Practice: Trickling Filters

Description: Trickling filters are currently being evaluated for use at AFOs to address the high concentrations of organic pollutants in AFO wastewater. The technology is a type of fixed-growth aerobic biological treatment process. Wastewater enters the circular reactor and is spread over media that support biological growth. The media are typically crushed rock, plastic-sheet packing, or plastic packing of various shapes. Wastewater contaminants are removed biologically.

The top surface of the media bed is exposed to sunlight, is in an aerobic state, contains microorganisms that are in a rapid growth phase, and is typically covered with algae. The lower portion of the bed is in an anaerobic state and contains microorganisms that are in a state of starvation (i.e., microorganism death exceeds the rate of reproduction). The biofilm covering the filter medium is aerobic to a depth of only 0.1 to 0.2 millimeters; the microbial film beneath the surface biofilm is anaerobic. As wastewater flows over the microbial film, organic matter is metabolized and absorbed by the film. Continuous air flow is necessary throughout the media bed to prevent complete anaerobic conditions (Viessman, 1993).

Components of a trickling filter include a rotary distributor, underdrain system, and filter medium. Untreated wastewater enters the filter through a feedpipe and flows out onto the filter media via distributor nozzles, which are located throughout the distributor. The distributor spreads the wastewater at a uniform hydraulic load per unit area on the surface of the bed. The underdrain system, typically consisting of vitrified clay blocks, carries away the treated effluent. The clay blocks have entrance holes that lead to drainage channels and permit the circulation of air through the media bed. Figure 8-9 below shows a cutaway of a typical trickling filter. Rock

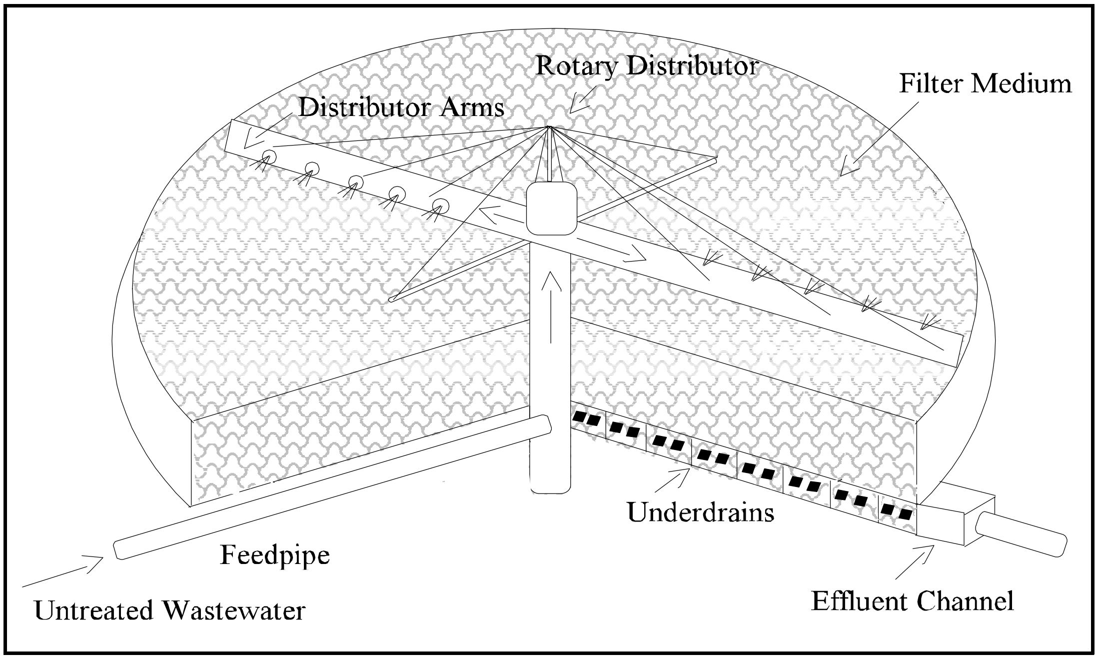

Figure 8-9. Trickling filter.

media beds can be up to 200 feet in diameter and 3 to 8 feet deep, with rock sizes ranging from 1 to 4 inches. Plastic media beds are narrower and deeper, ranging from 14 to 40 feet deep. These systems look more like towers than conventional rock-media systems. It is also common to have single- or two-stage systems for N removal. A two-stage system allows for greater flexibility because each stage can be operated independently and optimized accordingly. Flow capacity of trickling filters can range between 200 and 26,000 gallons per day; however, units can be installed in parallel to handle larger flows (AWT Environment).

Application and Performance: Traditionally, the trickling filter medium has been crushed rock or stone; however, this type of media occupies most of the volume in a filter bed, reducing the void spaces for air passage and limiting surface area for biological growth. Many trickling filters now use a chemical-resistant plastic medium because it has a greater surface area and a large percentage of free space. These synthesized media forms offer several advantages over naturally available materials, particularly in terms of surface contact area, void space, packing density, and construction flexibility (Viessman, 1993).

Although stone-media trickling filters are not as common, they are still used in shallow filters. BOD loads, expressed in terms of pounds of BOD applied per unit of volume per day, are typically 25 to 45 pounds per 1,000 ft^3 per day for single-stage stone filters and 45 to 65 pounds per 1,000 ft^3 per day for two-stage stone filters (based on the total media volume of both filters). The recommended hydraulic load ranges from 0.16 gallons per minute per ft^2 to 0.48 gallons per minute per ft^2 (Viessman, 1993).

Other shallow filters use random packing (e.g., small plastic cylinders, 3.5 x 3.5 inches), with a specific surface area of 31 to 40 ft^2/ft^3 and a void space of 91 to 94 percent. Deep filters use corrugated PVC plastic sheets that are 2 feet wide, 4 feet long, and 2 feet deep stacked on top of each other in a crisscross pattern. The specific surface area ranges from 26 to 43 ft^2/ft^3 and a void space of approximately 95 percent. The BOD loads for plastic media towers are usually 50 pounds per 1,000 ft^3 per day or greater with surface hydraulic loadings of 1 gpm/ft^2 or greater (Viessman, 1993).

A single or two-stage trickling filter can remove N through biological nitrification. The nitrification process uses oxygen and microorganisms to convert NH_3 to nitrite N, which is then converted to nitrate N by other microorganisms. Nitrate N is less toxic to fish and can be converted to N_2, which can be released to the atmosphere through denitrification, a separate anaerobic process following nitrification. Note that trickling filters are not capable of denitrifying.

A single-stage trickling filter removes BOD in the upper portion of the unit while nitrification occurs in the lower portion. A two-stage system removes BOD in the first stage while nitrification occurs in the second stage. Trickling filters do not typically remove P, but can be adapted to remove P from the wastewater effluent by chemical precipitation following BOD removal and nitrification (AWT Environment, ETI, 1998).

It is critical to have a properly designed trickling filter system. An improperly designed system can impact treatment performance and effluent quality. Media configuration, bed depth, hydraulic loading, and residence time all need to be carefully considered when designing a trickling filter system (Viessman, 1993).

In a study using municipal wastewater, the average BOD removal was greater than 90 percent and TSS removal was greater than 87 percent using a trickling filter. The average effluent BOD concentration was 13 mg/L, while the average effluent TSS concentration was 17 mg/L (AWT Environment). In another similar study that included municipal and dairy waste, BOD and TSS concentrations were slightly greater, but never exceeded 100 mg/L (Bio-Systems, 1999).

In another study using municipal wastewater and an anaerobic upflow filter prior to the trickling filter, the average effluent BOD and TSS concentrations both ranged from 5 to 10 mg/L, and the total N removal ranged from 80 to 95 percent. Pathogen reduction for this particular system is expected to be good, due to the upflow filter component. The estimated cost for this system is approximately $18,000 in annualized present day (Year 2000) costs (annualized over 20 years and not including design and permitting) (City of Austin, 2000).

Information on the reduction of pathogens, antibiotics, and metals in trickling filters is not available, but it is expected to be minimal based on engineering judgment.

Advantages and Limitations: An advantage of operating a trickling filter is that it is a relatively simple and reliable technology that can be installed in areas that do not have a lot of space for a treatment system. This technology is also effective in treating high concentrations of organics and nutrients. It can be cost-effective because it entails lower operating and maintenance costs than other biological processes, including less energy and fewer skilled operators. The wasted biomass, or sludge, can be processed and disposed of, although it contains high concentrations of nutrients. Finally, it also effectively handles and recovers from nutrient shock loads (ETI, 1998).

Disadvantages of operating a trickling filter are that additional treatment may be needed to meet stringent effluent limitations, the operation generates sludge that needs to be properly disposed of, poor effluent quality results if the system is not properly operated, and regular operator attention is needed. The system is susceptible to clogging from the biomass as well as odors and flies. The high solids content of CAFO waste would most likely require solids separation prior to treatment to also prevent clogging. Only the liquid waste may be treated in this system. In addition, a high investment cost may also prevent certain farms from installing this technology (ETI, 1998).

Operational Factors: Trickling filters are typically preceded by primary clarification for solids separation and are followed by final clarification for collection of microbiological growths that slough from the media bed. They can also be preceded by other treatment units such as septic tanks or anaerobic filters. Trickling filters effectively degrade organic pollutants, but can also be designed to remove N and P from the wastewater.

Trickling filters are relatively simple to operate, are lower in cost than other biological treatment processes, and typically operate at the temperature of the wastewater as modified by that of the air, generally within the 15 to 25°C range. A high wastewater temperature increases biological activity, but may result in odor problems. Cold wastewater (e.g., 5 to 10°C) can significantly reduce the efficiency BOD removal (Viessman, 1993).

Demonstration Status: Trickling filters are most commonly used to treat municipal wastewater, although the technology is applicable to agricultural wastewater treatment. They are best used to treat wastewaters with high organic concentrations that can be easily biodegraded. EPA was not able to locate any AFO facilities that currently operate trickling filters; however, based on the information gathered, several wastewater treatment vendors market this technology to such facilities.

Practice: Fluidized Bed Incinerators

Description: Fluidized bed incinerators (FBIs) are currently being evaluated for use at CAFOs given the high volume of manure they generate. The technology is typically used for wastewater sludge treatment (e.g., municipal sludge), but may be used for wastewater treatment. The main purpose of an FBI is to break down and remove volatile and combustible components of a waste stream and to reduce moisture. Its most prominent application to CAFO industries would be for animal waste disposal and treatment, because manure has a higher solids content than wastewater from CAFO operations.

An FBI is a vertical, cylindrical-shaped apparatus that requires media (typically sand), injected air, and an influent fuel to operate. An FBI contains three basic zones: a windbox, a sand bed, and a freeboard reactor chamber. Air enters the windbox and moves upward into the media bed through orifices called “tuyeres” at a pressure of 3 to 5 pounds per square inch. The injected air acts to fluidize the bed and to generate combustion. The term “fluidized bed” refers to the “boiling” action of the sand itself, which occurs when air is injected into the reactor. The fuel, or animal waste, directly enters the fluidized sand bed and is mixed quickly within the bed by the turbulent action. Any moisture in the animal waste evaporates quickly, and the sludge solids combust rapidly. Combustion gases and evaporated water flow upward through the freeboard area to disengage the bed material and to provide sufficient retention time to complete combustion. Gases and ash exit the bed out the top of the FBI. Exit gases may be used to preheat the injected air or may be recovered for energy. Exit ash is removed from exit gas in an air pollution device such as a venturi scrubber. Ash can either be disposed of or reused (typically as fertilizer) depending on its characteristics (Metcalf and Eddy Inc., 1991).

Prior to injection, the sand media is kept at a minimum temperature of 1300 °F and controlled at between 1400 and 1500 °F during treatment. This temperature range varies with specific design criteria. The FBI typically ranges in size from 9 to 25 feet in diameter; the media bed is typically 2.5 feet thick, when settled (Metcalf and Eddy Inc., 1991). The system has a capacity of up to 30 tons per hour (UNIDO, 2000). The combustion process is optimized by varying the animal waste and air flow, with exit gas retention times greater than 1 second and solids retention times greater than 30 minutes (Versar, 2000). Figure 8-10 represents a typical FBI.

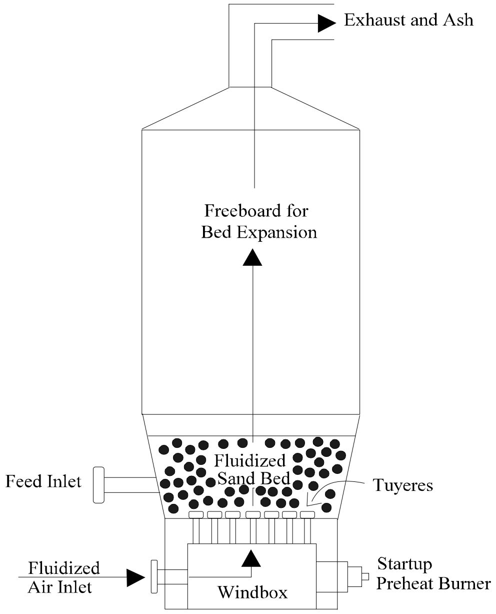

Figure 8-10. Fluidized bed incinerator.

Application and Performance: Animal waste enters the FBI and quickly combusts in the media bed. Organic constituents of the waste are burned to produce carbon dioxide and water, while volatile pollutants are evaporated and captured in the air control device. Solid material may be recycled through the system for further treatment. The ash contains many of the pollutants in the animal waste itself, although waste volume is reduced and most of the N in the waste is evaporated. The ash will still contain high levels of metals, P, and K.

The high temperature of the system typically eliminates the spread of pathogens, reducing biosecurity concerns. Similarly, any antibiotics or hormones remaining in the waste will also be broken down and reduced. Although FBIs operate at very high temperatures, they typically operate at lower temperatures than other types of incinerators, which results in lower air emissions, particularly of (NO_x) compounds and volatile organic compounds (VOCs).

Advantages and Limitations: Fluidized bed incineration is an effective and proven technology for reducing waste volume and for converting the waste to useful products (e.g., energy). Resulting ash may be used as an end-product fertilizer, or as an intermediate product used in manufacturing commercial fertilizers. Animal waste incineration eliminates aesthetic concerns (e.g., odors) as well as nuisance concerns (e.g., pest attraction) (Versar, 2000).

Although fluidized bed incineration is viewed as an efficient system, it is very sensitive to moisture content and fuel particle size. The higher the moisture content, the less efficient the system is because the moisture acts to depress the reactor temperature, thereby reducing combustion capabilities. Moisture can be reduced in animal waste by combining the waste with other biomass such as wood chips or straw. Air drying or dewatering the animal waste also reduces moisture content before treatment in the FBI. Blockages may often occur in input and output pipes triggering shut-down and maintenance (Versar, 2000).

Air emissions must also be considered when operating any type of incinerator. Organic and N compounds are easily removed from the waste; however, they are then emitted to the air, potentially creating a cross-media impact if not properly controlled. Furthermore, nutrients such as P, K, and metals typically remain in the ash and are not treated. Finally, FBIs entail high operating and maintenance costs, especially compared with other types of incinerators (Versar, 2000).

Operational Factors: As discussed above, FBIs are most sensitive to moisture content and fuel particle size. The less moist the influent fuel, the more efficient the system is. Acceptable influent moisture levels range from 15 to 20 percent. Fuel particle size should also be minimized to avoid clogging the system. Another consideration is that, depending on the metals concentrations and local regulations, the ash, if intended for disposal, may need to be handled as hazardous waste (Versar, 2000).

FBI costs depend on size and capacity. Capital costs can range from approximately $5 to $25 million for a 5-ton-per-hour and a 30-ton-per-hour FBI, respectively (UNIDO, 2000). FBIs are complex technologies and require operation by trained personnel. Because of this, FBIs are more economical for medium to large facilities, or when operated in cooperation with several businesses that are able to provide fuel sources. Therefore, FBIs may not be a cost-effective waste management technique for an individual farm, but, when operated on a larger scale, they may prove to be cost-effective. Capital and annual operating costs are generally higher for FBIs than for other types of incinerators because of the sensitive design parameters (e.g., moisture content and solid particle size). On the other hand, the system operates efficiently, and energy can usually be recovered from the process and may be sold to another party or used to reduce on-site operating costs.

*Demonstration Status***:** ERG is not aware of any U.S. feedlots currently operating FBIs or sending animal waste to larger-scale municipal or private FBIs. According to information gathered for this program, FBIs are more commonly used in Europe and in Japan to treat animal waste, although some U.S. companies using waste-to-energy technology may be operating FBIs using animal waste with other fuel sources. FBIs are most commonly used in the United States to manage municipal sludge.

In a study done to assess the engineering and economic feasibility of using poultry litter as a fuel to generate electric power, researchers found that combusting poultry litter (combined with wood chips) can be an effective waste-to-energy technology (Versar, 2000). Although the study did not specifically evaluate fluidized bed incineration, the application and results are expected to be similar. The study found litter samples to have a heat content between 4,500 and 6,400 BTU per pound at approximately 16 percent moisture, which is a slightly higher content than the wood chips alone. The ash content of the litter was reported to be between 9 and 20 percent, which is significantly higher than the wood chips alone. However, although the air emissions data in this study were considered preliminary, they showed that the facility could trigger air permitting requirements. The study also found that poultry litter ash may be classified as hazardous waste under individual state regulations (Versar, 2000).

Practice: Constructed Wetlands

Description: Constructed wetlands (CWs) can be an important tool in the management of animal waste by providing effective wastewater treatment in terms of substantial removal of suspended solids, BOD_5, fecal coliform, and nutrients such as N and P. The treatment process in CWs generates an effluent of better quality that can be applied on agricultural land or discharged to surface waters (CH2M Hill, 1997). Wastewater treatment in CWs occurs by a combination of mechanisms including biochemical conversions, settling/filtration, litter accumulation, and volatilization. Removal of pollutants in CWs is facilitated by shallow water depth (which maximizes the sediment-water interface), slow flow rate (which enhances settling), high productivity, and the presence of aerobic and anaerobic environments.

Wetland media (soil, gravel) and vegetation provide a large surface area that promotes microbial growth. Biochemical conversion of various chemical compounds through microbial activity is the main factor in the wetland treatment process. Through microbial activities, Org-N is converted to NH_3 (ammonification), which is used by plants as a nutrient; NH_3 is converted to nitrate and nitrite (nitrification), which is used by microbes and some plants for growth; and N is volatilized (denitrification) and is lost to the atmosphere (CH2M Hill, 1997). NH_3 may be removed through volatilization, uptake by plants and microbes, or oxidized to nitrate. Volatilization of NH_3 in CWs appears to be the most significant mechanism for N removal for animal waste treatment (Payne Engineering and CH2M Hill, 1997).

P removal is achieved mainly by fixation by algae and bacteria, plant uptake, and (Cronk, 1996) when oxidizing conditions promote the complexing of nutrients with iron and aluminum hydroxides (Richardson, 1985). Plant uptake of P is only a short-term sink because plant P is rapidly released after the death of plant tissues (Payne Engineering and CH2M Hill, 1997). Fixation of P by microbes ultimately results in the storage of P in the bottom sediments (Corbitt and Bowen, 1994), yet they may become saturated with P, resulting in an export of excess P (Richardson, 1985).

Rooted emergent aquatic plants are the dominant life form in wetlands (Brix, 1993) and are the only aquatic plants recommended for planting in CWs used for animal waste treatment (Payne Engineering and CH2M Hill, 1997). These aquatic plants have specialized structures that allow air to move in and out as well as through the length of the plant, have roots that allow adsorption of gases and nutrients directly from the water column, and are physiologically tolerant to chemical products of an anaerobic environment (Brix, 1993). For these reasons, emergent aquatic plants can survive and thrive in wetland environments. The most common emergent aquatic plants used in CWs for animal waste treatment are cattail (*Typha* spp.), bulrush (*Scirpus* spp.), and common reed (*Phragmites* spp.) (CH2M Hill and Payne Engineering, 1997).

Roles of emergent aquatic plants in the wastewater treatment process include the following:(1) providing a medium for microbial growth and a source of reduced carbon for microbial growth, (2) facilitating nitrification-denitrification reactions, (3) assimilating nutrients into their tissue, (4) facilitating entrapment of solids and breakdown of organic solids, and (5) regulating water temperature by shading the water (Payne Engineering and CH2M Hill, 1997). The vascular tissues of these plants move oxygen from overlying water to the rhizosphere and thus provide aerobic microsites (within the anaerobic zone) in the rhizosphere for the degradation of organic matter and growth of nitrifying bacteria (Brix, 1993). Dissolved nitrates, from nitrification, can then diffuse into the surrounding anaerobic zone where denitrification occurs. Furthermore, wetland macrophytes remove small amounts (<5 percent) (Hammer, 1992) of nutrients, for nutritional purposes, by direct assimilation into their tissue. Removal of nutrients, however, increases slightly in CW systems that incorporate periodic harvesting of plants (Hammer, 1992) or may be considerably higher (67 percent) in specially designed systems that maximize influent-root zone contact (Breen, 1990).

The two principal types of CWs for treating wastewater are surface flow (SF) and subsurface flow (SSF) systems. The SF systems are shallow basins or channels, carefully graded to ensure uniform flow, planted with emergent vegetation, and through which water flows over the surface at relatively shallow (~30 cm) depths. The SSF systems consist of a trench or bed with a barrier to prevent seepage, and planted emergent vegetation growing in a permeable media (soil, gravel) designed such that the wastewater flows horizontally through the media with no open surface flow. The base media and plant roots provide large surface areas for biofilm growth and thus, functions somewhat like a rock trickling filter at a municipal wastewater treatment plant (Payne Engineering and CH2M Hill, 1997).

Some authors also refer to the SF system as the free water surface system, while the SSF type is also referred to as the vegetated rock-reed filter, vegetated submerged bed system, gravel-bed system, and root-zone system. Compared with SSF systems, the SF wetlands are capable of receiving a wider range of wastewater loads, have lower construction costs, and are relatively easy to manage (Payne Engineering and CH2M Hill, 1997). Additionally, mass removal of NH_3-N, the major form of N in animal wastewater (CH2M Hill and Payne Engineering, 1997), in SSF wetlands is significantly less compared with the SF type because there is less time and oxygen to support necessary nitrification reactions (USEPA, 1993). For these reasons, the SF system is the most commonly used wetland type for treating animal waste (Payne Engineering and CH2M Hill, 1997) and is the only one recommended for animal waste treatment by the USDA NRCS (USDA NRCS, 1991).

Application and Performance: A database, developed by CH2M Hill and Payne Engineering (1997), containing design, operational, and monitoring information from 48 livestock CW systems (in the United States and Canada), indicates that CWs have been and continue to be used successfully to treat animal waste including wastewater from dairy, cattle, swine, and poultry operations. The majority of CW sites included in the database have begun operations since 1992. SF systems constitute 84 percent of cells in the database, and the remainder consists of SSF or other wetland systems. Cattail, bulrush, and reed, in that order, dominate the aquatic vegetation planted in the surveyed CWs.

Typically, effluent from a CW treating animal waste is stored in a waste storage lagoon. Final dispersal occurs through irrigation to cropland and pastureland, though the potential for direct discharge of effluent exists. Direct discharge may, however, require a permit under the EPA’s NPDES.

A performance summary of CWs used for treating animal waste indicates a substantial reduction of TSS (53 to 81 percent), fecal coliform (92 percent), BOD_5 (59 to 80 percent), NH_3-N (46 to 60 percent), and N (44 to 63 percent) for wastewater from cattle feeding, dairy, and swine operations (CH2M Hill and Payne Engineering, 1997). In a study by Hammer et al. (1993), swine effluent was treated in five CW cells, located below lagoons, that were equipped with piping that provided a control for variable application rates and water level control within each cell. Performance data indicate notable (70 to 90 percent) pollutant removal rates and reliable treatment of swine lagoon effluent to acceptable wastewater treatment standards for BOD_5, TSS, N, and P during the first year of the reported study.

Removal efficiency of N is variable depending on the system design, retention time, and oxygen supply (Bastian and Hammer, 1993). Low availability of oxygen can limit nitrification, whereas a lack of a readily available carbon source may limit denitrification (Corbitt and Bowen, 1994). Fecal coliform levels are significantly reduced (>90 percent) by sedimentation, filtration, exposure to sunlight, and burial within sediments (Gersberg et al., 1990). Compared with dairy systems, higher reduction of pollutants have been reported for swine wastewater treatment in CWs, probably because loading rates have tended to be lower at swine operations (Cronk, 1996).

Advantages and Limitations: In addition to treating wastewater and generating water of better quality, CWs provide ancillary benefits such as serving as wildlife habitat, enhancing the aesthetic value of an area, and providing operational benefits to farm operators and their neighbors (CH2M Hill, 1997). CWs, in contrast to natural wetlands, can be built with a defined (desired) composition of substrate (soil, gravel) and type of vegetation and, above all, offer a degree of control over the hydraulic pathways and retention times (Brix, 1993). An SF system is less expensive to construct than an SSF system, the major cost difference being the expense of procuring and transporting the rock or gravel media (USEPA, 1993). An SSF system, however, has the advantage of presenting an odor- and insect-free environment to local residents.

Major limitations include a need for relatively large, flat land areas for operation (Hammer, 1993), a possible decrease in SF system performance during winter in temperate regions (Brix, 1993), and a reduction in functional sustainability of the SSF systems if the pore spaces become clogged (Tanner et al., 1998). Other limitations include (1) an inadequacy of current designs of SF systems to store flood waters and use stored water to supplement low stream flows in dry conditions, and (2) potential pest problems and consequent human health problems from improperly designed or operated SF systems (Hammer, 1993). Moreover, because CW technology for animal waste treatment is not well established, long-term status and effects, including accumulation of elemental concentrations to toxic levels, are poorly documented. Further research is needed to better understand the nutrient removal mechanisms in CWs so that improved designs and operating criteria can be developed.

Operational Factors: Because untreated wastewater from AFOs has high concentrations of solids, organics, and nutrients that would kill most wetland vegetation, wastewater from AFOs is typically pretreated in a waste treatment lagoon or settling pond prior to discharge to a CW (Payne Engineering and CH2M Hill, 1997). Incorporating a waste treatment lagoon in the treatment process reduces concentrations of BOD_5 and solids considerably (>50 percent) and provides storage capacity for seasonal application to the wetlands (Hammer, 1993).

Figure 8-11 shows the typical components and a typical treatment sequence of a CW. Constructed wetlands may be built with cells that are parallel or in a series. Construction of cells needs to be determined by the overall topography as well as by the drainage slope of individual cells to maintain shallow water depth for the wetland plants (CH2M Hill and Payne Engineering, 1997). The land slope should be small (<0.5 percent), and the length-to-width ratios should be between 1:1 and 10:1, with an ideal ratio being 4:1 (USDA NRCS, 1991). Data for the surveyed CWs, reported by CH2M Hill and Payne Engineering (1997), indicate the following average design conditions: water depth of 38 cm; bottom slope of 0.7 percent; length-to-width ratio of 6.5:1; hydraulic loading rate of 4.7 cm/day; and a size of 0.03 hectare.

Design criteria for CWs for animal waste treatment are described in USDA NRCS (1991), including methods to determine the surface area of a proposed wetland. The NRCS *Presumptive Method* is based on an estimate of BOD_5 loss in the pretreatment process, which is used to calculate BOD_5 concentration in the pretreatment effluent. Size of the wetland is then determined based on a loading rate of 73 kg BOD_5/ha/day that would achieve a target effluent of <30 mg/L of BOD_5, <30 mg/L TSS, and <10 mg/L NH_3-N. The NRCS *Field Test Method* is based on laboratory data for average influent BOD_5 concentration to the CW. The influent BOD_5 concentration, together with average temperature data, is used to determine the hydraulic residence time needed to obtain a desired effluent BOD_5 concentration.

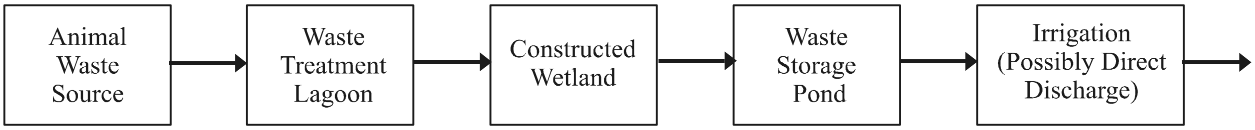

Figure 8-11. Schematic of typical treatment sequence involving a constructed wetland.

Advances in research and technology of CW during the 1990s have provided additional information to allow modification of the USDA NRCS (1991) methods. CH2M Hill and Payne Engineering (1997) developed the *Modified Presumptive USDA-NRCS Method*, which takes into account pollutant mass loading and volume of water applied, and relates the results to a data table developed from existing CWs for animal waste treatment. The *Field Test Method #2* was also proposed by CH2M Hill and Payne Engineering (1997) based on the areal loading equation developed by Kadlec and Knight (1996), which includes rate constants specific to concentrated animal waste.

Operation and maintenance requirements for CWs include maintenance of water level in the wetland cells, monitoring water quality of influent and effluent, regular inspection of water conveyance and control structures to ensure proper flow, and maintenance of the embankments to avoid damage from rodents.

Demonstration Status: CWs have been demonstrated successfully as a management technology treatment for swine waste (Maddox and Kinglsey, 1990; Hammer et al., 1993) and dairy waste (Chen et al., 1995; Tanner et al., 1995; Schaafsma et al., 2000), and have been relatively less successful in the treatment of poultry waste (Hill and Rogers, 1997). Results of several other successful case studies, performed in several regions of North America, are reported in DuBowy and Reaves (1994), DuBowy (1996), and Payne Engineering and CH2M Hill (1997).

Practice: Vegetated Filter Strips

Description: Vegetated filter strips are an overland wastewater treatment system. They consist of strips of land located along a carefully graded and densely vegetated slope that is not used for crops or pasture. The purpose of a vegetated filter strip is to reduce the nutrient and solids content of wastewater and runoff from AFOs. The filters are designed with adequate length and limited flow velocity to promote filtration, deposition, infiltration, absorption, adsorption, decomposition, and volatilization of contaminants. These filters consist of three parts: a sediment basin, a flow distribution device, and a filter strip area (Harner, 2000).

The wastewater is distributed evenly along the width of a slope in alternating application and drying periods. The wastewater may be applied to the slope by means of sprinklers, sprays, or gated, slotted, or perforated pipe. As the wastewater flows down the slope, suspended solids are deposited and some nutrients are absorbed into the vegetation. The effluent from the system is collected in a channel at the bottom of the slope and then discharged (see Figure 8-12).

Application and Performance: The design of a vegetated filter strip is typically based on the BOD concentration of the wastewater (Metcalf and Eddy, 1991). The total treatment area required is calculated from the hydraulic loading rate, assumed length of slope (generally 100 to 150 feet), and an operating cycle. The operating cycle and application rate can be varied to optimize the system. An operating cycle of 1 day is typical, with 8 to 12 hours of application and

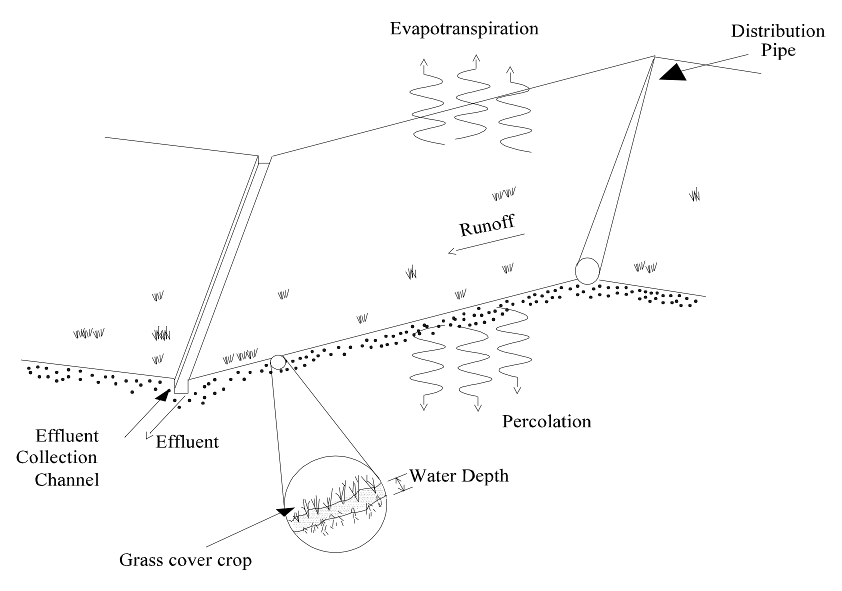

Figure 8-12. Schematic of a vegetated filter strip used to treat AFO wastes.

12 to 16 hours of drying. NH_3 removal from primary effluent can be expected to vary inversely with the ratio of application period to drying period. A properly designed system can remove up to 95 percent of NH_3. The application rate is critical for considering BOD removal because it is important to maintain aerobic conditions that are required for microbial decomposition. Too high an application rate can create anaerobic conditions because the oxygen transfer through natural aeration from the atmosphere will be insufficient.

The vegetative cover should be dense in growth, such as a grass, and well suited to the climatic conditions. The vegetation must be dense enough to slow the wastewater flow to allow adequate treatment and prevent erosion. Consideration should also be given to the nutrient uptake potential of the vegetation to maximize nutrient removal rates.

Proper grading is also critical to the design of a vegetated filter strip to prevent the channeling of wastewater and allow for efficient treatment. Sites with an existing slope of 2 to 6 percent are best suited for vegetated filter strips to keep regrading costs to a minimum without causing water to pond. The shape and area of the field being drained changes the filter strips effectiveness, as does the method of installation (Franti, 1997). It is best for runoff from areas of clean storm water to avoid passing through the filter. Allowing storm water into the filter strip could overwhelm the system causing inadequate filtration on the wastewater (Harner, 2000).

Vegetated filter strips are also best suited to sites that have low permeability soils to prevent wastewater from infiltrating the subsurface. In areas where soils are relatively permeable, it may be necessary to amend the existing soils or install an impermeable barrier.

Vegetated filter strips can be unsuccessful if the plants are not absorbing enough nutrients. Plants must be healthy, dense, swift growing, have fibrous roots to fight erosion, and be perennials. The plants must also endure being waterlogged and grow well in the spring and fall. The most effective type of plants to use are sod-forming grasses (Harner, 2000).

A study conducted to determine the effectiveness of milkhouse wastewater treatment using a vegetative filter strip at a dairy farm in Vermont (Clausen and Schwer, 1989) found that removals of TSS, total P, and TKN were 92 percent, 86 percent, and 83 percent, respectively. However, the total P concentration in the effluent was more than 100 times greater than the average P concentration of streams draining agricultural areas in the northeast. Moreover, only 2.5 percent of the total input of P, and 15 percent of the input of N were removed in the vegetation (Nebraska Cooperative Extension, 1997).

The EPA Chesapeake Bay Program studied the use of vegetative filter strips to reduce agricultural nonpoint source pollutant inputs to the bay (Dillaha et al., 1988). A series of nine experimental field plots were constructed, each containing a simulated feedlot source area and a vegetated filter strip of known length. A rainfall simulator was used to produce runoff, which was collected from the base of each vegetated filter strip. Analysis indicated that 81 to 91 percent of incoming sediment, 58 to 69 percent of the applied P, and 64 to 74 percent of the applied N were removed.

Advantages and Limitations: Compared with many treatment technologies, vegetated filter strips effectively reduce the nutrient and solids concentration of wastewater with relatively low construction and maintenance costs. This is particularly true for sites where available land is well suited for such a system.

However, to effectively treat high volumes of wastewater, such as from a milking parlor, excessive acreage may be required. In addition, because overland flow systems such as vegetated filter strips depend on microbiological activity at or near the surface of the soil, cold weather adversely affects their performance. Winter use of this in colder climates will therefore be limited and an appropriate amount of wastewater storage will be required. Storage is recommended when the average daily temperature is below 32 °F. The filter's performance is limited by the level and duration of rainfall and the type of vegetation (EPA, 2001).

Operational Factors: Maintenance of a vegetated filter strip consists of periodic removal of the vegetative growth, which contains many of the nutrients. The biomass has various potential uses—as forage, fiber, or mulch, for example. Sediment accumulation should be inspected (Harner, 2000). In addition, the slope needs to be periodically inspected and regraded to ensure a level flow surface and prevent channeling and erosion. When sparse plant coverage is observed, it should be reseeded. Undesirable plants in the filter should be managed (Harner, 2000).

Demonstration Status: Vegetated filter strips have been used to treat milkhouse wastewater in New York and North Carolina. They have also been used to treat a variety of other wastes including feedlot runoff.

Practice: Composting—Aerobic Treatment of Solids

Description: Composting is the aerobic biological decomposition of organic matter. It is a natural process that is enhanced and accelerated by the mixing of organic waste with other ingredients in a prescribed manner for optimum microbial growth. Composting converts an organic waste material into a stable organic product by converting N from the unstable NH_3 form to a more stable organic form. The end product is safer to use than raw organic material and one that improves soil fertility, tilth, and water holding capacity. In addition, composting reduces the bulk of organic material to be spread, improves its handling properties, reduces odor, reduces fly and other vector problems, and can destroy weed seeds and pathogens. There are three basic methods of composting: windrow, static pile, and in-vessel.

Windrow composting consists of placing a mixture of raw organic materials in long, narrow piles or windrows, which are agitated or turned on a regular basis to facilitate biological stabilization. Windrows aerate primarily by natural or passive air movement (convection and gaseous diffusion). Windrow composting is suitable for large quantities of organic material. For composting dense materials like manure mixtures, windrows are usually no more than 3 feet high and 10 to 20 feet wide. The equipment used for turning, ranging from a front-end loader to an automatic mechanical turner, determines the size, shape, and spacing of the windrows.

The **static pile method** consists of mixing the compost material and then stacking the mix on perforated plastic pipe or tubing through which air is drawn or forced. Forcing air (by suction or positive pressure) through the compost pile may not be necessary with small compost piles that are highly porous or with a mix that is stacked in layers with highly porous material. If layering is not practiced, the materials to be composted must be thoroughly blended before they are placed in a pile. The exterior of the pile is typically insulated with finished compost or other material. The dimensions of the static pile are limited by the amount of aeration that can be supplied by the blowers and by the stacking characteristics of the waste. The pile height generally ranges from 8 to 15 feet, and the width is usually twice the height. The spacing between individual piles is usually equal to about half the height.

The **in-vessel method** involves the mixing of manure or other organic waste with a bulking agent in a reactor, building, container, or vessel, and may involve the addition of a controlled amount of air over a specific detention time. This method has the potential to provide a high level of process control because moisture, aeration, and temperature can be maintained in some of the more sophisticated units (USDA, 1999).

Application and Performance: Composting is an accepted process for the biological stabilization of the organic material in waste, providing an alternative to long-term liquid and semisolid manure storage. It turns waste organic material (dead poultry, manure, garbage, and so forth) into a resource that can be used as a soil amendment and fertilizer substitute. Proper composting minimizes nutrient loss while killing pathogenic organisms by process generated heat. For example, two waste products from a municipal and a dairy source were composted in the lab under controlled temperature and air flow rates (Hall and Aneshansley, 1997). Researchers found that maintaining high and constant temperatures destroys pathogens and accelerates decomposition.

In general, only manure from confined animals is available for composting. Usually, manure must be dewatered or mixed with sawdust or wood chips to lower the moisture content, which may range from 60 to 85 percent. The presence of plant nutrients such as N, P, and K; the organic content; and the absence of significant levels of heavy metals makes animal manure a very attractive raw material for producing compost. In-vessel composting has been conducted successfully with dairy cattle manure, swine manure, horse manure, and poultry and turkey litter.

Advantages and Limitations: Compost and manure are both good soil conditioners that contain some fertilizer value. On a growing number of farms, however, manure is considered more of a liability than an asset. Animal waste generators may find themselves with surpluses of manure in the winter, yet lacking manure by spring planting. Odor complaints associated with manure are common in populated areas. Other concerns include polluted runoff from manure spread on frozen ground and nitrate contamination of wells.

Composting converts the nutrients in manure into forms that are less likely to leach into ground water or be carried away by surface runoff. Compost releases its nutrients more slowly than commercial fertilizers, so it does not burn crops and can feed them over a longer period of time. The nutrient value of manure was demonstrated in a study in which five combinations of composted cattle feedyard manure and liquid phosphate were applied to provide 100 percent of the P requirement for corn (Auvermann and Marek, 1998). Five replicates were tested for each treatment. No significant difference was determined between corn yields in treatment-by-treatment comparisons, indicating that composted feedlot manure may be an adequate substitute for chemical fertilizers.

A well-managed composting operation generates few odors and flies, and the heat generated by the composting process reduces the number of weed seeds contained in the manure. Composting also reduces the weight, moisture content, and volatility of manure, making it easier to handle and store. Because of its storage qualities, compost can be held for application at convenient times of the year. Composted manure and composted manure solids can also be used as bedding material for livestock.

Different types of in-house, deep litter manure management systems were tested at a 100,000-chicken high-rise layer operation in Georgia (Thompson et al., 1998). Composting was conducted using raw manure, a manure and leaf mixture, and manure and wood chip mixture. The in-house composting was found to reduce the weight and volume of wastes more efficiently than conventional methods of stacking manure under the house. Wood chip and leaf manure both had lower moisture content and more concentrated nutrients compared with the raw manure.

Disposal is less of a problem for compost than for manure because there is usually someone willing to take the compost. One of the strongest incentives for composting is that a market exists for the product, especially in populated areas. Potential buyers include home gardeners, landscapers, vegetable farmers, garden centers, turf growers, golf courses, and ornamental crop producers. Bulk compost prices range from $7 to $50 per cubic yard, depending on the local market, compost quality, and the raw materials used.

Countering these advantages are several limitations. Managing and maintaining a composting operation takes time and money, and compost windrows and storage facilities for raw materials can take land, and possibly building space, away from other farming activities. When processing only small volumes of farm wastes, the equipment needed is probably already available on the farm, but composting may become a very capital- and labor-intensive task for larger operations. Farmers might need to invest in special composting equipment, which can cost anywhere from $7,000 to more than $100,000. The main equipment needed for composting on a moderate to large scale is machinery to construct, mix, and move material in a compost pile or windrow. A front-end loader and truck may be all that is required. Other equipment, such as chipping or shredding equipment, a windrow turner, screening equipment, aeration equipment, and a composting thermometer or temperature probe, might be needed as well.

Although the end product of composting is odor-free, the raw materials used to make compost may not be. Even the compost piles themselves, if not maintained properly, can become malodorous. Cold weather slows the composting process by lowering the temperature of the composting material. Heavy precipitation adds water to the composting mix, and snow and mud can limit access to windrows.

There is also some ambiguity as to whether manure or compost provides crops with more N. Compost can contain less than half the N of fresh manure; however, the N in manure is less stable than that in compost. Farmers must apply more compost than manure to farmland to achieve the same results because compost nutrients are released very slowly. Generally, less than 15 percent of the N in compost is released in the first year.

Last, although compost is a salable product, selling compost involves marketing. This means searching out potential buyers, advertising, packaging, managing inventory, matching the product to the customer's desires, and maintaining consistent product quality.

In addition to these general limitations, there are specific limitations associated with composting different types of animal manure. Wastes containing excessively high water content, such as poultry manure from egg-laying operations and wet manure from free-stall dairy CAFOs, may require additional processing prior to composting. The conditions for optimal composting (see Operational Factors below for greater detail) are not always met with these wastes; for example, the water content is too high (usually greater than 70 percent), the biomass is poorly aerated, and the (Carbon:Nitrogen) ratio is often less than 15:1. In these cases, bulking agents such as wood chips or similar wood products are added to make the mix more suitable for efficient composting, but bulking agents must be purchased if not readily available on the farm. Table 8-17 summarizes some of the key advantages and disadvantages of composting.

Operational Factors: Because composting is a biological process, environmental factors influence organism activity, thus determining the speed of decomposition and the length of the composting cycle. The composting period typically lasts from 3 to 8 weeks for conventional composting methods under normal operating conditions. Users of some highly controlled mechanical systems claim to produce compost in as little as 1 week. The length of time depends upon many factors, including the materials used, temperature, moisture, frequency of aeration, and ultimate use of the material. Conditions that slow the process include lack of moisture, a high C:N ratio, cold weather, infrequent or insufficient aeration, and large or woody materials. A month-long "curing" period usually follows the active composting stage. Curing continues to stabilize the compost but at a much slower pace. At this stage, the compost can be stockpiled without turning or aeration and without the fear of odor problems (Rynk, 2000).

The characteristics of the raw organic material are the most important factors determining the quality of compost, including moisture content, C:N ratio, aeration, material particle size, and temperature. Acceptable and preferred ranges for nutrient balance (C:N ratio), moisture content, pH, and bulk density are provided in Table 8-18 (NREAS, 1992). Additional factors considered when formulating a raw organic material recipe are degradability, odor potential, and cleanness. For example, swine manure is very odorous and should not be composted on locations prone to odor complaints. Cleanness refers to the degree of contamination from unwanted materials (glass and heavy metals), chemicals (pesticides), and organisms (human pathogens). If the compost is to be sold off site, the raw material content will greatly affect its market value.

Table 8-17. Advantages and Disadvantages of Composting.

Advantages of Composting	Disadvantages of Composting
Compost is an excellent soil conditioner.	Composting is labor and management intensive.
Compost is a salable product.	Selling compost involves marketing costs (advertising, packaging, management, customer service, and so forth).
Compost reduces the weight, moisture content, and activity of manure, making it easier to handle and store.	The composting site, raw materials storage, and compost storage require a large land area.
Composting converts the N content of manure into a more stable organic form. Manure that has been composted provides a better C:N ration in the soil, contains fewer weed seeds, and poses a lower risk of pollution and nuisance complaints (due to less odor and fewer flies).	Nutrients in compost are in complex form and, therefore, need to be mineralized for plant intake; thus a greater volume of compost is needed to meet crop demands.
Composting kills pathogens.	Effectiveness is weather dependent.
Compost is a suitable bedding substitute.	Large operations require expensive equipment.
Land-applied compost has proven to suppress soil-borne plant diseases without the use of chemical controls.	Odors can be a recurring problem.
Some farmers have begun accepting payment (referred to as “tipping fees”) to compost off-site wastes.	Acceptance of off-site organic wastes may result in the operation being classified as commercial and increase compliance costs under zoning and environmental regulations.

Table 8-18. Desired Characteristics of Raw Material Mixes.

Characteristic	Reasonable Range	Preferred Range
C:N Ratio	20:1–40:1	25:–30:1
Moisture Content	40–65 percent	50–60 percent
pH	5.5–9	6.5–8.5
Bulk Density (lbs/y^3)	Less than 1,100	No preferred range

Source: NREAS, 1992.

The optimum **moisture content** for composting varies with particle size and aeration. At high moisture content, voids fill with liquids and aeration is hindered. Low moisture levels, on the other hand, retard or stop microbial activity, although some composting occurs with moisture as low as 25 percent. Depending on the raw materials, there is ultimately a 30 to 60 percent reduction in volume of the compost material, much of it due to water loss. If the water content falls below 40 to 50 percent, water should be added and mixed into the composting feedstocks. Warm weather enhances water loss from compost windrows by surface evaporation. Increased turning also results in a higher evaporation rate. This can be an advantage if a drier compost is desired, but if the evaporation rate becomes too high, water should be added to reduce potential fire hazards.

Periods of high rainfall can also be a problem for windrow composting. Windrows usually absorb water from normal rainfall or snow without saturating the materials. If the windrows become wetter than desired, more turnings are required to evaporate the added moisture. Rain can also produce muddy conditions, making it difficult to operate turning equipment. Snow can halt operation altogether until plowed from equipment paths. In addition, puddles and standing water can lead to anaerobic conditions at the base of a windrow. It is important that the composting site has adequate drainage to compensate for periods of high rainfall.

C and N serve as nutrients for the microorganisms, and for efficient composting they should be available in the right balance. A good **C:N ratio** falls between 25:1 and 35:1, although recommendations vary based upon site-specific conditions. For example, a study by Virginia Polytechnic Institute and State University concluded that the best combination of straw and raw swine manure for composting has a C:N ratio of 16:1 and a moisture level of 50 to 70 percent (Collins and Parson, 1993). Above the optimum range of C:N ratio, the materials break down at a slower rate, while a lower ratio results in excess N loss. For example, a study of poultry litter composting as a function of the C:N ratio and the pH of the starting materials showed that NH_3 emissions decreased substantially as the C:N ratio increased through addition of short paper fiber (C:N ratio(> 200:1) to broiler litter (Ekinci et al., 1998). As composting progresses, the C:N ratio will fall gradually because the readily compostable carbon is metabolized by microorganisms and the N is converted to nitrate and organic forms.

In animal manure, the C:N ratio is usually 10:1 to 15:1. The C:N ratios for different manures vary: poultry litter 10:1, layer manure 5:1, cattle feedlot manure 13:1, dairy manure 18:1, swine feedlot manure 3:1, and horse stable manure 25:1. Bulking materials can be added to increase the C:N ratio in the compost pile. Typical bulking materials include grass clippings (C:N ratio of 12:1 to 25:1), hay (15:1 to 32:1), oak leaves (50:1), shrub and tree trimmings (50:1 to 70:1), straw, cornhusks, and cobs (50:1 to 100:1), pine needles (60:1 to 100:1), sawdust (150:1 to 700:1), wood chips (500:1 to 600:1), or newspaper (400:1 to 850:1). For example, dairy manure is a good substrate for composting because it breaks down quickly and supplies the microorganisms with most of the required nutrients, but it is also N-rich, excessively wet, and has a C:N ratio ranging from 12:1 to 18:1. Moisture content varies from about 75 percent for manure collected from stanchion barns to about 85 percent from free-stall operations, with the variability determined primarily by the amount of bedding used. To make dairy manure more suitable for composting, it must be mixed with bulking agents that can be easily incorporated into the composting mix by using them as bedding.

The feasibility of using sawdust and chopped fescue hay as a low-cost waste carbon source to compost with separated swine manure solids was investigated using 21-liter vessels and bin composting units (Hoehne et al., 1998). Manure and fescue hay produced the lowest C:N ratio in both small and large composting units. Temperature trends were used to indicate biological activity. Composting manure with a carbon source was recommended because the product was easy to transport, appropriate for transport through residential areas, and odor-stable, even though composting is labor intensive.

The rate of air exchange and effectiveness of aeration of windrows depends on the porosity of the windrow. For example, a wet, dense windrow containing manure is less porous than a windrow of leaves. Windrows that are too large may result in anaerobic zones occurring near the center and causing odors when the windrow is turned. Periodic turning of window compost piles exposes the decomposing material to the air and keeps temperatures from getting too high (exceeding 170 ^{o}F). The most important effect of turning is rebuilding the windrow's porosity. Turning fluffs up the windrow and restores pore spaces lost from decomposition and settling, thereby restoring oxygen within the pore spaces for microorganisms and improving passive air exchange. Turning also exchanges the material at the surface with material in the interior. The materials compost evenly and, as a result, more weed seeds, pathogens, and fly larvae are destroyed by the high temperatures. The minimum turning frequency varies from 2 to 10 days, depending on the type of mix, volume, and ambient air temperature. As the compost ages, the frequency of turning can be reduced.

A study in Ohio measured NH_3 concentrations from dairy manure and rice hulls composted with various aeration rates (Hong et al., 1997). Temperature and NH_3 concentrations peaked 48 days after aeration begins and then declined steadily, leveling off after 150 hours. The effect of intermittent aeration on composting swine waste was studied to determine changes in NH_3 emissions and dry matter loss (Hong et al., 1998). Continuous and intermittent aeration treatments were tested on composting hog manure amended with sawdust in pilot-scale 200-liter vessels. NH_3 emissions were 39 percent lower from the intermittent aeration treatments, and N losses as NH_3-N were 26 percent lower for continuous aeration and 14 percent lower for intermittent aeration. Dry solids loss and other physicochemical properties were similar between the two treatments. It was concluded that intermittent aeration may be a practical method of reducing N loss and NH_3 emissions when composting swine manure with sawdust.

Smaller particle size provides greater surface area and more access for the degrading organisms. It may be necessary to reduce by grinding the particle size of some material such as corn stalks. Windrow turning blends raw materials and breaks up particles into smaller pieces, thus accelerating biodegredation through increased surface area.

Heat produced during the composting process raises the temperature of the composting materials. Because the heat produced is directly related to the biological activity, temperature is the primary gauge of the composting process. During the first few days of composting, pile temperatures increase to between 104 and 158 ^{o} F. This range enhances the growth and activity of the microorganisms. In addition, temperatures above 131^{o} F kill most pathogens, fly larvae, and weed seeds. The high temperature might be maintained for several days, until the microorganisms begin to deplete their food source or until moisture conditions become less than optimal. Mixing the composting feedstock brings more undecomposed food into contact with the microorganisms, replenishing their energy supply. Once the optimum moisture level is restored and the feedstocks have been remixed, the temperature increases again. After the readily decomposable material is depleted, the compost pile no longer heats upon remixing. The temperature continues to drop to ambient, and only very slow decomposition continues.

Although composting can be accomplished year-round, seasonal and weather variations often require operational adjustments. This is especially true for windrow composting. Cold weather can slow the composting process by increasing the heat loss from piles and windrows. The lower temperatures reduce the microbial activity, which decreases the amount of heat generated. To compensate for cold weather, windrows should be large enough to generate more heat than they lose to the environment, but not so large that the materials become excessively compacted. Windrows that are too small can lose heat quickly and may not achieve temperatures high enough to cause moisture to evaporate and kill pathogens and weed seeds.

Demonstration Status: Agricultural composting is experiencing a resurgence of activity, particularly in the northeastern United States. A growing number of farmers are now composting significant quantities of organic materials. These farmers have incorporated composting of a wide variety of organic wastes generated on and off farm into their normal operations. Some own large commercial enterprises; others are small “hobby” farms. A number operate otherwise traditional dairy enterprises, and several are organic vegetable growers. Some use all or most of the finished compost on the farm, and some produce compost and soil mixes as a primary agricultural product. Many use existing on-farm technology to manage the compost piles, and others have invested in specialized compost production equipment.

Several Massachusetts dairy farms have adopted composting as a manure management technique. In a study of five farms practicing composting in that state, it was found that three used the windrow method of composting, one used the passive method, and one experimented with several composting methods, finding the windrow method the most successful (Rynk, 2000). The Rosenholm-Wolfe Dairy Farm in Buffalo County, Wisconsin, has successfully produced compost for the commercial market using organic solids separated from manure that had been flushed from a 250-head, free-stall barn (Rosenow and Tiry, n.d.). The raw composting material has a C:N ratio of 30:1 and a moisture content of 60 percent, which is ideal for rapid production of a high-quality product using windrow composting.

A pilot project conducted at the Purdue Animal Science Research Center has shown that composting can be an efficient way to manage waste from dairy farms, hog farms, beef feedlots, and poultry operations at a lower cost than that associated with other waste management methods (*Purdue News,* August 1998). The composting site has 13 rows of compost material, each 5 feet tall, 10 feet wide, and 250 feet long. The rows are turned using a specialized windrow turner.

Three fundamental factors driving this renewed interest in composting are environmental and community constraints on traditional manure management options, increased understanding of the agronomic benefits of compost use, and rising disposal costs for such materials as municipal yard waste and food processing wastes, which might be managed for a profit in an agricultural setting. Despite growing interest, however, the environmental and possible economical benefits of composting are challenged by a variety of constraints. An agricultural composting study conducted by Cornell University (Fabian, 1993) concluded that governmental agencies need to take a number of steps to further encourage agricultural composting including minimizing regulatory constraints on farm-composted materials, encouraging local zoning to allow compost facilities as a normal agricultural operation, providing governmental assistance for composting equipment and site preparation, developing procurement guidelines for state agencies to use compost in preference to peat and topsoil, and supporting research and demonstration programs that explore new applications for compost in the agricultural sector.

Practice: Dehydration and Pelleting

Description: Dehydration is the process by which the moisture content of manure is reduced to a level that allows the waste to be used as a commercial product, such as fertilizer for horticulture.

Applicability and Performance: Dehydration has been used on a variety of animal waste products including poultry manure and litter. The output material (dried to about 10 percent moisture content) is an odorless, fine, granular material. With a moisture content of 10 to 15 percent, a slight odor may be noted. Crude protein levels of 17 to 50 percent have been reported in dried poultry waste (USEPA, 1974). The material can also be formed into pellets prior to drying. Pelleting can make the material easier to package and use as a commercial fertilizer.

Operational Factors: Manure is collected and dried from an initial moisture content of about 75 percent to a moisture content of 10 to 15 percent. The drying process is usually accomplished using a commercial drier. The input requirement for most commercial driers is that the raw material be mixed with previously dried material to reduce the average moisture content of the input mixture to less than 40 percent water.

The mixture is fed into a hammer mill, where it is pulverized and injected into the drier. An afterburner is generally incorporated to control offensive odors. The resultant dried material is either stockpiled or bagged, depending on the ultimate method of disposal selected. Units reported range in size from small portable units to systems capable of processing 150,000 tons per year (USEPA, 1974).

Advantages and Limitations: The drying of animal waste is a practiced, commercial technology with the dehydrated product sold as fertilizer, primarily to the garden trade. It is an expensive process that can be economical only where the market for the product exists at the price level necessary to support the process.

Development Status: The status of dehydrating animal manure is well established. Full-scale drying operations have been established with animal manure, in some cases since the late 1960s. A number of manufacturers offer a line of dehydration equipment specifically designed for this purpose. At least one large-scale facility, currently under construction on the Delmarva Pennisula, will be used to treat broiler manure.

Practice: Centralized Incineration of Poultry Waste

Description: Centralized incineration is an alternative method of disposing of excess poultry litter. Most poultry litter has energy content and combustion qualities similar to those of other biomass and commercially used alternative fuels (e.g., wood and refuse-derived fuels from municipal trash). Under a centralized incineration approach, poultry litter that is removed from the houses is collected and transported to a centralized facility that has been designed or retrofitted to burn poultry litter. The concentration of the poultry industry in several areas of the country and the dry composition of the manure facilitates litter transport, which is critical to the success of this alternative treatment technology. The centralized incineration unit could be located at a processing plant to provide power to the plant or at a stand-alone facility that would generate power for public use.

Application and Performance: Most of the nutrients in the litter would not be destroyed by combustion, but would be captured in the combustion ash and could be managed safely and economically. Consequently, the most immediate environmental benefit from burning litter is that its nutrients would not be applied to cropland and therefore would not run off into waterways.

Advantages and Limitations: The incineration of poultry litter to generate energy offers several clear advantages over current practices. The energy recovered by burning poultry litter would displace conventional fossil fuels and thereby avoid greenhouse gas emissions. The pollution control equipment required for major fuel burning units would likely minimize other combustion emissions when the manure is burned.

Limitations of using poultry litter as fuel include variability in litter composition, litter production rates, and litter caloric content. One of the most important determinants of the suitability of any substance as a fuel is its moisture content, and there is no guarantee that litter would undergo any sort of drying process prior to combustion. Moisture in a fuel represents a reduction in its heating value because some of its energy content must be used to vaporize the moisture, reducing the fuel’s effective energy output. Poultry litter has a much lower British thermal unit (Btu) content, higher moisture content, and higher ash content than conventional fuels. It can pose greater operational problems (such as corrosion) and would probably be convertible to steam at a lower efficiency than conventional fuels. Moreover, because of its much higher ash content, litter will yield far more unburned residuals than other fuels. Metals, P, and K from the litter will concentrate in the residual ash; however, bottom ash and fly ash can be sold as fertilizer, contributing to the profitability of the technology.

Metals (e.g., Cu, arsenic, Zn) may be present in litter because they are added to poultry feed as a dietary supplement. Other metals may be unintentionally present in feed and bedding, or may be scraped from the floor of a poultry house when the litter is removed. Aluminum may be found in litter because alum is added to limit NH_3 volatilization, and aluminum sulfate is added to bind the P in litter, reducing P in runoff when applied to land. Metals in poultry litter can affect its suitability for combustion in several ways. First, the concentration of metals could affect the nature of air emissions from a poultry-fired boiler. Second, metals might pose a problem in the ash created from litter combustion. Most toxic metals concentrate significantly in combustion ash relative to the unburned litter.

Although litter combustion has significant environmental advantages, adverse environmental impacts might result from using poultry litter as a fuel source. Air emissions and treatment residuals result from the incineration of any fuel, however, and the chemical and physical properties of litter as a fuel do not suggest that burning litter would result in significantly worse pollution emissions than would burning conventional fuels. When compared with the combustion of conventional fuels, combustion of poultry litter produces fewer tons of NO_x, sulfur oxides (SO_x), and filterable particulate matter (PM) emissions at the boiler than coal or residual (No. 6) oil. In comparison with distillate fuel oil, litter has a less desirable emissions profile. A comparison with wood is mixed; litter shows lower emissions of carbon monoxide (CO), filterable PM, and methane, whereas wood shows lower emissions of NO_x, SO_x, and carbon dioxide (CO_2). Despite the high N content of poultry litter, burning litter should not increase NO_x emissions. NO_x emissions from combustion primarily depend on the nature of the combustion process itself (affecting the degree to which atmospheric N is oxidized) and only secondarily on the amount of N in the fuel. In fact, the high NH_3 levels in poultry litter may act to reduce much of the NO_x that is formed during combustion back into elemental N. This is the reaction that underlies most of the modern NO_x control technologies (selective catalytic and noncatalytic reduction) used in utility boilers.

SO_x formation in combustion processes depends directly on the sulfur content of the fuel. Therefore, SO_x emissions from burning poultry litter should be lower than those from high-sulfur fuels (residual oil or higher-sulfur coal) and higher than those from low-sulfur fuels (distillate oil, low-sulfur coal, wood, natural gas). The relatively high alkali (K and Na) content of litter and litter combustion ash may cause problems in the combustion system: a low ash melting point, which can lead to slagging and deposition of “sticky” ash on combustion surfaces, and high particulate emissions in the form of volatile alkali compounds. However, this high alkali ash content also has the likely benefit of reducing SO_x in the flue gas through a “scrubbing” effect. If the uncontrolled emissions from burning poultry litter appear likely to exceed emission standards, an appropriate air pollution control device would be installed at the unit, just as it would be at a conventional fuel-burning unit.

Costs for this technology include cleanout and storage/drying costs, as well as the cost of transporting the litter to the incineration facility. A fuel user might hire a contractor to remove litter from a poultry house and load it onto a truck for delivery, hire a contractor to load the litter and pay a grower for the litter and cleanout, or hire a contractor to get the litter from the shed and load it onto a truck, paying the grower for the litter, cleanout, and storage. In addition, fuel users may also need to install new fuel-handling and management equipment and perform some redesign of the combustion process. Burning litter effectively might entail new plant construction, such as construction of a direct-fired biomass facility, retrofitting of an existing plant for direct firing poultry litter, or retrofitting of an existing cogeneration facility or boiler to co-fire poultry litter with conventional fuels (such as oil or coal). Most operations would also require a storage structure and litter supply system. The costs of retrofitting a processing plant boiler or feed mill boiler to co-fire litter do not appear excessive. The cost savings from burning litter would continue indefinitely and would increase as fuel users find more effective and efficient ways of burning litter.

Operational Factors: One of the first steps in using poultry litter as a fuel is to estimate the amount of litter produced by a feedlot. This amount is then compared with the quantity of litter that could be spread appropriately on local cropland to meet agricultural nutrient needs. The amount by which litter production exceeds the litter needed for crop nutrient purposes is the measure of the amount available for fuel. Several approaches are in use to project the volume of litter that a poultry operation will generate. The differing results of these approaches are mostly a function of the wide range of variables that affect poultry litter production—type of bird, feed and watering programs, bird target weight, type of bedding, litter treatment for NH_3 control, house type, crusting procedures, and cleanout schedules. One method uses a calculation of 10.8 lb of manure produced per broiler per year, another assumes an average of 35 lb of manure per 1,000 birds per day, and another assumes an average of 2.2 lb of litter per bird. Other more sophisticated methods apply a rate of litter produced per unit of bird weight produced. However, the most straightforward and commonly used calculation relies on an assumption of 1 ton of litter per 1,000 birds. It should be noted that since a significant portion of the weight of litter is water, having drier litter means fewer tons per bird. Therefore, the 1 ton of litter per 1,000 birds assumption should be treated strictly as a rough estimate.

The most important characteristic of litter with regard to its value as a fuel is its caloric content. Although the energy content of litter varies significantly, there is less variation after it is air-dried or oven-dried. For example, research conducted on the Btu content of several litter samples under varying moisture conditions showed that litter with a moisture content ranging from 0 to 30 percent had a caloric content ranging from 7,600 Btu per pound to 4,700 Btu per pound. Litter has a much lower caloric value than conventional fuels, but it has an energy content similar to that of several other commonly used alternative fuels. In addition, when litter is used as a fuel, its density affects the nature of the fuel feed systems and boiler configurations required. The density of litter also affects how the litter can be stored, handled, transported, and land-applied. Estimates of litter density vary widely, depending largely on the moisture content of the litter. Estimates range from 19 to 40 pounds per ft^3, with the average being roughly 30 pounds per ft^3.

Because poultry litter is quite variable with respect to several characteristics important to its use as a fuel, the fuel user must develop quality control and quality assurance guidelines to ensure that the litter is of consistent quality and well suited for combustion. Criteria for accepting litter may include acquiring only litter that has been covered in storage for some period of time to avoid excessive moisture and increase Btu content per ton, or mixing a large quantity of litter on site prior to burning to reduce fluctuations in quality across individual loads of litter. One plant in operation in the United Kingdom employs the following measures: (1) litter shipments are examined for moisture content with infrared equipment, and shipments with excessive moisture are rejected; (2) core samples are taken and analyzed for moisture, ash, and Btu content; (3) based on the results of the analysis, the load is sorted into one of several storage pits; and (4) an overhead crane draws from the different storage pits in a manner providing an appropriate blend of wet and dry material, giving a reasonably constant caloric value when fed to the furnace.

Demonstration Status: This technology is not currently used in the United States for poultry waste; however, existing boilers could be retrofitted to co-fire litter with conventional fuels such as oil or coal, or litter could be burned in a direct-fired biomass facility to generate electricity, steam, or heat at power plants or in boilers at poultry processing plants to supplement energy needs. Other agricultural and silvicultural wastes such as bagasse, almond shells, rice hulls, and wood wastes are burned for energy recovery in scattered utility and industrial plants in the United States. In the United Kingdom, several medium-sized, profitable electric power plants are fueled by poultry litter. This indicates that centralized incineration of poultry waste has the potential to develop into a commercially viable alternative treatment technology for poultry growers.

A British company, Fibrowatt, conceived of, developed, and operates the electricity plants in the United Kingdom that use poultry litter as fuel. Fibrowatt’s three plants (two operating, one under construction) are all new and are all electricity-generating plants rather than industrial boilers for steam heat or cogeneration facilities. Fibrowatt’s litter storage and handling system is proprietary. The Fibrowatt plant at Eye in Suffolk, the first plant fueled by poultry litter, came on line in July 1992. The second plant, in Glanford at Humberside, came on line in November 1993. The third and largest plant is at Thetford in Norfolk, which was scheduled to begin operations in 1998.

The basic operations at the three plants are similar. Each plant is situated in the heart of a poultry-producing region. Trucks designed to minimize odor and the risk of biocontamination transport the litter from farms to the power plants. The trucks enter an “antechamber” to the litter storage structure, and the doors of the antechamber are closed before the truck unloads. Upon arrival, the litter is sampled for nearly 40 different traits including Btu content and moisture. The litter is stored and conditioned in a way that homogenizes the fuel. It is kept under negative pressure to control odor, and the air from the fans in the storage structure is directed to the boilers and used in combustion. The Glanford plant uses Detroit Air-jet spreader-stokers (reciprocating grate, solid-fuel combustors) to burn fuel. The Eye plant employs a stepped grate stoker. The boilers are Aalborg Ciserv three-pass, natural-circulation, single-drum water tube boilers. There are modifications to the ash removal process because the high alkali content of the litter can cause corrosion in the boiler. The steam from the boiler is passed to a turbo-alternator, and electricity is sold to the grid. The Fibrowatt plants are commercially viable in the United Kingdom because the prices Fibrowatt can charge for the electricity delivered to the grid are far higher than the prices charged in the United States. In addition, farmers are charged a disposal fee for their litter, and Fibrowatt is able to earn money on the ash produced by combustion, which the plants collect and sell as concentrated fertilizer with a guarantee analysis. Theoretically, the process could be replicated in the United States, but a full-market study would be needed.

Poultry litter is not currently used as fuel in the United States; however, research into the feasibility of burning litter for electricity, steam, or heat is under way. Maryland Environmental Services (MES) has asked the Power Plant Research Program (PPRP), an arm of the Maryland Department of Natural Resources, to help investigate the possibility of burning poultry litter at the cogeneration plant at the Eastern Correctional Institute. In February 1998, Exeter Associates published a report for MES projecting the costs of various scenarios for using poultry litter at the plant. One of the recommendations in the report was that a full engineering study be done to obtain a better estimate of the costs involved. MES submitted a request for proposals on this basis in April 1998 and received bids from several companies. Among the companies that bid were Fibrowatt and two companies that build gasifiers. As of July 1998, the gasifier company bids had been rejected and the remaining bids were still under consideration. MES is determined to turn the cogeneration plant at the Eastern Correctional Institute into a working facility and is interested in a Fibrowatt-style system, the technology of which is proven and currently operational.

Other Technologies for the Treatment of Animal Wastes

Practice: Aquatic Plant Covered Lagoons

Aquatic plant covered lagoons provide low-cost wastewater treatment by removing suspended solids, BOD, N, and P in structures that are mechanically simple, relatively inexpensive to build, and low in energy and maintenance requirements (WPCF-TPCTF, 1990). Wastewater treatment occurs through a combination of mechanisms including biochemical conversion through plant-microbial reactions, plant uptake, settling, volatilization, and adsorption onto sediments. Free-floating aquatic plants such as duckweed (*Lemnaceae*), and water hyacinth (*Eichhornia crassipes*) grow rapidly (in a matter of days) and take up large amounts of nutrients from wastewaters (Reddy and De Busk, 1985). In addition, the extensive root system of water hyacinth provides a large surface area for microbial growth, which promotes degradation of organic matter and microbial transformation of N (Brix, 1993). Greater than 70 percent removal of pollutants by aquatic plant covered lagoons has been reported for domestic wastewater treatment (Orth and Sapkota, 1988; Alaerts et al., 1995; Vermaat and Hanif, 1998). Depending on the lagoon design, water depth, and retention time, effluent from hyacinth- and duckweed-covered lagoons can potentially meet secondary and sometimes advanced wastewater discharge standards for BOD, suspended solids, N, and P (Buddhavarapu and Hancock, 1991; Bedell and Westbrook, 1997).

In addition to providing wastewater treatment, nutrient uptake by water hyacinth and duckweed produces a protein rich biomass (Reddy and Sutton, 1984; Oron et al., 1988) that can be harvested and used as an agricultural fertilizer or a feed supplement (Oron, 1990). Furthermore, duckweed and hyacinths provide a dense cover that restricts algal growth by impeding sunlight at the water surface (Brix, 1993), reduces odor by preventing gaseous exchange, and acts as a physical barrier to reduce the breeding of mosquitoes (Buddhavarapu and Hancock, 1991). Limitations of aquatic plant covered lagoons include a need for large treatment areas, pretreatment of wastewater in settling ponds, and floating grid barriers to keep plants from drifting (Brix, 1993). Cold temperature reduces the growth rate of floating plants (Brix, 1993). Although duckweed removes fewer nutrients than do water hyacinths (Reddy and De Busk, 1985), duckweed has higher protein and lower fiber, a faster growth rate, and lower harvesting costs (Oron, 1990), and can grow at temperatures as low as 1 to 3 °C (Brix, 1993). Duckweed prefers NH_3 over nitrate (Monselise and Kost, 1993), transforms nutrients to a protein-rich (25 to 30 percent) biomass (Oron, 1990), and selected duckweed species (*Lemna gibba*, *Lemna minor*) have been demonstrated to grow on undiluted swine lagoon effluent (Bergmann et al., 2000). For these reasons, duckweed is potentially effective in the treatment of animal waste. Further studies are needed to better understand the application and performance of aquatic plant covered lagoons for animal waste treatment.

Practice: Nitrification-Denitrification Systems—Encapsulated Nitrifiers

Description: Nitrification-denitrification refers to the biological conversion of ammonium first to nitrate, then to N_2. Many schemes for nitrification-denitrification have been researched including the use of nitrifying bacteria encapsulated in polymer resin pellets to speed up the reaction (Vanotti and Hunt, 1998). The theory is that elevated populations of nitrifying bacteria immobilized on resin pellets that are retained in a treatment system will convert more NH_3 to nitrate faster than free swimming bacteria. There is ample evidence that attached media systems that retain bacteria on their surface remove the target pollutants more effectively than bacteria that have to swim to their food and can be washed from the system.

Vanotti and Hunt demonstrated in the lab that an enriched solution of encapsulated nitrifiers in an oxygen-saturated solution at 30 ^{o}C, with 150 ppm BOD and 250 ppm TKN, could nitrify 90 percent of the NH_3 in a batch if sufficient alkalinity was added. The research also documented that a solution with encapsulated nitrifiers had more and faster nitrification than an aerated equivalent volume of anaerobic lagoon effluent with no nitrifiers added.

A pilot plant using imported pellets operating on anaerobic lagoon effluent followed the laboratory work. The effluent was first screened, and then introduced into a contact aeration treatment to reduce BOD. The aeration sludge was settled next, and then treated effluent was introduced into a nitrification tank in which another aeration blower was used to maintain a dissolved oxygen concentration of 3 milligrams per liter. The pH was maintained at 7.8 or greater with sodium hydroxide as necessary. The results of 3 months of operation were that, given adequate pretreatment, high nitrification rates of swine wastewater could be attained using enriched nitrifying populations immobilized on polymer resins.

Application and Performance: The technology specifically targets nitrification of NH_3, and could reduce the loss of NH_3-N to the atmosphere. When set up and operated properly, the treatment can convert 90 percent of the NH_3-N remaining in pretreated lagoon effluent to nitrate. A nitrified farm effluent can be denitrified easily by either returning it to an anaerobic environment resulting in release of N_2. This technology will have little if any effect on pathogens, metals, growth hormones, or antibiotics. It can be assumed that most of these constituents were removed in the process of aerating the manure to reach oxygen-saturated conditions, which would enable the encapsulated nitrifiers to function.

Advantages and Limitations: A facility to support this process would be expensive to build, operate, and maintain. It is difficult to imagine this process being used on a farm. One area not considered is the sludge generated by aerobic pretreatment. Another limitation is the anaerobic lagoon pretreatment step used to reduce initial BOD and limit sludge production.

Operational Factors: Nitrifying bacteria are temperature sensitive, but the effect of temperature was not discussed by Vanotti. Rainfall and varying concentration should not affect performance; however, seasonal temperature variation may reduce nitrification.

Demonstration Status: NCSU has operated a pilot plant in Duplin County, North Carolina.

Disinfection—Ozonation and UV Radiation

Ozonation is commonly used to disinfect wastewater after biological treatment. Ozone is a highly effective germicide against a wide range of pathogenic organisms, including bacteria, protozoa, and viruses. It oxidizes a wide range of organics, can destroy cyanide wastes and phenolic compounds, and is faster-acting than most disinfectants. Moreover, unlike chlorine, ozone does not generate toxic ions in the oxidation process.

UV radiation is used primarily as a disinfectant. It inactivates organisms by causing a photochemical reaction that alters molecular components essential to cell function. It is very effective against bacteria and viruses at low dosages and produces minimal disinfection by-by products. To enhance the inactivation of larger protozoa, UV radiation is often considered in conjunction with ozone.

Disinfection measures such as ozonation and UV radiation are not commonly practiced in the United States for treatment of animal wastes. Animal wastewater would require primary and/or biological treatment prior to disinfection . Ozone is generally effective for aqueous waste streams with less then 1 percent organic content. Both processes are costly and require higher levels of maintenance and operator skill. Wastewater with high concentrations or iron, calcium, turbidity, and phenols may not be appropriate for UV disinfection. The effectiveness of UV disinfection is greatly hindered by high levels of suspended solids.

Vermicomposting

Composting is the controlled decomposition of organic materials and involves both physical and chemical processes (see Composting—Aerobic Treatment of Solids). During decomposition, organic materials are broken down through the activities of various invertebrates that naturally appear in compost, such as mites, millipedes, beetles, sowbugs, earwigs, earthworms, slugs, and snails. Vermicomposting is accomplished by adding worms to enhance the decomposition process.

Vermicomposting uses "redworms" (*Eisenia foetida*), which perform best at temperatures between 50 and 70 ^{o}F. Bones, meats, fish, or oily fats should not be added to a worm compost box because of odors and rodent problems they could create. Successful operation requires a great amount of maintenance because the worms are highly sensitive to alterations in oxygen levels, temperature, moisture, pH, nutrients, and feed composition and volume. Heavy metals are not treated by any means of composting and can be toxic to the microorganisms and invertebrate population.

Farm-scale systems for vermicomposting have been developed. They tend to be simple systems using conventional, material-handling equipment. Labor and equipment are required to add material to the bed, remove composted material, separate the compost from the worms by screening, and process the compost and worms for their respective markets (the compost as a protein additive to animal feed, the worms as fish bait). Flies are a potential problem since this process occurs at a lower temperature than the general composting process. Pathogen destruction and drying are also reduced. A drying or heating step may be required to produce the desired compost.

Chemical Amendments

Chemical treatments have been applied to facility wastewater, animal waste, or directly to soils. A number of chemical amendments have been evaluated, mainly metal salts or by-products containing Al, Fe, or Ca, similar to methods used to remove P in municipal wastewater treatment. The P fixation capacity of soils is positively correlated with the Al content; Al and orthophosphate ions interact strongly to form either stable surface complexes or insoluble Al phosphate minerals (Moore and Miller 1994). Precipitation reactions with Fe and Ca form insoluble iron and calcium phosphates. Moore and Miller (1994) conducted laboratory studies of 100 different treatments with various Al, Fe, and Ca compounds at different rates and found that many of these compounds drastically reduced soluble P levels in poultry litter.

Amendments reported in the literature, mostly from laboratory or plot studies, include:

- **Water treatment residuals (WTR).** WTR, also known as alum sludge or alum hydrosolids (HS), are wastes generated from drinking water pretreatment. Peters and Basta (1996) added HS to soils previously treated with poultry litter and reported 50–60 percent reductions in Mehlich-III P. Haustein et al. (2000) found that high rates of both WTR and HiClay Alumina (HCA) applied directly to test plots decreased Mehlich-III soil test P levels due to the increased levels of soil Al.

- **Ferric Chloride ($FeCl_3$).** Ferric Chloride additions to poultry litter decreased P solubility at lower rates of about 20–50 g Fe/kg litter, but increased solubility at higher rates (Moore and Miller 1994). Barrow et al. (1997) reported that adding high levels of ferric chloride to dairy wastewater improved sedimentation of P by almost 50 percent. Sherman et al. (2000) reported significant P removal from dairy flushwater using ferric chloride.

- **Coal combustion byproducts**. Stout et al. (1998) reported that addition of fluidized bed combustion flyash (FBC) and flue gas desulfurization product (FGD) to soils significantly reduced Mehlich-III P (45 percent), Bray-I P (50 percent), and water extractable P (72 percent) due to converting readily desorbable soil P to less soluble Ca-, Al-, or Fe-bound forms. Dao (1999) observed that application of Class C fly ash to cattle manure reduced water-extractable P by 85-93 percent and Mehlich-III P concentrations by up to 98 percent. FBC and FGD additions reduced water soluble inorganic P in by fresh dairy and swine manure by 50–80 percent (Toth et al. 2001a). Dou and Ferguson (2002) reported water soluble P reductions of 23–59 percent in swine and dairy manure treated with FBC and FGD. It should be noted that these byproducts can contain significant concentrations of heavy metals that may be toxic to plants and the loadings of these elements must be considered in the use of combustion byproducts.

- **Zeolite.** Lefcourt and Meisinger (2001) reported that addition of zeolite (primarily Si, AL, Na, and K oxides) to dairy slurry reduced soluble P content by over 50 percent.

- **Polyacrylamide (PAM).** PAM has been used to reduce sediment, nutrients, and pesticides in furrow-irrigated agriculture. In lab and field studies, PAM alone or in combination with Al and Ca reduced PO_4 by 47–64 percent in soil column leachate when manure was applied and by about 50 percent in water flowing over surface-applied cattle manure (Entry and Sojka 2000).

- **Limestone Dust.** Barrington and Gelinas (2002) reported precipitating about 93 percent of total P in swine manure into a sludge by the addition of 2 percent fine limestone dust.

- **Wollastonite.** Application of wollastonite (alkaline calcium and ferrous silicates) to soils has been proposed as a means to reduce P solubility in hydrologically sensitive areas (Willett et al. 1999). However, no experimental data have been reported.

By far, the most widely proposed and most thoroughly evaluated manure amendment is aluminum sulfate ($Al_2(SO_4)_3$), commonly called alum.

Alum Treatment

Although alum has been used for P precipitation in wastewater treatment for several decades, the use of alum additions to animal waste has been studied extensively only since the early 1990s. Applications have ranged from pretreatment of agricultural wastewaters, manure treatment, and soil amendment. While the majority of the studies have focused on effects on P solubility and runoff, significant effects on nitrogen volatilization and runoff of metals have also been documented.

Alum treatment for P control. Alum is thought to reduce soluble P through two mechanisms, formation of relatively insoluble aluminum phosphate compounds:

$$AL_2(SO_4)_3\text{-}14H_2O + 2H_3PO_4 \rightarrow 2AlPO_4 + 6H^+ + 3SO_4^{2-} + 14H_2O$$

or sorption of P by amorphous aluminum hydroxides:

$$AL(OH)_3 + H_3PO_4 \rightarrow AL(OH)_3\text{-}H_3PO_4$$

Over time, amorphous aluminum phosphate could be transformed to crystalline minerals such as variscite or wavellite, which are stable under acid conditions (Moore et al. 1998).

Much of the work on alum treatment has been done on poultry litter. Poultry litter is a particular problem because most P in litter occurs in the soluble form and intensive poultry production often occurs with a limited land base for waste application. Moore and Miller (1994) conducted early laboratory studies of alum additions to poultry litter and reported that alum additions decreased water soluble P from 2,000 to about 1 mg P/kg and concluded that treating litter prior to field application could significantly reduce soluble P runoff. In another study, the soluble P content of poultry litter amended with alum was reduced by up to 94 percent, from 2022 mg/kg to 111 mg/kg (Moore et al. 1995).

Shreve et al. (1995) evaluated the effects of alum treatment of poultry litter on runoff P and on forage production. Amending poultry litter with alum resulted in an 87 percent reduction in soluble P concentrations in runoff from plots compared with untreated litter in the first runoff event after application, and a 63 percent reduction for the second runoff event. Runoff soluble P load in the first runoff event was reduced 86 percent by alum addition. Litter application increased fescue yields, with yield having the greatest response to alum-amended litter, probably due to increased available N resulting from decreased NH_4 volatilization from the alum-treated litter. Based on these field trials, the authors concluded that alum treatment for poultry litter had significant promise for use as an environmental and economic management practice in the poultry industry.

A subsequent examination of long-term solubility of P in soils receiving treated poultry litter reported that after addition of litter containing 200 mg alum/kg, soil soluble P decreased from initial concentrations of 4.5-11.5 mg P/kg to about 1 mg P/kg after about 100 days over a wide pH range and remained low through nearly 300 days (Shreve et al. 1996).

Moore et al. (1997) determined the effect of alum treatment of poultry litter on phosphorus runoff from field-scale watersheds. Soluble reactive P concentrations in runoff averaged 1.05 and 3.23 mg P/L for the alum-treated and untreated litter, respectively; alum reduced soluble P runoff by 67 percent during the first year after application. Total P concentrations responded similarly (average 1.49 and 4.23 mg P/L for alum-treated and untreated litter, respectively). Soluble P concentrations averaged 74 percent lower from alum-treated litter runoff during the second year after application. Overall, soluble reactive P concentrations were decreased 70 percent with alum.

Moore et al. (1997) also assessed agronomic rates of alum-treated poultry litter. The authors observed that application of normal poultry litter resulted in dramatic increases in water soluble P in soils, whereas application of alum-treated litter did not. Data showed that P bound by alum does not re-solubilize with time, indicating that litter application rates can be based on N, rather than P, if alum-treated litter is used, without risk of increasing soil test P levels. The study also found that the pH of soils fertilized with alum-treated litter was slightly higher than unfertilized soils, indicating that the use of alum in litter will not result in soil acidification.

Pre-treatment of poultry litter with alum significantly affects soil P as well as runoff. After three years of treating grass plots with alum-amended litter, no significant differences in soil water soluble P were observed when compared to the unfertilized control (Self-Davis et al. 1998, Moore et al. 2000). Water-soluble P levels in plots receiving untreated litter, however, increased each year. Alum-amended litter plots had significantly lower Mehlich-III P values compared to equivalently-managed untreated litter plots after two years of litter applications.

In an evaluation of treatment to fields already excessively high in soil test P, Haustein et al. (2000) applied water treatment residuals (WTR, composed of coagulated alum mixed with sand, silt, bacteria, and other compounds removed from raw water in the water treatment process) to grassed plots high in P. High rates of WRT (9–18 Mg/ha) decreased Mehlich-III soil test P levels 44–50 percent due to increased soil Al levels. Dissolved P in runoff from treated plots were less than or equal to levels in runoff from the control (no litter) plot.

A recent on-farm evaluation of alum as a poultry litter amendment showed that a poultry litter alum-treatment BMP can be effectively implemented under a wide range of real-world conditions (Sims and Luka-McCafferty 2002). Alum was applied over a 16-month period to 97 poultry houses on working poultry farms on the Delmarva peninsula, with 97 other houses serving as controls. Alum decreased water soluble P concentrations in litter by about 70 percent, from an average of 1475 mg P/kg in untreated litter to an average 405 mg P/kg in alum treated litter.

While the effects of alum treatment on P in other animal wastes have received considerably less evaluation, results seem to be similar to those observed with poultry litter. Alum addition to stockpiled and composted cattle waste reduced water-extractable P in the waste by 85–93 percent (Dao 1999). Sherman et al. (2000) demonstrated removals of 11–17 mg P/ mmol Al^{+3} added to flush waters containing 1 percent dairy manure solids. Alum has been shown to be very effective in reducing soluble P in dairy manure (Lefcourt and Meisinger 2000). Even a 0.4 percent addition rate reduced soluble P about 75 percent compared to the control; a 6.25 percent addition reduced soluble P by about 97 percent. Toth et al. (2001b) reported that alum addition significantly reduced soluble P in dairy manure (by 36–99 percent), and, to a lesser extent, in swine manure (7–80 percent). Addition of alum at 0.5 percent by volume to a swine waste settling basin improved P removal from the liquid fraction to 75 percent, compared to 38 percent without alum (Worley and Das 2000).

Addition of alum to horse bedding prior to application to grass plots decreased runoff soluble P concentrations by 97 percent, which was less than the mean soluble P concentration in runoff from control plots (Bushee et al. 1998). Alum addition to horse manure decreased P concentrations by >50 percent in plot runoff; runoff P concentrations from alum-treated application did not differ significantly from runoff from non-manured plots (Edwards et al. 1999).

Alum treatment effects on nitrogen. Ammonia (NH_3) volatilization from poultry litter results in accumulation of atmospheric NH_3 in the poultry house, which is detrimental to human and bird health and reduces poultry productivity. Ammonia loss from litter and other animal waste also reduces the N content of the manure and can contribute to both acid deposition and eutrophication (Kithome et al. 1999).

Numerous studies have confirmed that addition of alum to poultry litter can reduce NH_3 volatilization up to 99 percent (e.g., Moore et al. 1995, 1998, and 2000). Alum reduces NH_3 losses because the acid generated in the hydrolysis of alum reduces litter pH; the H^+ produced in this reaction will react with NH_3 to form non-gaseous NH_4^+, which can react with sulfate ions to form ammonium sulfate, a water-soluble fertilizer.

Moore et al. (1995) documented 36-99 percent reductions in NH_3 volatilization with alum application to poultry litter, noting that the preservation of N in the litter added to its fertilizer value. The authors attributed a lower poultry mortality rate in alum-treated litter due to decreased levels of atmospheric NH_3 in the house. Shreve et al. (1995) observed a higher forage yield with alum-treated litter compared to untreated litter, an effect they attributed to improved N content due to reduced NH_3 loss.

Moore et al. (1999, 2000) reported results of field trials where alum was applied to broiler litter. Alum applications lowered litter pH significantly during the entire growout period. Reductions in litter pH decreased NH_3 volatilization and resulted in significant reductions in atmospheric NH_3 in the alum-treated houses. Alum applications reduced NH_3 fluxes from litter by 97 percent for the first four weeks of the growout and by 75 percent for the full 6-week period. Additional benefits of the reduction of NH_3 loss included improved growth of broilers, improved feed conversion, lower mortality, and lower energy costs for ventilating and heating.

Addition of alum to poultry litter during composting has been shown to be effective in conserving nitrogen. Addition of 20 percent alum to poultry litter resulted in a 26 percent reduction in NH_3 loss (Kithome et al. 1999), resulting in a final compost significantly higher in total N and NH_4^+ compared to untreated compost.

In farm-scale evaluations of alum treatment, Sims and Luka-McCafferty (2002) reported that litters from alum-treated poultry houses had higher total N, NH_4-N concentrations and therefore a higher fertilizer value.

Again, relatively little work has been reported on alum amendment to other animal wastes for the reduction of ammonia volatilization. Lefcourt and Meisinger (2000) reported that the addition of 2.5 percent alum to dairy slurry reduced ammonia emissions by about 60 percent. In a laboratory test of potential amendments to reduce ammonia emissions from beef cattle feedlots, Shi et al. (2001) reported that alum application reduced NH_3 volatilization by up to 98 percent.

Alum treatment effects on metals. Poultry litter often contains significant concentrations of heavy metals such as As, Co, Cu, Mn, Se, and Zn. Trace metals are added to feed to prevent disease and improve feed conversion; most of the metals added pass directly through the bird, which leads to elevated metal levels in the manure. Research has indicated that the potential exists for nonpoint source metal pollution from fields receiving poultry litter (Moore et al. 1998).

Moore et al. (1997 and 1998) conducted plot studies to determine if alum treatment reduces metal runoff and uptake by plants from poultry litter; the authors present extensive data on alum effects on copper, zinc, arsenic, aluminum, selenium, and other elements. Concentrations and loads of water-soluble metals (Al, As, Ca, Cu, Fe, K, Mg, Na, and Zn) increased with increasing litter application rates, regardless of litter type. The metal of greatest concern was copper, which was found in high concentrations in runoff from untreated litter. Alum treatment significantly reduced concentrations of As, Cu, Fe, and Zn compared to untreated litter, but increased Ca and Mg levels. Reductions in trace metal runoff due to alum were thought to be related to reduction in concentrations of soluble organic carbon (SOC) due to alum treatment. The authors concluded that metal runoff from alum-treated litter is less likely to cause environmental harm than from untreated litter because the water quality impacts of Ca and Mg are far less than those caused by Cu, As, and Zn. The study also showed that aluminum runoff and uptake by plants was not affected by alum treatment.

Little work on the effects of alum on metals associated with other animal waste has been reported in the literature. Edwards et al. (1999) studied the runoff of metals from alum-treated horse manure and found few detectable effects on metals in runoff from manured plots. Runoff concentrations of Al, S, Ca, and K increased in response to alum.

Summary: Alum Treatment

Benefits of alum treatment. Alum treatment of animal waste, particularly poultry litter, has important beneficial effects as a P management BMP. These direct effects include:

- **Reduced P solubility in waste.** Reductions in water-soluble P content of poultry litter and other animal wastes of 70 to >90 percent have been cited (e.g., Moore and Miller 1994, Moore et al. 1995, Lefcourt and Meisinger 2000, Sims and Luka-McCafferty 2002). This effect has been documented from the laboratory to the farm scale.

- **Reduced soil P levels.** Use of alum-treated poultry litter significantly reduces soil P. For example, after three years of treating grass plots with alum-amended litter, no significant differences in soil water soluble P were observed when compared to the unfertilized control (Self-Davis et al. 1998, Moore et al. 2000). Alum-amended litter plots had significantly lower Mehlich-III P values compared to equivalently-managed untreated litter plots after two years of litter applications. Use of treated litter can also reduce soil test P on soils already excessively high in soil test P (Haustein et al. 2000).

- **Reduced runoff P.** Use of alum-treated animal waste can dramatically reduce P runoff losses compared to untreated waste. Reductions of about 60–90 percent in soluble P concentrations in runoff have been widely reported from alum-treated poultry litter and other animal wastes (Shreve et al. 1995, Moore et al. 1997, Bushee et al 1998). In several reported cases, P concentrations in runoff from land-applied alum-treated waste were not significantly different from P levels in runoff from un-manured land (Self-Davis et al. 1998, Edwards et al 1999, Moore et al. 2000).

- **Reduced ammonia loss.** Numerous studies have shown that addition of alum to poultry litter can reduce NH_3 volatilization up to 99 percent (e.g., Moore et al. 1995, 1998, and 2000). Reduction in ammonia loss from poultry litter not only reduces airborne ammonia inside the poultry house but improves the fertilizer value of the litter by conserving N. Higher N content in alum-treated litter has been widely documented (Shreve et al. 1995, Kithome et al. 1999, Sims and Luka-McCafferty 2002).

- **Reduced runoff losses of metals.** Alum amendment decreases litter pH and the solubility of metals such as As, Cu, and Zn, which should reduce the movement of these soluble forms into surface or ground waters (Sims and Luka-McCafferty 2002). Runoff losses of some trace metals that pose significant environmental risk (e.g., copper) have been shown to be lower from land application of alum-treated poultry litter, compared to conventional litter (Moore et al. 1997 and 1998).

These documented effects of alum treatment have led to the conclusion that alum treatment offers great promise as an animal waste management BMP, particularly for poultry production (Moore et al. 1999, Sims and Luka-McCafferty 2002). Long-term studies of alum use have reported few negative impacts. The aluminum-phosphate minerals formed when alum is added to manure are believed to be stable for geologic time periods (Moore at al. 1999). Soil acidfication from alum use does not appear to be a problem, as increases in soil pH have been reported with alum-treated litter (Moore et al. 1997, 2000).

At typical rates of addition, alum treatment would not be expected to raise soil Al content significantly for several centuries (Moore et al. 2000). Even then, alum additions would not generally increase Al concentrations in runoff because soil pH does not typically become low enough for Al to be soluble. Thus, increases in Al in runoff from application of alum-amended waste would not be expected (Moore et al. 1999, 2000). In one reported case, however, elevated

Al levels were found in runoff from plots that received high-aluminum water treatment residuals in direct application; this was attributed to washing of freshly applied material from the soil or plant surface (Haustein et al. 2000).

Moore et al (1997) reported no significant differences in aluminum levels in plants due to application of alum treated litter. This is expected because alum-treated litter contains only trace quantities of soluble Al; most Al in treated litter and soil occurs as insoluble minerals.

Treatment of poultry litter with alum has a number of potential indirect benefits, including:

- **Improved fertilizer value.** Reduction of N losses and decreases in soluble P changes the N:P ratio of the litter. If alum-treated litter is used, it may be possible to apply litter based on N needs of a crop, rather than P, without risk of increasing soil P levels. Improved fertilizer value could also increase the economic feasibility of animal waste export or transport to facilitate nutrient trading.

- **Odor control.** Reduction of ammonia volatilization from animal waste, particularly poultry litter, may offer significant benefits in reduction of odor problems with animal production.

- **Health and productivity.** The reduction of ammonia production in poultry litter by alum has many important benefits to human and bird health and to productivity. Reduced ammonia levels in poultry houses will reduce exposure of farm workers to harmful levels of ammonia. Reductions in flock mortality, improved weight gains and feed conversion, and reduction in incidence of disease have all been documented in response to alum treatment of litter in poultry houses (Moore et al. 1999). Reduction in energy costs due to decreases in need for ventilation and heating have also been documented in response to reduced ammonia levels.

- **Solids separation.** The ability of alum to precipitate P in liquid dairy or swine waste may facilitate solids separation for composting and manure transportation.

- **Recycling of byproducts.** Use of Al-based materials like alum hydrosolids, water treatment residue, or flyash are used for waste treatment may replace expensive landfill disposal of these byproducts.

In addition to the broad environmental benefits, alum use seems likely to be a cost-effective practice to poultry growers and integrators. Moore et al. (1999) estimated a benefit:cost ratio of 1.96 for alum treatment of poultry litter, accounting for the cost of the alum treatment and the savings associated with improved productivity, lower mortality, and lower energy costs.

Cautions. While the benefits of alum treatment of animal waste have been clearly documented and few serious environmental risks have been identified, a few qualifications and concerns remain that must be considered.

- The reported reduction in P loss in runoff due to alum treatment generally assumes that erosion from source areas is minimized. Erosion and soil loss would transport particulate P in runoff, which may pose a long-term threat to water quality despite reductions in solubility due to alum treatment.

- Alum amendment of animal waste must be done in the context of a sound nutrient management program. Use of alum treatment as a BMP would be of little value if nutrients continue to be applied in excess of crop requirements.

- The effectiveness of alum may be lower than reported for poultry litter in other wastes if more of the P is already in a stable (nonsoluble) form, e.g., biosolids.

- Alum treatment is not an unlimited solution to the problem of excessive P loading from animal waste. For example, even when high P soils were treated to reduce soil test P by about 50 percent, the level of plant-available P remaining in the soil was twice that required for maximum crop production (Haustein et al. 2000).

- Because alum treatment conserves N in animal waste, there may be an increased potential for N loss in runoff or leaching.

- Whereas alum-treated animal wastes are neutral or alkaline, untreated aluminum sulfate may result in undesirable soil acidification and lead to release of toxic levels of dissolved Al (Peters and Basta 1996).

- Alum dose must be carefully controlled; excess alum addition can increase soluble Al in manure slurries (Lefcourt and Meisinger 2001); excessive application of some alum could immobilize enough P so that crop yields suffer from induced P deficiency.

- Although most studies have indicated that P compounds formed with Al are quite stable, some authors have suggested that the effects of changing redox potential on long-term stability of these compounds should be evaluated (Shreve et al. 1996).

- Because Al solubility is controlled by pH, soil pH may need to be monitored in areas vulnerable to acid deposition or if alum-treated manure applications are discontinued and replaced by inorganic N fertilizers, which tend to reduce soil pH.

- While alum will decrease the solubility of elements such as P, As, Cu, and Zn, it will have little or no effect on the total quantity of these elements in the waste. Research is needed on long term stability, transformations, and potential mobility of P and trace metals in soils amended with alum-treated animal waste (Sims and Luka-McCafferty 2002).

Chemical Treatment for Pathogen Reduction

Treatment of manure with lime (calcium hydroxide, calcium oxide) has been proposed as a means to reduce pathogens in animal waste. There is scant information in the scientific literature directly concerning animal waste treatment; most of the justification for this proposed treatment comes from the use of lime materials to reduce pathogens and odors in biosolids. It is important to note that the lime discussed here is not the same material as the limestone (calcium carbonate, “agricultural lime”) that is used to raise the pH of agricultural soils.

Biosolids treatment

Federal regulations classify biosolids into two classes, based on pathogen content; these classes specify the degree of treatment the biosolids must receive before land application or disposal. To meet Class A requirements (very low pathogen concentrations), biosolids must be treated by thermal drying (80 °C, dried to ≥90 percent solids), composting (55 °C for three days, aerobic conditions), or lime stabilization. Lime stabilization to meet Class A requirements requires that pH be raised to ≥12 for 2 hours and be maintained at pH 11.5 for 22 hours, combined with high temperatures (70 °C for 30 minutes). Lime stabilizaton involves addition of dry quicklime (CaO) to raise the pH and temperature of the biosolids.

In a comparison of stabilization techniques, Rothberg, Bamburini & Winsor, Inc. (undated), cited a number of advantages of lime stabilization, including pathogen reduction to Class A levels, low capital cost, dilution of metals concentrations, fixing of metals under alkaline conditions, and value of end product as a soil liming agent. Disadvantages cited include high annual cost, odor problems for ammonia offgas, and product applicability to alkaline soils. Currently, almost 20 percent of biosolids in the U.S. are treated with lime.

Lime inhibits pathogens by controlling environmental conditions required for bacterial growth. At pH >12, cell membranes of microorganisms are destroyed; hydrated lime (calcium hydroxide) is capable of creating pH levels as high as 12.4 (NLA 2001). Furthermore, use of quicklime (calcium oxide) involves an exothermic reaction with water, potentially raising temperatures to levels inimical to microorganisms.

Lime as an agricultural disinfectant

Lime is reportedly used in Europe as a disinfectant for barn and milking center floors, for disease control in carcass disposal, and for disinfection of animal wastes (NLA 2001).

Cooper Hatchery, Inc. (1987) reported that total bacteria counts, molds, and coliform bacteria were decreased in turkey litter after three days of fermentation following addition of hydrated lime.

Shand and Associates (1998) conducted a project to test the effectiveness of a lime pasteurization process to partially dehydrate and stabilize organic wastes in the Fraser River Basin (Canada). Although no pathogen data were reported, it is interesting to note that addition of lime accelerated ammonia emissions from animal wastes (probably due to elevated pH in the waste). This ammonia offgassing has been cited as a possible agent of disinfection in alkaline treatment of waste (Logan 1999).

Hogan et al. (1999) reported that hydrated lime effectively inhibited bacteria in recycled dairy manure bedding in 1 day. Lime was effective on reducing gram-negative bacteria, coliform counts, *Klebsiella spp*., and *streptococci*.

Logan (1999) reported mixed results of pathogen reductions in animal waste using a proprietary alkaline stabilization process; the process apparently did not use lime. Several different waste types were tested in a processing plant where alkaline materials (unspecified coal-burning byproducts) were mixed with animal waste. The process achieved reductions in fecal coliform of one to three orders of magnitude in digested dairy manure; however fecal coliform counts were still as high as 10^3–10^4/g after treatment. Alkaline treatment was effective in treating undigested manures, reducing fecal coliform counts from 10^6/g to 10^1/g in dairy manure and from 10^4/g to 10^1/g in beef manure. However, fecal streptococci, total aerobic bacteria, and gram-negative organisms were relatively unaffected by the treatment. Treatment of turkey manure was highly effective, reducing fecal coliform counts from 10^5/g to $<10^2$/g. The applicability of this proprietary, facility-based process to the farm scale was not addressed.

Given the lack of specific data on the ability of lime addition to reduce pathogen counts in animal waste, it is worth noting that environmental factors such as temperature, pH, moisture, nutrient supply, and solar radiation have significant effects on bacteria survival outside their host (Moore et al. 1988). Waste storage alone results in a significant reduction of bacteria numbers compared to those in fresh waste; reduction of 2–3 orders of magnitude in fecal coliform are typical with storage for 2–6 months (Patni et al. 1985, Moore et al. 1988**.** Microorganisms in land-applied waste are subject to mortality from high temperatures, dessication, UV light, and other stresses (Moore et al. 1988).

Summary: Lime Treatment

Given the lack of specific, objective literature on the subject, it is difficult to recommend the use of lime to reduce pathogens in animal waste at this time. More research is needed that specifically focuses on the effectiveness of lime treatment on reduction of indicator and pathogenic microorganisms in animal waste and on the practical application of lime addition at the farm scale as a practical BMP. There is insufficient data on these subjects at present.

Possible benefits of lime treatment:

- Proven effective and widespread use to achieve Class A biosolids standards

- Documented reductions of some microorganisms in some animal wastes
- Fixation of metals and phosphorus
- Odor control of hydrogen sulfide (NLA 2001)
- Potential value of end product in soil pH management

Major unknowns or possible disadvantages

- Little solid performance data specific to animal waste
- Possible ineffectiveness of alkaline treatment on some organism groups
- Variation in effectiveness on different waste types
- Acceleration of NH_3 generation reduces N content of final product and may pose environmental or health risks
- Unknown scalability to cost-effective farm management

Gasification

The fuel produced by gasification is viewed today as an alternative to conventional fuel. A gasification system consists of a gasifier unit, purification system, and energy converters (burners or internal combustion engines). The gasification process thermochemically converts biomass materials (e.g., wood, crop residues, solid waste, animal waste, sewage, food processing waste) into a producer gas containing carbon dioxide, hydrogen, methane and some other inert gases. Mixed with air, the producer gas can be used in gasoline and diesel engines with little modification.

Gasification is a complex process best described in stages: drying, pyrolysis, oxidation, and reduction. Biomass fuels have moisture contents ranging from 5 to 35 percent. For efficient operation of a gasification system, the biomass moisture content must be reduced to less than 1 percent. The second stage of the process, pyrolysis, involves the thermal decomposition of the dried biomass fuels in the absence of oxygen. The next stage, oxidation, produces carbon dioxide and steam. The last stage, reduction, produces methane and residual ash and unburned carbon (char).

Gasification is one of the cleanest, most efficient combustion methods known. It eliminates dependence on fossil fuel and reduces waste dumping. It extracts many substances, such as sulfur and heavy metals, in elemental form. Factors limiting the use of this process include stringent feed size and material-handling requirements. Process efficiency is strongly influenced by the physical properties of the biomass (surface, size, and shape), as well as by moisture content, volatile matter, and carbon content (see Pyrolysis below for additional limitations).

Gasification of animal wastes is still in the developmental stages. It is currently considered a better alternative to incineration for its lower NO_x emissions. However, this treatment option is limited to the AFOs that have a market in which to sell the excess power or heat generated by the gasification unit. Without this advantage, such facilities would be inclined to resort to less expensive waste treatment technologies.

Pyrolysis

Pyrolysis is a major part of the gasification process described above. It is formally defined as chemical decomposition induced in organic material by heat in the absence of oxygen. Pyrolysis transforms organic materials into gaseous components, small quantities of liquid, and a solid residue (coke or char) containing fixed carbon and ash. Pyrolysis of organic materials produces combustible gases including carbon monoxide, hydrogen and methane, and other hydrocarbons. If the off-gases are cooled, liquids condense, producing an oil/tar residue and contaminated water.

Target contaminant groups for pyrolysis are volatile organic compounds and pesticides. The process is applicable for the separation of organics from refinery wastes, coal tar wastes, wood-treating wastes, creosote-contaminated soils, hydrocarbon-contaminated soils, mixed (radioactive and hazardous) wastes, synthetic rubber processing wastes, and paint waste.

Economic factors have limited the applicability of pyrolysis to the animal waste management field. There are also a number of handling factors that limit applicability. Pyrolysis involves specific feed size and material-handling requirements. The technology requires that the biomass be dried to low moisture content (<1 percent). Slight inconsistencies in moisture content and biomass properties (both physical and chemical) greatly increase operational costs. These considerations make it difficult to apply this technology to animal waste. Pyrolysis is not effective in either destroying or physically separating inorganics from the contaminated medium. Volatile metals may be removed as a result of the higher temperatures associated with the process but are not destroyed. Biomass containing heavy metals may require stabilization.

Pyrolysis is still an emerging technology. Although the basic concepts of the process have been validated, the performance data for this technology have not been validated according to methods approved by EPA and adhering to EPA quality assurance/quality control standards. Site characterization and treatability studies are essential for further refining and screening of this process. Pyrolysis has been considered for animal waste treatment as part of the gasification technology, but is currently not in high demand because of operation and maintenance costs.

Freeze Drying and Freeze Crystallization or Snowmaking

Freeze drying involves freezing the waste, which causes the solids and liquids to separate. When the frozen sludge melts, the liquid is easily drained away for reprocessing. The remaining sludge is high in solids, completely stabilized, and capable of being spread on land with conventional agricultural equipment. The process has proven to lower waste management costs by reducing waste volume.

Freeze crystallization, or snowmaking, is a treatment process in which wastewater is turned to snow, thus readily stripping volatile gases from water. Other contaminants are precipitated from the water in a process called atomizing freeze-crystallization. Meltwaters may have a nutrient reduction of up to 60 percent, with almost 100 percent of pathogens killed (MacAlpine, 1997).

Both processes are scarcely utilized due to applicability limitations. These processes are suited only to colder climates. The freeze-drying process requires significant storage capacity, and facilities must be capable of storing up to 1 year's production of sludge on site.

Practice: Photosynthetic Purification

A proprietary new animal waste treatment technology, Photosynthetic Purification, uses the nutrients in concentrated animal waste to grow algae and photosynthetic bacteria that yield a harvestable crop (Biotechna, 1998). Photosynthetic Purification technology is reported to treat high-strength, high-moisture waste streams with minimal loss of manure nutrients and generate a clean effluent that can be recycled or safely discharged. The resultant biomass can be used as a high protein animal feed supplement. Nutritional value of the biomass is at least equivalent to that of soy protein. Along with producing a valuable biomass, the main advantage of this technology is that it reduces the potential environmental impact of land application or discharge of animal waste in regions with CAFOs. A possible disadvantage is that animal waste will need to be transported to a processing facility.

The technology has been under development by Biotechna Environmental (2000) Corporation (BE2000) since the early 1990s. Successful tests are reported to have been carried out at pilot scale in Ireland (1994-95), and Connecticut (1998). A laboratory-scale system and a full-scale commercial demonstration plant are planned. Photosynthetic Purification produces high-protein feed supplements and a range of other value added products for the feed and nonfood markets. Because of proprietary information and patent pending status, little information on this technology is currently available to the public.

Deep Stacking of Poultry Litter

Research dating back to the 1960s (Bhattacharya and Fontenot, 1965) has shown that poultry litter has significant nutritive value as a feedstuff for ruminants. Subsequently, concerns about the potential public health impacts of using poultry litter as well as other animal manures as feedstuffs emerged. The presence and impact of pathogens, such as species of Salmonella and Clostridium, in manures being used as feedstuffs was one of these concerns. There have been a number of reports from foreign countries of botulism in animals fed diets containing animal wastes (Fontenot et al., 1996).

For poultry litter, the response to this concern about potential pathogen transmission was the development of the practice known as deep or dry stacking (McCaskey, 1995). It consists simply of piling litter in a conical pile or stack after it is removed from a poultry house and is raised in temperature to a maximum of 140 °F (60 °C) by microbes. Litter with a moisture content exceeding 25 percent may reach temperatures above 140 °F if not covered to exclude air.

McCaskey et al. (1990) have shown that higher temperatures produce a material with a “charred” appearance and reduced nutritive value. They reported that excessively heated litter has about 50 percent of the dry matter digestibility of litter that has not been excessively heated. This estimate was based on the percentage of litter dry matter solubilized in rumen fluid after 48 hours. Also, it was observed that the amount of N bound to acid detergent fiber and considered not available approximately tripled in overheated litter.

The practice of deep stacking poultry litter enhances its value as a feedstuff for ruminants by reducing concern about possible pathogen transmission. However, deep-stacked poultry litter cannot be considered pathogen free because the stacked litter is not mixed out of concern that reaeration will create the potential for excessive heating. Thus, outer regions of the deep stacked litter might not reach the temperatures necessary for pathogen destruction. In reality, deep stacking is composting in which oxygen availability limits the temperature and the degree to which dry matter (VS) are destroyed.

When deep stacking is done in a roofed structure such as a litter storage shed or in covered piles, the potential water quality impacts are essentially nil; however, deep stacking in uncovered piles creates the potential for leaching and runoff losses of nutrients, oxygen-demanding organics, and pathogens, as well as producing a feedstuff with reduced nutritive value. Because of the heat generated, some NH_3 volatilization is unavoidable, but is probably no greater than the losses associated with land application. With proper management, odor is not a significant problem.

The impact of deep stacking on land application for litter disposal is a direct function of the ability to market poultry litter as a feedstuff. If such a market exists, on-site land application requirements are reduced or become unnecessary; however, the impact on a larger scale is less clear. Although the utilization of litter N by ruminants can be relatively high, much of the litter P consumed will probably be excreted. Thus, typical values for the P content of beef cattle manure might not be appropriate for developing nutrient management plans for beef operations that feed significant quantities of broiler litter. Also, total manure production by beef cattle fed poultry litter-amended rations may increase, depending on the dry matter digestibility and the ash content of the litter (Martin et al., 1983).

As with the temporary storage of solid poultry manure in a dedicated structure, fire due to spontaneous combustion is a risk associated with deep stacking of poultry litter. Thus, structure design to exclude precipitation and routine monitoring of litter temperature are important operational factors.

Although reliable data regarding the extent of the use of deep stacking are unavailable, anecdotal evidence indicates that the use of poultry litter as a feedstuff for beef cattle is fairly extensive in regions with significant broiler or turkey, and beef cattle production. Thus, it appears reasonable to assume that the use of deep stacking is also fairly extensive.

Practice: The Thermo Master™ process

Thermo Tech™ Technologies, Inc., is a Canadian corporation in the business of converting food wastes into a high-energy and high-protein animal feed supplement, and converting municipal wastewater treatment sludges into a fertilizer material. The company has constructed several organic waste conversion facilities, known as "Thermo Master™ Plants," that employ the company's proprietary microbial organic waste digestion technology. The technology is protected by U.S. and Canadian patents with patent applications pending in several other countries.

The Thermo Master™ process was originally developed to create an animal feed supplement from relatively high solids content food wastes such as fruit and vegetable processing wastes and wastes of animal origin including meat, dairy, and fish processing wastes. Animal manures and wastewater treatment sludges were also considered for conversion into a fertilizer material. The process has been modified to enable processing of materials with a lower solids content.

In the Thermo Master™ process, autoheated aerobic digestion is operated at the relatively short residence time of 30 hours to maximize single-cell protein production using the influent waste material as substrate. The effluent from the digestion process is then dried and pelletized.

The Thermo Master™ process could, in theory, be a viable method for poultry and swine carcass disposal. In addition to recovering nutrients for use as an animal feed supplement, the absence of any pollutant discharges is an attractive characteristic of this process. Given that the process operates at thermophilic temperatures, at least a two- to three-log $_{10}$ reduction in pathogen densities should be realized (Martin, 1999). The process, however, has never been used for animal carcass disposal.

As with rendering, the problems of preserving, collecting, and transporting carcasses could limit use of this disposal alternative. A more significant limitation is the lack of any operating Thermo Master™ plants in the United States. Only two plants are in operation as of April, 2000, and they are both located in Canada near Toronto, Ontario. A third, located near Vancouver, British Columbia, is being rebuilt following a fire. Even if new plants were to be constructed in the United States, it is likely that they would be located in or near major metropolitan areas given the nature of the primary sources of process feedstocks. This would exacerbate the problem of carcass transportation.

8.2.3.2 Mortality Management

Improper disposal of dead animals at AFOs can result in ground water contamination and health risks. Most mortality management is accomplished through rendering of the dead animals. Rendering involves heating carcass material to extract proteins, fats, and other animal components to be used for meat, bone, and meal. Beef and dairy operations handle mortality management almost exclusively through rendering operations. In most instances the rendering operation will pick up the dead animals, resulting in no environmental impact on the operation.

For this reason, the remainder of this section focuses on swine and poultry mortality management, and it will cover rendering, composting, and incineration.

Mortality Management: Swine

Large swine operations must dispose of significant numbers of dead pigs on a daily basis. For example, a 1,000 sow farrow-to-wean operation with an average of 22 piglets per litter and a prewean mortality rate of 12 percent will generate almost 16 tons of piglet carcasses per year, assuming an average weight of 6 pounds per carcass. Assuming an average sow weight of 425 pounds and a sow mortality rate of 7 percent per year, the total carcass disposal requirement increases to over 30 tons per year.

Improper disposal of swine carcasses can lead to surface or ground water contamination, or both, as well as noxious odors and the potential for disease transmission by scavengers and vermin. Historically, burial was the most common method of carcass disposal. Burial has been prohibited in many states, largely because of concerns regarding ground water contamination. The following subsections briefly describe and discuss the principal alternatives to burial for swine carcass disposal: composting, incineration, and rendering.

Practice: Composting

Description: Composting is the controlled decomposition or stabilization of organic matter (Gotaas, 1956). The process may be aerobic or anaerobic. If the composting mass is aerobic and suitably insulated, the energy released in the oxidation of organic carbon to carbon dioxide and water will produce a fairly rapid increase in the temperature of the composting mass. With suitable insulation, thermophilic temperature levels will be reached. The higher temperature increases the rate of microbial activity and results in quicker stabilization. Under anaerobic conditions, the rate of biological heat production is lower because fermentation generates less heat than oxidation, so the temperature increase in the composting mass is less rapid. Thermophilic temperature levels can still be attained with suitable insulation; however, the rate will be slower.

Application and Performance: Composting is a suitable method of carcass disposal for all swine operations. The compost produced can be spread on site if adequate land is available. Another recently cited disposal option for the compost is distribution or marketing as an organic fertilizer material or soil amendment. Thorough curing to preclude development of odor or vermin problems, and screening to remove bones are necessary to make marketing a viable option. Another requirement for composting as a method of swine carcass disposal is the availability of a readily biodegradable source of organic carbon, such as sawdust, wood shavings, or straw.

When carcass composting is managed correctly, potential negative impacts on water and air quality are essentially nonexistent, assuming proper disposal of the finished compost. Mismanagement, however, can lead to seepage from the composting mass. This seepage has high concentrations of oxygen-demanding organics, N, and P; is a source of noxious odors; and attracts vermin.

Advantages and Limitations: One of the advantages of swine carcass composting is the relatively low capital cost of the necessary infrastructure. Depending on the volume of carcasses generated daily, one or more of a series of two composting bins are required. These bins should be located on a concrete pad in an open or partially enclosed shed-like structure. Critical to this capital cost advantage is the availability of a skid-steer or tractor-mounted, front-end loader for handling materials. Federal and, in some instances, state cost sharing has been used to encourage the construction and use of swine mortality composting facilities.

A recent comparison of carcass composting and incineration for disposal of poultry mortalities suggests that the lower capital cost of carcass composting is offset by higher labor costs (Wineland et al., 1998). The development of more fuel-efficient incinerators has made incineration more cost competitive in recent years.

While the temperatures that can be attained in a mass of composting carcasses (130 to 150 °F) will result in significant reductions in pathogen densities, finished swine mortality compost cannot be considered pathogen free. Therefore, appropriate biosecurity measures are necessary in the handling and ultimate disposal of the finished compost. Collection of carcasses by renderers presents a higher biosecurity risk, especially the risk of introducing disease from other operations. In contrast, the ash from carcass incineration is sterile.

Carcass composting in the swine industry appears to be best suited for the disposal of prewean and nursery mortalities because of the relatively small size of these carcasses. For larger animals (sows, gilts, boars, and feeder pigs), at least partial carcass dismemberment, an unpleasant task, is necessary.

Operational Factors: In the composting of swine mortalities, a single layer of carcasses or carcass parts is placed on a layer of the carbon source and finished compost or manure, followed by another layer of the carbon source and finished compost, and then carcasses. The pattern is repeated until a height of about 5 feet is reached. The pile is capped with a carbon source. Inadequate moisture will retard decomposition, whereas too much moisture will result in anaerobic conditions and process failure.

A proper facility is critical to the success of composting swine carcasses. As noted above, one or more of a series of two composting bins are required depending on the daily volume of carcasses generated. To maximize the rate of carcass decomposition and also to ensure complete decomposition of soft tissue, the composting mass should be transferred to a second bin after about 2 weeks of decomposition. This transfer process results in both mixing and aeration of the composting mass. Following an additional 2 weeks, the compost should be ready for storage and curing or ultimate disposal. While satisfactory decomposition can be realized without transfer and mixing, the time required is significantly longer.

Also critical to the success of composting swine carcasses is the initial combination of carcasses, a source of biodegradable carbon such as sawdust or chopped straw, a source of adapted microorganisms, and moisture. Although some cooperative extension publications recommend using manure as the source of an adapted microbial population, finished compost is equally suitable (Martin and Barczewski, 1996). The ratio, on a volume basis, of these ingredients should be 1 part carcasses, 1.5 parts of the carbon source, 0.5 to 0.75 part finished compost, and 0 to 0.5 part water. The objective is to create an initial C:N ratio of 20:1 to 30:1.

Demonstration Status: The first use of composting for animal carcass disposal occurred in the poultry industry during the 1980s (Murphy, 1988; Murphy and Handwerker, 1988). Since that time, this method of carcass disposal has also been adopted by the swine industry. It was estimated that 10.5 percent of swine operations use composting for mortality disposal (USDA APHIS, 1995).

Practice: Incineration

Description: Incineration or cremation is the reduction of swine carcasses to ash by burning at a high temperature under controlled conditions using specially designed equipment. Incineration temperatures can be as high as 3,500 °F, depending on equipment design. Incinerators using natural gas, propane, or No. 2 distillate fuel oil are available.

Application and Performance: Incineration of swine carcasses is applicable to all operations where the cost of the equipment required can be justified by the volume of carcasses generated.

The potential for surface or ground water contamination associated with incineration is minimal, provided that liquid fuel tanks are contained properly and residual ash is disposed of properly. The P, K, and other elements contained in the carcasses are concentrated in the ash. Because of the high temperature of incineration, this ash is pathogen-free if cross-contamination with carcasses is avoided.

Odors and other air quality concerns led to a significant decline in carcass incineration in the past. Newly designed equipment, however, incorporates secondary combustion of stack gases, essentially eliminating these problems. Yet the emission of low levels of some air pollutants is unavoidable, as with any combustion process. Improper operation of the incinerator (e.g., reducing process temperature by overloading) can result in unacceptably high air pollutant emissions.

Advantages and Limitations: One of the more attractive aspects of incineration relative to other swine carcass disposal options, such as composting and rendering, is the complete destruction of pathogens. Another advantage is the relatively small mass of residual material (ash) requiring some form of ultimate disposal, especially in comparison with composting. Moreover, incineration has a relatively low labor requirement.

The principal perceived limitation of incineration is cost. The initial investment required is relatively high. A recent comparison of incineration and composting costs for poultry carcass disposal, however, suggests that the former has become cost competitive with the latter because of lower labor costs and improvements in incinerator fuel efficiency (Wineland et al., 1998).

Another limitation of incineration for swine carcass disposal is fixed capacity. This can be problematic when disease or other factors such as heat stresses cause a sizable increase in the rate of mortality.

Operational Factors: Because of the fixed capacity of incineration equipment, incineration of swine carcasses must occur on a regular basis. Ideally, carcass incineration should occur at least on a daily basis to minimize the potential for disease transmission. Routine maintenance of incineration equipment is also important to ensure reliability and minimize emission of air pollutants. An air pollutant emissions permit, a siting permit, or both, may be required for an incinerator.

Demonstration Status: Incineration has been used in the swine industry as a method of carcass disposal for many years. With recent technological advances in incinerator fuel efficiency and odor control, a reversal in the shift away from incineration and to other carcass disposal options, such as composting, may occur. It was estimated that 12.5 percent of swine operations use incineration, described as burning, for mortality disposal (USDA APHIS, 1995).

Practice: Rendering

Description: Rendering is the process of separating animal fats and proteins, usually by cooking. The recovered proteins are used almost exclusively as animal feedstuffs, while the recovered fats are used both industrially and in animal feeds.

There are two principal methods of rendering (Ensminger and Olentine, 1978). The first and older method uses steam under pressure in large closed tanks. A newer and more efficient method is dry rendering, in which all of the material is cooked in its own fat by dry heat in open steam-jacketed drums until the moisture has been evaporated. One advantage of dry rendering is the elimination of a separate step to evaporate the moisture in the material being rendered. Cooking temperatures range from 240 to 290 °F. Rendering can be a batch or a continuous flow process.

The two basic protein feedstuffs derived from rendering are meat meal and meat and bone meal. The basis for this differentiation is P content (National Academy of Sciences, 1971). Meat meal contains a maximum of 4.4 percent P on an as-fed basis. Meat and bone meal contains a minimum of 4.4 percent P.

Application and Performance: Most of the animal fat and protein recovered by rendering is derived from meat and poultry processing, but rendering can also be used to recover these products from swine carcasses. The ability to use rendering as a method of swine carcass disposal depends on the presence of a rendering facility servicing the area. Rendering plants are not widely distributed and are generally located near meatpacking and poultry processing plants. As the meatpacking and poultry processing industries have consolidated into fewer but larger operations, a similar pattern of consolidation in the rendering industry has also occurred. Because swine carcasses have minimal monetary value as a raw material for rendering, transportation only over limited distances can be justified economically.

Rendering is a capital-intensive process and requires careful process control to generate acceptable products. In addition, product volume has to be substantial to facilitate marketing. Because on-farm rendering is unlikely to be a viable option for swine carcasses, performance measures are not included.

Advantages and Limitations: For swine producers, disposal of mortalities by rendering has several advantages. One is that capital, managerial, and labor requirements are minimal in comparison with other carcass disposal options. A second advantage is the absence of any residual material requiring disposal, as is the case with both composting and incineration, albeit to a lesser degree. If carcass volume is adequate to justify daily pickup by the renderer, capital investment for storage is also minimal.

As discussed above, rendering is a feasible option for swine carcass disposal only if the swine production operation is located in an area serviced by a rendering plant. Also, not all rendering operations will accept mortalities, largely because of concerns about pathogens in the finished products.

Well-managed rendering operations will not accept mortalities more than 24 hours after death because of the onset of decomposition of fats and proteins, adversely affecting the quality of the final products. For swine operations that do not generate an adequate volume of carcasses to justify daily pickup by the renderer, carcass preservation by freezing, for example, is a necessity. While preservation of piglet carcasses by freezing may be justifiable economically, the cost of preserving larger animals is probably not justifiable because payment by renderers for carcasses is usually nominal at best. Typically, payment is no more than one to two cents per pound. Payment can be less, or there may even be a charge for removal, depending on transport distance.

Operational Factors: Since renderers usually pick up carcasses, stringent biosecurity precautions are essential to prevent disease transmission by vehicles and personnel serving several swine operations. Ideally, trucks should be disinfected before entering individual farms, and collection personnel should use disposable shoe coverings. Also, necessary carcass preservation measures should be employed to ensure that the renderer will continue to accept carcasses.

Demonstration Status: It was estimated that 32 percent of swine operations use rendering for mortality disposal, with 25.1 percent allowing the renderer to enter the operation and 6.9 percent placing carcasses at the perimeter of the operation for pickup (USDA APHIS, 1995).

Mortality Management: Poultry

Large poultry operations generate significant numbers of dead birds on a daily basis. For example, a flock of 50,000 broilers with an average daily mortality of 0.1 percent (4.9 percent total mortality) will result in approximately 2.4 tons of carcasses over a 49-day grow-out cycle (Blake et al., 1990). A flock of 100,000 laying hens averaging a 0.5 percent monthly mortality (6 percent annual mortality) will generate 11.25 tons of carcasses per year (Wineland et al., 1998). For a flock of 30,000 turkeys averaging 0.5 percent weekly mortality (9 percent total mortality), approximately 13.9 tons of carcasses will require disposal (Blake et al., 1990).

Improper disposal of poultry mortalities can lead to surface or ground water contamination, or both, as well as noxious odors and the potential for disease transmission by scavengers and vermin. The following subsections briefly describe and discuss the principal alternatives to burial used for dead bird disposal: composting, incineration, and rendering. Burial of dead birds has been prohibited in many states, principally because of concerns regarding ground water contamination. These alternatives for carcass disposal are also used in the swine industry and have been described in the previous section. Differences between the two sectors, however, are briefly noted.

Practice: Composting

Description: The general description of composting presented in the preceding section on swine mortality management also applies to poultry.

Application and Performance: As with swine, composting as a method of carcass disposal is suitable for all poultry operations. The compost produced can be spread on site if adequate land is available. Another disposal option for the compost is distribution or marketing as an organic fertilizer material or soil amendment. Thorough curing to preclude development of any odor or vermin problems and screening to remove bones are necessary to make marketing of carcass compost disposal a viable option. Another requirement for composting as a method of poultry carcass disposal is the availability of a readily biodegradable source of organic carbon such as sawdust, wood shavings, or straw.

When poultry carcass composting is managed correctly, potentially negative impacts on water and air quality are essentially nonexistent, assuming proper disposal of the finished compost. Mismanagement, however, can lead to seepage from the composting mass. This seepage has high concentrations of oxygen-demanding organics, N, and P; is a source of noxious odors; and attracts vermin.

Advantages and Limitations: As with swine carcass disposal, one of the advantages of poultry carcass composting is the relatively low capital cost of the necessary infrastructure, especially when compared with incineration. Depending on the volume of carcasses generated daily, one or more of a series of two composting bins are required. These bins should be located on a concrete pad in an open or partially enclosed shed-like structure. Critical to this capital cost advantage is the availability of a skid-steer or tractor-mounted, front-end loader for handling materials. Federal and, in some instances, state and integrator cost sharing has been used to encourage the construction and use of poultry mortality-composting facilities.

A recent comparison of carcass composting and incineration for disposal of poultry mortalities suggests, however, that the lower capital cost of carcass composting is offset by higher labor costs (Wineland et al., 1998). The development of more fuel-efficient incinerators has made incineration more cost competitive in recent years.

While the temperatures that can be attained in a mass of composting carcasses (130 to 150 °F) will result in significant reductions in pathogen densities, finished poultry mortality compost cannot be considered pathogen-free. Therefore, appropriate biosecurity measures are necessary in the handling and ultimate disposal of the finished compost. Collection of carcasses by renderers presents a higher biosecurity risk, especially the risk of introducing disease from other operations. In contrast, the ash from carcass incineration is sterile.

Operational Factors: In the composting of poultry mortalities, a single layer of carcasses is placed on a layer of the carbon source and finished compost or litter, followed by another layer of the carbon source and finished compost, and then carcasses. The pattern is repeated until a height of about 5 feet is reached. The pile is capped with a carbon source. Inadequate moisture will retard decomposition, while too much moisture will result in anaerobic conditions and process failure.

A proper facility is critical to the success of composting poultry carcasses. As noted above, one or more of a series of two composting bins are required depending on the daily volume of carcasses generated. To maximize the rate of carcass decomposition and also to ensure complete decomposition of soft tissue, the composting mass should be transferred to a second bin after about 2 weeks of decomposition. This transfer process results in both mixing and aeration of the composting mass. Following an additional 2 weeks, the compost should be ready for storage and curing, or ultimate disposal. While satisfactory decomposition can be realized without transfer and mixing, the time required increases significantly.

Also critical to the success of composting poultry carcasses is the initial combination of carcasses, a source of biodegradable carbon such as sawdust, wood shaving, or chopped straw, a source of adapted microorganisms, and moisture. Although some cooperative extension publications recommend using litter or cake as the source of an adapted microbial population, finished compost is equally suitable (Martin and Barczewski, 1996). Martin et al. (1996) have suggested that use of cake be avoided. One recommendation, on a volume basis, is 1 part dead birds, 1.5 parts straw, 0.5 to 0.75 part litter, and 0 to 0.5 part water (Poultry Water Quality Handbook, 1998). Sawdust or shavings have been used successfully in place of straw. Basically, this same combination of materials is used for swine carcass composting. Again, the objective is to create an initial C:N ratio of 20:1 to 30:1.

Demonstration Status: The first use of composting for animal carcass disposal occurred in the poultry industry during the 1980s (Murphy, 1988; Murphy and Handwerker, 1988). Currently, composting for disposal of poultry mortalities is readily accepted by producers and used extensively. In a recent survey of broiler producers on the Delmarva Peninsula, 52.7 percent of 562 respondents reported using composting for dead bird disposal (Michel et al., 1996).

Practice: Incineration

Description: The general description of incineration presented in the preceding section on swine mortality management also applies to poultry.

Application and Performance: As with swine, the use of incineration for poultry carcass disposal is applicable to all operations where the cost of the equipment required can be justified by the volume of carcasses generated.

As with swine carcass incineration, the potential for surface or ground water contamination associated with incineration is minimal, provided that liquid fuel tanks are properly contained and residual ash is disposed of properly. The P, K, and other elements contained in the carcasses are concentrated in the ash. Because of the high temperature of incineration, this ash is pathogen-free if cross-contamination with carcasses is avoided.

Odors and other air quality concerns led to a significant decline in carcass incineration in the past. Newly designed equipment, however, incorporates secondary combustion of stack gases, essentially eliminating these problems. Yet the emission of low levels of some air pollutants is unavoidable, as with any combustion process. Improper operation of the incinerator (e.g., reducing process temperature by overloading) can result in unacceptably high air pollutant emissions.

Advantages and Limitations: One of the more attractive aspects of incineration relative to other poultry carcass disposal options, such as composting and rendering, is the complete destruction of pathogens. Another advantage is the relatively small mass of ash requiring some form of ultimate disposal, especially in comparison with composting. Moreover, incineration has a relatively low labor requirement.

The principal perceived limitation of incineration is cost. The initial investment required is relatively high. A recent comparison of incineration and composting costs for poultry carcass disposal, however, suggests that the former has become cost competitive with the latter because of lower labor costs and improvements in incinerator fuel efficiency (Wineland, et al., 1998).

Another limitation of incineration for poultry carcass disposal is fixed capacity. This can be problematic when disease or other factors such as heat stresses cause a sizable increase in the rate of mortality.

Operational Factors: Because of the fixed capacity of incineration equipment, incineration of poultry carcasses must occur on a regular basis. Ideally, carcass incineration should occur at least on a daily basis to minimize the potential for disease transmission. Routine maintenance of incineration equipment is also important to ensure reliability and minimize emissions of air pollutants. An air pollutant emissions permit, a siting permit, or both, may be required for an incinerator.

Demonstration Status: Incineration has been used to a limited degree in the poultry industry for carcass disposal for many years. In recent years, cost and odor problems resulted in a shift away from incineration to more seemingly attractive options such as composting. In a recent survey of broiler producers on the Delmarva Peninsula, only 3.3 percent of 562 respondents reported using incineration for dead bird disposal (Michel et al., 1996). Improvements in fuel efficiency and odor control, however, have renewed interest in this option for carcass disposal.

Practice: Rendering

Description: The general description of rendering presented in the previous section on swine mortality management also applies to poultry.

Application and Performance: As with swine, the ability to use rendering as a method of poultry carcass disposal depends on the presence of a rendering facility servicing the area. Because on-farm rendering is unlikely to be a viable option, performance measures are not included.

Advantages and Limitations: Rendering has the same advantages for poultry producers that it has for swine producers: (1) minimal managerial and labor requirements, and (2) the absence of any residual material requiring disposal.

Limitations include the need to preserve carcasses, because many operations will not generate a sufficient volume of carcasses to justify daily collection by a renderer. Several options have been demonstrated to be technically feasible for poultry carcass preservation. They include freezing, preservation using organic or mineral acids (Malone et al., 1998; Middleton and Ferket, 1998), preservation using sodium hydroxide (Carey et al., 1997), and lactic acid fermentation (Dobbins, 1988; Murphy and Silbert, 1990). All of these preservation strategies increase the cost of carcass disposal, and all but freezing increase labor requirements.

Another factor limiting the use of rendering for poultry carcass disposal is the problems that feathers create in the rendering process. Feathers absorb the fat separated by rendering and make the product difficult to handle and market. Feathers also dilute the nutritional and resulting market value of poultry by products meal, especially when used as a feedstuff for nonruminant animals which cannot digest feathers.

Although feathers can be removed by hydrolysis, cooking at high temperature under pressure degrades protein quality. It has been shown, however, that feathers can be removed successfully up to 24 hours postmortem, using a batch scalding and picking system (Webster and Fletcher, 1998). Thus, renderers with feather-picking equipment can accept significant quantities of poultry mortalities without compromising product quality.

Operational Factors: As with swine, stringent biosecurity precautions are essential to prevent disease transmission by vehicles and personnel serving several poultry operations. Moreover, carcass preservation measures are generally necessary.

Demonstration Status: Overall, the use of rendering for disposal of poultry mortalities is minimal because of the necessity of carcass preservation and the problem of feathers described above. In a recent survey of broiler producers on the Delmarva Peninsula, none of the 562 respondents reported using rendering for dead bird disposal (Michel et al., 1996). One of the major broiler integrators, however, is currently evaluating the use of rendering after the grower preserves the carcasses by freezing. The integrator supplies the freezer and the grower pays for the electricity. Preliminary indications are that the growers are pleased with this approach.