VERMICOMPOSTING OF POULTRY LITTER

USING EISENIA FOETIDA

By

ARBAB ASAD KHAN

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Thesis Approved:

Dr. D. W. Hamilton

Thesis Advisor

Dr. M. L. Stone

Dr. G. G. Wilber

A. Gordon Emslie

Dean of Graduate College

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Chapter I

Introduction

Poultry litter is usually applied as a fertilizer. Excessive land application of poultry litter can lead to surface water runoff of plant nutrients, which in turn can cause eutrophication of water reservoirs. Transportation of poultry litter out of the affected areas may decrease the negative environmental effects related to its land application; however, high transportation costs require adding value to poultry litter. Vermicomposting can potentially add value to poultry litter. Vermicomposting involves consumption and stabilization of organic matter by earthworms. Vermicomposting of poultry litter can not only produce value added fertilizer but it can also produce worms which could be sold as fish bait and a protein source. Although several studies have been conducted on vermicomposting, limited available data presents numerous challenges while vermicomposting poultry litter. High ammoniacal-nitrogen concentration, auto-heating, and high bulk density are some of the major concerns that need to be addressed while vermicomposting poultry litter.

This study investigated the effects of different parameters that might be necessary to successfully vermicompost poultry litter. Several experiments were conducted using *Eisenia foetida* (red wrigglers) to determine the optimal parameters. The study was divided into three phases. The first phase studied the effects of microbial pre-composting and pH adjustment of raw poultry litter on vermicomposting without adding any bulking agent. The second phase investigated the effects of carbon to nitrogen ratio (C/N ratio) by adding bulking material, microbial pre-composting and feeding frequency on vermicomposting. The third phase optimized C/N ratio for a given feeding frequency and pre-treatment method. The main objectives of this study were:

1. To study the effects of microbial pre-composting of raw poultry litter on earthworm biomass growth and volatile solids degradation,
2. To evaluate the effects of pH adjustment of raw poultry litter on earthworm biomass growth and volatile solids degradation,
3. To study the effects of C/N ratio on earthworm biomass growth and volatile solids degradation, and
4. To investigate the effects of feeding frequency on earthworm biomass growth and volatile solids degradation.

Chapter II

Overview of Poultry Industry

Industry Structure and Economics

The poultry industry is divided into three major sectors: (1) Layers and Eggs, (2) Broilers, and (3) Turkeys. Over the last few decades, the poultry industry has experienced tremendous growth; however, broiler sector has been the most dominant. Therefore, this study primarily focuses on the litter production by the broiler facilities.

Over the last few decades, production of broilers has been on a constant rise. During the 50 year period of 1956 to 2005, broiler production in the United States of America increased almost 20 times the increase in cattle production and almost 10 times the increase in hog production (Figure 1). During the same period, the broiler industry had 700% increase in production value, while the hog and the cattle industries had 300% and 500% increase in the production value, respectively. Figure 2 shows the production value trends for different livestock industries for the last 55 years.

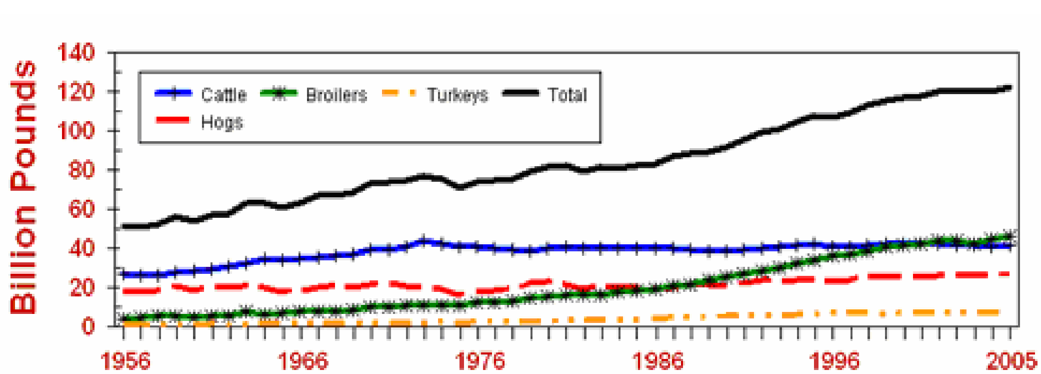

Figure 1. Cattle, hog, and broiler production, 1945—2001(from USAD-NASS, 2007)

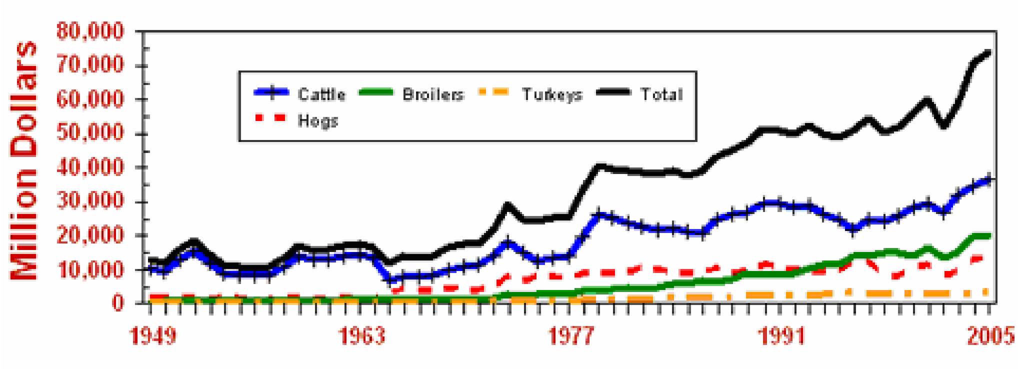

Figure 2. Cattle, hog, and broiler production value, 1948—2005 (from USDA-NASS, 2007)

Broiler Production Facilities

Broiler production, as it is practiced on the commercial scale, is an integrated enterprise. Broiler farms are provided with hatched chicks, usually delivered on the day of hatch, after which each flock is grown for 6-7 weeks, and an average of 5-6 flocks are grown per year.

The size of a broiler house can vary. According to Fairchild (2005), average size of a broiler house is 16,000 square foot with a capacity for 20,000 birds. Therefore, a typical broiler house of 20,000 birds with 5-6 flocks grown per year can produce up to 100,000 to 120,000 birds per year.

Litter Production and Characteristics

The clean out of a broiler house depends on the farmer, the concentration of birds per area, and the location of the broiler house. Typically, litter is cleaned out of a broiler house after one year of production cycle. The amount of litter produced by a broiler house also depends on several factors, such as broiler house location, feed type, climate, etc. Dozier et al. (2001) reports 80 tons of litter per year for a broiler house with 20,000 birds and 5-6 flocks per year. Rasnake (1996) reports an average amount 140 to 150 tons of litter per broiler house per year.

The nutrient content of poultry litter depends on several factors, such as type of beddings, clean out frequency, and number of birds per area. The major nutrients reported by Lorry (2006) for poultry litter are given in Table 1.

Table 1. Estimated range of nutrient concentration in selected types of poultry litter (pounds per wet ton) obtained from J.A. Lory

Litter Type	Total Nitrogen	Ammonia Nitrogen	Phosphate	Potassium
Broiler Clean-out	45 to 70	8 to 20	50 to 80	35 to 75
Broiler Cake-out	40 to 60	5 to 15	50 to 80	45 to 90
Broiler Breeders	20 to 50	5 to 15	40 to 70	40 to 70

Environmental Concerns

In 2005, the state of Oklahoma produced 2.5 billion broilers, with the majority of the production in eastern Oklahoma (USDA-NASS, 2007). Figure 3 shows the concentration of broiler farms in Oklahoma.

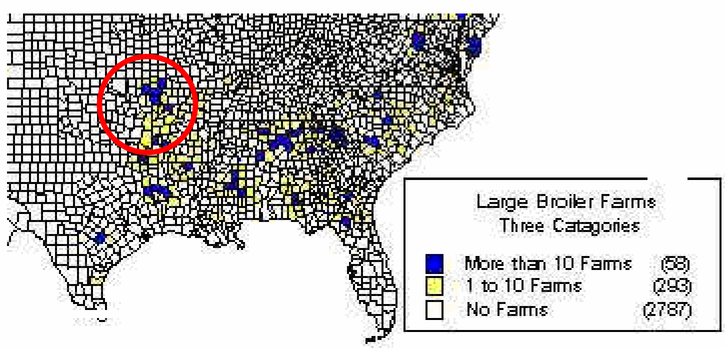

Figure 3. Concentration of poultry farms (modified from Molnary et al., 1997)

Poultry litter is rich in plant nutriments, such as nitrogen and phosphorus, making it an excellent fertilizer. Poultry farmers usually apply litter to their own crops or sometime sell it to other farmers. According to a report by Donald Stotts (2005), poultry farmers are currently being paid an average of $2 per ton of litter. Stotts also reports that haulers in Oklahoma are currently receiving an average of 2.6 cents per ton-litter per loaded mile, up to $8 per ton for 308 miles or more.

Poultry litter has average nitrogen to phosphorus ratio of 1.0. This ratio is fairly small as compared to the required nitrogen to phosphorus ratio of 2.4 to 3.9 for most corps. The high demand of nitrogen leads to excessive or misapplication of poultry litter which can cause build up of phosphorus. The surface water runoff and leaching of the excess phosphorus can cause eutrophication of water reservoirs. The eutrophication process leads to excess algal growth which in turn causes high biochemical oxygen demand, bad order, and bad taste of water (Blackstock, 2003).

A report by Blackstock (2003) showed the effects of litter application on phosphorus build up for two water reservoirs in Oklahoma, Lake Sapvinaw and Lake Eucha. He found that the median phosphorus concentration of Lake Sapvinaw and Lake Eucha to be three and ten times higher, respectively, than the concentration predicted by OWRB (Oklahoma Water Resource Board). A similar study by Storm et al. (2001) indicated the majority of phosphorus in Lake Eucha was due to the non-point sources (litter land application). Figure 4 shows phosphorus contribution by different sources (Storm et al., 2001).

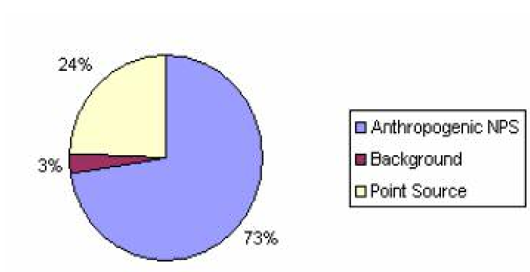

Figure 4. Phosphorus contribution due to different sources (modified from Storm et al., 2001)

Due to the eutrophication concerns, state and federal governments have decided to take several initiatives to move poultry litter out of the watershed sensitive areas. For example, in Oklahoma under EQIP (Environmental Quality Incentive Program), farmers are receiving \$2 to \$10 (depending on distance) in tax credit to transport litter out of the watershed sensitive areas and buyers of poultry litter are receiving \$5 per ton tax credit for litter purchased and transported out of the watershed sensitive areas (Stotts, 2005).

Chapter III

Literature Review of Vermicomposting

The degradation and stabilization of organic material by earthworms is known as vermicomposting (Dominguez et al., 2000; Edwards, 1995; Ndegwa and Thomson, 2000; Ndegwa et al., 2000). *Eisenia foetida,* also known as red wrigglers, and *Eisenia andrei* are two of the most common earthworms used for vermicomposting. In addition to earthworms, vermicomposting also includes micro-organisms; however, earthworms are the major contributors (Dominguez et al., 2003).

Breeding Methods

There are several types and designs of vermicomposting metods; however, most of them fall into two basic groups: the bin method, and the windrow method.

Bin Method

Bins are used for small scales vermicomposting process. Vermicomposting bins are usually constructed from non-aromatic wood or suitable plastic containers. Bottom of the bins include several holes for drainage. Top of the bins are usually covered by porous material, such a burlap sack, to provide aeration and prevent moisture loss. A layer of bedding, lining the bottom is placed in the bin. Worms are placed in the beddings and feed is continuously added on top of the beddings in small amounts, usually less than 10 cm at a time. Vermicomposting based on bin method is usually performed indoors which makes it easier to avoid harsh environmental conditions (Sherman, 2002). There are several commercially available vermicomposting bins, ranging in different size and price.

Windrow Method

Windrows are usually used for large scale vermicomposting process. Windrows are generally built outdoors on a concrete sloped surface to drain water and avoid pests. A typical height of a windrow is three feet or less and distance between each windrow is no more than twenty feet (Sherman, 2002). Windrow vermicomposting can be carried out in several different ways; however, static pile or batch windrow vermicomposting is the most common. In static pile windrow vermicomposting large amount of organic material mixed with bedding is provided to worms. Then, vermicomposting is performed until the entire feed is consumed.

Food Processing

A variety of wastes can be used as a feed substrate for vermicomposting. Generally, these wastes can be divided into three main classes: (1) animal wastes, (2) plant wastes, and (3) urban wastes (Gunadi and Edwards, 2003). Wastes from animals such as cattle, ducks, horses, and sheep have been used for vermicomposting. Plant wastes include composted and non-composted grasses, tree prunings, river weeds, potato wastes, and vegetable wastes. Urban wastes include municipal solid waste, aerated biosolids, paper sludge, etc (Gunadi and Edwards, 2003).

The rate of food/waste processed by earthworms depends on the breeding environment, the type of food/waste, and the type of earthworms used for vermicomposting. For example, *Eisenia foetida* with biosolids as a feed substrate can process 75% of their body weight per day (Ndegwa et al., 2000). Hartenstein and

Hartenstein (1981) showed that earthworms can consume 0.8 kg-biosolids/(kg-worms * day).

Digestion System

Worms intake food through their mouths. The food is then transferred to gizzard and intestines where breakdown of the particles occurs. The breakdown of food takes place through the physical grinding of gizzards and by the micro-organisms present in gizzards and intestines. Worms uptake the nutrients necessary for their growth and excrete the waste through the anus (Edwards, 1995).

Breeding Conditions

Several studies have been conducted to determine optimal conditions for a successful vermicomposting process. Physical and chemical conditions such as moisture content, feed type, temperature, light, pH, electrical conductivity, ammonia concentration, C/N ratio, feeding rate, stocking density, and bulking material need to be considered to perform successful vermicomposting.

Moisture content

Moisture content plays an important role in the growth of earthworms. Low moisture content can significantly affect earthworm survivability and reproduction (Wever et al., 2001). Dominguez and Edwards (1997) observed almost two times the individual biomass increase by increasing the moisture content of pig manure fed to worms from 65% to 85%. Moisture preference of earthworms varies for different feed substrate. Reinecke and Venter (1987) recommend a moisture content of 65% to 70% for using cow manure for vermicomposting. Ndegwa and Thomson (2000) and Ndegwa et al. (2000) used moisture content of 75% for vermicomposting of biosolids.

Temperature

Temperature can also affect earthworm growth and reproduction (Wever et al., 2001). A temperature range of 15 ^{0}C to 20 ^{0}C is considered to be optimum for vermicomposting (Wever et al., 2001). Edwards (1998) showed *Eisenia foetida* to grow significantly better when vermicomposting was performed at 15 ^{0}C and 20 ^{0}C as compared to 10 ^{0}C.

Light

Composting worms prefer dark environment. They move away from light towards darkness. The dislike of earthworms for light is one of the properties used to separate earthworms from vermicastings.

C/N ratio

Carbon and nitrogen are two primary nutrients required for cell growth; therefore, an optimal carbon to nitrogen ratio is necessary for a successful vermicomposting process. There is not a fixed C/N ratio for vermicomposting. The optimal C/N ratio depends on the type of feed substrate, the species of earthworm, and the desired final product (stabilization of feed or earthworm production). Ndegwa and Thomson (2000) found that decreasing C/N ratio increased earthworm biomass production, while increasing C/N ratio produced a more stable end-product. Ndegwa recommended a C/N ratio of 25 for the production of stable vermicompost and a C/N ratio of 10 for the earthworm breeding using biosolids as a feed substrate. Contrary to Ndegwa, Aira et al.

(2006) showed that earthworm biomass increased as C/N ratio increased when pig slurry was used as a feed substrate. Aira (2006) showed the number of earthworms to increase 5.5 times as C/N ratio increased from 11 to 19.

Ammoniacal Nitrogen (Total Ammonia)

Ammoniacal nitrogen, also known as total ammonia, is considered toxic to earthworms. Typically, ammoniacal-N refers to a sum of free ammonia (NH_3) and ammonium (NH_4^+). NH_3 is a gaseous chemical whereas NH_4^+ is an ionized form and remains soluble in liquid. Earthworms can excrete NH_4^+ through special excretory organs known as nephridia; however, the exchange of gaseous materials in earthworms mainly takes place through skin via diffusion (Edwards, 1996). If NH_3 concentration in the surrounding environment is higher than the NH_3 concentration in the skin cells, earthworms cannot diffuse NH_3 out of their body, which can cause toxificatoin. Edwards (1996, 1998) recommended total ammonia concentration of 500 mg/kg or less for successful vermicomposting.

Pre-microbial composting

Microbial composting includes the degradation of organic matter by micro-organisms such as bacteria. Compost is considered stable when reheating upon mixing stops and the microbial activity decreases. Several parameters such as C/N ratio, volatile solids, temperature trend, and respiration rate, can be used to measure compost stability.

A number of authors have reported on improvement of vermicomposting process when feed was microbially composted prior to vermicomposting (Gunadi et al 2002; Nair, et al., 2006). Microbial pre-composting can decrease the concentration of ammoniacal-N which can be toxic to earthworms. Gunadi et al. (2002) tested the effects of microbial pre-composting of cattle solids on vermicomposting. They observed a decrease in ammoniacal-N concentration from 15.9 mg/kg to 5.4 mg/kg after three weeks of microbial composting. They also found the lowest earthworm mortality for the feed that was pre-composted for one week.

In addition to decreasing ammoniacal-N concentration, microbial pre-composting can also decrease auto-heating capability of feed/waste used for vermicomposting. This can eliminate the danger of high temperatures during vermicomposting.

pH

Kaplan et al. (1980) determined an optimal pH range of 5 to 8 for vermicomposting of activate sludge. He found 100% earthworm mortality for feed with pH values smaller than 5 and greater than 8. The pH of feed plays an important role in vermicomposting, especially if the feed contains high ammoniacal nitrogen. According to Blake and Hess (2001), the typical pH of broiler litter ranges between 9 and 10. NH_3 exists in equilibrium with NH_4^+, at pH 9-10, NH_3 concentration dominates and ranges between 35% and 80%. At a pH of 7.2 or below, majority of NH_3 changes to NH_4^+; therefore, decreasing the pH of a feed below 7.2 can decreases the amount of NH_3. Figure 5 shows the dependence of ammonia and ammonium on pH.

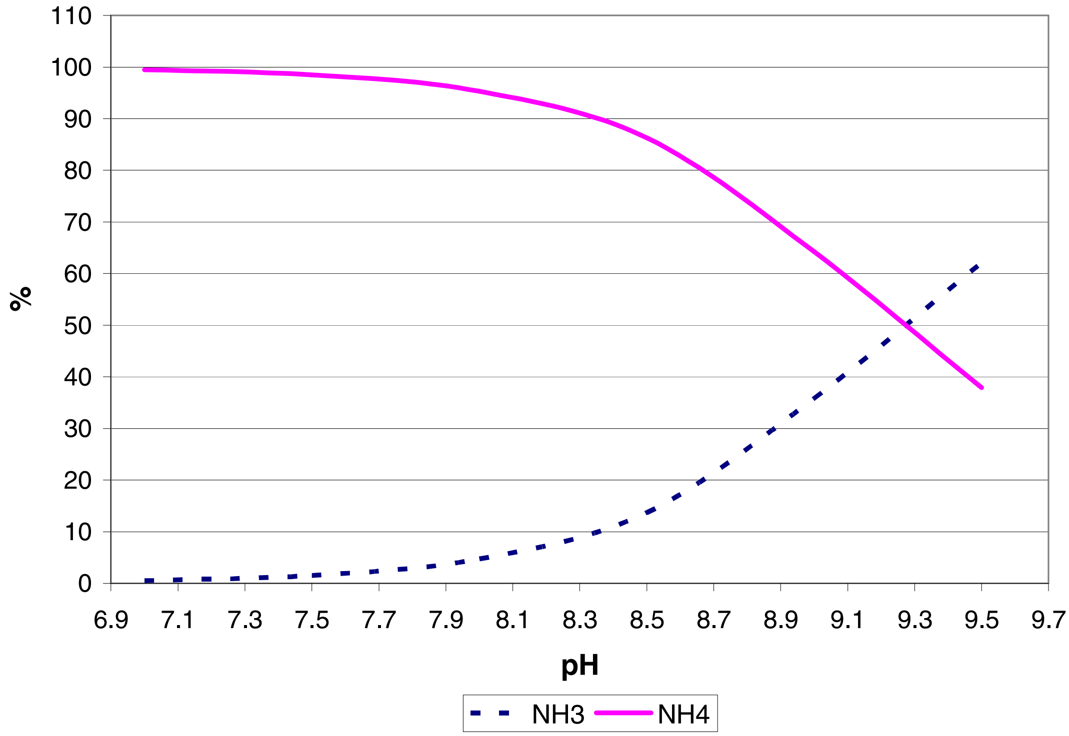

Figure 5. pH equilibrium curve for NH_3 and NH_4^+

Feeding rate and stocking density

The amount of feed provided to earthworms over a given period of time is known as feeding rate, while the amount of worms added per area is known as stocking density. Feeding rate and stocking density of earthworms depend on a desired objective. For example, a high stocking density and low feed rate is recommended if the desired objective is to produce stable vermicomposted material, while low stocking density and high feeding rate is recommended if the desired objective is to increase earthworm biomass (Ndegwa, et al., 2000). Feeding rate and stocking density also depends on a type of feed substrate and species of earthworms. Ndegwa et al. (2000) recommend a stocking density of 1.6 kg-worms/m^2 and feed rate of 0.75 kg-feed/kg-worms-day for vermicomposting of biosolids using *Eisenia foetida*. Neuhauser et al. (1980), recommended an optimum stocking density of 2.95 kg-worms/m^2 for activated sludge and 0.77 kg -worms/m^2 for horse manure when unlimited feed was supplied to earthworms.

Bulking Materials

Feed substrates such as animal manure, biosolids, and paper sludge are dense and require bulking material, such as shredded paper, straw, and peat moss, for aeration and bulking purposes. Dominguez et al. (2000) showed higher growth rate of earthworms when fed a mixture of sewage sludge and paper as compared to the sewage sludge by it self.

Vermicompost Properties

Vermicompost obtained from most of the organic materials is finely-shredded, peat-like material with excellent porosity, aeration, drainage, and water-holding capacity (Edwards, 1995, 1998). Edwards also explained that vermicompost may contain hormones, soil enzymes, and high microbial populating which can significantly increase plant growth. The above properties make vermicompost an excellent horticultural media. Atiyeh et al. (2000a,b) showed a significant increase in margigold and tomato plants when a traditional potting media was mixed with vermicomposted pig solids and food wastes. Arancon et al. (2005), showed a noticeable increase in pepper plant leaf area, shoot biomass, and marketable fruit weights when vermicomposted food waste was used as a fertilizer.

Vermicomposting Economics

Since it is an excellent horticultural media, the demand for vermicompost has been constantly rising. Vermicompost can be easily sold for $30 to $ 40 per cubic yard

(Edwards, 1995). In some cases vermicompost has been marketed for up to $120 per cubic yard (Edwards, 1995). Online stores, such as vermiculture.com, are currently selling vermicompost for $1.5/lb, $3000/ton.

The production of earthworms is another marketable product of vermicomposting. Vermicomposters are currently selling earthworms as fishing baits and protein source. Online stores, such as wormswrangler.com, vermiculture.com and topline-worms.com are currently selling composting worms, such as *Eisenia foetida*, for $15/lb to $25/lb.

Chapter IV

Problem Statement

What conditions are necessary to successfully vermicompost poultry litter? Does poultry litter need to be microbially pre-composted for successful vermicomposting? Does C/N ratio of poultry litter need to be adjusted for successful vermicomposting? What kind of feeding frequency should be used for vermicomposting of poultry litter?

In the past, vermicomposting has been performed using cow, pig, and horse manure, feedlot wastes, food wastes, and plant wastes. Vermicomposting has also been performed on a mixture of feeds mentioned above (Gunadi and Edwards, 2003; Edwards, 1996; Edwards, 1998). However, researchers and vermicomposters have avoided using pure poultry litter as a feed substrate due to its high ammonia content, high density, and auto-heating capability. Edwards (1996, 1998) recommended pre-treatment of poultry litter prior to vermicomposting.

Edwards (1996, 1998) recommended total ammoniacal-N concentration of 500 mg/kg or less for vermicomposting. Gunadi et al. (2002) studied the effects of microbial pre-composting of cattle solids on vermicomposting. They showed a decrease in ammoniacal-N concentration from 15.9 mg/kg to 5.4 mg/kg after three weeks of microbial composting. Gunadi showed the lowest earthworm mortality of 0% for cattle solids pre-composted for one week; however, the mortality rate increased up to 47% for cattle solids pre-composted for three weeks. Gunadi could not show or establish a relationship between ammoniacal-N concentration and earthworm growth because all of the feed substrates used in his study had ammoniacal-N concentration lower than the recommended toxic concentration of 500 mg/kg (Edwards, 1996, 1998). Also, there were no significant trends for the mortality of earthworms with respect to the ammoniacal concentration. In poultry litter, where ammoniacal-N concentration ranges from 4,000 to 10,000 (mg/kg), microbial composting prior to vermicomposting, may enhance earthworm growth by decreasing total ammoniacal-N concentration.

Previous authors studied the effects of ammoniacal-N concentration on earthworm reproduction; however there is no published data available regarding the reduction of NH_3 by pH adjustment. By adjusting the pH value of the poultry litter to near neutral, 7.0 to 7.25, NH_3 concentration could be decreased to 0% to 1%. Since there is no published data available regarding the effects of pH adjustment of feed on earthworm growth, it will be advantageous to study the effects of pH adjustment of poultry litter on the vermicomposting process.

Bulking material plays an important role in vermicomposting. Shredded paper, shredded cardboard, straw, and peat moss are some of the bulking materials that have been used for vermicomposting. Generally, bulking materials cost significantly higher than the main feed substrate used for vermicomposting; therefore, optimizing the amount of bulking material can enhance vermicomposting economics. Several authors have studied the effects of bulking materials on vermicomposting qualitatively; however, there is a lack of quantative data. For example, Dominguez et al. (2000) showed a 600 fold increase in earthworm cocoon production when fed a mixture of sewage sludge and paper as compared to the sewage sludge by it self; however, they did not quantify the amount of bulking material used for vermicomposting. Also, different feed substrates, depending on particle size and density, may require different amounts of bulking material. There is no published data regarding the amount of bulking material used for vermicomposting of poultry litter; therefore, it is necessary to quantify the effects of bulking material on vermicomposting of poultry litter.

The adjustment of C/N ratio plays an important role in successful vermicomposting. Optimal C/N ratio can enhance cell production and earthworm biomass; however, different feed substrates have different physical and chemical properties and require different C/N ratio for successful vermicomposting. Edwards and Bohlen (1996) observed that the amount of material processed by earthworms depends on suitable organic matter of a feed substrate. Ndegwa and Thomson (2000) conducted a study on the effects of C/N ratio on vermicomposting of biosolids. The optimal C/N ratios recommended by Ndegwa and Thomson cannot be used for vermicomposting of poultry litter because poultry litter has different physical as well as chemical properties as compared to biosolids. Therefore, it is necessary to quantify and optimize C/N ratio for vermicomposting of poultry litter.

Chapter V

Effects of Microbial Pre-composting and pH Adjustment of Poultry Litter on Vermicomposting

Objective

To determine the effects of microbial pre-composting and pH adjustment of poultry litter on earthworm biomass growth and vermicompost quality

Materials and Methods

Experimental Setup

The experiment was performed as a completely randomized design with four main factors and four replications per main factor. The four main factors were raw poultry litter, hot composted poultry litter, cured composted poultry litter, and pH adjusted poultry litter. Each test bin was considered a single replication. The two response variables were: (%) earthworm biomass change, and (%) volatile solids change.

Worm Culture

Purchased worms (*Eisenia foetida*) were continuously multiplied in the breeding bins by using shredded office paper and horse manure. Worm breeding bins were constructed using untreated and non-aromatic plywood. A total of six breeding bins, each measuring 1m x 1m x 0.5m (L x W x H), were constructed. Each breeding bin was stocked with 1.6 kg-worms/m^2 and fed at 0.75 kg-feed/kg-worm-day, optimal parameters determined by Ndegwa et al. (2000). Worms from the breeding bins were used to carry out the main experiment.

Test Bins

Test bins were constructed from commercially available plastic containers. The test bins measured 22.5” x 15.5” x 12” (L x W x H). This provided an open surface area of 0.22 m^2. Eleven ½ inch holes were drilled in the bottom and the sides of the bins for drainage and aeration. Plastic trays were placed under the test bins to collect any liquid (tea) that seeped out. Each test bins was filled with 4 lb of shredded paper bedding. Earthworms were placed in a corner of a test bin. Moisture content of each litter type was adjusted close to 70% and placed on top of the paper bedding.

Each test bin had an earthworm (*Eisenia foetida*) live biomass loading of 0.35 kg-worms corresponding to a stocking density of 1.6kg-worms/m^2 (Ndegwa et al., 2000) and feeding rate of 0.12 kg-VS/kg-worm-day

All the test bins were fed weekly for the first seven weeks. The experiment was terminated at the end of eight weeks after which worms were separated from the vermicompost. Eight weeks experimental time was chosen to coincide with an approximate generation time of *Eisenia foetida* (Hartenstein and Hartenstein, 1981; Gaddie and Douglas, 1977; Ndegwa et al., 2000b). Test bins were kept in a dark, constant temperature room at 70 ^{0}F. Each test bin was sprinkled daily with water to keep the feed wet.

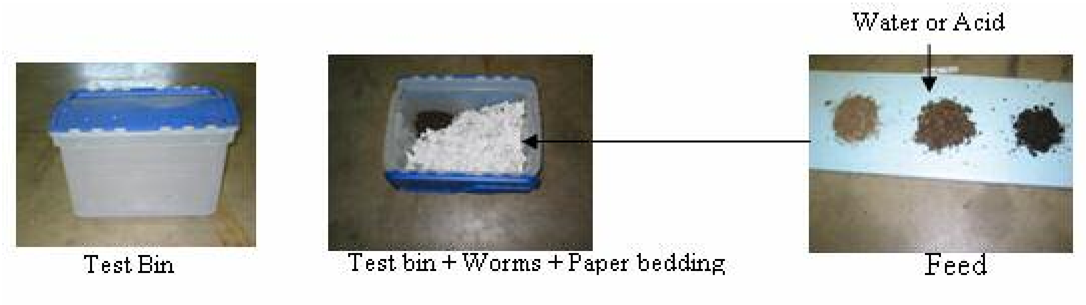

Figure 6. Feeding description for test bins

Chemical Analysis

Feed substrates were analyzed for the following parameters: moisture content, total solids, volatile solids, pH, total kjeldahl nitrogen (TKN), ammoniacal nitrogen, ortho-phosphate, total phosphorus, respiration rate and germination index.

Solid matter and moisture content were determined by drying samples at 103 ^{0}C for 18-24 h. Volatile solids were obtained by ashing at 550 ^{0}C for 2.0 hr (USCC-3.02, 2002). pH was determined potentiometrically in 1:10 suspension of sample in de-ionized water (Page et al., 2002). TKN was determined using macro-Kjeldahl method (APHA-4500-N, 1998) and FOSS Kjeltec^{TM} 2400 nitrogen analyzer. A 2 molar KCl extraction (Recommended Methods of Manure Analysis, 2002) was analyzed for ammoniacal-nitrogen by using Phenate method (APHA-4500-NH_3, 1998). KCl extract was obtained from "As Is" sample by making 1:60 solids to KCl solution. Total phosphorus was determined using nitric-acid/hydrogen-peroxide digestion (Recommended Methods of Manure Analysis, 2002) and ascorbic acid colorimetric method (APHA-4500-P E, 1998). Ortho-phosphate was determined from a mixture of 4 g dried grounded sample in 60 ml of de-ionized water and using the ascorbic acid colorimetric method (APHA-4500-P E, 1998). Electrical conductance of 1:5 compost/water was determined by using YSI 30 conductivity meter.

Respiration rate was measured using method 5.08 described by USCC (2002) and using BI-2000® respirometer. Before measuring respiration rate, each sample was incubated for 48 hr at 34 ^{0}C. For incubation, each sample was placed in a perforated Ziploc® bag and covered by semi-wet cotton cloth to avoid any moisture loss. The BI-2000® respirometer measured the respiration rate in terms of oxygen uptake rate for at least three hours.

Germination index, a measure of phytotoxicity, was measured using method 5.05 described by USCC (2002). Cucumber seeds were used to measure the germination index. Ten cucumber seeds were germinated in a Petri-dish for a period of seven days. For each sample, one Petri-dishes was used. De-ionized water was used a control for measuring the germination index. The following equation was used to measure the germination index.

$$GI = \left(\frac{A}{B}\right) * \left(\frac{C}{D}\right) * 100 \qquad (1)$$

Where,

GI = Germination Index

A = Average number of seeds germinated for a given sample

B = Average number of seeds germinated for de-ionized water

C = Average root elongation for a given sample

D = Average root elongation for de-ionized water

Feedstocks Preparation

Raw litter was obtained from a commercial broiler facility near Poteau, Oklahoma. The raw litter was divided into three lots. One of the lots was immediately frozen to avoid any microbial activity; the remaining two were used to perform microbial pre-composting to obtain hot composted poultry litter and cured composted poultry litter.

Two reactors, each with a capacity of 60 L, were constructed to carry out microbial pre-composting. Each reactor was instrumented with a thermocouple and a data logger to monitor temperature trends. Each thermocouple was connected to a temperature control unit which in turn was connected to an actuator and a baffle. All the reactors were connected to a fan that provided a source of aeration to control temperature This setup allowed the fan to automatically turn on when temperature in the rectors moved above 65 ^{0}C. Figure 7 shows the reactor setup used to achieve microbial pre-composting.

Figure 7. Reactor setup for microbial pre-composting

Microbial composting was achieved by a combination thermophilic and mesophilic bacterial activity. Hot composted poultry litter resulted due to thermophilic bacterial activity, while cured compost was a product of thermophilic decomposition followed by mesophilic decomposition. Each reactor was automated to prevent temperature rising above 75 ^{0}C and maintain an optimum temperature range of 55 ^{0}C to 65 ^{0}C during hot composting (Metcalf and Eddy, 2003). Respiration rate of chicken litter in the reactors was measured during the microbial composting to determine compost maturity. Chicken litter was considered to be hot composted when a respiration rate of 19 mg-O_2/(g-VS*day) was achieved. Raw litter was composted for 16 days to obtain hot composted poultry litter. Cured poultry litter was obtained after 50 days of microbial composting. Cured litter had a final respiration rate of 12 mg-O_2/(g-VS*day). Figure 8 shows the temperature trends during microbial composting of raw poultry litter.

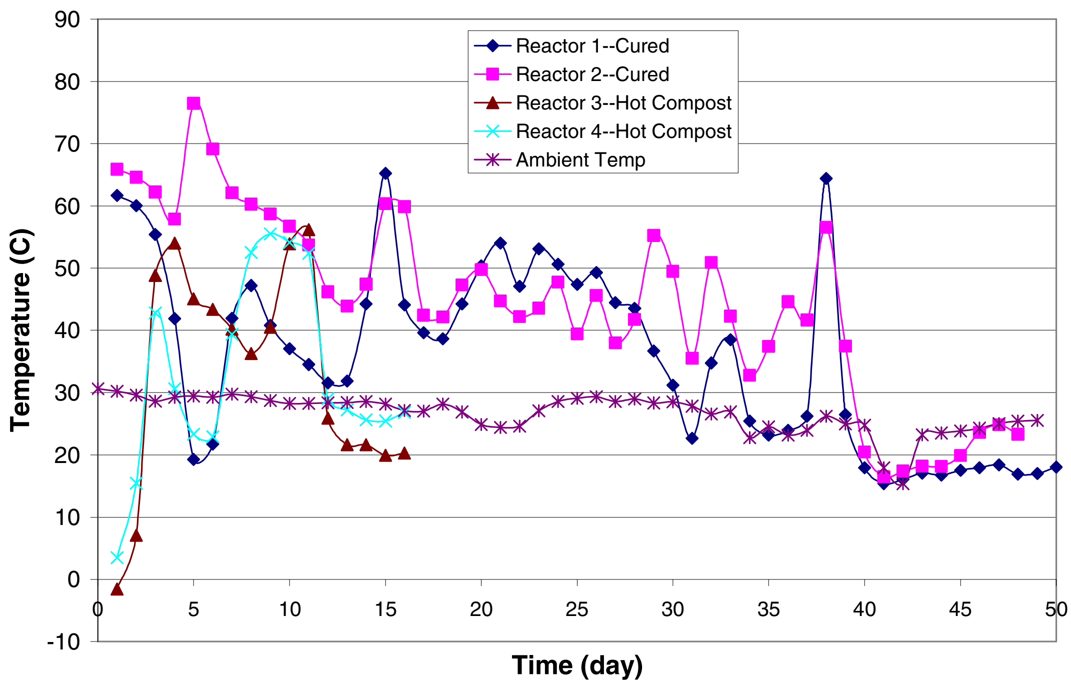

Figure 8. Temperature trends during microbial pre-composting

The frozen lot was thawed and divided between raw and pH adjusted treatments. The pH of the raw litter was adjusted close to neutral (7.0) by using 0.1N H_2SO_4. Measured feedstock parameters are listed in Table 2. Characteristics for the pH adjusted raw poultry litter were considered to be the same as raw poultry litter, except for the pH and ammonia values.

Table 2. Feed substrate properties---Phase I

	RL		pH		HC		CC	
	$\bar{X}$	Std	$\bar{X}$	Std	$\bar{X}$	Std	$\bar{X}$	Std
Moisture Content (%, wb)	32	0.27	32	0.27	38	1.2	37	2.1
Volatile Solids (%, db)	68	0.56	68	0.56	60	0.54	57	4.7
TKN (mg/kg, db)	43,000	1,800	43,000	1,800	40,000	1,000	41,500	5100
Ammoniacal-N (mg/kg, db)	2,625	260	2,625	250	2,315	185	720	100
NH_3-N (mg/kg, db)	363	*	15	*	720	*	285	*
NH_4^+-N (mg/kg, db)	2,262	*	2,610	*	1,595	*	435	*
Total Phosphorus (mg/kg, db)	23,000	970	23,000	970	21,000	1,100	20,000	970
Ortho-Phosphate (mg/kg, db)	4,300	230	4,300	230	4,000	180	3,700	450
pH	8.45	0.02	7	0.26	8.9	0.18	9.06	0.09
EC	17.5	0.5			16.81	0.2	15.77	0.6
Respiration Rate (mgO2/gVS*day)	37	3	2.8		19	0.3	12	1.6
GI (%)	0	0	0	0	0	0	0	0

Std = Standard deviationRL = Raw poultry litter, pH = pH adjusted poultry litter, HC = Hot composted poultry litter, CC = Cured composted poultry litter, NH_3 and NH_4value for pH adjusted poultry litter were based on NH_3/NH_4^+ equilibrium curve

Results and Discussion

A few days after starting the experiment, worms started to crawl out of all the test bins, and the earthworms that stayed in the test bins never moved into the feed substrate. About seven days into the experiment all the worms remaining in the test bins died, leading to 100% mortality. Since there was no movement of earthworms into the feed substrate, the final product could not be qualified as a vermicompost. No chemical analyses were performed on the material left in the test bins.

Hot composted and cured composted poultry litter had significantly lower ammoniacal-N concentration than the raw poultry litter (Figure 9); however, the ammoniacal-N concentration was still higher than the recommended toxic amount of 500 mg/kg (Edwards, 1998). The high amount of ammoniacal-N could have resulted in earthworm mortality.

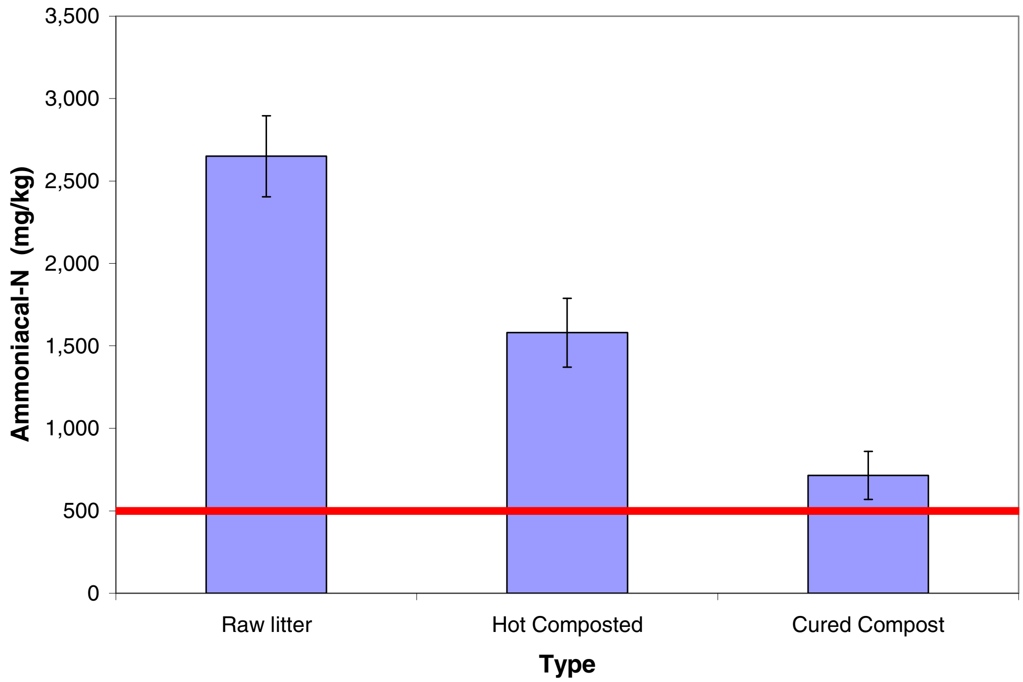

Figure 9. Ammonia concentration for raw and composted poultry litter

The pH adjusted raw poultry litter had an initial pH value of 7.0. At this pH, NH_3 concentration was significantly reduced (Table 2); however, the earthworm mortality was still 100%. This finding showed that the earthworm growth, and in turn vermicomposting, is not solely a function of NH_3 concentration of a poultry litter. To perform successful vermicomposting, the concentration of ammoniacal-N, not just NH_3, needs to be reduced.

Low bulking material in feed substrates can be another cause for the failure of this experiment. Previous studies showed that mixing feed substrates with materials that have low bulk density can significantly enhance vermicomposting process. Dominguez et al. (2000) showed earthworm cocoon production to be 600 times higher when fed a mixture of sewage sludge and paper than sewage sludge by itself.

Conclusions

Vermicomposting of poultry litter cannot be achieved by performing microbial pre-composting or pH adjustment. Microbial pre-composting significantly decreased the amount of ammoniacal-N; however, it was still higher than the toxic amount of 500 (mg/kg). The effects of other parameters such as the addition of bulking material and adjustment of carbon-to-nitrogen ratio (C/N) on vermicomposting of poultry litter should also be analyzed. Materials such as shredded paper, straw, and peat moss have high amounts of carbon, low total nitrogen, low ammoniacal-N, and low bulk density. The addition of materials, mentioned above, to poultry litter could increase C/N ratio, decrease ammoniacal-N, and enhance bulking capability.

Chapter VI

Effects of C/N ratio, Microbial Pre-composting, and Feeding Frequency on Vermicomposting

Objective

To investigate the effects of microbial pre-composting, carbon to nitrogen ratio, bulking material, and feeding frequency on vermicomposting of poultry litter.

Materials and Methods

Experimental Setup

The experiment was performed as a completely randomized design with 3*3*2 factorial arrangement of treatments and three replications per treatment. The three main factors investigated in this experiment were: C/N ratio, feed type, and feed rate. The feeds were adjusted for three C/N ratios: 50, 100, and 150. The feed consisted of raw poultry litter, microbially pre-composted poultry litter, and horse manure. Horse manure was used as a control because it is proven to be a good source of feed for vermicomposting (Card et al., 2006). The two feeding frequencies were 1/week (simulating bin method) and 1/8-weeks (simulating windrow method). The experiment was conducted for a total of eight weeks to coincide with the approximate generation time of *Eisenia foetida* (Hartenstein and Hartenstein, 1981; Gaddie and Douglas, 1977; Ndegwa et al., 2000). The total amount of feed over the eight weeks of experimental duration was the same for the two feeding frequencies. The response variable was the (%) earthworm biomass change. Equation 2 was used to calculate (%) earthworm biomass change for each test bin.

$$EBC\ (\%) = \left(\frac{FEB - FEB}{IEB} \right) * 100 \qquad (2)$$

Where,

EBC = Earthworm biomass change

IEB = Initial earthworm biomass

FEB = Final earthworm biomass

Worm Culture

Purchased worms, *Eisenia foetida*, were multiplied using horse manure as described in Chapter V.

Test Bins

Due to the higher number of treatments, the size of test bins was reduced to 500 ml plastic bottles. Each 500 ml bottle was considered an experimental unit with three experimental units per treatment. Several holes were drilled at the bottom of the plastic bottles for drainage and the top of each bottle was cut-off to enhance aeration. Each plastic bottle had an open surface area of 4.15 in^2 and earthworm biomass loading of 4.3 g corresponding to the optimal stocking density of 1.6 kg-worms/m^2. The feed rate was standardized so that each of the test bins, regardless of the treatment type, received the same amount of volatile solids. However, the total amount of feed and the feed rate for each of treatment varied (Table 4). Test bins were kept in a dark, constant temperature(70 ^{0}F) room for the entire duration of the experiment. Each test bin was sprinkled daily with water to keep the feed wet.

Chemical Analysis

Chemicals were analyzed by using the methods given in Chapter V.

Percent carbon was determined from the amount of volatile solids by using a formula given below (Adams et al., 1951):

$$\%\ Carbon = \frac{\%\ VS}{1.8} \qquad (3)$$

Where,

$$\%\ VS = 100 - \%\ Ash \qquad (4)$$

Preparation of Feedstocks

Raw poultry litter and hot composted poultry litter was used from the same batch as described in Chapter V. Horse manure was obtained from a horse barn at Oklahoma State University. Office paper was obtained from the paper recycling bins at Oklahoma State University. The office paper was shredded into smaller pieces by using Troy-Belt® chipper shredder. The initial physical and chemical properties of the feedstocks are listed in Table 3. Before every feeding, the moisture content of manure/litter was adjusted close to 70%. Manure was then mixed with wet shredded office paper and finally transferred to the test bins. This feeding method was slightly different than the one used in Chapter V where no initial mixing of paper and litter was performed. Each test bin, regardless of the feed type, was fed at 0.12 kg-volatile-solids/kg-worms-day. The C/N ratio for raw poultry litter, hot composted poultry litter, and horse manure was adjusted by adding shredded office paper. Equation 5 was used to adjust C/N ratio.

$$C/N_{mixture} = \frac{m_w\left(C_w * (100 - MC_w)\right) + m_p\left(C_p * (100 - MC_p)\right)}{m_w\left(N_w * (100 - MC_w)\right) + m_p\left(N_p * (100 - MC_p)\right)} \quad (5)$$

Where,

m_w = mass of waste ("as is", or "wet weight")

C_w = carbon (%) of waste

m_p = mass of paper

C_p = carbon (%) of paper

N_p = nitrogen (%) of paper

N_w = nitrogen (%) of waste

The amount of manure and paper used to achieve a certain C/N ratio is given in Table 4. Table 4 shows that the amount of paper in the feed mixture increases as C/N ratio increases. Also, horse manure initially had a C/N ratio of 50; hence no paper was added to horse manure to adjust C/N ratio to 50.

Table 3. Feed substrate properties---Phase II

	RL		HC		Paper		HM	
	$\bar{X}$	Std	$\bar{X}$	Std	$\bar{X}$	Std	$\bar{X}$	Std
Moisture Content (%, wb)	32	0.27	38	1.2	2	1	46	3.3
Volatile Solids (%, db)	68	0.56	60	0.54	84	1	91	0.3
TKN (mg/kg, db)	43,000	1,800	40,000	1,000	200	100	10,000	0.0
Ammonical-N (mg/kg, db)	2,625	260	2,315	185	-	-	70	1
Total Phosphorus (mg/kg, db)	23,000	970	21,000	1,100	-	-	14000	1200
Ortho-Phosphate (mg/kg, db)	4,300	230	4,000	180	-	-	840	225
pH	8.45	0.02	8.9	0.18	8.74	0.01	7.02	0.01
EC	17.5	0.5	16.81	0.2	-	-	3.55	0.56
Respiration Rate (mgO2/gVS*day)	37	3	19	0.3	*	*	98	7.09
GI (%)	0	0	0	0	*	*	*	*

"-" = Undetected, "*" = Not measured, $\bar{X}$ = Average, Std = Standard deviation
RL = Raw poultry litter, HC = Hot composted poultry litter, HM = Horse manure

Table 4. Total amount of feed, paper, manure and volatile solids fed to the test bins

C/N Ratio	Substrate	Manure (g, As Is)	Paper (g, As Is)	Total Feed (g-VS/Test-bin)	Total Feed (g, As Is)
50	RL	9.37	25.34	25.00	34.71
	HC	11.39	25.90	25.00	37.29
	HM	50.75	0.00	25.00	50.75
100	RL	4.73	27.83	25.00	32.56
	HC	5.63	28.16	25.00	33.79
	HM	24.74	15.56	25.00	40.30
150	RL	2.88	28.82	25.00	31.70
	HC	3.76	28.90	25.00	32.65
	HM	16.15	20.70	25.00	36.85

RL = Raw poultry litter, HC = Hot composted poultry litter, HM = Horse manure

Results and Discussion

Statistical Transformation

The (%) change in earthworm biomass was analyzed by using Analysis of Variance (ANOVA) and the computer program SAS®. To analyze the data by using ANOVA, the distribution of the data had to be normal with equal variances; however, the original data lacked both qualities. The problem was fixed by transforming the data as shown below:

$$Transformed\ data = \sqrt{(Percent\ Biomass\ Change + 100)} \qquad (6)$$

Change in Earthworm Biomass

The final earthworm biomass and the standard deviation of each treatment are given in Table 5. The standard deviation for most of the treatments was found to be quite high, showing the unpredictability of earthworm growth.

The significance of treatments was based on (%) earthworm biomass change. Figure 11 and 12 show the effects of C/N ratio and manure type at a given feeding frequency.

Table 6 gives the effects of feed type on percent biomass change at a constant frequency and C/N ratio. For the feeding frequency of 1/8-weeks, pre-composted poultry litter performed better than the other two treatments, except for C/N ratio of 150 where hot composted poultry litter and horse manure performed equally better. These trends show that at the feeding frequency of 1/8-weeks, raw poultry litter had to be microbially pre-composted to ensure earthworm survivability.

Table 5. Final average earthworm biomass and standard deviation

Feeding frequency = 1/week				Feeding frequency = 1/week			
Type	C/N	$\bar{x}$	Std	Type	C/N	$\bar{x}$	Std
RL	50	0.22	0.37	RL	50	1.05	1.14
RL	100	0.96	0.89	RL	100	15.03	4.01
RL	150	3.16	1.23	RL	150	6.50	3.37
HC	50	11.21	6.39	HC	50	4.06	2.69
HC	100	18.46	3.61	HC	100	10.71	5.95
HC	150	8.95	5.24	HC	150	8.37	1.71
HM	50	2.90	0.91	HM	50	6.61	4.73
HM	100	5.96	1.64	HM	100	71.18	6.17
HM	150	7.18	2.85	HM	150	-0.59	4.74

$\bar{x}$ = Average, Std = Standard deviation
RL = Raw poultry litter, HC = Hot composted poultry litter, HM = Horse manure

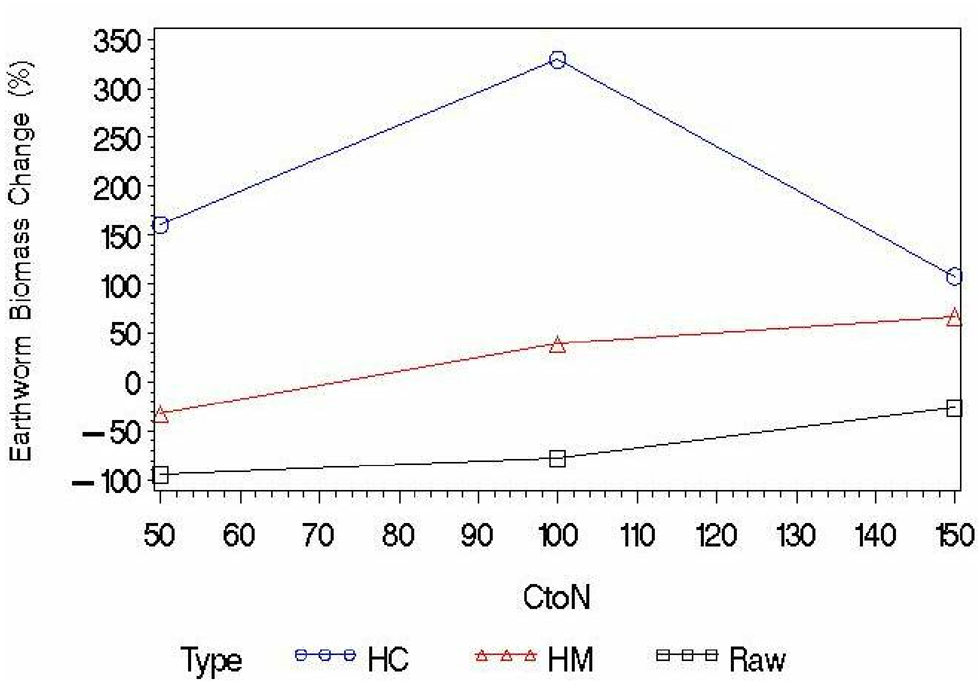

Figure 10. Trend analysis of average percent biomass change at frequency = 1/8-wks
RL = Raw chicken litter, PC = Hot composted manure, HM = Horse manure, C/N = C/N ratio, ,

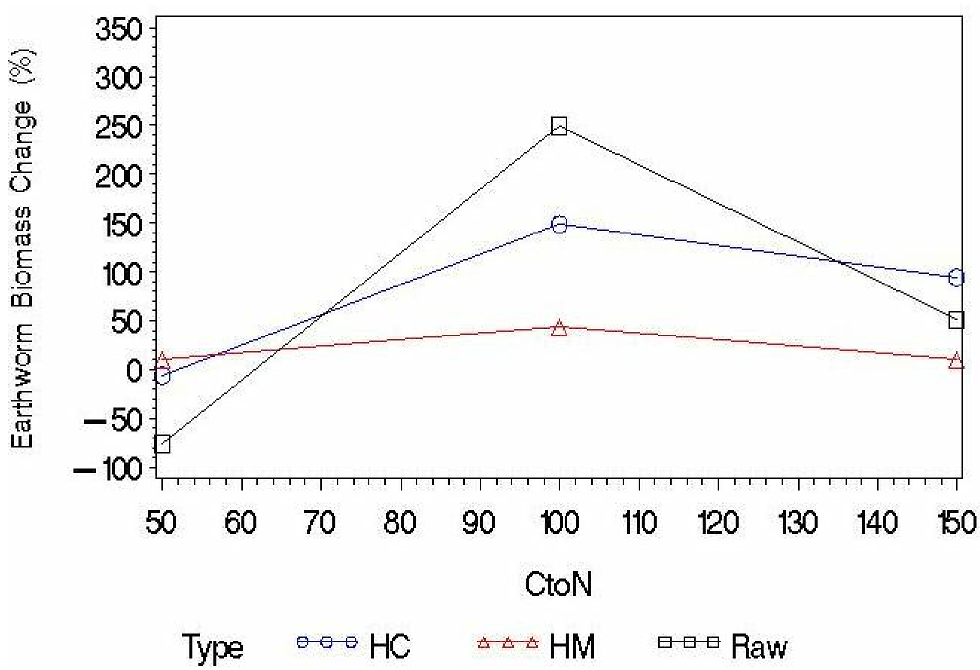

Figure 11. Trend analysis of average percent biomass change at frequency = 1/wk
RL = Raw chicken litter, PC = Hot composted manure, HM = Horse manure, C/N = C/N ratio

Table 4. Pair wise comparisons of biomass change (%): C/N ratio at a given feeding frequency and feed type (alphabets, horizontal), feed type at a given feeding frequency and C/N (numbers, vertical) at α = 0.05.

	Frequency = 1/week			Frequency = 1/8-weeks		
	C/N Ratio			C/N Ratio		
	50	100	150	50	100	150
	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$	$\bar{X}$
RL	-76a,1	249b,2	51a,4	-95e,5	-78e,7	-27f,10
HC	-5c,1	149c,2,3	95c,4	161f,6	329f,8	108f,10
HM	10d,1	43d,3	10d,4	-33g,5	39g,h,9	67h,11

HM = Horse manure, PC = Pre-composted manure, RL = Raw chicken litter

For feeding frequency of 1/week, an overall trend like 1/8-weeks was not observed. At the C/N of 50 and 150, there were no significant differences between the feed types. The only significant difference was observed at C/N of 100, where raw poultry litter and hot composted poultry litter performed significantly better as compared to the horse manure.

Adjusting C/N ratio played an important role in earthworm survivability. Although, there were not very many differences based on C/N ratio, there was a definite trend displayed, whereby earthworm biomass increased as C/N ratio increased from 50 to 100. These findings were similar to the study by Aira et al. (2006), who showed that the number of earthworms increased by 5.5 times when C/N ratio for pig slurries was increased from 11 to 19. However, most of the treatments reached a maximum earthworm growth at C/N ratio of 100 and increasing C/N ratio to 150 did not change or lowered earthworm biomass growth as compared to C/N ratio of 100.

Conclusion

Regardless of the feed type and the feeding frequency, there needs to be a sufficient amount of bulking material to successfully vermicompost poultry litter. In Chapter V, vermicomposting was performed with out any bulking material, resulting in 100% mortality. However, in this experiment, none of the treatments resulted in 100% mortality, except for horse manure at C/N of 50 where no bulking material was added.

The results also showed that for successful vermicomposting, poultry litter has to be microbially pre-composted if a feeding frequency of 1/8-weeks, simulating windrow method, is used.

Though most of the treatments reached a maximum earthworm growth at C/N ratio of 100, the effects of C/N ratio on earthworm growth between 50 and 100 are unknown. Optimizing C/N ratio can significantly decrease the amount of bulking material and increase the amount of poultry litter utilized by vermicomposting process.

Chapter VII

C/N Ratio Optimization for a given Feeding Frequency and Feed Type

Objective

To optimize carbon to nitrogen ratio for a given feed type and feeding frequency

Materials and Methods

Experimental Setup

The experiment was performed as a completely randomized design with 4*7*2 factorial arrangement of treatments and five replications per treatment. Three main factors were: feed type, C/N ratio, and feeding frequency. The feed types consisted of raw poultry litter, microbially pre-composted poultry litter (hot composted poultry litter and cured poultry litter), and pH adjusted poultry litter. The carbon to nitrogen ratios included: 10, 30, 50, 70, 90, 110, and "As Is". The experiment was conducted for a total of eight weeks to coincide with the approximate generation time of *Eisenia foetida* (Hartenstein and Hartenstein, 1981; Gaddie and Douglas, 1977; Ndegwa et al., 2000). Test bins were fed for the first seven weeks at two frequencies. The two feeding frequencies were 1/week, simulating bin method, and 1/8-weeks, simulating windrow method. The end amount of feed for the two feeding frequencies was the same. Each test bin was considered a replication; with five replications per treatment. The response variables were the (%) earthworm biomass change and the (%) volatile solids change.

Worm Culture

Purchased earthworms, *Eisenia foetida*, were multiplied by the same method as described in chapter V.

Test Bins

Test bins were constructed by using 4" by 7" (diameter * height) PVC pipes with a surface area of 0.008 m^2. The bottom of each PVC pipe was covered with wire gauze for draining excess water. Earthworm live biomass loading was 13 g-worms/bin corresponding to optimal stocking density of 1.6 kg-worms/m^2 (Ndegwa et al., 2000). The feed rate was standardized so that each of the test bins, regardless of the treatment type, received the same amount of volatile solids. However, the total amount of feed and the feed rate for each of treatment varied (Table 7). Test bins were fed using the same methods as described in Chapter VI. Test bins were kept in a dark, constant temperature room at 70 ^{0}F. Each test bin was sprinkled daily with water to keep the feed wet.

Chemical Analysis

Chemical analysis was performed by using the same methods as described in Chapter V and VI.

Feedstocks Preparation

Raw poultry litter was obtained from the same source as described in Chapter V and VI; however it was a different batch than the one used previously. Therefore, the physical and chemical properties of the litter, whether raw or micorobially pre-composted, were different than the properties described Chapter V and VI. Before every feeding, the moisture content of manure/litter was adjusted close to 70% by using water for raw poultry litter and pre-composted poultry litter, and 0.1N H_2SO_4 for pH adjusted raw poultry litter. Litter was mixed with wet shredded paper and transferred to the test bins.

Microbial composting was carried out by using the reactors described in Chapter V. Figure 13 shows the temperature trends during microbial composting. Raw poultry litter was considered hot composted when reheating upon mixing stopped and respiration rate of 26 [mgO_2]/[gVS*day] achieved. Raw litter was composted for 31 days to obtain hot composted poultry litter. Cured poultry litter was obtained after 50 days of microbial composting. Cured litter had a respiration rate of 17 [mgO_2]/[gVS*day]. The initial physical and chemical properties of the feedstocks are listed in Table 6.

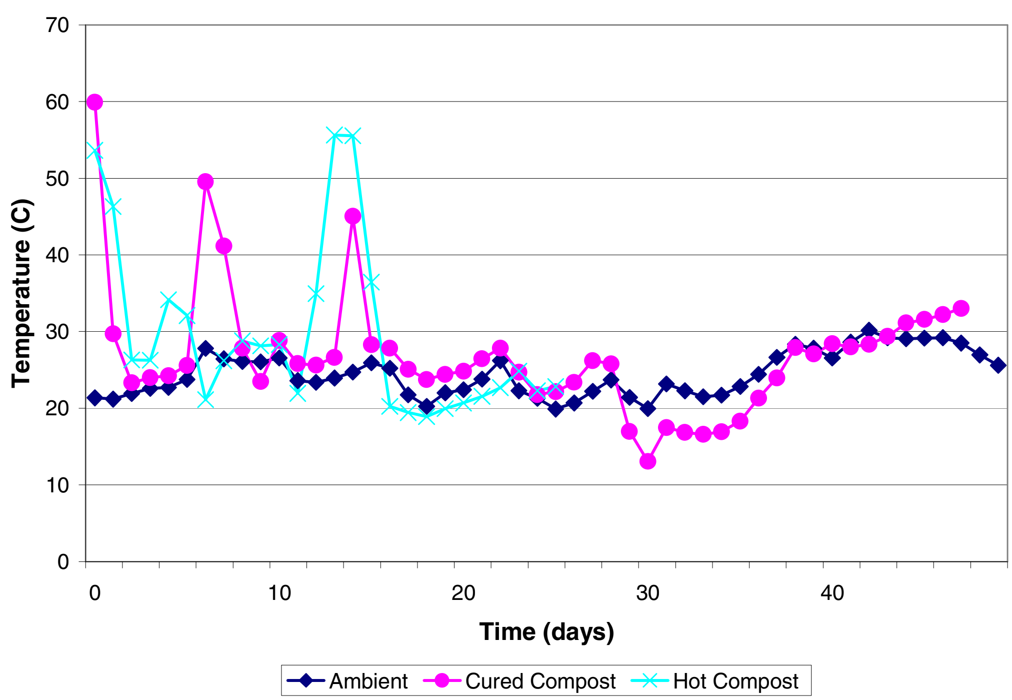

Figure 12. Temperature trends during microbial composting

The physical and chemical parameters for different feeds are given in Table 6. The carbon to nitrogen ratios were adjusted by using equation 5 in Chapter VI. The total amount of litter and paper used for different C/N ratios over the eight weeks of experimental duration is listed in Table 7. The total amount of volatile solids regardless of the feed type and C/N ratio were 67 g.

Table 6. Analysis of feedstocks

	Raw Litter		pH Adjusted		Hot Compost		Cured Compost		Paper	
	$\bar{X}$	Std	$\bar{X}$	Std	$\bar{X}$	Std	$\bar{X}$	Std	$\bar{X}$	Std
TS (%, wb)	76	1	76	1	65	4	66	2	98	1
VS (%, db)	63	2	63	2	52	3	46	1	84	1
TKN (mg/kg, db)	48,100	3,300	48,100	3,300	33,000	800	38,000	400	200	100
Ammoniacal-N (mg/kg, db)	5,100	60	5,100	60	560	60	760	55	-	-
TP (mg/kg, db)	27,400	1,065	16,000	1,800	23,000	360	28,000	2,500	-	-
Ortho-P (mg/kg, db)	5,300	500	5,300	500	4,500	100	4,000	170	-	-
pH	8.3	0.03	7.1	0.18	8.3	0.03	8.3	0.04	8.74	0.01
EC (dS/m)	12.5	0.6	12.5	0.6	12.9	1.1	12.1	0.4	*	*
Resp. Rate (mgO_2/gVS*day)	78.5	4.7	37	3	26	2	17	1	*	*
GI (%)	0	0	0	0	0	0	0	0	*	*

"-" = Undetected, "*" = Not measured, Std = Standard deviation, RL = Raw poultry litter, pH = pH adjusted raw poultry litter, HC = Hot composted poultry litter, CC = Cured poultry litter

Table 7. Amount of litter and paper for each of the treatments

Substrate	Litter (g)	Paper (g)	Substrate	Litter (g)	Paper (g)
RL-As IS	142	0	HC-50	35	68
pH-AS IS	142	0	CC-50	29	70
HC-AS IS	197	0	RL-70	14	73
CC-AS IS	222	0	pH-70	14	73
RL-10	102	23	HC-70	24	72
pH-10	102	23	CC-70	21	73
HC-10	174	10	RL-90	11	75
CC-10	148	27	pH-90	11	75
RL-30	34	62	HC-90	19	74
pH-30	34	62	CC-90	16	76
HC-30	58	58	RL-110	9	76
CC-30	49	63	pH-110	9	76
RL-50	20	70	HC-110	15	76
pH-50	20	70	CC-110	13	77

RL = Raw poultry litter, HC= Hot composted poultry litter, CC = Cured poultry litter, pH = pH adjusted poultry litter

Results and Discussion

Statistical Analysis

A computer based statistical analysis software, SAS®, was used to perform statistical analysis. The (%) earthworm biomass change and the volatile solids (%, db) lacked normal distribution (at $\alpha = 0.05$). However, the methods used by SAS are quite robust to handle a slight departure from normality.

The hypothesis of equal variance was tested by using Chi Square test. The data lacked equal variance (at $\alpha = 0.05$). To account for heterogeneity of variance, Generalized Least Square model was used to test treatment effects on percent earthworm biomass change.

Earthworm Biomass Change

The final average earthworm biomass change and the standard deviation are given in Table 8. Even though the number of replications per treatment was increased to five, the standard error was still quite high.

Figure 14 and 15 show the effects of C/N ratios and feed types on (%) earthworm biomass change at the feeding frequency of 1/week and 1/8-weeks, respectively. The treatment effects on earthworm growth were analyzed by performing pair-wise comparisons. The mean (%) earthworm biomass change and pair-wise comparisons for all possible treatment combinations are given in Table 9.

Adjustment of C/N ratio played a significant role in earthworm survivability and growth. At C/N ratio of 10 and below, regardless of the feed type and the feeding frequency, earthworm mortality was 100%. The survivability rate of earthworms increased as C/N ratio increased from 10 to 50 for all the feed types at both the feeding frequencies. These finding were similar to the one determined by Aira et al. (2006), where earthworm biomass increased as C/N ratio increased. However, a majority of the treatments reached a maximum earthworm growth at C/N ratio of 50 and increasing C/N ratio above 50 did not produce significant differences. The C/N ratio of 50 is considered optimal because it produced highest earthworm biomass with least amount of bulking material.

Table 8. Live biomass per test bin after 8 weeks of worm growth, five replications per treatment

C/N Ratio	Manure Type	Frequency = 1/week		Frequency = 1/8weeks	
		$\bar{X}$	Std	$\bar{X}$	Std
	RL	8.5	11.9	1.6	2.6
	pH	2.4	1.9	1.0	1.0
	HC	4.1	4.0	0.0	0.0
30	CC	6.5	7.0	2.1	3.9
	RL	22.3	11.0	12.3	12.5
	pH	20.0	6.1	6.5	7.7
	HC	22.2	7.3	4.2	3.8
50	CC	22.0	9.1	18.3	1.7
	RL	19.4	7.8	16.3	16.9
	pH	21.2	5.1	12.7	10.0
	HC	23.7	3.3	14.4	6.6
70	CC	18.1	3.8	12.8	7.9
	RL	17.1	7.0	11.1	10.1
	pH	16.3	7.1	9.2	11.2
	HC	24.2	9.7	18.3	15.3
90	CC	25.9	14.8	24.3	6.0
	RL	17.7	3.4	13.0	14.4
	pH	18.0	2.4	7.4	8.7
	HC	12.5	7.1	16.5	4.8
110	CC	18.2	7.6	15.9	5.1

RL = Raw poultry litter, HC= Hot composted poultry litter, CC = Cured poultry litter, pH = pH adjusted poultry litter

The results show that the microbial pre-composting of poultry litter and the pH adjustment of poultry litter, alone, cannot accomplish vermicomposting (Figure 14 and 15). A sufficient amount of bulking material needs to be present to perform successful vermicomposting, whether poultry litter is used as raw, microbially pre-composted, or pH adjusted. Although microbial pre-composting decreased ammoniacal-N concentration, it was still higher than the recommended toxic concentration of 500 mg/kg (Edwards, 1996; Edwards, 1998).

Not many differences were observed for the effects of feeding frequency on (%) earthworm biomass change; however, there was a definite trend displayed, whereby, earthworm biomass was found to be higher for a feeding frequency of 1/week as compared to 1/8-weeks for a majority of the treatments. Also, based on the results for the feeding frequency of 1/8-weeks (Figure 15), it was found that poultry litter had to be microbially pre-composted with sufficient amount of bulking material to ensure earthworm survivability. On the other hand, for the feeding frequency of 1/week, poultry litter did not have to be microbially pre-composted; however, it did required sufficient amount of bulking material.

Table 9. Pair wise comparisons of earthworm biomass change (%): C/N ratio at a given feeding frequency and feed type (alphabets, vertical), feed type at a given feeding frequency and C/N ratio (numbers, horizontal) at $\alpha = 0.05$

	Frequency = 1/week				Frequency = 1/8-weeks			
	RL	pH	HC	CC	RL	pH	HC	CC
C/N Ratio	$\overline{X}$	$\overline{X}$	$\overline{X}$	$\overline{X}$	$\overline{X}$	$\overline{X}$	$\overline{X}$	$\overline{X}$
30	-35a,1	-82c,1	-68e,1	-50g,1	-88a,1	-92c,1	-100e,1	- 84h,1
50	72b,2	54d,2	71f,2	69h,2	-6.0b,2,3	-50c,d,3	-68e,f,3	41i,2
70	49b,3	63d,3	82f,3	39h,3	26b,4	-2d,4	11f,g4	-2i,4
90	31b,4	25d,4	86f,4	99h,4	-14a,b,5,6	-29c,d,6	41g,5	87i,5
110	36b,5	39d,5	-4e,5	40h,5	0b,7	-43c,d,7	27g,7	22i,7

RL = Raw poultry litter, HC= Hot composted poultry litter, CC = Cured poultry litter, pH = pH adjusted poultry litter

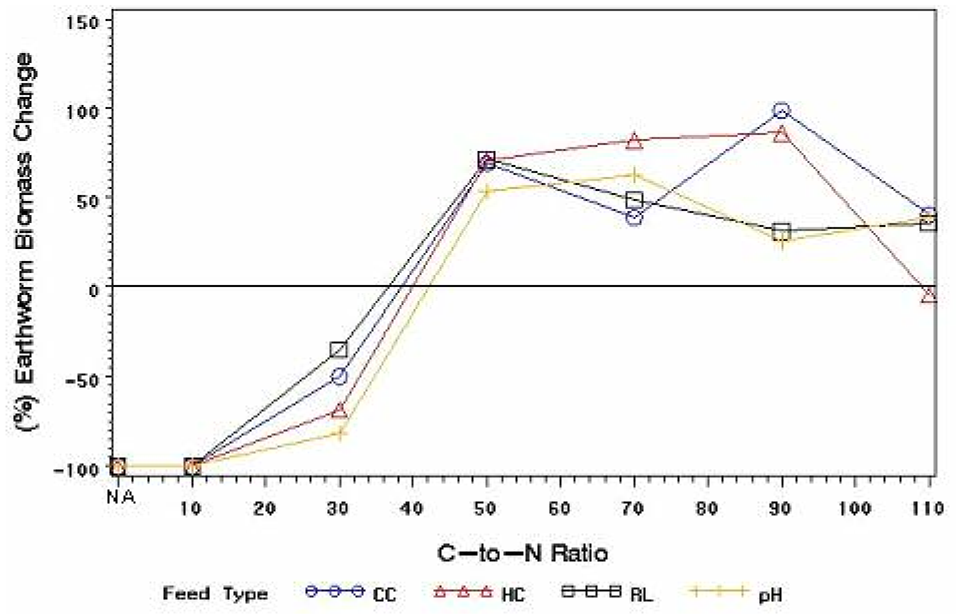

Figure 13. Trend analysis of average (%) biomass change at rate at Frequency 1/wk
RL = Raw poultry litter, HC= Hot composted poultry litter, CC = Cured poultry litter,
pH = pH adjusted poultry litter

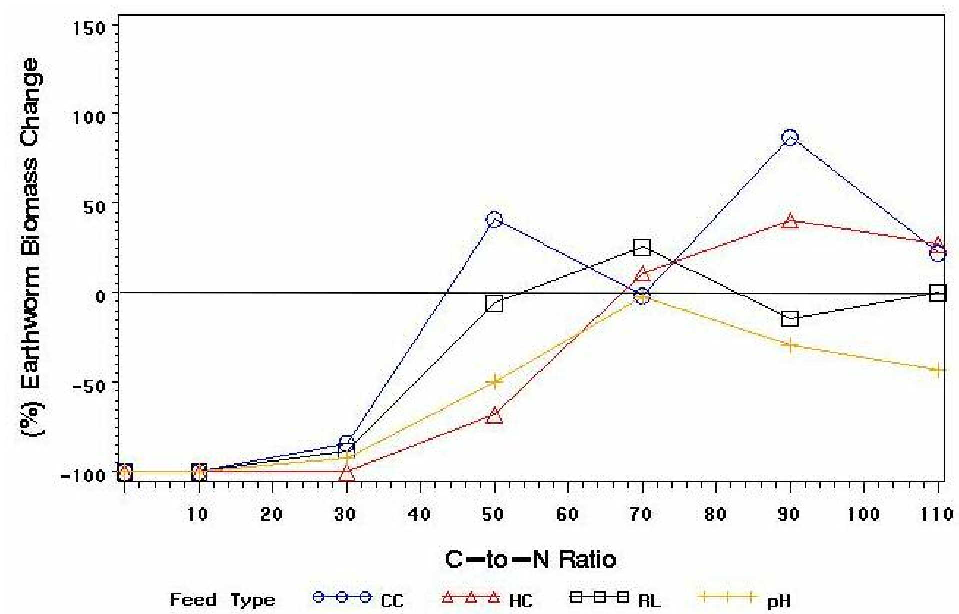

Figure 14. Trend analysis of average (%) biomass change at frequency of 1/8- wks
RL = Raw poultry litter, HC= Hot composted poultry litter, CC = Cured poultry litter,
pH = pH adjusted poultry litter

Volatile Solids Degradation

Since earthworms never moved into the feed for treatments with C/N ratio lower than 10, the materials were not qualified as vermicompost and no volatile solids analyses were performed. The highest percent decrease for volatile solids occurred at C/N ratio of 30 and 50, with no significant differences between C/N ratio of 30 and 50 for a majority of treatments. The percent change for volatile solids decreased as C/N ratio increased from 30 to 70; however, at C/N ratio of 70 to 110, no significant differences were observed for any of the feed types and the feeding frequencies (Table 10).

The pair-wise comparisons for the effects of feed type on percent volatile solids change for a given C/N ratio and feeding frequency are summarized in Table 10. For most of the treatments, at a given feeding frequency and C/N ratio, feed type did not have significant effects on percent volatile solids change. Therefore, raw poultry litter is considered the optimal feed type because it does not involve any pre-treatments prior to vermicomposting.

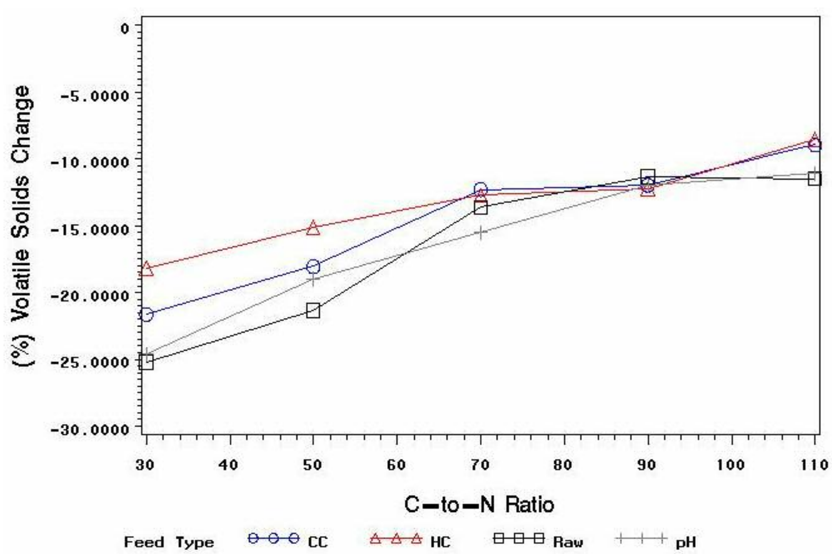

Figure 15. Trend analysis of average (%) volatile solids change at frequency of 1/wk
RL = Raw poultry litter, HC= Hot composted poultry litter, CC = Cured poultry litter, pH = pH adjusted poultry litter

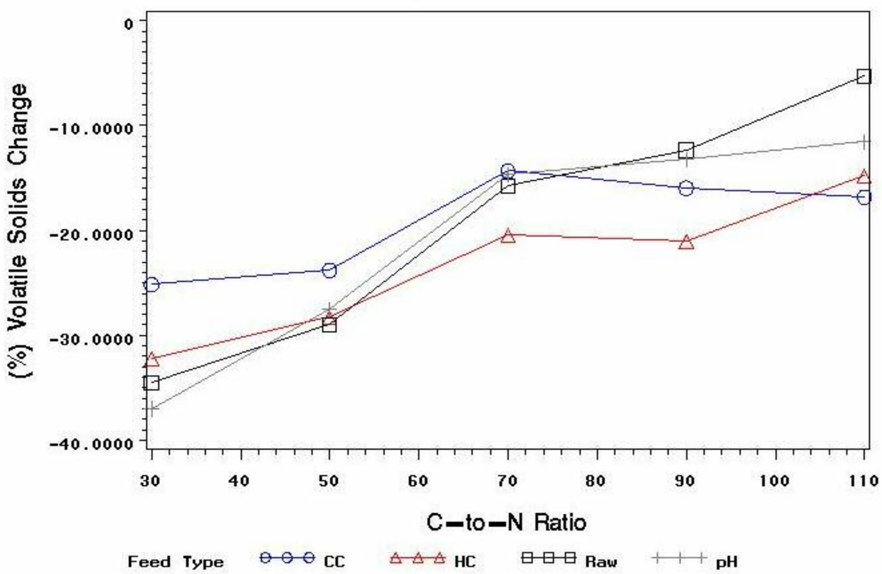

Figure 16. Trend analysis of average (%) volatile solids change at frequency of 1/8- wks
RL = Raw poultry litter, HC= Hot composted poultry litter, CC = Cured poultry litter, pH = pH adjusted poultry litter

Table 10. Pair wise comparisons of volatile solids change (%): C/N ratio at a given feeding frequency and feed type (alphabets, vertical), feed type at a given feeding frequency and C/N ratio (numbers, horizontal) at α = 0.05

C/N Ratio	Frequency = 1/week				Frequency = 1/8-weeks			
	RL	pH	HC	CC	RL	pH	HC	CC
30	-25a,1	-25c,1	-18e,2	-22g,1,2	-34a,1,2	-37c,2	-32e,1,2	-25g,2
50	-21a,3	-19c,3,4	-15e,f,4	-18g,3,4	-29a,3	-28c,3	-28e,f,3	-24g,3
70	-14b,5	-16d,5	-13f,5	-12h,5	-16b,4	-15d,4	-20f,4	-14h,4
90	-11b,6	-12d,6	-12f,6	-12h,6	-12b,5	-13d,5	-21f,5	-16h,5
110	-11b,7	-11d,7	-9f,7	-9h,7	-5b,6	-12d,6	-15f,6	-17h,6

RL = Raw poultry litter, HC= Hot composted poultry litter, CC = Cured poultry litter, pH = pH adjusted poultry litter

Quality of Vermicomposted Poultry Litter as Plant Growth Media

Based on the results described above, feeding frequency of 1/week is considered optimal because it produced higher earthworm biomass growth. At the feeding frequency of 1/week, the C/N ratio of 50 and raw poultry litter is considered optimal The C/N ratio of 50 is considered optimal because it produced the highest earthworm biomass growth with a least amount of bulking material. The raw poultry litter is considered optimal because it did not require any pre-treatments, and it performed equally better as compared to the other feed types. Therefore, raw poultry litter at the C/N ratio of 50 and feeding frequency of 1/week is considered the optimal treatment combination. The characteristics of the optimal treatment combination are given in Table 11.

At the end of eight weeks of vermicomposting, the volatile solids concentration (%, db) decreased by 21%. These results were similar to Ndegwa et al. (2000) where he showed 10%-12% (db) volatile solids decrease after eight weeks of vermicomposting

Table 11. Weighted average plant growth parameters for raw poultry litter and vermicomposted poultry litter/shredded paper mixture after removing worms

	Raw Litter	Raw Litter mixed with Paper to C/N = 50 Start of 8 weeks	End of 8 weeks
VS (%, db)	63	76	60
TKN (mg/kg, db)	48,100	9,000	17,200
NH_3-N (mg/kg, db)	5,100	940	500
TP (mg/kg, db)	27,400	5,180	10,500
Ortho-P (mg/kg, db)	5,300	1,150	55
pH	8.3	*	7.3
EC (dS/m)	12.5	*	0.15
Respiration Rate (mgO_2/gVS-day)	78.5	*	35
GI (%)	0	*	42

* = Not measured

The concentration for TKN and total phosphorus had an increase of 47% and 51%, respectively. This shows that TKN and total phosphorus were not taken up by earthworms during vermicomposting. A study by Mitchell (1997) showed a similar increase of 25% in total nitrogen concentration after thirteen weeks of vermicomposting cow manure. The results for total phosphorus were similar to Ndegwa et al. (2000) where he showed an increase of 14% to 45% for total phosphorus concentration after eight weeks of vermicomposting of biosolids.

A look at water soluble plant nutrients, NH_3 and ortho-phosphate, indicates a decrease of 47% and 95%. This decrease could have resulted due to earthworm growth or due to leaching during the daily sprinkling of water on the test bins.

Table 11 shows that the germination index of the vermicomposted material increased from 0% to 42% as compared to the raw poultry litter; however, according to USCC (2002), at this germination index the vemicompost was still considered unstable. Atiyeh et al. (2000b) showed 100% death of raspberry plants when soil in potting media was mixed with 4% poultry litter. However, they showed a decrease in raspberry mortality when 20% vermicomposted pig manure was added to a mixture of chicken manure and soil. Atiyeh et al. (2000a) showed that tomato and lettuce plants when fed vermicomposted cow manure performed significantly better as compare to the plants grown on non-vermicomposted cow manure.

Respiration rate for the vermicomposted material decreased by half as compared to the raw poultry litter (Table 11); however, at this respiration rate vermicomposted material is still considered unstable (USCC, 2002). High micro-organism concentration with sufficient amount of food source can yield high respiration rate. Atiyeh et al. (2000a) showed an increase in microbial biomass concentration during the vermicomposting period. Since vermicomposting increases microbial biomass, it also increases reparation rate.

Conclusions

The earthworm mortality for all the treatments at C/N ratios below 10 was 100%. Poultry litter, whether used as raw, pH adjusted, or microbially pre-composed, should not be vermicomposted without adding sufficient amount of bulking material to raise C/N ratio to 50 or above. This finding shows that bulking material plays an important role in vermicomposting. The addition of bulking material to poultry litter can also dilute ammoniacal-N concentration and enhance aeration.

The earthworm survivability and growth increased between C/N ratios of 10 and 50; however, it reached a maximum at C/N ratio of 50. Increasing C/N ratio above 50 did not make significant impact on earthworm growth. This finding shows 50 to be the C/N ratio where maximum earthworm growth can be achieved by adding least amount of bulking material.

Poultry litter at the feeding frequency of 1/8-weeks (simulating windrow vermicomposting) should be microbially pre-composted and bulking material should be added to bring C/N ratio to 50 or above to ensure earthworm survivability. However, the feeding frequency of 1/week, simulating bin vermicomposting, did not require microbial pre-composting to get positive earthworm growth.

Based on above conclusions, raw poultry litter at C/N ratio of 50 and a feeding frequency of 1/week was considered an optimal treatment combination for vermicomposting. Further analysis of this treatment showed that it had a higher germination index than the raw poultry litter and it retained most of the plant nutrients.

Chapter VIII

Recommendations for Future Research

Future research should be conducted in order to examine what factors optimize vermicomposting of poultry litter. There is a limited published data regarding vermicomposting of poultry litter; therefore, the breeding conditions such moisture content, temperature, and stocking density used in this experiment were based on previous studies where feed substrates different than poultry litter were used. Previous studies showed that the breeding conditions, mentioned above, play an important role in the earthworm growth and survivability, therefore, it is recommended to investigate the effects of these conditions on vermicomposting of poultry litter.

One of the objectives of this study was to investigate the effects of bulking material and C/N ratio on vermicomposting of poultry litter. Adding shredded office paper to poultry litter increased C/N ratio and bulking capacity. The addition of shredded paper to reach the C/N ratio of 50 and above significantly enhanced earthworm biomass production; however, it could not be determined whether it was the increase in C/N ratio or the bulking capacity that resulted in the higher earthworm biomass. It would be advantageous to design an experiment that could investigate the effects of bulking material and C/N ratios, separately, on vermicomposting of poultry litter. For example, the effects of bulking material should be examined by adding materials with low amount of carbon such as styrofoam beads and the effects of carbon to nitrogen ratio should be investigated by using a material that would not effect the bulking capacity of poultry litter but would increase carbon to nitrogen ratio.

The experiments conducted in this study used only one feeding rate and stocking density. It would be useful to investigate the effects of different feeding rates and feeding frequencies on vermicompost stabilization and earthworm biomass production.

In this study, vermicomposting was performed for eight weeks; however, at the end of eight weeks of experimental duration, most of the feed was left in tact. It is recommended to perform a study that would determine the time duration needed to completely utilize all the feed at a given feeding rate and stocking density.

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Appendix A

Raw data for the Feedstocks

used in Chapter V and Chapter VI

List of Tables

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Table A I. Data for moisture content and volatile solids

Raw poultry litter						
	Rep 1	Rep 2	Rep 3			
Tin	0.9558	0.9604	0.9621			
Tin +Sam.	11.0285	11.4577	11.0178			
After Dry	7.7997	8.0393	7.7512			
Ignition	3.135	3.2157	3.19	Average	Std	%CV
TS (% g/g)	67.95	67.44	67.51	67.63	0.27	0.41
TVS (% g/g)	68.16	68.14	67.18	67.83	0.56	0.82
MC (% g/g)	32.05	32.56	32.49	32.37	0.27	0.85
Hot composted poultry litter						
	Rep 1	Rep 2	Rep 3			
Tin	0.9564	0.9574	0.9589			
Tin +Sam.	18.7508	16.9426	15.3915			
After Dry	11.807	11.0565	9.8114			
Ignition	5.3915	4.9813	4.5087	Average	Std	%CV
TS (% g/g)	60.98	63.18	61.34	61.83	1.18	1.91
TVS (% g/g)	59.13	60.16	59.90	59.73	0.54	0.90
MC (% g/g)	39.02	36.82	38.66	38.17	1.18	3.09
Cured poultry litter						
	Rep 1	Rep 2	Rep 3			
Tin	0.9585	0.9529	0.9589			
Tin +Sam.	17.2836	16.9426	15.3915			
After Dry	11.6519	11.0565	9.8114			
Ignition	6.1	4.9813	4.5087	Average	Std	%CV
TS (% g/g)	65.50	63.19	61.34	63.34	2.09	3.30
TVS (% g/g)	51.92	60.13	59.90	57.32	4.68	8.16
MC (% g/g)	34.50	36.81	38.66	36.66	2.09	5.69
Horse manure						
	Rep 1	Rep 2	Rep 3			
Tin	1.21142	1.2341	1.239			
Tin +Sam.	4.6565	7.1975	4.7202			
After Dry	3.2069	4.2689	3.0909			
Ignition	1.3867	1.4908	1.4069	Average	Std	%CV
TS (% g/g)	57.92	50.89	53.20	54.00	3.58	6.64
TVS (% g/g)	91.22	91.54	90.93	91.23	0.30	0.33
MC (% g/g)	42.08	49.11	46.80	46.00	3.58	7.79
Shredded paper						
	Rep 1	Rep 2	Rep 3			
Tin	0.9954	0.9586	0.9584			
Tin +Sam.	2.0113	2.4865	2.4693			
After Dry	1.9858	2.3311	2.4486			
Ignition	1.1624	1.1672	1.198	Average	Std	%CV
TS (% g/g)	97.49	89.83	98.63	98.06	0.81	0.82
TVS (% g/g)	83.14	84.80	83.92	83.95	0.83	0.99
MC (% g/g)	2.51	***10.17***	1.37	1.94	0.81	41.55

Values in Bold and Italic text were omitted to get %CV less than 10%

Table A II. Data for TKN

Raw poultry litter				
Rep	Sample Wt. (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	1.0992	2.87	4.22	42206
2	0.9889	3.03	4.46	44559
3	0.9751	2.87	4.22	42206
Average	1.02	2.92	4.30	42990
Std	0.07	0.09	0.14	1358
%CV	6.66	3.16	3.16	3
Hot composted poultry litter				
Rep	Sample Wt. (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	1.1064	2.52	4.08	40757
2	1.2518	2.51	4.06	40595
3	1.095	2.38	3.85	38493
Average	1.151	2.47	3.99	39948
Std	0.087	0.078	0.126	1263
%CV	7.60	3.16	3.16	3.16
Sample = Cured poultry litter				
Rep	Sample Wt. (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	2.0043	2.3	3.97	39689
2	1.3161	2.39	4.12	41242
3	1.6332	2.51	4.33	43313
Average	1.6512	2.40	4.14	41415
Std	0.3445	0.11	0.18	1818
%CV	20.86	4.39	4.39	4.39
Horse Manure				
Rep	Sample Wt. (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	***1.15223***	***0.81***	***1.50***	***15000***
2	1.423	0.54	1.00	10000
3	1.9455	0.54	1.00	10000
Average	1.51	0.63	1.17	10000
St Dev	0.40	0.16	0.29	0
%CV	26.76	24.74	24.74	0
Shredded Paper				
Rep	Sample Wt. (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	0.478	0.02	0.02	204
2	0.4174	0.02	0.02	204
3	***0.4371***	***0.03***	***0.03***	***306***
Average	0.44	0.02	0.02	238
Std	0.03	0.01	0.01	0
%CV	6.96	24.74	24.74	0

Values in Bold and Italic text were omitted to get %CV less than 10%

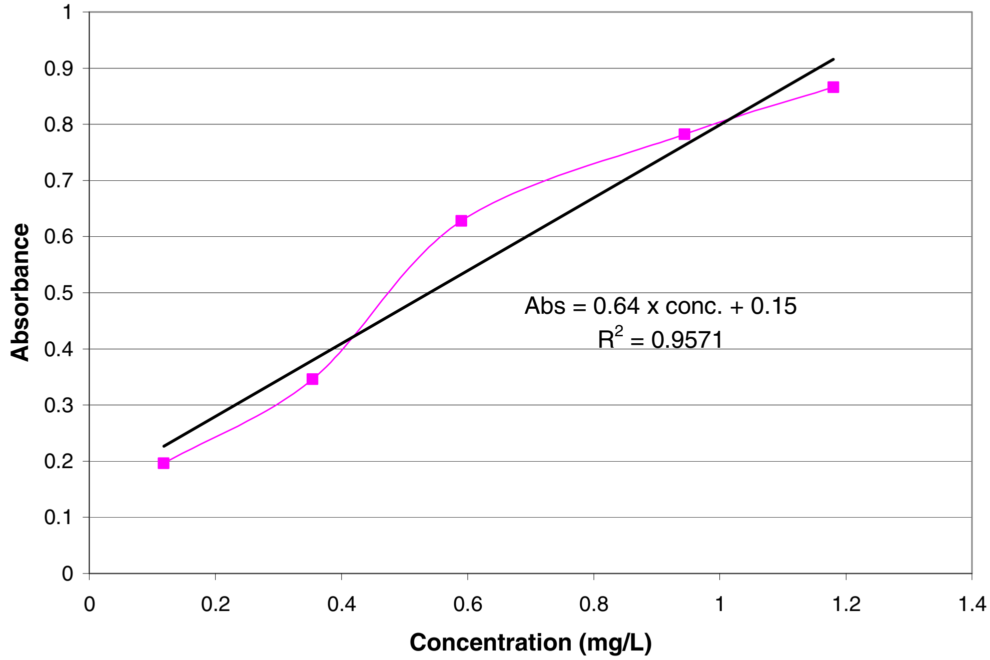

Figure A I. Calibration curve for ammonia analysis based on Phenate Method

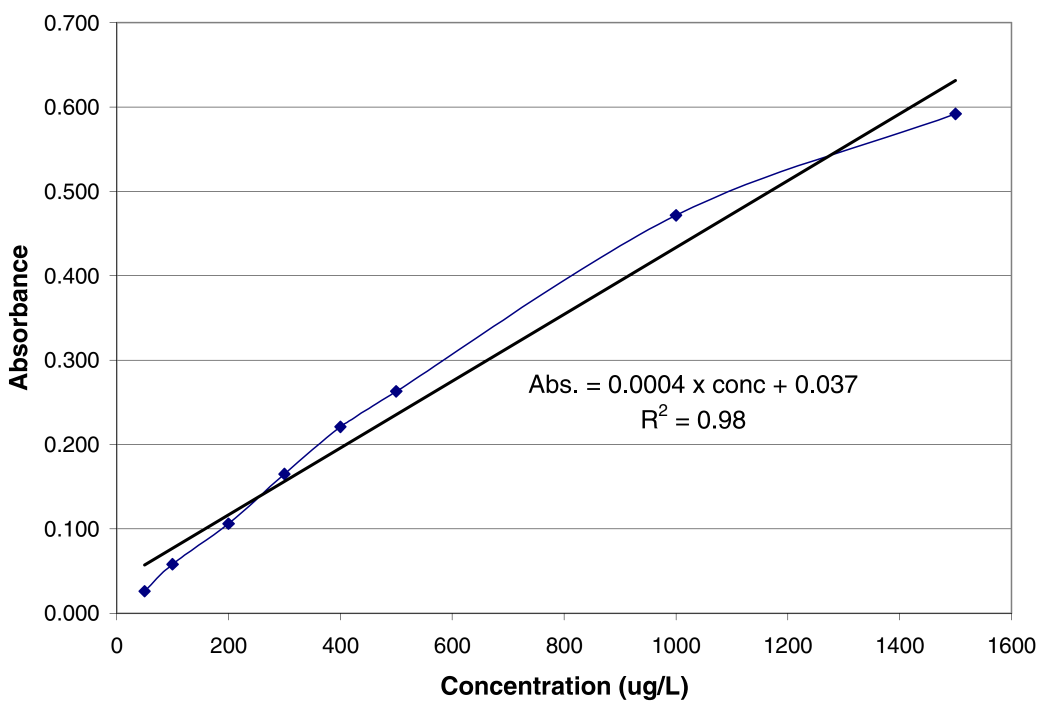

Figure A II. Calibration curve for Phoshphate analysis based on Ascorbic Acid Method

Table A III. Data for Ammoniacal-N

Rep	Sample Wt. (g)	Abs	Am-N (mg/L)	NH3 (mg/kg, db)	NH3 (mg/kg, db)	
Raw poultry litter						
1	1.1193	0.205	42.96875	2578.125	Average	2625
2	1.0920	0.212	48.4375	2906.25	Std	260.989
3	1.1532	0.201	39.84375	2390.625	%CV	9.942436
		df	500			
Hot composted poultry litter						
Rep	Sample Wt. (g)	Abs	Am-N (mg/L)	NH3 (mg/kg, db)	NH3 (mg/kg, db)	
1	1.0675	0.369	34.21875	2053.125	Average	2315.625
2	1.6500	0.397	38.59375	2315.625	Std	185.6155
3	***1.0828***	***0.328***	***27.8125***	***1668.75***	%CV	8.015785
		df	100			
Cured poultry litter						
Rep	Sample Wt. (g)	Abs	Am-N (mg/L)	NH3 (mg/kg, db)	NH3 (mg/kg, db)	
1	1.3035	0.242	14.375	862.5	Average	721.875
2	1.4012	0.227	12.03125	721.875	Std	99.43689
3	***1.2025***	***0.195***	***7.03125***	***421.875***	%CV	13.77481
		df	100			
Horse Manure						
Rep	Sample Wt. (g)	Abs	Am-N (mg/L)	NH3 (mg/kg, db)	NH3 (mg/kg, db)	
1	2.8367	0.108	1.2121	72.7273	Average	71.15818
3	2.1434	0.107	1.1729	70.3736	Std	1.358871
4	2.08	0.107	1.1729	70.3736	%CV	1.909648
		df	40			

Values in Bold and Italic text were omitted to get %CV less than 10%

Table A IV. Data for Total P

Raw poultry litter						
Rep	Sample (g)	Abs	TP (µg/L)	TP (mg/kg,db)		TP (mg/kg,db)
1	0.9958	0.48	221350	22228	Average	22913
2	***0.9982***	***0.304***	***133350***	***13359***	Std	968
3	0.8554	0.441	201850	23597	%CV	4
		df	200			

Hot composted poultry litter						
Rep	Sample (g)	Abs	TP (µg/L)	TP (mg/kg,db)		
1	1.0068	0.503	1001	19893	Average	20821
2	1.0487	0.567	1129	21539	Std	843
3	0.9276	0.49	975	21031	%CV	4
		df	20			

Cured poultry litter						
Rep	Sample (g)	Abs	TP (µg/L)	TP (mg/kg,db)		
1	0.9140	0.445	885	19374	Average	19730
2	1.1071	0.583	1161	20981	Std	1117
3	1.0167	0.481	957	18833	%CV	6
		df	20			

Horse manure						
Rep	Sample (g)	Abs	TP (µg/L)	TP (mg/kg,db)		
1	0.5581	0.059	54	13546	Average	14309
2	0.5048	0.06	56.5	15670	Std	1181
3	0.5003	0.057	49	13712	%CV	8
		df	140			

Shredded paper						
Rep	Sample (g)	Abs	TP (µg/L)	TP (mg/kg,db)		
1	0.5137	0.01	-68.5	-66673	Average	-64913
2	0.5100	0.009	-71	-69608	Std	5780
3	0.5859	0.01	-68.5	-58457	%CV	-9
		df	500			

Values in Bold and Italic text were omitted to get %CV less than 10%
Values for Shredded Office Paper were negative and considered to be un-detected

Table A V. Data for Ortho-P

Raw poultry litter

Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg,db)		OP (mg/kg,db)
1	4.0000	0.599	280850	4213	Average	4287
2	4.0200	0.619	290850	4341	Std	66
3	3.9900	0.61	286350	4306	%CV	2
		df	200			

Hot composted poultry litter

Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg,db)		OP (mg/kg,db)
1	4.0800	0.598	280350	4123	Average	3971
2	4.0700	0.551	256850	3777	Std	177
3	4.0100	0.583	272850	4013	%CV	4
		df	200			

Cured poultry litter

Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg,db)		OP (mg/kg,db)
1	4.08	0.481	221850	3319	Average	3723
2	4.0500	0.525	243850	3649	Std	446
3	4.0100	0.599	280850	4202	%CV	12
		df	200			

Horse Manure

Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg,db)		OP (mg/kg,db)
1	4.03	0.177	58325	868	Average	841
2	3.99	0.18	59577	887	Std	63
3	4.01	0.161	51645	769	%CV	8
4	4.02	0.187	62500	931		
5	4.02	0.168	54567	812		
		df	167			

Shredded paper

Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg,db)		OP (mg/kg,db)
1	4	0.025	-6150	-90	Average	-90
2	4	0.026	-5650	-83	Std	7
3	4	0.024	-6650	-98	%CV	-8
		df	200			

Values for Shredded Office Paper were negative and considered to be un-detected

Table A VI. Data for Electrical Conductivity (dS/m)

	Rep 1	Rep 2	Rep 3	Average	Std	%CV
Raw Litter	17.5	16.8	18.12	17.47	0.66	3.78
pH Adjusted	17.5	16.8	18.12	17.47	0.66	3.78
Hot Compost	16.8	16.85	16.78	16.81	0.04	0.21
Cured Compost	15.77	15.69	15.86	15.77	0.09	0.54
Horse Manure	3.55	3.45	***4.47***	3.50	0.07	2.02

Values in Bold and Italic text were omitted to get %CV less than 10%

Table A VII. Data for pH

Rep	pH	Average	Std	%CV
Raw poultry litter				
Rep	pH	Average	Std	%CV
1	8.44	8.45	0.02	0.25
2	8.47			
3	8.43			
Hot composted poultry litter				
Rep	pH	Average	Std	%CV
1	8.98	8.90	0.18	2.03
2	8.77			
3	8.65			
4	9.08			
5	8.83			
6	9.10			
Cured poultry litter				
Rep	pH	Average	Std	%CV
1	8.98	9.05	0.09	0.97
2	8.98			
3	9.01			
4	9.08			
5	9.21			
6	9.02			
Horse manure				
Rep	pH	Average	Std	%CV
1	7.01	7.02	0.01	0.08
2	7.02			
3	7.02			
Shredded paper				
Rep	pH	Average	Std	%CV
1	7.01	7.02	0.01	0.08
2	7.02			
3	7.02			

Table A VIII. Daily mean temperature values during microbial composting

	Hot Compost		Cured Compost			Cured Compost	
Time (Day)	R1 (^{0}C)	R2 (^{0}C)	R3 (^{0}C)	R4 (^{0}C)	Time (Day)	R3 (^{0}C)	R4 (^{0}C)
1	-2	3	62	66	26	49	46
2	7	15	60	65	27	44	38
3	49	43	55	62	28	44	42
4	54	31	42	58	29	37	55
5	45	23	19	76	30	31	49
6	43	23	22	69	31	23	36
7	40	39	42	62	32	35	51
8	36	53	47	60	33	39	42
9	41	56	41	59	34	25	33
10	54	54	37	57	35	23	37
11	56	52	35	54	36	24	45
12	26	29	32	46	37	26	42
13	22	27	32	44	38	64	57
14	22	26	44	47	39	26	37
15	20	25	65	60	40	18	20
16	20	27	44	60	41	15	16
17			40	42	42	16	17
18			39	42	43	17	18
19			44	47	44	17	18
20			50	50	45	18	20
21			54	45	46	18	24
22			47	42	47	18	25
23			53	44	48	17	23
24			51	48	49	17	24
25			47	39	50	18	23

R1 = Reactor 1, R2 = Reactor 2, R3 = Reactor 3, R4 = Reactor 4

Table A IX. Earthworm live biomass after 8 weeks of vermicomposting—Chapter VI

		Feeding frequency 1/week		Feeding frequency 1/8-weeks	
C/N Ratio	Feed Type	Rep.	Worm biomass (g)	Rep.	Worm biomass (g)
		1	0.88	1	0.65
		2	2.26	2	0.00
	RL	3	0.00	3	0.00
		1	1.78	1	4.78
		2	7.02	2	17.56
	HC	3	3.38	3	11.29
		1	4.58	1	3.56
		2	5.02	2	1.86
50	HM	3	4.58	3	3.27
		1	12.78	1	1.15
		2	19.66	2	1.74
	RL	3	12.64	3	0.00
		1	17.03	1	*
		2	9.88	2	21.02
	HC	3	5.21	3	15.91
		1	7.36	1	6.01
		2	9.19	2	4.30
100	HM	3	1.96	3	7.58
		1	8.59	1	4.38
		2	8.29	2	3.17
	RL	3	2.62	3	1.92
		1	8.76	1	8.68
		2	9.85	2	14.31
	HC	3	6.50	3	3.84
		1	4.27	1	9.97
		2	6.43	2	4.27
150	HM	3	3.52	3	7.31

RL = Raw poultry litter, HC = Hot composted poultry litter, HM = Horse manure
* = Replication was damaged during the experiment

Appendix B

Raw data for the Feedstocks

used in Chapter VII

TABLE B ....PAGE

Table B I. Data for Moisture Content and Volatile Solids

Raw poultry litter						
Tin	1.2365	1.2181	1.2224			
Tin +Sam.	8.7627	8.9859	7.3528			
After Dry	7.0153	7.086	5.8169			
Ignition	3.4808	3.3207	2.8729	Average	Std	%CV
TS (% g/g)	76.78	75.54	74.95	75.76	0.94	1.24
TVS (% g/g)	61.16	64.17	64.08	63.14	1.71	2.71
MC (% g/g)	23.22	24.46	25.05	24.24	0.94	3.86
Hot composted poultry litter						
Tin	1.2088	1.2158	1.2315			
Tin +Sam.	19.92	21.9228	27.3893			
After Dry	13.817	15.1954	17.2424			
Ignition	7.2175	7.8301	9.0952	Average	Std	%CV
TS (% g/g)	67.38	67.51	61.21	65.37	3.60	5.51
TVS (% g/g)	52.34	52.69	50.89	51.97	0.96	1.84
MC (% g/g)	32.62	32.49	38.79	34.63	3.60	10.40
Cured poultry litter						
Tin	1.2106	1.2331	1.2199			
Tin +Sam.	20.4169	19.9841	23.5055			
After Dry	13.389	13.7081	16.3339			
Ignition	7.676	7.9122	9.7082	Average	Std	%CV
TS (% g/g)	63.41	66.53	67.82	65.92	2.27	3.44
TVS (% g/g)	46.91	46.46	43.84	45.74	1.66	3.63
MC (% g/g)	36.59	33.47	32.18	34.08	2.27	6.66
Shredded Paper						
	Rep 1	Rep 2	Rep 3			
Tin	0.9954	0.9586	0.9584			
Tin +Sam.	2.0113	2.4865	2.4693			
After Dry	1.9858	2.3311	2.4486			
Ignition	1.1624	1.1672	1.198	Average	Std	%CV
TS (% g/g)	97.49	89.83	98.63	98.06	0.81	0.82
TVS (% g/g)	83.14	84.80	83.92	83.95	0.83	0.99
MC (% g/g)	2.51	***10.17***	1.37	1.94	0.81	41.55

Values in Bold and Italic text were omitted to get %CV close to 10%

Table B II. Data for TKN

Sample	Sample (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
Raw poultry litter				
1	0.8843	3.02	4.44	44412
2	0.9331	3.44	5.06	50588
3	0.9546	3.36	4.94	49412
Average	0.94	3.27	4.81	48137
Std	0.02	0.22	0.33	3280
%CV	1.61	6.81	6.81	6.81
Hot composted poultry litter				
Sample	Sample (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	1.0639	2.11	3.23	32278
2	0.9963	2.11	3.23	32278
3	0.9522	2.2	3.37	33655
Average	0.97	2.14	3.27	32737
Std	0.03	0.05	0.08	795
%CV	3.20	2.43	2.43	2.43
Cured poultry litter				
Sample	Sample (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	0.8817	2.52	3.82	38228
2	1.0805	2.49	3.78	37773
3	0.9289	2.55	3.87	38683
4	0.8951	2.5	3.79	37925
Average	0.97	2.52	3.82	38127
Std	0.10	0.03	0.04	488
%CV	10.20	1.05	1.05	1.28
Shredded Paper				
Sample	Sample (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	0.478	0.02	0.02	204
2	0.4174	0.02	0.02	204
3	0.4371	0.03	0.03	306
Average	0.44	0.02	0.02	238
Std	0.03	0.01	0.01	59
%CV	6.96	24.74	24.74	24.74

Table B III. Data for Ammoniacal-N

Raw poultry litter						
Rep.	Sample (g)	Abs	NH3 (mg/L)	Am-N (mg/L)		Am-N (mg/kg, db)
1	2.26	0.25	78.91	4734	Average	4664
2	2.34	0.25	76.56	4594	Std	99
3	1.98	0.30	117.19	7031	%CV	2
		df	500			
Hot composted poultry litter						
Rep.	Sample (g):	Abs	NH3 (mg/L)	Am-N (mg/L)		Am-N (mg/kg, db)
1	***2.46***	***0.17***	***2.97***	***178***	Average	567
2	2.07	0.22	10.16	609	Std	60
3	2.36	0.21	8.75	525	%CV	11
		df	100			
Cured poultry litter						
Rep.	Sample (g):	Abs	NH3 (mg/L)	Am-N (mg/L)		Am-N (mg/kg, db)
1	***1.97***	***0.31***	***24.22***	***1453***	Average	759
2	2.07	0.23	12.03	722	Std	53
3	2.84	0.24	13.28	797	%CV	7
		df	100			

Values in Bold and Italic text were omitted to get %CV close to 10%

Table B IV. Data for Total Phosphorus

Raw poultry litter						
Rep.	Sample (g)	Abs	TP (µg/L)	TP (mg/kg, db)		TP (mg/kg, db)
1	0.5309	0.336	747	28131	Average	27378
2	0.5212	0.32	707	26625	Std	1066
3	***0.5627***	***0.417***	***949***	***35760***	%CV	4
		df	200			
Hot composted poultry litter						
Rep.	Sample (g)	Abs	TP (µg/L)	TP (mg/kg, db)		TP (mg/kg, db)
1	0.5563	0.293	639	22982	Average	23192
2	0.5651	0.293	639	22982	Std	363
3	0.5744	0.3	657	23611	%CV	2
		df	200			
Cured poultry litter						
Rep.	Sample (g)	Abs	TP (µg/L)	TP (mg/kg, db)		TP (mg/kg, db)
1	0.5033	0.298	652	25899	Average	25866
2	0.551	0.319	704	27985	Std	2136
3	0.5737	0.276	597	23713	%CV	8
		df	200			
Shredded paper						
Rep	Sample (g)	Abs	TP (µg/L)	TP (mg/kg, db)		TP (mg/kg, db)
1	0.5137	0.01	-69	-66673	Average	-64913
2	0.51	0.009	-71	-69608	Std	5780
3	0.5859	0.01	-69	-58457	%CV	-9
		df	500			

Values in Bold and Italic text were omitted to get %CV close to 10%

Table B V. Data for Ortho-Phosphate

Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg, db)	OP (mg/kg, db)	
Raw poultry litter						
Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg, db)	OP (mg/kg, db)	
1	4	0.2	406750	6101	Average	5301
2	4	0.177	349250	5239	Std	486
3	4	0.162	311750	4676	%CV	9
4	4	0.17	331750	4976		
5	4	0.179	354250	5314		
6	4	0.184	366750	5501		
		df	1000			
Hot composted poultry litter						
Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg, db)	OP (mg/kg, db)	
1	4	0.266	285875	4288	Average	4401
2	4	0.272	293375	4401	Std	112
3	4	0.278	300875	4513	%CV	3
		df	500			
Cured poultry litter						
Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg, db)	OP (mg/kg, db)	
1	4	0.26	278375	4175.625	Average	4107
2	4	0.246	260875	3913.125	Std	170
3	4	0.263	282125	4231.875	%CV	4
		df	500			
Shredded paper						
Rep	Sample (g)	Abs	OP (µg/L)	OP (mg/kg, db)	OP (mg/kg, db)	
1	4	0.025	-6150	-90.44117647	Average	-90
2	4	0.026	-5650	-83.08823529	Std	7
3	4	0.024	-6650	-97.79411765	%CV	-8
		df	200			

Negative values for shredded paper are considered undetected

Table B VI. Data for pH

Raw poultry litter				
Rep.	pH	Average	Std	%CV
1	8.23	8.26	0.03	0.37
2	8.25			
3	8.29			
Hot Composted poultry litter				
Rep.	pH	Average	Std	%CV
1	8.32	8.30	0.03	0.32
2	8.27			
3	8.31			
Cured poultry litter				
Rep.	pH	Average	Std	%CV
1	8.91	8.94	0.04	0.40
2	8.93			
3	8.98			
pH adjusted poultry litter				
Rep.	pH	Average	Std	%CV
1	7.35	7.13	0.18	2.52
2	7.38			
3	7.33			
4	7.03			
5	7.05			
6	7.09			
7	6.91			
8	6.93			
9	7.09			
Shredded Paper				
Rep	pH	Average	Std	%CV
1	7.01	7.02	0.01	0.08
2	7.02			
3	7.02			

Table B VII. Data for Electrical Conductivity (dS/m)

	Rep. 1	Rep. 2	Rep. 3	Average	Std	%CV
Raw litter	***10.08***	12.90	12.10	12.50	0.57	4.53
Hot composted	12.09	***13.69***	10.54	11.32	1.10	9.69
Cured compost	12.39	11.65	12.21	12.08	0.39	3.19

Values in Bold and Italic text were omitted to get %CV close to 10%

Table B VIII. Daily mean temperature values during microbial composting

	Temperature (^0C)			Temperature (^0C)
Time (Day)	Hot Compost	Cured Compost	Time (Day)	Cured Compost
0	54	60	25	22
1	46	30	26	23
2	26	23	27	26
3	26	24	28	26
4	34	24	29	17
5	32	26	30	13
6	21	50	31	17
7	26	41	32	17
8	29	28	33	17
9	28	23	34	17
10	28	29	35	18
11	22	26	36	21
12	35	26	37	24
13	56	27	38	28
14	56	45	39	27
15	36	28	40	28
16	20	28	41	28
17	19	25	42	28
18	19	24	43	29
19	20	24	44	31
20	21	25	45	32
21	22	26	46	32
22	23	28	47	33
23	25	25	48	31
24	22	22	49	30

Table B IX. Earthworm live biomass after eight weeks of vermicomposting at feeding frequency 1/wk

C/N Ratio	Litter Type	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5
As Is	All	0.00	0.00	0.00	0.00	0.00
10	All	0.00	0.00	0.00	0.00	0.00
30		2.43	29.64	2.60	1.89	5.86
50		23.35	29.19	12.14	10.48	36.22
70		15.17	15.70	12.46	32.17	21.31
90		22.90	13.50	17.37	7.27	24.33
110	RL	17.99	13.50	20.43	14.93	21.40
30		0.00	3.84	4.06	0.69	3.40
50		22.76	23.70	11.78	15.48	26.30
70		16.55	16.88	19.24	26.44	26.72
90		16.26	11.39	10.13	28.10	15.57
110	pH	17.34	16.13	15.59	20.45	20.73
30		0.00	10.69	2.79	3.16	4.05
50		15.42	21.97	34.21	22.05	17.43
70		20.09	20.06	25.91	25.16	27.04
90		10.12	20.48	24.64	30.33	35.51
110	HC	15.92	14.95	9.56	1.68	20.15
30		0.00	10.36	0.00	16.23	5.95
50		13.74	22.59	12.74	26.24	34.60
70		11.77	17.38	20.17	20.59	20.44
90		18.00	12.57	27.99	50.45	20.41
110	CC	16.67	12.35	17.73	31.27	13.22

Table B X. Earthworm live biomass after eight weeks of vermicomposting at feeding frequency 1/wk

C/N Ratio	Litter Type	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5
As Is	All	0.00	0.00	0.00	0.00	0.00
10	All	0.00	0.00	0.00	0.00	0.00
30		0.00	0.00	0.00	5.94	1.83
50		0.00	2.40	8.96	20.41	29.66
70		0.00	0.24	20.91	40.30	20.20
90		7.76	11.59	1.51	28.04	6.80
110	RL	0.00	0.45	13.79	15.46	35.36
30		0.00	0.00	1.99	1.89	1.35
50		0.00	3.18	0.00	16.33	13.22
70		0.00	5.83	14.89	17.23	25.57
90		2.24	8.99	6.72	0.00	28.20
110	pH	0.00	0.00	7.23	8.65	21.22
30		0.00	0.00	0.00	0.00	0.00
50		1.12	3.77	8.98	7.02	0.00
70		17.04	5.67	9.37	21.66	18.36
90		6.40	0.00	21.17	38.29	25.45
110	HC	15.44	10.31	18.22	15.19	23.53
30		0.00	0.00	1.27	9.05	0.00
50		15.63	18.67	18.86	18.27	20.20
70		7.76	3.36	13.36	15.21	24.12
90		22.66	18.16	31.42	19.60	29.70
110	CC	9.52	13.26	18.46	15.35	22.91

Table B XI. Volatile solids (%) after eight weeks of vermicomposting at feeding frequency of 1/wk

C/N ratio	Litter Type	Rep. 1	Rep. 2	Rep. 3	Rep. 4	Rep. 5
30		63.04	53.06	57.74	57.07	58.92
50		61.97	64.68	61.25	63.86	62.86
70		73.46	68.99	71.73	68.93	67.56
90		74.12	74.32	70.77	69.89	73.21
110	RL	75.17	74.57	72.59	70.23	70.95
30		62.70	56.77	57.97	57.26	57.47
50		68.41	62.05	63.79	66.50	63.20
70		69.59	68.11	68.05	68.80	68.38
90		75.45	72.63	71.56	69.50	70.35
110	pH	74.01	75.48	71.34	71.46	72.78
30		61.59	59.01	57.53	56.92	56.16
50		70.08	63.23	64.73	65.41	58.60
70		71.03	69.21	67.60	65.21	67.72
90		71.73	71.27	71.11	66.36	67.48
110	HC	76.67	73.55	72.80	71.26	72.66
30		57.28	56.13	56.21	53.41	54.98
50		66.12	62.12	63.38	59.27	59.43
70		70.25	67.73	69.86	65.41	68.51
90		73.06	70.40	72.53	69.55	63.41
110	CC	74.77	74.97	68.57	74.12	72.15

Table B XII. Volatile solids (%) after eight weeks of vermicomposting at feeding frequency of 1/8-wks

C/N ratio	Litter Type	Rep. 1	Rep. 2	Rep. 3	Rep 4	Rep. 5
30		49.23	58.04	48.59	55.64	42.43
50		75.92	59.10	55.95	45.09	47.87
70		71.73	75.37	69.68	65.53	59.54
90		68.10	72.07	74.11	67.80	76.07
110	RL	75.67	74.71	73.58	92.82	72.15
30		53.38	45.36	48.07	49.70	47.87
50		65.66	55.51	68.51	48.54	51.44
70		70.64	73.14	69.78	66.87	65.97
90		71.07	74.84	71.00	71.02	66.67
110	pH	74.51	73.51	73.73	71.94	69.59
30		45.66	53.26	46.63	51.34	44.28
50		64.03	57.10	53.81	45.89	51.39
70		65.27	62.66	61.31	59.88	61.37
90		69.92	66.14	59.99	56.39	60.45
110	HC	72.27	71.63	64.97	60.52	72.47
30		55.89	48.74	51.66	51.66	57.58
50		61.01	60.65	58.11	56.28	52.53
70		66.99	65.09	67.98	67.32	66.45
90		72.35	68.32	61.76	68.55	62.10
110	CC	70.21	71.62	67.51	64.76	58.96

Appendix C

Raw data for the Vermicomposted Raw Poultry litter at C/N of 50 and feeding frequency of 1/week

Table C I. Data for TKN

Rep.	Sample (g)	TKN (%, wb)	TKN (%, db)	TKN (mg/kg, db)
1	1.62	0.35	1.42	14200
2	1.64	0.47	1.85	18500
3	1.92	0.5	2.03	20300
4	1.35	0.48	2.11	21100
5	1.12	0.35	1.20	12000
Average	1.78	0.43	1.72	17220
Std	0.20	0.07	0.40	3954
%CV	11.12	17.17	22.96	23

Table C II. Data for Ammoniacal-N

Rep	Sample (g)	Abs	Am-N (mg/L)	Am-N (mg/kg, db)		Am-N (mg/kg, db)
1	1.0232	0.1832	1.04	62	Average	639
2	2.2631	0.189	1.22	73	Std	629
3	2.2631	0.399	7.78	467	%CV	99
4	2.3090	0.916	23.94	1436		
5	2.1678	0.766	19.25	1155		
		df	20			

Table C III. Data for Total Phosphorus

Rep.	Sample (g)	Abs	TP (μg/L)	TP (mg/kg, db)		TP (mg/kg, db)
1	1.0595	0.472	1087	10235	Average	10518
2	1.0378	0.535	1244	11718	St. Div	1661
3	1.0799	0.531	1234	11624	%CV	16
4	1.0858	0.366	822	7739		
5	1.0774	0.516	1197	11271		
		dilution:	50			

Table C IV. Data for Ortho-Phosphate

Rep	Sample (g)	Abs	OP (μg/L)	OP (mg/kg, db)		OP (mg/kg, db)
1	4	0.068	1535	23	Average	54
2	4	0.244	10335	155	St. Div	61
3	4	0.031	-315	-5	% CV	114
4	4	0.085	2385	36		
5	4	0.118	4035	61		
		dilution:	20			

Table C V. Data for Electrical Conductivity

Rep.	EC (dS/m)		
1	0.1	Average	0.15
2	0.2	Std	0.06
3	0.2	%CV	38
4	0.1		
5	0.3		

Table C VI. Data for pH

Rep.	pH	Average	St. dev	% CV
1	7.28	7.29	0.19	2.62
2	7.06			
3	7.2			
4	7.32			
5	7.58			

Table C VII. Data used to calculate Germination Index

Sample	No. of Seeds Germinated
DI Water	10
R-50-W-1	4
R-50-W-2	8
R-50-W-3	7
R-50-W-4	5
R-50-W-5	5

Sample	Seed Number	Root length (in)	Average (in)	Std (in)	%CV
DI water	1	4.5	4.06	1.18	29.13
	2	3.9			
	3	4.5			
	4	5.0			
	5	2.9			
	6	4.9			
	7	5.5			
	8	4.5			
	9	1.5			
	10	3.4			
R-50-1	1	4.0	3.35	0.59	17.66
	2	3.7			
	3	2.8			
	4	2.9			
R-50-2	1	4.8	3.21	1.41	43.85
	2	3.4			
	3	3.9			
	4	4.0			

	5	2.5			
	6	4.7			
	7	1.5			
	8	1.0			
R-50-3	1	2.9	2.53	0.56	22.24
	2	3.1			
	3	3.2			
	4	2.0			
	5	1.8			
	6	2.3			
	7	2.5			
R-50-4	1	1.8	1.98	1.02	51.65
	2	1.8			
	3	3.0			
	4	2.9			
	5	0.5			
R-50-5	1	3.9	3.68	1.26	34.30
	2	4.8			
	3	5.0			
	4	2.3			
	5	2.5			

R-50 = Raw poultry litter at C/N of 50

VITA

Arbab Asad Khan

Candidate for the Degree of

Master of Science

Thesis: VERMICOMPOSTING OF POULTRY LITTER USING EISENIA FOETIDA

Major Field: Biosystems Engineering

Biographical:

Personal Data: Born on January 3, 1979 in Peshawar, Pakistan. Son of Arbab Ayub Jan and Zohra Khatoon.

Education: P.A.F High School, Peshawar, Pakistan; Associate of Science, Tulsa Community College, Tulsa, Oklahoma; Bachelors of Science, University of Oklahoma, Norman, Oklahoma; Completed the requirement for the Master of Science at Oklahoma State University in December, 2006.
Experience: Research Assistant, University of Oklahoma, summer 2000; Research Assistant, University of Oklahoma, 2004; Graduate Assistant, Oklahoma State University, 2005-Present.