Compost Science & Utilization, (2005), Vol. 13, No. 3, 180-193

Carcass Composting for Management of Farm Mortalities: A Review

A. Kalbasi[1], S. Mukhtar[2], S. E. Hawkins[3] and B. W. Auvermann[4]

1. Assistant Prof., Food Technology & Engineering Department, Tehran University, Karaj, Iran

2. Associate Prof., Biological and Agricultural Engineering Department, Texas A&M University, College Station, Texas

3. Assistant Prof. of Agricultural Engineering Department, Purdue University, Lafayette, Indiana

4. Associate Prof., Biological and Agricultural Engineering Department, Texas A&M University, Amarilo, Texas

For the last two decades, carcass disposal by burial is being replaced with alternatives such as composting. Improper animal mortality disposal may generate various environmental and health hazards such as odor nuisance (resulting from the anaerobic breakdown of proteins) that can reduce the quality of life and decrease property values. Pathogens, which may still be present in the decomposed material, are capable of spreading diseases in soil, plants, animals and humans. The potential leaching of harmful nitrogen and sulfur compounds from animal mortalities to ground water is another concern. To control these side effects, compost facility operators need to know and understand the science, and guidelines of the carcass composting. While basic principles of carcass composting are similar to those for composting of organic materials, its management issues including appropriate composting methods for large or small scale carcass composting, quantities and types of carbon sources, composting time, odor and leachate control, and equipment requirements differ from composting of organics. The purpose of this study is to review the previous works related to carcass composting and provide information on recent advances in small and large-scale carcass composting enabling higher decomposition rates, minimum usage of carbon source materials, easier and shorter management control strategies and reduced land requirement while producing a useful end product without negative impact on public safety and environmental parameters.

Introduction

The livestock and poultry industry has historically been one of the largest agricultural businesses in the United States. According to Spark Company Inc. (SCI 2002), the market for U.S. meat and meat-based products require the annual slaughter of roughly 139 million head of cattle, calves, sheep, hogs, and other livestock, as well as 36 billion pounds of poultry.

More than 8.5 billion broilers were raised for commercial sale in the United States in 2003. Out of this production, about 78 million birds died from diseases, natural causes, or from other reasons such as natural disasters before they were marketable (U.S. Department of Agriculture, Economics and Statistics System 2003). As more poultry is consumed, the gross liveweight of nonconsumable carcasses is expected to climb. The weight of ruminants' mortalities (cattle, sheep, lamb, and goats) accounts for about 67% of the total food animal production death loss prior to slaughter each year (SCI 2002).

The high rate of animal mortality coupled with disposal of carcasses poses considerable economic burden on livestock and poultry producers. In 1998, Texas Floods resulted in livestock losses estimated to be approximately $11 million over 20 counties (Ellis 2001). In 1999, the Hurricane Floyd in North Carolina resulted in estimated losses of livestock and poultry valued at approximately $13 million (North Carolina State Animal Recovery Team, NCSART 2001). The high costs of incineration, rendering and, to some extent, burial for carcass disposal were the additional economic drain as a result of these disasters. Carcass composting is relatively less capital intensive than incineration and rendering, a better alternative to burial in areas with shallow water tables, and provides for a quick removal and isolation of farm mortalities. In addition to economic consequences, catastrophic mortality losses and their disposal methods may threaten the public health or environment. Regulatory agencies have established rules and standards to prevent the undesirable environmental impacts from improper carcass disposal. These rules not only prohibit carcass disposal in a manner that may contaminate air and water resources but also require timely isolation and removal of the dead animals from the premises to control disease transmission. For example in Ontario, Canada, livestock producers must dispose of their dead animals within 48 hours of death (Ontario Ministry of Agriculture and Food, "Managing On-Farm Mortalities Act" 2001). In Minnesota, Texas and Indiana, dead animal carcasses must be properly disposed of within 24 hours of euthanasia (Morse 2001, Texas State Soil and Water Conservation Board 2002, and Indiana State Board of Animal Health 2002).

"Carcass Composting" began in the poultry industry during the late 1980s, when dead chickens were fully biodegraded in only 30 days (Murphy and Handwerker 1988). In the 1990s, turkey producers used composting successfully for the larger carcasses. Since this process was a relatively simple technique, it was quickly adopted by the poultry industry in the southern and eastern coastal states. However, producer concerns about its year round applicability in colder climates slowed the adoption of carcass composting in northern states (Glanville and Trampel 1997). According to Dougherty (1999), over 8,000 farms were composting animal mortalities, manure, crop residues, and selected organic materials from communities and industries.

Definition, Basic Parameters And Their Consequences

The process of carcass composting can be described as temporarily burying dead animals above ground in a mound of supplemental carbon and allowing decomposition by thermophilic microorganisms to heat up the pile, kill most of the pathogens and digest the carcass tissues under predominantly aerobic conditions. Furthermore, the carcass compost pile is an inconsistent mixture of (a) an animal mass with relatively large amounts of water, high nitrogen, low carbon content, and low porosity surrounded by (b) a cocomposting material of good porosity, high carbon, low nitrogen, and low to moderate moisture. Documenting the role of various factors in carcass composting and their effects in changing the physical, chemical and biological properties of the carcass will provide information needed for better composting control and management.

Effective Factors and Performance Indicators

Temperature

Composting biomass components is a nonsteady-state process. Many researchers (Murphy and Carr 1991; Rynk 1992; Haug 1993; Diaz *et al.* 1993; Manser & Keeling 1996; Morris *et al.* 2002; Reinikainen and Herranen 1999; Keener *et al.* 2001; Harper *et al.* 2002; and Langston *et al.* 2002) have divided the composting process into two major phases. The first phase, the *developing* or *heating phase,* is characterized by high oxygen consumption, thermophilic temperatures (> 55°C or 131°F), rapid reductions in biodegradable volatile solids (BVS), and odor potential. In the *maturation* or *curing* (second) *phase*, a series of slower reactions (e.g., the digestion of lignins) occur, and aeration is no longer a limiting factor.

Harper *et al.* (2002), Keener and Elwell (2000), and Langston *et al.* (2002) indicated that the rate of the decomposition process at thermophilic temperatures ranging from (40°C [105°F] to 71°C [160°F]) is much faster than that of a mesophilic range of (10°C [50°F] to 40°C [105°F]). Since weed seeds are usually destroyed at 62°C (144°F), thermophilic temperatures inactivate weed seeds, which may be present if the animals ingested weeds (Looper 2002).

The temperature rise in composted piles lasted one and five months respectively for the horse carcass with 2.5 cm (1 in) and the cow carcass with 20 cm (8 in) gross rainfall (Mukhtar *et al.* 2003). Furthermore, within a few days of pile construction, the temperatures measured below and above cow and horse carcasses in compost piles exceeded 55°C (131°F). The temperature below the carcasses remained 5-10°C (41-50°F) higher than the above temperature, presumably due to higher moisture content below the carcasses.

While thermophilic temperatures eliminate pathogens more effectively than mesophilic or ambient process, cold weather does not seriously affect composting process as long as the piles are adequately sized and properly loaded (Kashmanian and Rynk 1996). In other words, the cold weather may decreases the carcass decomposition rate and prolong composting time due to reduced microbial activity at or near the pile surface. Conversely, excessively high temperatures may also inactivate beneficial microorganisms, primarily *Aspergillus niger* and *Trichoderma reesei.* These organisms convert cellulose, hemicellulose, and lignin of supplemental carbon from the cocomposting material to smaller molecules, and finally, to CO_2 to neutralize the free ammonia and maintain pH at or near neutral. These microorganisms are destroyed when exposed to temperatures of 60°C (140°F) to 70°C (158°F) for more than two to three hours (Jimenez *et al.* 1995, Busto *et al.* 1997, and Kube 2002). Hoitink and Keener (1993) confirmed that fungi effectively assimilate complex carbon sources such as lignin or cellulose that are not available to most bacteria; however, fungal activity is greatly restricted above 55°C (131°F). They observed that at high temperatures [60-70°C (140-158°F)], many carbon-digesting enzymes will be inactive, nitrogenous compounds will be lost, and unpleasant nitrogen gases will be produced. Therefore, most desirable temperatures during the first phase of carcass composting range between 55°C (131°F) and 60°C (140°F).

Time, Weight and Volume Loss

The composting time depends on the size and weight of carcasses, temperature profile, material formulation, preparation processes, aeration and management decision (e.g., monitoring of pile conditions, turning and moving piles that have transitioned from the primary to secondary phase, and moving to storage/curing areas). Keener *et al.* (2001) classified carcasses into four different weight groups, small, or less than 23 kg (50 lb) with an average of 10 kg (22 lb), such as turkey; medium, or 23 to 114 kg with an average of 70 kg (50-250 lb, with an average of 154 lb), such as swine; large, or 114 to 227 kg with an average of 170 kg (250-500 lb, with an average of 374 lb), such as a calf; and very large and heavy carcasses, those exceeding 227 kg (500 lb), such as mature bovines and horses.

Composting of 183.7 kg (405 lb) swine mortality was accomplished successfully in 171 days or at an approximate composting rate (ACR) of 1 kg/day (Harper *et al.* 2002). Decomposition of a mature dairy cow carcass with the average weight of 455-545 kg (1000-1200 lb), generally takes up to eight months (ACR=2kg/day), with a few pieces of bones remaining (Granatstein 1999, Looper *et al.* 2002, and Mukhtar *et al.* 2003). It takes approximately 10, 90 and 180 days respectively for small, medium and large carcasses (ACR=1kg/day) to finish their decomposition process (Murphy and Carr1991, Fulhage 1997, Mescher *et al.* 1997, Keener and Elwell 2000, and Sander *et al.* 2002). Composting of large and intact cattle carcasses takes nine months or ACR=1kg/day (Sander *et al.* 2002). Harper *et al.* (2002) reported that the final weight of 26.1 kg (58 lb) of afterbirth and dead piglets after composting for two weeks was only 3.1 kg (6.9 lb), and the remaining tissue was easily crumbled in the sawdust medium (ACR=1.6kg/day). It may be concluded that the overall composting rate of intact mortality in a properly managed pile during its two phases depends on the original carcass weight and is approximately 1-2 kg (2.2- 4.4 lb)/day. At compost pile temperatures below 40°C (105°F) the maturation phase could be as long as five months (Bollen *et al.* 1989).

Various carcasses and cocomposting materials have different rates of shrinkage during the compost process. After three months of composting swine and cow carcasses, the final volumes of the piles were 20% and 25% less, respectively, than those of the original piles (Langston *et al.* 2002 and Kube 2002). Looper (2002) and Fonstad *et al.* (2003) reported that in a properly managed compost pile in which a core or central temperature reached at 63°C (145°F) within three to four days, the volume of cattle carcasses was reduced from 55 to 65% of the original volume after two months.

Porosity

The air-filled porosity affects availability of oxygen, temperature, microbial activity, composting time, and bulk and packed densities. This porosity should be around 35% to facilitate the air penetration inside the pile and maintain optimum microbial growth (Keener *et al.* 2001, Harper *et al*., 2002, and Looper 2002). In a composting process, aeration and degradability can be improved by reducing the particle size while increasing the surface area, as long as porosity remains above 30% (Rynk, 1992). Looper (2002) indicated that the optimum particle size of cocomposting material for proper aeration of a carcass compost pile ranges from 3.1 to 12.7 mm (1/8 to 1/2 in). Compost pile moisture in excess of 60%, reduces its air-filled porosity and retards its aerobic activity (Murphy and Carr 1991, Kube 2002, and Looper 2002).

Oxygen and Aeration

When there is not enough air in the compost pile, its aerobic biodegradation to decompose organic material decreases, nitrogen loss by denitrification increases and the temperature diminishes (Henry 2003). Aeration by turning the compost piles containing cow and horse carcasses coupled with a series of rainfall events, resulted in temperature rise to 74°C (165°F) within five days of aeration (Mukhtar *et al.* 2003). The temperature remained above or near 55°C (131°F) for three months after aeration.

Due to the inconsistency of materials in carcass composting, proper aeration may be achieved by forcing air through the material, passive air exchange, mechanical turning and/or their combinations (Henry 2003). Chaw (2001) used a mechanical forced-aeration system to compost sheep offal mixed with carbon sources (mixture of coarse wood chips and sawdust with offal materials in volume ratio of 1:1). The blowers provided air to PVC pipes buried in the channels of a four-bin rotational bunker system. Within the first 10 days the temperature of first phase bunkers remained above 50°C (122°F) and the blowers were able to maintain adequate oxygen levels between 10-20% by volume.

C:N Ratio

Addition of carbon source materials to carcasses provides suitable conditions for successful composting. It facilitates proper aeration, speeds the escape of potentially toxic gases like ammonia, reduces the accessibility of composted material to insects and rodents and provides additional energy for microbial (specifically fungal) activities (Rynk 1992; Haug 1993; Sander *et al.* 2002). Acceptable C:N ratio generally ranges from 25:1 to 40:1, and may even reach as high as 50:1 (Murphy and Carr 1991; Glanville and Trampel 1997; Keener and Elwell 2000; Franco 2002; Bagley 1999).

Reduction of the C:N ratio during the composting process is a good indication of digestion of carbon sources by microorganisms and production of CO_2 and heat. Mukhtar *et al.* (2003) composted cow (909 kg, 2,000 lb) and horse (500 kg, 1,111 lb) carcasses using spent horse bedding as a cocomposting material. They reported that after nine months of composting, the C:N ratio of finished product was nearly one half of the C:N ratio of the mixed raw materials at the beginning of first phase.

pH

Alkaline (pH > 7) or acidic (pH < 7) environments are not well suited to carcass composting. A large amount of free carbon blended with the nitrogenous materials of carcasses not only helps nitrogen immobilization and prevents its loss by ammonification, but also maintains the pH of carcass pile at neutral (7.0) or slightly lower (Henry 2003). Since the biochemical reactions release CO_2 (a weak acid) and NH_3 (a weak base), the compost process can buffer pH near the neutral range as composting proceeds (Haug 1993). This CO_2/NH_3 buffering system requires that free carbon and nitrogen be present in a suitable ratio.

A proper C: N ratio keeps pH in the range of 6.5 to 7.2, which is optimum for composting (Carr *et al.* 1998). They suggested that the pH could be reduced by adding an inorganic compound, such as granular ferrous sulfate. When the pH of compost pile reaches a range of 8 to 9, strong ammonia and amine related odors may be generated for the first two weeks of composting (Henry 2003). Langston *et al.* (2002) indicated that a pH of 6.5-8.0 is optimal for dead swine composting.

Gases and Odors

Anaerobic decomposition of carcasses at the beginning of the first phase produces unpleasant gases (NH_3, H_2S, etc.) and odors associated with the liquid or solid biomass. By further decomposition, liquids and gases move away from the carcasses into the aerobic zone of cocomposting materials which act as a biofilter, where they are degraded by microorganisms to carbon dioxide and water (Keener *et al.* 2001 and Bagley 1999). A biofilter is a layer of sorptive and reactive carbon, which deodorizes the unpleasant gases released, treat potential air pollutants in gas streams from compost materials, and maintain proper conditions of moisture, pH, nutrients, and temperature to enhance the microbial activities (Hoitink and Keener 1993).

Using Olfactometry, Glanville (2002) evaluated odors released from compost piles constructed with silage and carcasses, cornstalk and carcasses, and hay/manure and carcasses. It was reported that within seven days of composting, the odor levels of all piles were reduced by more than 80% compared to the original fresh materials.

Odorants associated with composting include dimethyl disulfide, dimethyl sulfide, carbon disulfide, ammonia, trimethyl amine, acetone, and methyl ethyl ketone. Wood ash, with about 32% carbon and 85 m^2/g surface area , possessed odor neutralizing characteristics similar to activated carbon (87% purity and 520 m^2/g surface area) and was able to absorb compost odors effectively (Rosenfeld and Henry 2001). The odor reduction was probably a result of the neutralization of acidic gases by the alkaline portion of the wood ash.

Raw Materials And Energy Requirements

Carcass alone is not a suitable substrate for proper composting and it is necessary to prepare the cocomposting materials such as moisture and carbon sources.

Moisture

Water, as a medium, transports nutrients to the beneficial microorganisms thereby facilitating production of required enzymes in the compost process. The required moisture content (wet basis by mass) for the carcass compost pile depends on the material characteristics but ranges from 40-60% (Murphy and Carr 1991, Keener *et al.* 2001, and Franco 2002). As it was noted before, excess water (> 60%) removes oxygen from small pores of compost pile and inhibits its aerobic activity. Additionally, it creates conditions that favor odor production in the pile and restrict its temperature rise (Murphy and Carr 1991, Kube 2002, and Looper 2002). Saturated piles quickly exclude the oxygen needed to degrade the more odorous compounds and support thermophilic microbes. However, turning the compost over and adding more dry absorbent materials likely solves the problem. As a rule of thumb, if the compost mixture feels moist without water dripping from a handful when squeezed, the moisture is adequate (Looper 2002).

Carbon Sources

Raw materials that provide supplemental carbon to microorganisms also absorb excess moisture from the carcass, distribute moisture content throughout the compost bulk, maintain porosity (low bulk weight) and modify the C:N ratio of the pile. For example, sawdust is an excellent carbon source because of its small particle size, high specific surface area and ability to absorb excess moisture or leachate generated during carcass composting (Fulhage 1997). Mixtures of sawdust and straw may be used to construct compost piles (Keener and Elwell 2000). Sometimes, straw or ground corn stover, which has a high C: N ratio and is a good absorbent, can be used alone in compost pile. Additionally, other carbon sources including poultry litter, ground corncobs, baled corn stalks, and semi-dried screened manure, hay, wood shavings, paper, silage, leaves, peat, rice and peanut hulls, cotton gin trash, low nitrogen yard wastes, vermiculite, and a variety of waste materials like matured compost could be used.

A 50:50 mixture (by volume) of separated solids from manure and a carbon source can be used as a base material for carcass composting (Looper 2002). Recently, Mukhtar *et al.* (2003) used spent horse bedding, a mixture of horse manure and pinewood shavings, for composting cow and horse carcasses and obtained successful results. Bulking agents, such as hay and straw, should have a three-dimensional matrix of solid particles capable of providing structural support and maintaining air spaces within the compost matrix (Haug 1993).

Materials such as spent horse bedding, wood chips, rotting hay bales, peanut hulls, and tree trimmings can be used as bulking amendments. Although there is not enough information on the necessary amounts of bulking agent and biofilter materials needed for specific weight of carcasses, they tend to be added in excess of the optimum 30:1 C:N ratio for composting. A minimum of 30 cm (12 in) biofilter materials is required to cover each carcass compost pile [Colorado Governor's Office of Energy Management and Conservation (Colorado GOEMC) 2003, Morse 2001, and Underwood 1999]. According to Haug (1993) and Morris *et al.* (2002), the ratio of bulking agent to the mixed materials (carcass and carbon sources) should provide adequate air spaces (around 35% air-filled porosity) within the compost pile and the bulk density of final compost mixture should not exceed 600 kg/m^3 (37.5 lb/ft^3). Morse (2001) reported that dry hay will have a higher C:N ratio than green or leguminous hay. Crop residues such as wheat straw or corn stalks can be used as a bulking agent for carcass composting but may require shredding or grinding.

Carcass Composting Microorganisms

The mesophilic and thermophilic species of three groups of microorganisms [bacteria (main portion), fungi, and actinomycetes] are present and active in carcass composting materials. The microbial flora and their activities in different sections of similar compost piles at a given time are not the same and are continuously changing. To provide good microbial flora for the new carcass composting pile and reduce the volume of storage for mature compost, it is often helpful to inoculate (up to 50:50 by volume) fresh material with active compost made from that same material and retain nearly one-half of the original carbon sources (Fulhage 1997 and Langston *et al.* 2002).

Bacteria tend to flourish in the early stages of composting and are faster decomposers than other microbes. However, the fungi and actinomycetes become more important near the end of the composting process. The fungi are more tolerant of low moisture and low pH conditions, but less tolerant of low-oxygen environments than bacteria, and are better decaying agents on woody substrates (Rynk, 1992). Nearly all active microorganisms of a compost pile will die if the temperature continues to rise above 70°C (158°F) leaving only the heat-resistant spores formed by certain species of bacteria and actinomycetes.

Determining Composting Recipes

Producing a good end product without any offensive environmental aspects depends heavily on achieving a proper ratio of carbon to nitrogen. Fulhage (1997) obtained good results by adding 2.8 m^3 (100 ft^3) of sawdust per 454 kg (1,000 lb) of carcasses in a compost bin and by amending the mixture with ammonium nitrate to increase the available nitrogen for carcass composting. Lawson and Keeling (1999) were able to decompose 188.5 kg of laying hens successfully with straw (18.85 kg), poultry litter (377 kg) and water (47.13 kg). In another experiment wheat straw, peanut hull, turkey cake and water were mixed with pig mortalities respectively in ratios of 10%, 20% 150% and 275% of carcass weight and infected with *Salmonella spp*, *Pseudorabies virus* and *Erysipelothrix rhusiopathiae.* The composting process of this mixture disintegrated most of the carcasses and reached temperatures sufficient to kill all of the infectious microorganisms (Sherman-Huntoon 2000).

Werry (1999) mixed sawdust with mortalities, and recommended 1 kg (2.2 lb) sawdust per 1 kg of mortalities in a static pile or windrow. Granatstein (1999) composted 500-545 kg (1100-1200 lb) dairy cow mortalities separately with equivalent volumes of two bedding materials (wheat straw and sawdust). Within two weeks the sawdust pile reached to 60°C (140°F) and straw pile to 49°C (120°F). Although the straw pile absorbed less leachate and produced more odor than sawdust bedding at similar moisture content, it had a faster rate of carcass decomposition than sawdust pile. It can be concluded that the right weight ratio of sawdust/wheat straw (most probably 4-5:1) will support an adequate heating phase for pathogen destruction, absorb more leachate and produce less odor than sawdust or straw bedding alone. Dougherty (1999) provided a table of cocomposting materials containing the optimum values of C:N ratio, moisture content, oxygen concentration, particle size, porosity, bulk density, pH, and temperature of an active compost pile.

Langston *et al.* (2002) reported that blending broiler litter and swine carcasses with high-carbon, low-nitrogen materials, such as wheat straw and sawdust, increased the average C:N ratios from 15:1 to between 25:1 to 30:1 and improved pile porosity. They reported that wheat straw has been the favored carbon amendment for poultry carcass composting due to its high C:N ratio (up to 150:1) and its moisture-absorbing capability. Adding sawdust to poultry litter increases the carbon content without substantially increasing the nitrogen content of the compost. They recommended blending sawdust uniformly with the litter and using 0.90-1.13 kg (2-2.5 lb) of this mixture to 0.45 kg (1 lb) of swine carcass (weight ratio of 2-2.5/1 for cocomposting materials to mortality). Carr *et al.* (1998) suggested ratios of 20:1 to 35:1 for C:N and 100:1 to 150:1 for carbon: phosphorus for desirable carcass composting. Sussman (1984), Rynk (1992) and Dougherty (1999), respectively prepared information regarding nutritional requirements for composting poultry mortality, recommended conditions for active composting and described properties of cocomposting materials.

Heat-Energy

The heat energy required for inactivation of microbes is a function of both temperature and length of exposure. The inactivation energy (obtained from time/temperature relationship equation or Arrhenius Model) is between 50 and 100 kcal/g-mol (200 and 400 BTU/g-mol) for many spores and vegetative cells (Haug 1993). Based on this theory, he calculated the heat inactivation of enteric (related alimentary tract or intestine) pathogens by considering the conditions common to composting, and concluded that the average temperatures of 55 to 60°C (131 to 140°F) for a day or two will provide this energy and should be sufficient to reduce essentially all pathogenic viruses, bacteria, protozoa (including cysts), and helminth ova (an intestinal or parasitic worm such as a tapeworm, liver fluke, Ascaris or leech) to an acceptably low level. However, the endospores produced by spore-forming bacteria (e.g. *Bacillus anthracis*) would not be inactivated under these conditions, nor are prions like the BSE (bovine spongiform encephalopathy).

Thermal inactivation within the compost pile is an effective way to destroy pathogenic microorganisms such as *Escherichia coli*. Jiang *et al.* (2003) studied thermal inactivation of a five-strain mixture of this microorganism and added it to (1) sterilized cow manure (autoclaved at 121°C [250°F] for 20 minutes for three successive days and at 1 bar [15 psi]) and (2) un-sterilized composted cow manure with a moisture content of 38%. Microbiological tests showed that for 6 log CFU (colony forming unit)/g reductions of E. coli O157:H7, the temperatures of 50, 55, 60, 65, and 70°C (122, 131, 140, 150, and 158°F) for a minimum of 14 hours, 4 hours, 25 minutes, 11 minutes, and 6 minutes, were needed, respectively for sterilized cow manure. Similarly, the temperatures of 50, 55 and 60°C were necessary for un-sterilized composted cow manure for a corresponding time of 14 hours, 4 hours and 24 minutes, respectively. These results indicate that temperatures of 55-60°C (131-140°F) for more than 4 hours will inactivate pathogenic microorganisms, as long as heating process is continuous and almost uniform throughout the compost pile.

Proper sizing of composting facilities has a considerable effect on heat retention during composting and becomes an important consideration in cold climates, in which, substantial heat loss can take place at the perimeter of the composting bin (Glanville and Trampel 1997). Within the temperature range desirable for composting (45 to 65°C); bacterial activity roughly doubles with each 10°C (18°F) increase in temperature. Glanville and Trampel (1997) also indicated that a small composting operation with a low volume and high surface area could be significantly impaired by low ambient temperatures. They studied the winter time composting process of poultry carcasses conducted in outdoor bins with external temperatures ranging from –15 to 0°C (5 to 32° F). They observed that temperature measured at locations less than 15 cm (0.5 ft) from bin walls were often 25 to 30°C (77 to 86°F) cooler than the temperature near the center of the bin. As the composting bins used in this work were relatively large (2.4 m long X 1.8 m wide X 1.5 m high), composting was not seriously hampered because the cool zone near the walls did not comprise a large portion of the total volume. Looper (2002) suggested that any compost pile should include a layer of inactive material approximately 30 cm (1 ft) thick to insulate and maintain high temperatures throughout the bulk of active compost.

Equipment

Carcass composting is becoming more widely used and animal producers are expanding their composting management strategies to use the best available and economically feasible equipment and devices for easy operation and to avoid any direct contact with raw materials.

Different types of agricultural equipment for moving, lifting, loading, unloading, dumping, displacement, formation, and turning of composting piles have been used in bin and windrow systems. In the event of catastrophic herd or flock mortality, the role and availability of suitable composting equipment will be more critical. However, extra equipment for pre-composting and post composting processes may accelerate composting processes and throughput.

Grinders and Shredders

Grinding of animal mortalities and carbon sources by Kube (2002) and Rynk (2003) produced a relatively homogenous mixture of raw materials that can be composted in bins, vessels or windrows. The basic design of the grinder-mixer was modified by including more knives on the auger, stationary knives mounted on the tub, and a different auger to adjust to the conditions of grinding and mixing large carcasses (Rynk 2003). In this system, the grinder-mixer was loaded with the appropriate amount of wheat straw and corn stalks. The amount of bulking agent was about 20% of the weight of the mortalities delivered. He recommended grinding and initially mixing the carcass with cocomposting materials for 15-45 min (depending on the nature of materials and particle sizes). After primary mixing, the materials are transferred by either loaders (to make windrow piles) or by conveyors into a composting drum for the first composting phase.

The most common shredding or grinding machinery used for reducing the particle size of raw feed stocks includes rotary augers with counter knife, tub grinder, shear shredders, and handfed chippers (disc type). In selecting a grinder, different criteria including capital investment, operating costs (including power consumption), appropriateness in relation to characteristics of carcasses and cocomposting materials, capacity and speed, safety aspects, compatibility with existing equipment, and maintenance requirements should be considered (Dougherty 1999).

Mixers

Mixing of ground carcasses with granules of a carbon source can take place in a rotating drum. Rynk (2003) suggested using a rotating drum 3 m (10 ft) in diameter and 15 m (50 ft) long for complete mixing as well as to complete the first phase of the composting process. Some of the larger rotating drums hold feedstock up to 90 cm (36 in) in diameter. The residence times of rotating drum mixers can vary from a few hours to several days, depending on the drum length, diameter, material depth, heat transfer coefficient of drum wall thickness, and rotation speed. The rotating process accelerates the decomposition to the point that the material leaving the drum is unlikely to produce odors or attract pests.

Screeners

The most common screeners used for separation of big particles from the finished compost product include disc screens, flexible oscillating (shaker) screens, belt screens, trommel screens, and vibrating screens (Dougherty, 1999). A trommel screen with perforations of less than 2.5 cm (1 in) was suggested for removing any remaining bones from the finished compost product (Sherman-Huntoon 2000 and Rynk 2003). Larger material remaining on the screen (primarily bones) is recycled back into active windrows. Fonstad, *et al.* (2003) successfully used a screener with a horizontal rotating tube and 19 mm openings and separated out any recognizable bone pieces form the composted carcasses.

Sometimes screening is done for adding carbonaceous raw materials with a desirable size to the compost pile. Carbon sources may have particle sizes ranging from 3.1-50 mm (0.125- 2 in) in diameter, Henry (2003) recommended using appropriate screen to remove particles bigger than 12.7 mm (1/2 in) from a carbon sources.

Loaders

Bucket loaders, skid loaders, and dump trucks have been used in carcass composting operations. Most skid-steer or front-end loaders convey either the whole carcasses and cocomposting materials or the mixture (ground and homogenized) of carcasses and carbon sources to the composting site and place them on the compost pile. Loaders can also cover the whole or ground carcasses with biofilter materials (such as finished compost), move compost from one bin to another for aeration and mixing, deliver, store, pile and load different materials (Fulhage 1997).

Sometimes, instead of bucket loaders and skid loaders, pickups fitted with (Tommy) lifts, wagons, dump trucks and farm trucks can be used for hauling and sorting carcasses along with transportation of mixed ingredients to the site and to build the initial pile or windrow if the composting site is far from the mixing area.

In case of composting intact carcasses, usually no need for mechanical disturbance until the pile is ready for the second composting stage. In the bin system, a front-end loader or skid-steer loader can be used to move materials from primary to secondary bins and can achieve optimum aeration.

Windrow Turners

Windrow turning is traditionally and conventionally associated with noncarcass composting. The term "turned" or "turning" in carcass composting is defined as a method used for aeration and if is applicable, tearing down a pile and reconstructing it (Haug 1993 and Diaz *et al.* 1993). The efficiency of this process arises from uniform decomposition that results from exposing, at one time or another, all of the composting material to the most active interior zone of a pile.

Manser and Keeling (1996) classified windrow turners into three groups: rotating-tiller turners, straddle turners, and side-cutting turners. The rotating-tiller turner is more common in carcass composting systems. Other types of turners include the auger-style, the elevating face conveyor, and the rotary drum with flails. Diaz *et al.* (2002) reported that self-propelled types of windrow turners are more expensive than towed types. However, the tow vehicle (tractor) can be used for other purposes between turnings. In addition to convenience, the self-propelled turners require much less space for maneuvering and therefore, the windrows can be closer to each other. Turning capacity of the machines ranges from about 727 metric tons/h (800 tons/h) to as much as 2,727 metric tons/h (3,000 tons/h) with the larger, self-propelled versions (Rynk 1992). Similarly, the dimensions and configuration of the windrows vary with type of the machine.

The windrow-rotating tiller (rototiller) has a small capacity and, because of its maneuverability, is most suitable for small operations. According to Diaz *et al.* (1993), it has the ability to tear down the pile and spread the composting material to form a 30-60 cm (12-24 in) layer and accomplish the turning process. The rototiller is then passed back through the layer. In order to have a uniform, high-quality, low-pathogenic end product, it is necessary to perform the agitation processes after the first phase for each kind of carcass. It is recommended that compost material be agitated and then reconstituted into another pile.

Some farmers use bulldozers and bucket loaders for turning windrows. Diaz *et al.* (2002) stated that bulldozers provide minimal aeration and the materials are often compacted instead of being mixed and restored to the original bulk density. While the large turners (mainly self propelled models) have higher windrow forming capacities and are less time consuming than small windrow turners such as bucket loader, their capital costs are much higher (Rynk 1992). This is why the use of a bucket loader for turning continues to be the predominant practice. Bucket loaders should be operated such that the bucket contents are discharged in a cascading manner rather than dropped as a single mass.

Devices for Monitoring and Control

The devices or instruments required for monitoring and controlling physical properties of a composting system include thermometers, oxygen measurement equipment, data acquisition devices or composting logs, pH meters, electrical conductivity or EC probe / meter, and moisture testers.

Thermometers

Experience has shown that monitoring temperature is a key diagnostic and management aid for carcass-composting operations. A probe-type thermometer with a 90 cm (3 ft) long stem preferably stainless steel is recommended (Rynk 1992). An alternative for the electronically inclined is the solid-state temperature data-loggers (e.g. Onset, Inc.). Monitoring temperature and anticipating problems such as odors or excessive moisture enables the operator to judge the progress of the composting process. This is particularly important in carcass composting because of both the increased odor potential and the possibility of sudden carcass collapse as compared to noncarcass compost pile.

Oxygen Measurement and Control

As mentioned earlier, measurement and control of oxygen content is a key to successful carcass composting. An advanced system for controlling the decomposition process in noncarcass composting was marketed as the Compo-Matic (Umwelt Elektronic GmbH and Co., 2003). This equipment represents a complete system for measuring, controlling and optimizing both oxygen and temperature during the composting process. It has a special insertion probe which contains an oxygen-temperature sensor. The oxygen saturation in the pile is monitored within the windrow, and then it is automatically regulated via an integrated aeration-control mechanism. A database system enables the parallel measurement and control of up to 16 oxygen and temperature measuring points and with a serial interface all measured data can be displayed by a personal computer. It is not necessary to automate all of these processes, however; they can be handled by a skilled manager familiar with optimum composting conditions if an O_2 sensor and long-stemmed thermometer are available.

Leachate Collector

Due to the high moisture content of carcasses (up to 75% for dairy cow) and effects of precipitation on the exposed compost pile, it may produce a considerable quantity of leachate. This leachate may run off or percolate the soil and contaminate surface or ground water.

Different instruments can be used to take leachate samples and measure their volumes and parameters such as ammonia, total nitrogen, chloride, phosphorus and biochemical oxygen demand. Half-sections of 15 cm (6 in) diameter PVC pipe mounted on a treated lumber support can be used as a leachate sample collector (Glanville 2002). These collectors are placed slightly higher in the center of the pile than at the edges and allow leachate to flow by gravity to plastic bottles at the end of the PVC troughs.

Composting Log

A logbook should be used to track dates, weights of carcasses placed in the composter, pile temperatures, amounts of bulking agent used, dates when compost is turned, amounts of finished compost and changes in moisture contents.

Carcass Composting Options

The primary goals of mortality composting are to prevent the transmission and dissemination of infection, minimize opportunities for infectious materials to contaminate important elements of the environment (air, water, soil, vegetation, etc) and to convert carcasses to beneficial end products. Usually, mortalities are layered into the pile with no mixing occurring until after the high rate sub-phase of composting has occurred and the carcasses have fully decomposed. Although most carcass composting systems work well with small amounts of mortalities (Mescher *et al.* 1997), their initial cost and management requirements differ widely. In this section, the two major systems of windrow and bin composting along with recently developed combined technique (vessel-windrow composting) will be discussed.

Windrow Composting

In this system, a pile is constructed on a compacted soil with low liquid permeability or sometimes on concrete pads. During emergencies, a windrow system that remains unturned for 90-120 days from initiation of composting can be used for 800-1,200 cattle carcasses with an average weight of 454 kg or 1000 lb (Glanville 2000).

Windrow system for carcass composting piles are generally located in open spaces and not protected from weather, rain, or wind. This situation exposes the pile to adverse weather conditions, which may affect the composting operation and its maturation process. On the other hand, loading, unloading and turning the composted carcasses from all sides of the pile is possible. Compost site operators extend the length of the compost pile and mound it to shed rainfall for better control of moisture, temperature, gases, and odors, and to maintain adequate biofilter cover. According to Henry (2003) aligning the uncovered stacks of carcass piles north to south and maintaining windrow with moderate side slopes maximizes solar warming and avoids accumulation of precipitation. Carcasses, nutrients, and bulking agents are placed in specific orders.

Bin Composting

Bin composting can be used for small and medium sized mortalities (swine and poultry). In this system, carcasses and cocomposting materials are confined within a container built by wooden and slatted walls, which usually have a roof. Temporary bins, which are constructed from large hay bales (with or without roof) are structurally adequate to confine the compost pile material and can be used for large carcasses (Fulhage 1997, Looper 2002 and Mukhtar *et al.* 2003). The simplest and cheapest can be constructed of large round bales placed end to end to form three-sided enclosures or bins. These so-called bale composters are unroofed and are therefore susceptible to precipitation and weather variations. Conversely, roofed composters are more expensive but have the advantages of reduced weather effects, better moisture control, lower leaching potential, and better working conditions for the operator during inclement weather (Fulhage, 1997). If less-absorbent carbon sources (e.g. ground cornstalks or straw) are used instead of sawdust, a roof may be required to exclude rainwater.

When the number and size of carcasses that can be placed in bins are few and usually limited to less than 18 kg (40 lb), a smaller version of a bin composter called a mini-composter may be used. In cold climates, additional insulation may be needed to enable the mini-composter to reach the desired temperatures (> 55°C or 131°F) for pathogen destruction and effective degradation (Keener and Elwell, 2000)

While the cost of installing some types of bin composting systems is higher than windrow-composting, bin systems have some advantages over windrows. The structure of bin composting allows higher stacking of materials, better use of floor space than free standing piles, elimination of weather problems when a roof is used, containment of odors, and better temperature control (Rynk 1992).

Mechanized Carcass Composting

Although bin composting of low volume of carcasses has proven to be a practical method with advantages that include simplicity and relatively low capital costs, using this system for a high volume of mortalities is more difficult and is greatly influenced by the type and number of mortalities, cocomposting materials and time. For massive mortality composting, Rynk (2003) indicated that this system requires diligence in filling bins, a large proportion of bulking agent and considerable space for the numerous bins and storage of bulking agents. To improve bin composting with fewer disadvantages and increase the rate of carcass decomposition, different methods have been practiced. Most of the efforts have been focused on making consistent and uniform raw materials (carcasses and carbon sources) by grinding and mixing and using either windrow system for the two phases or closed containers such as rotating vessel and aerated synthetic tube for the first phase and then windrow for the maturation phase of composting.

Grinding and Mixing

Small pieces of materials increase the ratio of surface area to volume in the carcass pile and composting process takes place much faster particularly if the particle sizes of carcass and cocomposting materials are similar (Bagley 1999; Looper 2002). To provide this condition, the grinding of carcasses and mixing with carbon source materials prior to composting has been practiced by some researchers. Cawthon (2000) used a horizontal, single auger feed mixer equipped with knives to macerate poultry carcasses and mix with bulking agents including sawdust, hay, and cotton gin trash. Kube (2002) compared two composting processes in a windrow system. One was ground Holstein steers (approximately 450 kg or 1000 lb) mixed with sawdust and the other, intact Holstein carcasses completely covered in sawdust. The grinding process reduced the number of turns from 3 to 1, and decreased the composting time from twelve to six months. In other words, grinding provided suitable conditions for early turning process and increased the composting rate considerably.

A study by the Colorado Governor's Office of Energy Management and Conservation or Colorado GOEMC (2003) used a vertical, dairy-type grinder mixer (up to 500 RPM) for preparation and mixing of mortalities and bulking agent prior to composting. Since the grinding process produced uniform materials with a much larger surface area exposed to oxygen, compost bacteria could attack and decompose the materials in a much shorter time than whole carcasses. By using this grinding step, the weight ratio of bulking agent to carcasses was reduced from 4:1 (for typical bin composting) to 1:4. Compared to bin composting, the composting time was also decreased between 30 to 60%. Colorado GOEMC (2003) concluded that in case of high mortality rate (more than 8000 lb/day or about 60000 lb/week), using a grinder before bin composting could save more than $80,000 due to the cost reduction in carbon sources, space, water and management. This saving is more than the cost of grinder (around $50,000).

A key advantage of grinding is the possibility of directly cutting and mixing carcass material with proper amounts of various bulking agents such as straw, grass, weeds, nonwoody yard waste, sawdust, wood shavings, old alfalfa, and woody materials (tree branches, processed wood, etc). Additionally, homogenizing and adjusting the moisture content to 50-60% is much easier than conventional bin or windrow carcass composting. Grinding makes it more practical to use bulking agents that have high C:N ratios, around 500:1, and are not as absorbent as straw for intact carcasses, peanut shells, and tree trimmings, which have been used mainly for plant residue composting.

Rotating Vessel

Using a vessel for the first phase of carcass composting is another approach to minimizing the time and management requirements. Cawthon (2000) used a macerated and blended mixture of poultry carcasses and different cocomposting materials (litter or sawdust as a carbon source) and then loaded the mixture into an in-vessel composter unit that was 1.8 m (6 ft) in diameter, 4.8 m (16 ft) long and turned at the rate of 4 revolutions per hour. Within hours compost temperature inside the vessel exceeded 60°C (140°F) and remained at this temperature for more than three days, after which materials were transferred into a bin for the second phase of composting. The temperature requirements for pathogen destruction of composting materials in vessel systems based on the Canadian Council of Ministers for the Environment (COME) regulations should be about 55°C (131°F) for three consecutive days (Chaw 2001).

Rynk (2003) reported that hog carcasses were ground and mixed with cocomposting material in a system in which the primary composting phase was carried out in a rotating vessel or drum followed by windrow composting. Results indicated that the in-vessel turning of mixture reduced the composting time to nearly 60% (180 days for large intact carcasses in bin system to about 75 days). He indicated that this method isolates mortalities from the surrounding environment, provides protection from weather effects, diminishes the risk of odor production and prevents scavenging. It also produced a more uniform product allowing better control over composting parameters such as temperature, moisture content, pH and particle size. Although processing of carcasses (splaying and grinding) and in-vessel composting requires higher initial capital investments, due to the higher throughput, lower consumption of carbon sources and shorter composting time, this approach has "significant effects on the economics of mortality composting." (Rynk 2003)

Cekmecelioglu *et al.* (2003) evaluated a similar system for composting a mixture containing food waste, manure, and bulking agent in a stationary polypropylene vessel for 12 days with aeration based on a 1/40 minute on/off cycle and compared its performance and final product with a conventional windrow composting system. They obtained the highest temperature rise of 50°C (122°F) with the in-vessel composting and reported that the best recipe for mixing food waste, manure, and bulking agent respectively was 50%, 40%, and 10% w/w. They observed similar inactivation trends for fecal *Coliforms* and pathogenic microorganisms in both in-vessel and windrow composting systems. While further research is needed to determine the applicability of this system, these results indicate that in-vessel composting has a good potential for carcass composting.

Aerated Synthetic Tube

An in-vessel system of composting organics using aerated synthetic tubes called EcoPOD (Preferred Organic Digester) or Ag Bags has been available commercially for the past 10 years (Ag-Bag Environmental, 2003). The system consists of a plastic tube about 60 m (200 ft) long and 1.5-3 m (5-10 ft) in diameter. These tubes are equipped with an air distribution system connected to a blower. Ground raw materials are loaded in to the tube with a feed hopper. Tubes used for medium or large intact carcasses are opened at the seam prior to loading raw materials and then sealed for forced air distribution during composting.

Farrell (2002) used the Ag Bag System and successfully composted biosolids with grass clippings and chipped brush and wood. The woody materials were ground to a 7.5 cm (3 in) size before composting, and reground to 3.8 cm (1.5 in) size after composting. The materials were composted in the bags for eight to ten weeks at temperatures reaching 70°C (160°F). He observed that the finished product can remain in the bags long after composting is completed. Ag-Bag Environmental (2003) in cooperation with the USDA-APHIS (Animal Plant Health Inspection Service) composted over 100,000 avian flu virus infected birds from depopulated poultry houses in West Virginia. According to their reports, the composting process was completely aerobic and acceptable to the USDA-APHIS.

Cawthon (1998) used a blower to transfer and compost a combined mixture of hay, poultry carcasses and litter at moisture contents of 30-35%. Temperatures inside the tube ranged from 70°C (160°F) to 82°C (180°F) within 5 to 7 days of composting. The high temperature of 82°C (180°F) was attributed to litter dust in the cocomposting materials. Cawthon and Beran (1998) also used this system for composting dairy manure. Compost temperatures in the tube at different locations ranged from 60°C (140°F) to 70°C 160°F after one week of composting. In both cases, some spoilage of ingredients and rotting parts of the carcasses were observed in the finished products.

Experiments have shown (Haywood, 2003) that the decomposition process of medium to large size intact carcasses inside the tube had gone anaerobic and end product disintegrated to solid and liquid portions with visibly rotting carcasses. This was attributed to the inconsistency of the materials inside the tube that prevented steady state uniform air distribution. While using aerated tube for composting of small carcasses (mainly poultry) may reduce composting time, space, odors, leachate and be minimally impacted by changing weather conditions, it is not practical for composting larger carcasses (swine and cattle etc.) unless they are ground and completely mixed with right amount of bulking agent to provide more than 30% porosity and needed aeration (Cawthon, 1998).

Conclusions

Carcass composting, if done properly, should result in a beneficial end product that can be utilized as fertilizer or cocomposting material. Every year millions of livestock and poultry perish due to diseases, natural causes, or from other reasons such as natural disasters before they are marketed. This review provides information on principles and processes of carcass composting to farmers and those with planning and decision making responsibilities to gain the necessary and practical information and determine whether it is suitable to the circumstances at hand. The following conclusions can be derived from the information provided in this review.

- In order to minimize the environmental impacts, composting of animal mortalities should begin within 24-48 hours of death.
- For a carcass compost pile, a carbon/nitrogen (C: N) ratio of 30-35:1, moisture content of 40-60% (wet basis by mass) and proper air movement (particle size of 3.1-12.7 mm and 35% air-filled porosity) provide thermophilic temperatures of 55-60°C for more than two weeks, accelerating aerobic degradation and pathogens inactivation.
- Using a 50:50 mixture (v/v) of composted carcasses and carbon sources to build a new carcass compost pile not only reduce the volume of storage for mature compost it also produces a suitable environment for beneficial microorganisms and decreases the number of surviving pathogens considerably.
- In-bin composting allows the pile to be protected from predators, pests, and runoff and it is efficient and suitable for small-scale carcass composting (less than 50,000 lb of mortalities/week).
- In an emergency situation, windrows are preferred to bins for composting massive amounts of intact mortality.
- For efficient and expeditious composting of massive animal mortality, a mechanized composting system equipped with grinders, mixers and aerators will be preferred over conventional bin or windrow composting. Grinding and mixing the carcasses and carbon sources reduces the weight ratio of bulking agent to carcasses from 4:1 (for typical bin composting) to 1:4. Forced aeration quickly raises and maintains thermophilic temperature (above 50°C) of the compost pile for several days inactivating most pathogens.

References

Ag-Bag Environmental. 2003. Avian flu virus infected fowl project. *A report of Ag-Bag Environmental.* 2320 SE Ag-Bag Lane, Warrenton, OR 97146. Retrieved December 21, 2003 from: http://www.ag-bag.com.

Bagley, C. V., Kirk, J. K. and Farrell-Poe, K. 1999. Cow mortality disposal. Electronic publishing, Utah State University Extension AG-507 October 1999. Retrieved on March 7, 2003 from http://www.wildwestspeakers.com/food_animal_1.htm.

Bollen, G. J., Volker, D., & Wijnen, A. P. 1989. Inactivation of soil borne plant pathogens during small-scale composting of crop residues. *Neth. J. Pl. Path*, 95 (Supplement 1): 19-30.

Busto, M. D., Ortega, N., & Perez, M. M. 1997. Stabilisation of cellulases by cross-linking with glutaraldehyde and soil humates. *Bioresource Technology*, 60 (1): 27-33.

Carr, L., Broide, H. L, John, H.M., Malcone, G. W., Palmer, D. H. and Zimmermann, N. 1998. Composting catastrophic event poultry mortalities. *Maryland Cooperative Extension*, University of Maryland, FS-723. Retrieved April 21, 2003 from: http://www.agnr.umd.edu/MCE/Publications/Publication.cfm?ID=35.

Cawthon, D. 1998. Composting of poultry litter/mortality, using Ag-bag technology. *Ag-Bag Poultry Litter Composting Demo*. Retrieved December 6, 2003 from: http://www7.tamu-commerce.edu/agscience/res-dlc/ag-bag/poultry/ag-bag-p.htm.

Cawthon, D. 2000. In-Vessel Composting of Poultry Mortality. *Department of Agricultural Sciences at Texas A&M University-Commerce*. Project FY98 CWA Section 319(h). Retrieved December 6, 2003 from: http://www7.tamu-commerce.edu/agscience/resdlc/poultry/wilhite.html.

Cawthon, D., and Beran, L. 1998. Composting of dairy cattle solid waste using *Ag-bag technology*. *Ag-Bag Dairy Cattle Waste Composting Demo*. Retrieved December 6, 2003 from: http://www7.tamu-commerce.edu/agscience/res-dlc/ag-bag/dairy/ag-bag-d.htm.

Cekmecelioglu, D., A. Demirci and R. E. Graves. 2003. Applicability of the optimized in-vessel food waste composting for windrow systems. *Proceedings of the ASAE Annual International Meeting*. Las Vegas, Nevada, Paper Number: 037016.

Chaw, D. 2001. Rotational bunker system composts sheep offal. *BioCycle*, 42:6: 45-47.

Colorado Governor's Office of Energy Management and Conservation or Colorado GOEMC. (2003). *Hog mortality composting, final report*. 225 E. 16th Ave., Suite 650, Denver, CO 80203. Retrieved on September 01, 2003 from http://www.state.co.us/oemc/pubs/hogs/hog-mortality.pdf. Also Presented and Distributed by Franklin Haywood at the Midwest Regional Carcass Disposal Conference, August 20-21, 2003. Kansas City, Missouri.

Diaz, L.F., Savage, G. M. and Golueke, C. G. 2002. Composting of municipal solid wastes, In: Tchobanoglous, G. and F. Kreith (eds) *Handbook of Solid Waste Management*. McGraw-Hill Handbooks, New York, New York 10121-2298, pp. 117-118 and 148-150.

Diaz, L.F., Savage, G. M., Eggerth, L.L. and Golueke C. G. 1993. Composting: Guidelines to selection of equipment and systems. *Composting and recycling municipal solid waste*. Lewis Publishers, CRC Press, Inc. 200 Corporate Blvd., N.W., Boca Raton, Florida 33431, Chapter 7, pp 143-155.

Dougherty, M. 1999. Composting livestock and poultry mortalities. *Field guide to on-farm composting*. Natural Resource, Agriculture, and Engineering Service

NRAES-114. Cooperative Extension. 152 Riley-Robb Hall, Ithaca. New York 14853-5701. NRAES-114. Chapter 5, pp. 75-90.

Ellis, D.B. (2001). Carcass disposal issues in recent disasters, Accepted Methods, and Suggested Plan to Mitigate Future Events. *Master of Public Administration Thesis*, Department of Political Science, Southwest Texas State University.

Farrell, M. 2002. Oregon composting project serves multiple purposes. *BioCycle, Journal of Composting & Organics Recycling*. 43:37-41. Retrieved Dec. 6, 2003 from: http://www.jgpress.com/BCArticles/2002/010237.html.

Fonstad, T. A., Meier, D. E., Ingram, L. J. and Leonard, J., 2003. Evaluation and demonstration of composting as an option for dead animal management in Saskatchewan. *Canadian Biosystems Engineering*. 45 (6): 19-25. Retrieved on May 5, 2004 http://www.engr.usask.ca/societies/csae/protectedpapers/c0129.pdf.

Franco, D. A. 2002. Animal disposal the environmental, animal disease and public health related implications: An assessment of options. *Proceedings of the California Department of Food and Agriculture Symposium*. April 8, 2002, Sacramento, California.

Fulhage, C. 1997. Composting swine carcasses. Carcass Composting, Feed Facts. University of Missouri, Columbia, Missouri. Retrieved December 6, 2003: http://www.moormans.com/feedfacts/swine/hogjan97/compost.htm.

Glanville, T. D. 2002. Emergency Livestock Mortality Composting in Iowa. I*owa State University and Iowa Department of Natural Resources*, USDA-NRI-CGP. Retrieved May 12, 2004 from: http://www.abe.iastate.edu/cattle-composting/purpose.asp.

Glanville, T. D. and D. W. Trampel. 1997. Composting alternative for animal carcass disposal (Special report). *Journal of the American Veterinary Medical Association*, 210:1116-1120.

Granatstein, D., 1999. Composting dairy cow mortalities in Utah. *The Compost Connection for Western Agriculture*. Compost Education & Resources for Western Agriculture. 10: pages, 1 and 4-6. Retrieved May 20, 2004 from: http://csanr.wsu.edu/programs/compost/Cc10.pdf.

Harper, A. F., Estienne, M. J. and Colline, E. R.. 2002. Composting as an environmentally safe means of dead pig disposal on Virginia swine farms. *Virginia Tech Tidewater Agricultural Research & Extension Center Suffolk*. Virginia. Retrieved June 16, 2003 from: http://vmirl.vmi.edu/ev/Paper%20Sessions/Early%20Bird/Absracts/Harper_Abstract.htm.

Haug, R. T. 1993. Composting systems, thermodynamic fundamentals, kinetics of inactivation, feed conditioning, aeration requirements and odor management. *The practical handbook of compost engineering*. Lewis Publishers, Press, Inc. 200 Corporate Blvd., N.W., Boca Raton, Florida 33431. pp 25-27, 119-120, 200-201, 257-258, 285-286, and 595-596.

Haywood, F. 2003. Composting mortalities. *Proceedings of the Midwest Regional Carcass Disposal Conference*. August 20-21, 2003. Kansas City, Missouri.

Heber, A., Lim, T., Ni, J., Kendall, D., and Sutton, A., 2001. Odor, ammonia and hydrogen sulfide emission factors for grow finished buildings. *Final Report Submitted to National Pork Producers Council*. 1776 NW 114th St., Clive, Iowa 50325.

Henry, S. T. 2003. Dead animal disposal. Certification Program for Animal Manure Managers. Chapter 8. Clemson University Extension Services. Clemson, South Carolina. Retrieved July 12, 2004 from: http://www.clemson.edu/peedeerec/certifi/Camm_p/Ch8/pch8_03a.pdf.

Hoitink, H. A. J. and H. M. Keener. 1993. Minimizing odor generation. S*cience and Engineering of Composting*, Renaissance Publications, Worthington, Ohio 43085: pp. 231-232.

Indiana State Board of Animal Health. 2002. Livestock Dealers, Marketing, Exhibitions, and Slaughter Livestock. *Indiana Administrative Code, Title 345, Article 7.* Retrieved March 15, 2004 from: http://www.in.gov/legislative/iac/title345.html.

Jiang X, Morgan J, Doyle MP. (2003). Thermal inactivation of Escherichia coli O157:H7 in cow manure compost. *Journal of Food Protection*, 66:10: 1771-7.

Jimenez, J., Dominquez, J. M., Castillon, M. P. and Acebal, C. 1995. Thermo inactivation of cellobiohydrolase I from *Trichoderma reesei QM 9414. Carbohydrate Research,* Amsterdam: Elsevier Science B.V., 268:2:257-266.

Kashmanian, R. M. and R. F. Rynk. 1996. Agricultural composting in the United States: Trend and driving forces. *Journal of Soil and Water Conservation.* 51(3):194-201.

Keener, H.M., Elwell, D.L and Monnin, M. J. 2001. Procedures and equations for sizing of structures and windrows for composting animal mortalities. *Journal of American Society of Agricultural Engineering*, 16: 681-692.

Keener, H.M. and D. L. Elwell. 2000. Mortality composting principles and operation. In: *Ohio's Livestock and Poultry Mortality Composting Manual*. Produced by The Ohio State University Extension, Ohio. Extension, 7/2000-200.

Kube, J. 2002. Carcass disposal by composting. *Proceedings of the American Association of Bovine Practitioners*. Madison, Wisconsin. 35:30-37.

Langston, J., Carman,D., VanDevender, K. and Boles, J. C., Jr. 2002. Disposal of swine carcasses in Arkansas. MP397-5M-9-97N, *Cooperative Extension Service, Division of Agriculture, University of Arkansas*. Little Rock, AR 72204. Retrieved April 6, 2003 from: http://www.uaex.edu/Other_Areas/publications/HTML/MP397/composting_swine_carcasses.asp#Recipe.

Lawson, M. J. and Keeling, A. A., 1999. Production and physical characteristics of composted poultry carcasses. *British Poultry Science*. 40: 706-708.

Looper, M. 2002. Whole animal composting of dairy cattle. *Dairy Business Communications*. Guide D- 108, 1-4p Retrieved May 2, 2003 from: http://www.dairybusiness.com/western/Nov01/NovWDBcompost.htm.

Manser, A. G. R. and A. A. Keeling. 1996. Simple windrow composting systems. *Practical handbook of processing and recycling municipal waste*. Lewis Publishers, CRC Press, Inc. 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431. pp147-198.

Mescher, T., Wolfe, K., Foster, S. and Stowell, R. 1997. Swine composting facility design. *Ohio State University Fact Sheet, AEX-713-97*. Food, Agricultural and Biological Engineering, 590 Woody Hayes Dr., Columbus, Ohio 43210. Retrieved May 12, 2003 from: http://ohioline.osu.edu/aex-fact/0713.html.

Morris, J. R., O'Connor, T., Kains, F. and Fraser, H. 2002. Composting livestock mortalities. Division of Agriculture and Rural, Information from GoatConnection.com

– Khimaira Inc. Retrieved on May 6, 2004 from http://goatconnection.com/articles/publish/printer_92.shtml.

Morse, D. E. 2001. Composting animal mortalities. *Agricultural Development Division, Minnesota Department of Agriculture*, St. Paul, MN 55107.

Mukhtar, S., Auvermann, B. W., Heflin, K. and Boriack C. N. 2003. A low maintenance approach to large carcass composting. *ASAE Annual International Meeting*, Riviera Hotel and Convention Center, Las Vegas, Nevada, Paper Number: 032263.

Murphy, D.W. and L. E. Carr. 1991. Composting dead birds. *Extension Sections in Departments of Poultry Science and Agricultural Engineering*, University of Maryland at College Park. Fact sheet 537. Retrieved April 11, 2003 from: http://www.agnr.umd.edu/MCE/Publications/Publication.cfm?ID=145&cat=3.

Murphy, D.W. and Handwerker T.S. 1988. Preliminary investigations of composting as a method of dead bird disposal. *Proceedings of the 1988 National Poultry Waste Management Symposium*. pp. 65-72.

North Carolina State Animal Recovery Team (NCSART). (2001). *Carcass disposal implications in recent disasters. Carcass disposal issues in recent disasters*, Accepted Methods, and Suggested Plan to Mitigate Future Events. Master of Public Administration Thesis, edited by Ellis, D.B. Department of Political Science, Southwest Texas State University.

Reinikainen, O. and Herranen, M. 1999. Different methods for measuring compost stability and maturity. *Proceedings of the International Symposium on Composting of Organic matter*. Sani Beach, Kassandra Halkidiki, Macedonia, Greece, pp. 95-104.

Rosenfeld, P. E. and Henry C. L. 2001. Activated carbon and wood ash sorption of wastewater, compost, and biosolids odorants. *Water Environment Research*, 73: 388-393.

Rynk, R. 2003. Large animal mortality composting goes mainstream. *BioCycle*, 44(6):44-49.

Rynk, R. 1992. The composting process and methods (Chapters 2 and 4). *On-farm composting handbook*. Northeast Regional Agricultural Engineering Service, 152 Riley-Robb Hall, Cooperative Extension, Ithaca, New York 14853-5701. pp. 6-13 and 24-42.

Sander, J. E., Warbington, M. C. and Myers, L.M. 2002. Selected methods of animal carcass disposal (Special report). *Journal of the American Veterinary Medical Association*, 220 (7): 1003- 1005.

Sherman-Huntoon, R. (2000). Composting animal mortalities in North Carolina. *BioCycle*, 41(12): 57-59.

Sparks Companies Inc. or SCI 2002. Livestock mortalities: Methods of disposal and their potential costs. *Prepared for: The National Renderers Association*. 6862 Elm Street, Suite 350 McLean, Virginia 22101-3897.

Sussman, V. 1984. *Easy composting*. Rodale Press; Emmaus, Pennsylvania.

Texas State Soil and Water Conservation Board (February 13, 2002). Catastrophic animal mortality management (burial method), technical guidance. *General Information Relating To All Type Animals*. USDA/Natural Resources Conservation Service, Texas State Soil and Water Conservation Board. Retrieved April 18, 2003 from: http://tammi.tamu.edu/burialguidance.pdf.

Umwelt Elektronic GmbH and Co. (2003). *The future of composting*. An information of Umwelt Elektronic GmbH and Co. KG Geislingen/Steige (D-73312) Seitenstr. 47. Website: Retrieved on August 22, 2003 from http://www.ue-online.com/alt/efachart.htm.

Underwood, W. 1999. Livestock to wormstock: composting large animal carcasses. *Proceedings of the National Institute for Animal Agriculture*. Nashville, Tennessee. Retrieved March 10, 2004 from: http://www.animalagriculture.org/Proceedings/1999_NatCon_Animal_Health/Livestock%20to%20Wormstock%20Composting%20Large%20Animal%20Carcasses.htm.

U.S. Department of Agriculture, Economics and Statistics System. 2003. Poultry: production and value-supplement. *USDA Economics, Statistics and Market information System*. Retrieved May 23, 2003 from: http://usda.mannlib.cornell.edu/.

Werry, M. 1999. Deadstock disposal. Ministry of Food, Agriculture. Ontario . Retrieved on June 23, 2003 from htttp://www.gov.on.ca/OMAFRA/english/livestock/beef/facts/info_dead.htm.