29 to 496 days indicating that the youngest windrow (W1) may not have been as stable as the other windrows when the first samples were collected. The total compost age was calculated as defined in equation 1 and included the entire time from the beginning of active composting to the day the samples were collected and ranged from 131 to 587 days on the first day of sampling. The windrows were sampled again 87 days later giving curing and storage times of 116 to 583 days and values of *CA* ranging from 218 to 674 days. These large storage times, associated with high *CA*, provided a large amount of time to determine if nitrogen, organic matter, and carbon were lost from finished compost during storage in open windrows.

IMPACT OF COMPOST AGE ON MOISTURE, EC, pH, AND BULK DENSITY

The data concerning the moisture content of the windrow samples are provided in table 3. It was found that the MC of the windrows ranged from 46.9% to 56.0% but was not significantly correlated with respect to *CA*. The average moisture content for all samples was 52.2 ± 1.4% with a CV of 4.8%. While the exact amount of rainfall on these windrows was not known, the data from the closest national weather station indicated that more rain fell on the windrows that were in the storage area for the longest period of time. However, the highest moisture content of 56.0% observed on 30 July 2021, was for W2 that had only been in the storage area for 51 days (table 2). These results suggest that increased exposure to rainfall during storage did not influence the average moisture content of the windrows.

The electrical conductivity of the compost in the seven different windrows varied from 1.87 to 6.21 mmhos/cm and was not significantly correlated with respect to compost age.

Table 1. Estimates of the average air temperatures and cumulative rainfall amounts for Central South Carolina while the windrows were stored outside.[a]

Windrow I.D.	Date Active Composting Began	Date Finished Compost Was Moved to Storage Area	Time in Storage on 7/30/2021	Average Air Temperature during Storage up to 7/30/2021 (°C)	Cumulative Rainfall during Storage up to 7/30/2021 (mm)
W1	3/21/2021	7/1/2021	29	27.1	155
W2	3/19/2021	6/9/2021	51	26.6	249
W3	1/10/2021	4/19/2021	102	23.0	336
W4	10/1/2020	1/4/2021	207	17.6	721
W5	7/18/2020	10/29/2020	274	16.2	922
W6	5/18/2020	9/15/2020	318	17.3	1036
W7	12/21/2019	3/21/2020	496	19.1	1762
Average air temperature for storage period between 7/30/2021 and 10/25/2021 = 24.1°C					
Cumulative rainfall for storage period between 7/30/2021 and 10/25/2021 = 372 mm					

[a] The weather data used was obtained from the NOAA weather station located about 50 miles from the study site (NOAA, 2023).

Table 2. Active composting times, number of turns, curing and storage times and compost age for seven windrows of turkey poult litter compost using the same recipe. Elapsed time between the two sampling dates was 87 days.

Windrow I.D.	Active Composting Time (days)	Total Number of Turns	Curing and Storage Time 1 (days)	Compost Age for First Samples[a] (days)	Curing and Storage Time 2 (days)	Compost Age for Second Samples[b] (days)
W1	102	7	29	131	116	218
W2	82	7	51	133	138	220
W3	99	6	102	201	189	288
W4	95	7	207	302	294	389
W5	103	8	274	377	361	464
W6	120	8	318	438	405	525
W7	91	8	496	587	583	674
Average	98.9	7.3				

[a] Samples collected on 30 July 2021.

[b] Samples collected on 25 Oct. 2021.

Table 3. Variation in moisture content (MC), and electrical conductivity (EC) of the seven windrows with respect to compost age.

	Windrow I.D.	Compost Age (days)	MC (%)	EC (mmhos/cm)
Sample 1 (30 July 2021)	W1	131	53.1	4.01
	W2	133	56.0	2.93
	W3	201	53.9	4.21
	W4	302	51.0	3.72
	W5	377	54.6	1.88
	W6	438	54.7	1.87
	W7	587	54.5	2.60
Sample 2 (25 Oct. 2021)	W1	218	51.2	6.21
	W2	220	49.7	6.09
	W3	288	51.7	5.73
	W4	389	50.6	3.31
	W5	464	52.6	2.05
	W6	525	50.1	5.07
	W7	674	46.9	3.53
		r	-0.366	-0.370
		p	0.20	0.19
		Mean	52.2	3.80
		CV (%)	4.8	39.7
		95% C.I.	1.4	0.87

The overall mean EC was 3.80 ± 0.87 mmhos/cm with a CV of 39.7%. The reason for the extreme variability in EC was unknown, however the compost in each of the seven windrows was sourced from different barns and may have been the cause of the variability observed.

Windrow pH was observed to decrease with respect to compost age from 131 to about 400 days and then leveled off to mean value as shown in figure 1. The pH was negatively correlated, r = -0.727 ($R^2 = 0.528$), with a p-value of 0.026 and reached a stable mean pH of 6.8 ± 0.3 with a CV of 3.2%. Using the linear regression equation shown in the figure, it was determined that the pH fell from 8.9 at a *CA* of 131 days to 6.8 at a *CA* of 363 days. The decrease in compost pH from a high of about 8.9 to a stable mean of 6.8 was believed to be the result of humic and other organic acid formation during storage (Rynk et al., 1992). Therefore, the reduction of pH during long-term storage provided evidence of biological activity many days after active composting had been completed.

The dry BD of the seven windrows correlated significantly (p = 0.0002) with respect to compost age as shown in figure 2. The R^2 was 0.693 and the standard error of the y-estimate was 42.4 kg DM/m^3. The average CV was 14.3% (100 × SEy/grand mean). The observed increase in BD during storage agreed with the trends observed by Al-Bataina et al. (2016). The BD measurement for W7 on the second day (*CA* = 674 days) was higher than all other samples (514 kg DM/m^3). This windrow had the least volume on the second day of sampling and may have been inadvertently mixed with soil from the compost yard as the product was removed with a loader and sold.

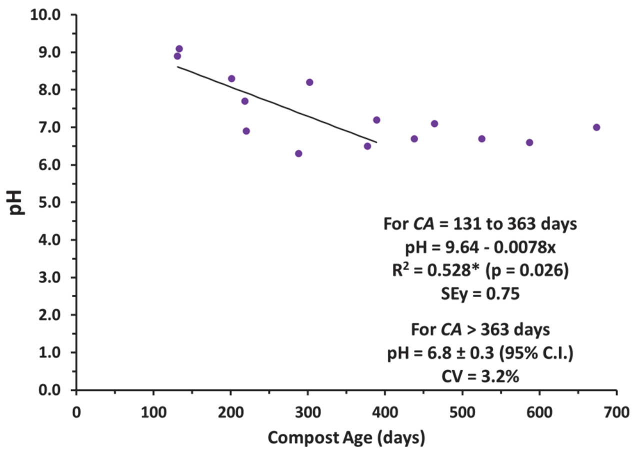

Figure 1. Variation in pH with respect to compost age.

IMPACT OF COMPOST AGE ON NITROGEN, ORGANIC MATTER, AND CARBON

The compost stored in the seven windrows in this study had already completed the active composting stage and most were well cured before the study began. As a result, most of the TN and C losses had already occurred. It was hypothesized that a small but significant amount of TN would be lost during long-term storage by way of ammonia volatilization or leaching of nitrate-N from the windrows. It was also thought that C would continue to be lost slowly as CO_2 and would result in a modest decrease in carbon and organic matter.

The variation in the total nitrogen with respect to compost age is provided in figure 3. The results from the ANOVAR indicated that the TN concentration did not correlate significantly with respect to *CA* (p = 0.272) indicating no

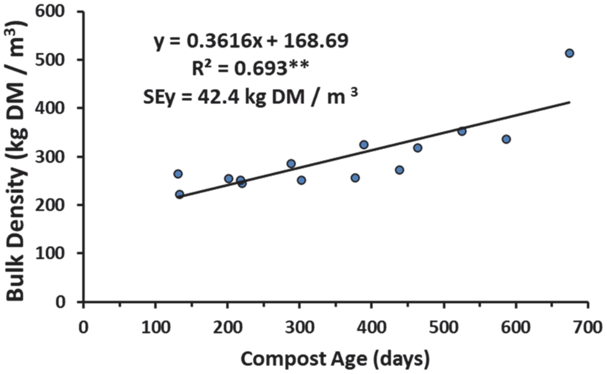

Figure 2. Variation in dry matter bulk density with respect to compost age. The correlation was highly significant (p = 0.0002).

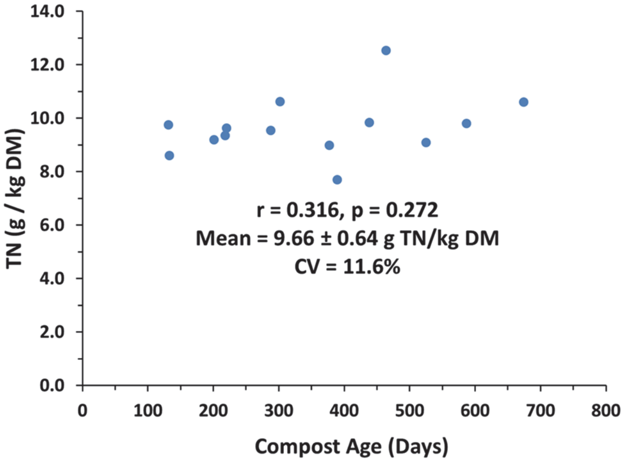

Figure 3. Variation in total nitrogen (TN) with respect to compost age. The correlation coefficient was not significant (p = 0.272).

significant change in TN during storage. The average TN concentration for all 7 windrows was 9.66 gTN/kg DM with a 95% C.I. of ±0.64 g TN/kg DM. The coefficient of variation was 11.6%. While the result was not expected, it indicated that nitrogen was not lost from the windrows while being stored after active composting had been completed. These results agreed with the trends observed by Al-Bataina et al. (2016) for storage periods of 28 and 63 days.

The variation in the TAN and NO_3-N contents of the seven windrows in the present study were plotted with respect to *CA* and are shown in figures 4 and 5. The TAN data indicated a highly significant ($p = 0.001$), negative correlation with respect to compost age between a *CA* of 131 days and 369 days (fig. 4). Using the regression equation shown in figure 4, it was determined that the mean TAN concentration fell from of 3.35 g TAN/kg DM for a *CA* of 131 days to 0.02 g TAN/kg DM for a *CA* of 369 days. The mean TAN concentration from day 369 to 674 was 0.060 g TAN/kg DM with a 95% C.I. of ±0.098 g TAN/kg DM indicating that the mean TAN content was not significantly different from zero. This decrease in TAN was not due to a significant loss by ammonia volatilization since it was already observed that the total nitrogen did not decrease significantly during storage (fig. 3). The TAN concentrations were plotted with the nitrate-N concentrations in figure 5 and the data clearly indicates that as the TAN content decreased the NO_3-N content increased. That is, the ammonium-N was converted to nitrate-N as expected. A least-squares best fit analysis indicated that the increase in NO_3-N was significantly correlated to the natural logarithm of *CA* ($R^2 = 0.327$, $p = 0.032$). It appears that most, it not all, of the TAN content was conserved by nitrification in the windrows. Again, since TN did not change significantly, it appears that NO_3-N loss from the windrows by leaching was not significant which was contrary to the initial assumption.

The organic-N content of the compost samples was calculated from the TN, TAN, and NO_3-N as shown previously in equation 2. The fact that this form of nitrogen was not measured, but calculated from other measurements, tended to slightly increase the scatter in the data. The organic-N was found to correlate significantly with respect to the natural logarithm of *CA* in a manner similar to NO_3-N as shown in figure 6. This modest, but significant, increase in organic-N during storage was believed to be due to an increase in the microbial biomass in the windrows. The microbes that decomposed the manure and wood shavings used the soluble nitrogen to grow and reproduce and converted the soluble N to microbial biomass. As the compost matured, the available C and N to support microbial growth diminished and the microbes remained in the compost resulting in an increase in Org-N (Rynk et al., 1992; McCauley et al., 2003; Claassen and Carey, 2007; Plant and Soil Sciences eLibrary, 2022). It is also believed that the conversion of TAN to NO_3-N and the increase in Org-N was the cause for the decrease in windrow pH to a stable value that was observed in figure 1. These results provided additional evidence of ongoing microbial activity in the windrows during storage that would tend improve the stability of the compost product.

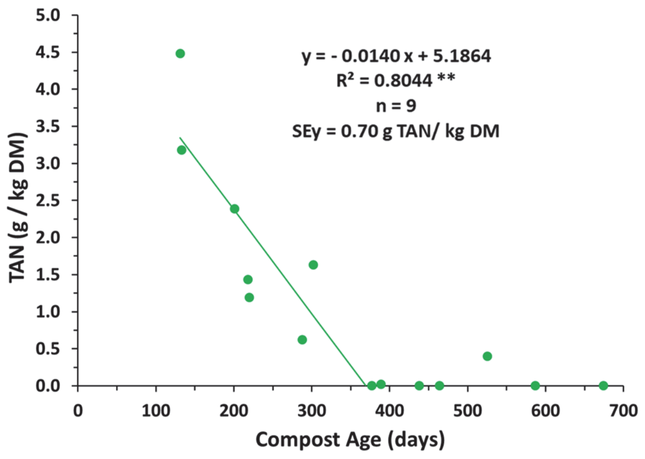

Figure 4. Variation in total ammoniacal nitrogen (TAN) with respect to compost age. The correlation from 131 to 369 days was highly significant (p = 0.001). Above 369 days the average was 0.060 ± 0.098 g TAN/kg DM (n = 7).

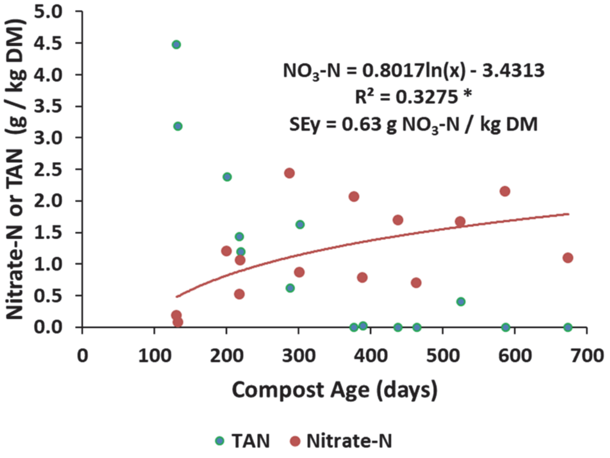

Figure 5. Variation in Nitrate-N with respect to compost age and decrease in TAN. The correlation of NO_3-N with respect to *CA* was significant (p = 0.032).

One of the most valuable soil-building components of compost is the total organic matter and the associated carbon. Regression analysis indicated that the OM and C concentrations in the seven windrows were negatively correlated with respect to total compost age as shown in figures 7 and 8. Both of the correlations were highly significant ($p < 0.001$) and the best fit equations, shown in the figures, were linear. The slope of the regression lines indicated that

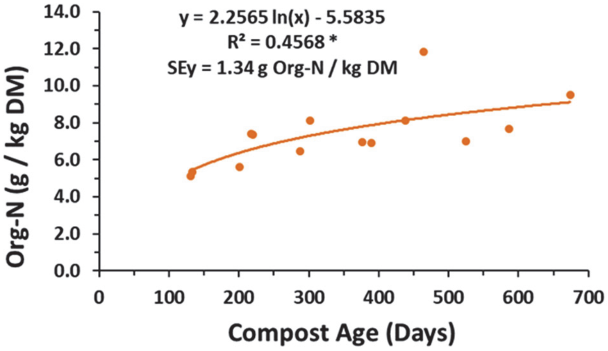

Figure 6. Variation in organic-N with respect to compost age. The correlation was significant (p = 0.013).

OM was lost at the rate of 0.623 g OM/kg DM/day and C was lost at the rate of 0.447 g C/kg DM/day. Using the regression equation shown in figure 7, it was determined that the compost contained 645.7 g OM/kg DM for a compost age of 131 days and compost that was 674 days old contained 307.3 g OM/kg DM. As a result, the maximum loss of OM was 52% over a curing and storage period of 543 days. In a similar manner, the carbon content fell from 387.0 to 144.1 g C/kg DM over the same 543-day period which indicated a maximum C loss of 63%. The percentage of the OM that was C (100 × C/OM) fell from 60% at a *CA* of 131 days to 47% on day 674. These results indicated that the greatest losses from compost during storage were in the valuable organic matter and carbon and agreed with the trends observed by Al-Bataina et al. (2016).

The highly significant loss of carbon during storage along with the insignificant loss of total nitrogen resulted in a highly significant decrease in C:N with respect to *CA* as shown in figure 9. The average C:N fell from 42:1 at 131 days to 14:1 on day 674. Michel et al. (2004) also observed a significant negative correlation in C:N due to losses of C during active composting ($r = -0.93$; $R^2 = 0.86$) and recommended adjusting compost recipes to provide an initial C:N of 40:1 or more to minimize nitrogen losses. The correlation and data shown in figure 9 indicated that this initial condition may have been met for this composting operation since the average C:N was 42:1 at a *CA* of 131 days using the regression equation shown in the figure.

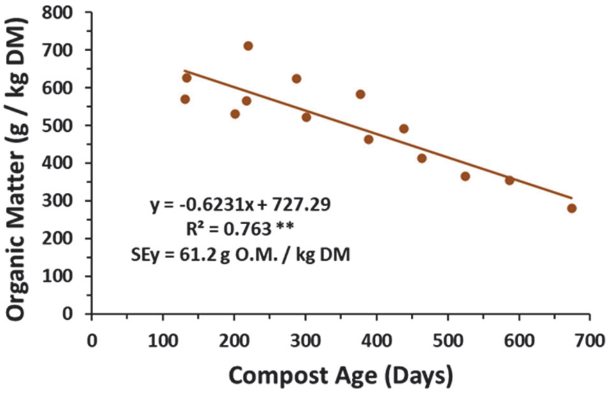

Figure 7. Variation in organic matter with respect to compost age. The correlation was highly significant (p = 0.00004).

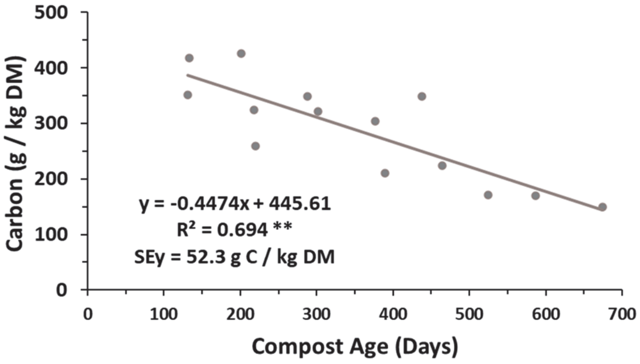

Figure 8. Variation in carbon with respect to compost age. The correlation was highly significant (p = 0.00022).

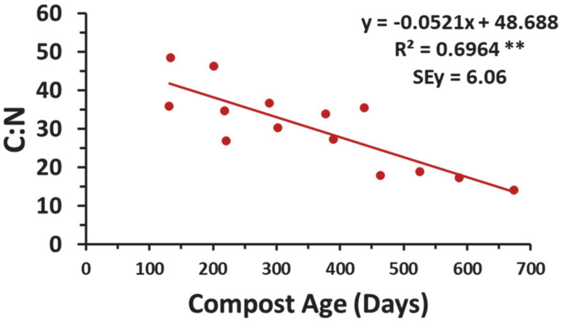

Figure 9. Variation in C:N with respect to compost age. The correlation was highly significant (p = 0.00020).

The decrease in C:N that occurred during storage may have a positive impact on the plant-availability of the mostly organic nitrogen contained in the compost. A study published by Claassen and Clarey (2007) concluded that only 0.9% to 13% of the TN in compost was mineralized 6 to 12 weeks following application depending on the amount of poultry manure used in the initial compost mix. Additional work by Gale et al. (2006) indicated that the C:N of a compost product was an indicator of the amount of organic nitrogen that would be mineralized following application. Their data indicated that the full-season mineralization in field trials ranged from -10% to 20% of the TN applied and that plant available N (PAN) decreased as C:N of the compost increased. At a C:N of 9:1 their data indicated that about 20% of the TN was mineralized during the first growing season. However, the mineralization rate fell to 0% at a C:N of 15:1 and ranged from -2% to -10% for C:N of 20:1 to 27:1. The average PAN for the compost products included in their study was 7% of TN applied to soil. A recent study by Kelley et al. (2020) indicated that the fraction of the TN in dairy manure-based composted that was recovered as PAN ranged from -5.5% to 0.6% with an average PAN of -3%. While the scatter in the available data from the literature is large, it appears that the decrease in C:N with respect to storage time in the current study may cause the product to move from being a net immobilizer of TN at C:N of 42:1 to a product that releases little to no soluble nitrogen with a PAN on the order of -3% to 0%. However, the large amount of organic-N contained in compost would be expected continue to be mineralized in subsequent years at a slow, but unknown rate (Claassen and Clarey, 2007).

IMPACT OF COMPOST AGE ON K_2O AND P_2O_5

The variation in the potassium (K_2O) content of the seven windrows of finished compost with respect to compost age is shown in figure 10. Correlation analysis indicated that the K_2O concentration was not significantly correlated with respect to *CA* (p = 0.681) indicating no significant loss during storage. The mean concentration was 7.1 g K_2O/kg DM with a 95% C.I. of ±0.99 g K_2O/kg DM. The scatter was quite large as indicated by a CV of 24.2%.

It was determined that the P_2O_5 content of the compost in the seven windrows also did not correlate significantly with respect to compost age (fig. 11). However, the mean P_2O_5 content of windrow seven appeared to be larger than the other six windrows. To check this observation, a one-way

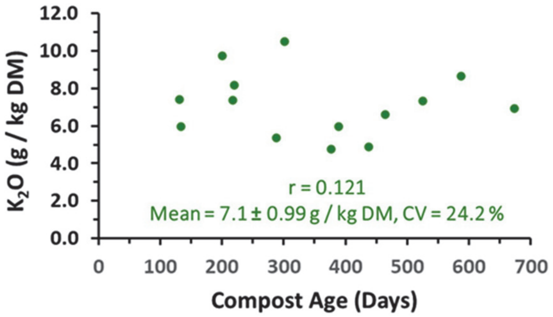

Figure 10. Variation in K_2O with respect to compost age. The correlation was not significant ($p = 0.681$).

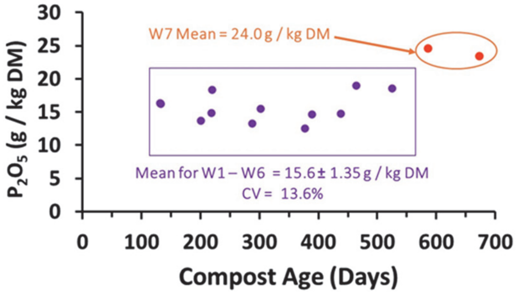

Figure 11. Variation in P_2O_5 with respect to compost age. Results of an LSD test indicated that windrow 7 was significantly different from the other 6 windrows.

ANOVA was performed in the same manner as was described previously for the minor plant nutrients. It was found that the average P_2O_5 concentration of the seventh windrow (W7) was significantly higher than the other six windrows. The mean concentration for six of the windrows was 15.6 ± 1.35 g P_2O_5/kg DM, but the product in windrow 7 contained 56% more at 24.0 g P_2O_5/kg DM. Since each windrow was composted poult litter obtained from different barns, the elevated P_2O_5 values for W7 may have been related to elevated amounts of P in the feed for the respective birds, or the source of extra P could have been the bedding used or soil from the turkey house floor that was mixed with litter during clean-out.

Potassium (expressed as K_2O) and phosphorous (expressed as P_2O_5) contained in compost products are more useful for substitution of commercial fertilizer than the nitrogen contained in compost (Michel et al., 2004; Chastain et al., 2013). The majority of the K_2O in compost is usable by plants during the first year following application and can be used as a direct substitute for a portion of K_2O fertilizer needed to grow a plant (Rynk et al., 1992). Therefore, K_2O is often the most valuable major plant nutrient in a compost product. By comparison, the plant availability of P_2O_5 contained in finished compost is only 25% to 40% as compared to commercial fertilizer (Rynk et al., 1992). Therefore, about 32% of the P_2O_5 contained in a compost product can be used to meet the P_2O_5 recommendations to grow a plant.

VARIATION IN MINOR PLANT NUTRIENTS, AL, AND NA

As was expected, the concentrations of the minor plant nutrients, Al and Na were not significantly correlated with respect to compost age. Plots of the concentrations of these elements with respect to *CA* were similar to those shown for K_2O and P_2O_5 (figs. 10 and 11). The results of the ANOVAs and LSD tests for Al, Na, and each of the minor plant nutrients measured are provided in table 4. The means shown in the table with a common letter were not significantly different for each element. The concentrations of Ca, Zn, Cu, Mn, Fe, and Al in windrow seven were significantly higher than the other six windrows. The only element for which there was no significant difference between windrows was S.

The only metals included in this study that are regulated by the USEPA as part of the regulations for land application of municipal sludge were Zn and Cu (USEPA, 2022). The maximum allowable monthly average concentration for Zn is 2800 mg/kg DM and the similar limit for Cu is 1500 mg/kg DM (USEPA, 2022). The maximum concentrations for both of these metals were in windrow 7. Conversion to mg/kg DM indicated that W7 contained 230 mg Cu and 340 mg Zn per dry kg. Therefore, the Zn and Cu contents of the compost products were below the concentration limits required by USEPA.

CONCLUSIONS

Samples were collected from seven windrows at a commercial composting facility for the purpose of determining the impact of storage time on key chemical and physical characteristics of compost. The only ingredient used to make the compost was turkey poult litter and records were available to determine how long each windrow had been kept in storage and the corresponding total compost age on the date that samples were collected. The analysis of the data indicated the following.

Table 4. Mean Na, Al, and minor plant nutrients contents (g/kg DM) in the seven compost windrows (n = 2, error degrees of freedom = 7).[a]

	Windrow I.D.								LSD
	W1	W2	W3	W4	W5	W6	W7	S_p[b]	(0.05)[c]
Ca	12.8 a	15.7 b	11.6 a	12.8 a	14.0 a	15.7 b	**21.1**	1.490	1.9
Mg	2.3 a	2.1 ab	1.8 b	2.1 ab	2.0 ab	2.1 ab	2.8 a	0.214	0.3
S	1.7 a	2.2 a	1.5 a	1.8 a	1.6 a	1.7 a	2.1 a	0.294	0.4
Zn	0.22 a	0.24 a	0.20 a	0.23 a	0.25 ab	0.27 ab	**0.34**	0.030	0.04
Cu	0.18 a	0.20 a	0.15 b	0.19 a	0.17 ab	0.18 a	**0.23**	0.018	0.02
Mn	0.32 a	0.30 ab	0.25 b	0.29 ab	0.34 a	0.33 a	**0.46**	0.041	0.05
Fe	2.6 ab	2.4 a	2.4 a	2.7 ab	3.4 c	3.0 bc	**4.5**	0.278	0.4
Na	0.63 ac	0.56 ab	0.58 ab	0.56 ab	0.41 b	0.52 ab	0.76 c	0.137	0.17
Al	5.6 ab	5.7 ab	4.7 a	5.6 ab	6.5 b	6.0 b	**9.0**	0.966	1.2

[a] Means with a common letter were not significantly different.

[b] Pooled standard deviation

[c] Least significant difference at p = 0.05, t (0.025, 7 edf) = 2.365 (Steel and Torrie, 1980).

- The moisture content of the windrows was not significantly correlated with compost age even though large amounts of rain fell on the uncovered windrows. The mean moisture content was 52.2 ± 1.4%.
- The total nitrogen content was not significantly correlated with respect to total compost age (*CA*) and the mean TN content was 9.66 ± 0.64 g TN/kg DM. However, the conversion of total ammoniacal nitrogen (TAN) to nitrate-N was observed as expected. The average TAN content fell linearly with respect to time and was not significantly different from zero at a total compost age of 369 days or greater.
- The organic-N in the finished compost was observed to increase significantly during storage indicating conversion of nitrogen to the organic form.
- The pH was observed to fall from an initial mean of 8.9 to 6.8 during storage providing evidence of formation of organic acids. This result provided additional evidence of biological activity during storage of finished compost.
- The concentrations of OM and C decreased significantly with respect to storage time and represented the greatest loss with regards to compost composition. Since the C content decreased and TN remained constant the C:N was observed to decrease with respect to storage time.
- The concentrations of K_2O and P_2O_5 and all of the measured minor plant nutrients (Ca, Mg, S, Zn, Cu, Mn, Fe), Na, and Al were not significantly impacted by storage time. The only significant differences in the concentrations of these elements were between individual windrows. These variations were believed to be the result of variations in the composition of the litter used to make the seven batches of compost in this study.
- The electrical conductivity of the seven windrows was not significantly correlated with respect to compost age. The mean EC was 3.80 ± 0.87 mmhos/cm.
- Two of the metals included in this study are regulated by US EPA (Zn, Cu) and the maximum concentrations observed were well below the allowable monthly average concentration limits.
- The physical property of compost that was the most affected by storage time was the dry bulk density which significantly increased with respect to compost age.

The current case study was limited to a single compost production facility, and only one type of compost product made from only two ingredients, namely turkey manure and wood shavings. Additional work is needed to study the impact of storage time on compost composition for compost products made from different types of ingredients (i.e., food waste, yard waste, other manure types, etc.) and from other compost production facilities.

ACKNOWLEDGMENTS

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