PATHOGEN SURVIVAL DURING FORCED AERATION COMPOSTING OF MUNICIPAL WASTEWATER SLUDGE

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TECHNICAL COMPLETION REPORT

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CHAPTER 1

INTRODUCTION

The United States produces over 5 million dry tons of sewage sludge per year. This is expected to double within the next few years due to the construction of new secondary and tertiary treatment facilities. This material must be disposed of in a manner both environmentally sound and economically feasible.

Several methods have been used for treatment and disposal of municipal sludges. These include thickening, stabilization by anaerobic or aerobic digestion or by lime treatment, sludge conditioning, dewatering by such methods as filters and centrifuges, incineration, pyrolysis, and wet air oxidation. Final disposal methods include cropland application, land reclamation, power generation, sanitary landfill and ocean disposal. The majority of these are not cost-effective, particularly for smaller communities thereby limiting the options available to them, and may only result in the exchange of one form of pollution for another. New regulations and public demands have further reduced the number of alternatives.

Reuse of sludge for agricultural land reclamation purposes is certainly a desirable alternative. However, it has only been since passage of the Water Pollution Control Act Amendments of 1972 (PL 92-500) and its 1977 Amendments that land application as a waste management alternative has been emphasized. Subsequent policy statements by the U.S. Environmental Protection Agency have mandated that land application be considered for any proposed wastewater treatment facility to receive federal funds. This is principally directed at liquid wastes, but also applies to sludges.

Unfortunately, wastewater sludges are highly putrescible and usually contain large numbers of pathogenic bacteria, protozoa, parasites and viruses which can pose public health problems. These sludges must be stabilized in

order to eliminate odors and destroy the pathogens prior to disposal or utilization. Composting of municipal sludges is one means of achieving this stabilization so that the sludge can be reused.

Composting sewage sludge offers several advantages (27,97):

1. Microbial decomposition oxidizes the organic material to a fairly stable state resistent to odor production within a reasonably short incubation period.
2. Heat produced during decomposition destroys many of the human pathogens.
3. Moisture content of the sludge is reduced, facilitating storage and handling operations.
4. The compost is a valuable product when used as a soil conditioner and a source of macro and micronutrients favorable to plant growth.
5. Composting uses very little external energy.

Composting is defined by Haug (46) as:

> "the biological decomposition and stabilization of organic substrates under conditions which allow development of thermophilic temperatures as a result of biologically produced heat, with a final product sufficiently stable for storage and application to land without adverse environmental effects".

The heat in the system is generated by indigenous organisms (bacteria, actinomycetes and fungi) carrying out the decomposition and stabilization. During this degradation, the temperature rises into the thermophilic range (i.e., above 50.0°C). In shifting into the thermophilic range, the temperatures become too hot to permit the growth or survival of mesophilic organisms. since most human pathogens thrive in the mesophilic range, maintenance of thermophilic temperatures results in pasteurization.

Sludge compost is a natural organic product with high humus content similar to peat. Compost, when applied to soil, increases the water holding capacity of sandy soils, improves the structure of heavy clay soils, increases the air content of the soils and provides small amounts of nitrogen, phosphorus, and potash.

New regulations, increases in the cost of sludge treatment, energy considerations, and citizen demands have limited the number of choices available for sludge disposal. A properly operated composting facility provides a method for stabilizing the sludge while also producing a useable product. Since raw wastewater sludge can be composted in a static pile forced aeration system without the production of offensive odors, the need for digestion of the sludge first is eliminated and the resulting energy requirements are minimal. These factors, in addition to the relatively low costs of composting operations, make the process particularly attractive.

The major problems facing the use of composting as a means of treating domestic wastewater sludge are primarily related to potential public health hazards posed by various bacterial and viral pathogens, certain parasites, and by the presence of heavy metals. Unknown consequences of the release of these materials to the environment presently inhibit the widespread use of composting as a means of sludge solids disposal, even though the U.S. Environmental Protection Agency has approved the process (96,97). In addition, social acceptability of the composted material is not yet at a level which will support the widespread implementation of this method. These problems must be overcome before greater acceptance of the process is possible.

This research was undertaken in order to develop answers to these questions. In particular, the project was designed to investigate the fate of pathogens during forced aeration, static pile composting of municipal wastewater sludges.

This was done by monitoring the presence of pathogens with time in compost piles operating under various conditions, and by evaluating the potential for survival and regrowth of pathogens during compost curing and subsequent soil application. In addition, the fate of nutrients in the sludge was followed through the composting process to assess the most efficient method for retaining essential nutrients in the compost.

CHAPTER 2

RESEARCH OBJECTIVES

The overall objective of this research was to evaluate the potential for survival of pathogens during composting of municipal wastewater sludge by the forced aeration static pile compost method, but there were many other objectives as well. These may be summarized as:

1. To determine the fate of total and fecal coliforms, total and fecal streptococci, Salmonella, Shigella and Aspergillus fumigatus during the composting of raw primary and primary/secondary sludges.
2. To compare the levels of fecal indicator organisms in compost with those in other parts of the community.
3. To determine the lower limit at which salmonella may be detected in compost.
4. To determine the lower limit at which the parasites Giardia and Ascaris may be detected in compost.
5. To assess the survival of salmonellae during the six-month holding period commonly used.
6. To determine the survival rate of salmonellae after incorporation of compost into soil.
7. To determine whether anaerobic thermophilic organisms are present in active static aeration compost piles.
8. To determine the patterns of heat generation, moisture removal, volatile solids reduction and oxygen content of sludge compost piles with time.
9. To determine the effect of aeration rate on the compost process.

10. To determine the effect of sludge:woodchip ratio on the compost process.

11. To evaluate the degree of mineralization of nitrogen and phosphorus in composting sludge, and the overall fate of these nutrients.

CHAPTER 3

STATIC PILE COMPOSTING OF WASTEWATER SLUDGES

Sludge Composting Systems

At present, there are three primary methods of sludge composting in use - the windrow system, the aerated static pile method, and mechanical methods. These are the outgrowth of thousands of years of experience by farmers with the conversion of organic wastes into soil amendments for use in agriculture, and much more recently with the composting of municipal refuse.

The oldest method for composting wastewater sludge is the windrow process. In this process, the sludge is mixed with previously composted material or other bulking agent to lower the moisture content; the material stacked in long, low parallel rows; and turned frequently by mechanical equipment to provide needed aeration. This process has been in use by the Los Angeles County Sanitation District since 1972 to compost approximately 90 dry tons (81,600 kg) per day of digested, dewatered sludge cake (45,46). Typical composting time for the windrow system is 3 to 4 weeks during most of the year, although this may need to be extended during periods of adverse weather. Indications are that the windrow method may not achieve complete destruction of pathogens (8), although stockpiling the finished compost may result in reduction of levels of these organisms. A further drawback to this process is that it is usually highly land and labor intensive.

Mechanical composting refers to those systems which use mechanized, enclosed devices to provide control of major environmental factors. These may consist of rotating drums, multistage tower silos, moving elevators or other mechanical devices which mix and aerate the compost while containing heat. These systems often speed up the composting process so that a shorter retention

period is required, but they are usually quite complex mechanically, and they are very expensive to build and operate (35,46).

The aerated static pile system consists of a stationary pile of sludge-bulking agent mix constructed over an aeration system. Aerobic conditions are maintained by forcing or sucking air through the pile. This process is the subject of this research and will be described in more detail here.

Process Description

The aerated static pile process was developed at the U.S. Department of Agriculture experimental station at Beltsville, Maryland in the mid-1970s. The researchers initially were investigating use of the windrow method for sludge composting, but found that when undigested sludge was used, an undesirable level of odors resulted. In addition, temperatures in the outer surfaces of the windrows were too low to provide the desired level of pathogen destruction. Therefore, they began mechanically aerating the windrow; this process then became known as the Beltsville Aerated Pile Method (28).

The aerated pile process differs from the windrow process in that composting material is not turned. Aerobic conditions are maintained by drawing or blowing air through the pile mechanically. Another difference is that dewatered sludge is mixed with a bulking agent, such as wood chips, for control of moisture content and porosity of the material, rather than with previously composted material as is done in the windrow system (45,46).

Partially dewatered sewage sludge, digested or undigested, is mixed with a bulking agent and then composted in a stationary pile for 21 days while air is drawn through the mass. The pile is constructed on top of a 12-inch (30.5 cm) porous bed, usually consisting of wood chips, in which lies a loop of

perforated drainage pipe which is connected to a suction or blower fan. The entire pile is then covered by a 12-inch (30.5 cm) layer of screened compost which helps to insulate the pile and control odors (see Figure 1). Aerobic composting conditions are maintained for 21 days during which time the sludge is stabilized by the rapid decomposition of organic solids, temperatures increase into the thermophilic range destroying pathogenic organisms, and odors are abated. At the end of this period, the composted material is transferred to an unaerated curing pile, where it is held for a 3 to 4 week period for further stabilization and drying. The compost is then separated from the woodchips by screening and the recovered woodchips are reused with incoming sludge (20,21,22,23,45,46,49,66,94,102).

Composting at Durham, NH

This research was carried out at the Durham, New Hampshire wastewater treatment facility. Although Durham uses the basic composting theories resulting from the Beltsville research, the town has made a number of modifications in the mechanical process. The most unique of these modifications was the incorporation of an automated composting process into the design of their new secondary wastewater treatment plant (11,12,13,19,62,103).

The new Durham treatment facility, which began operation in 1981, is designed to treat an average daily flow of 2.5 MGD (9500 m^3/d). The composting plant is designed to handle 43 tons (39,000 kg) of dewatered primary and secondary sludge per week. Present sludge production is approximately 30 tons (27,200 kg) per week.

Both the primary sludge and the waste activated sludge are stored in separate aerated holding tanks until pumped to the sludge dewatering building

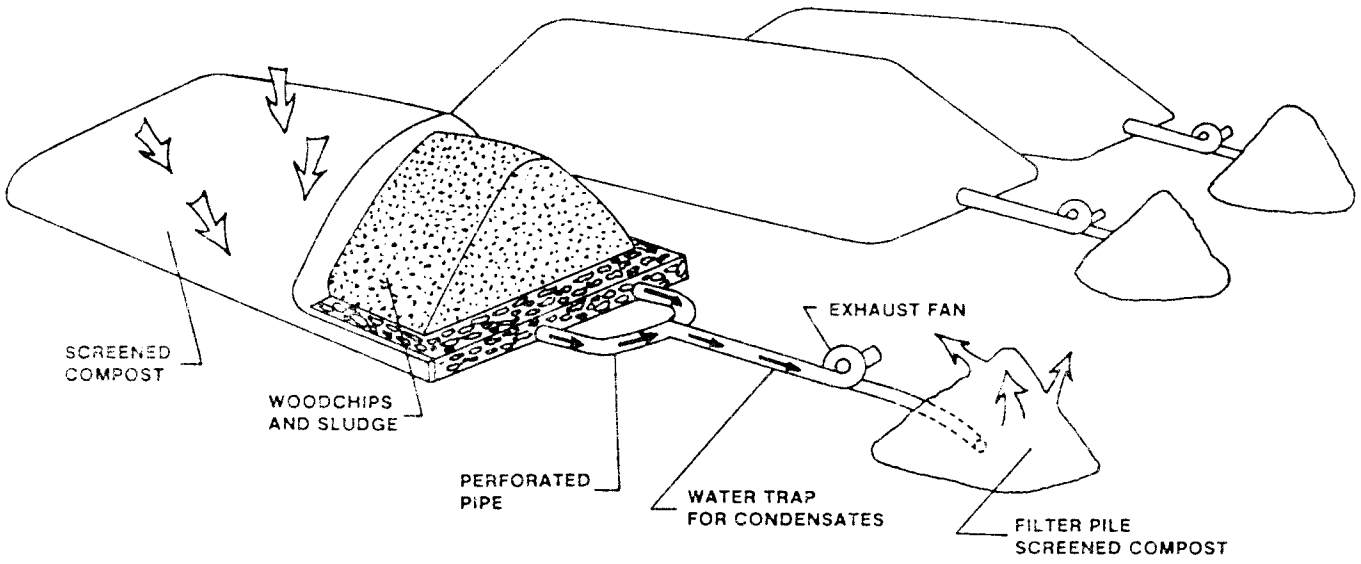
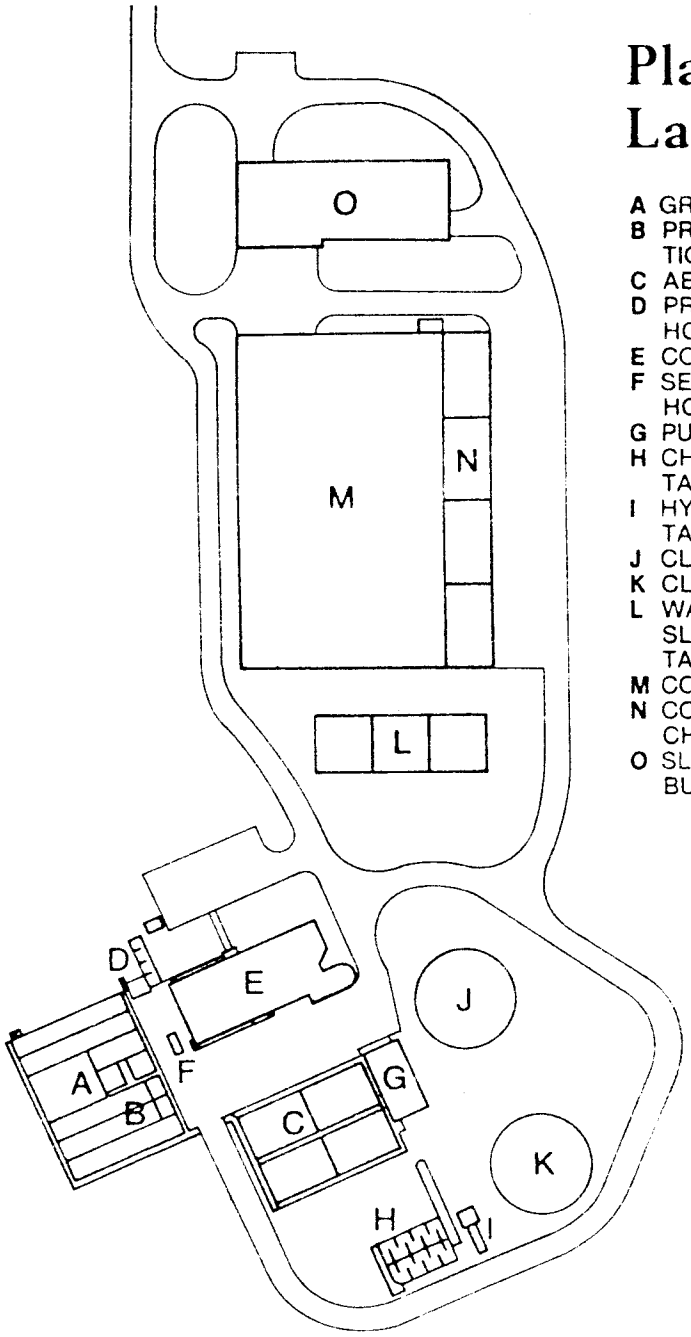


Figure 1
Diagram of a forced aeration, static compost pile. (102)

for processing (see Figure 2 for a schematic of the plant). At the sludge processing building, the activated sludge is thickened and mixed with the primary sludge (approximately a 1:1 mixture). The mixture is then chemically conditioned, dewatered on a vacuum filter, mixed with wood chips in a pug mill (3:1 wood chips to sludge ratio), conveyed to the sludge composting pad by conveyor belt, and formed into a compost pile by a front end loader.

The compost pad at Durham is constructed of concrete which provides a good year-round surface and avoids the problems created by picking up rocks from a gravel compost pad. The pad has trenches built into it so that leachate can be collected and diverted back to the head end of the wastewater treatment plant for processing, and so that the 4-inch (10.2 cm) diameter perforated aeration piping can be laid down and protected by metal perforated grates which lay flush with the pad. This enables the loader to break down the piles at the completion of composting without destroying the pipe. A base layer of wood chip is laid on the grating surface to prevent clogging by the sludge/ bulking agent mixture. A 4-foot (1.22 m) concrete retaining wall erected along one side of the pad has two main functions. First, it acts as a housing for the blowers and their switches; second, it provides a structure for the loader to work against when breaking down the pile. This is particularly important when trying to get the last few yards of a pile into the loader bucket.

The piles are constructed approximately 20 feet (6.1 m) wide, 60 feet (18.3 m) long and 12 feet (3.7 m) high. Each pile is made up of 60 cubic yards (46 m^3) of sludge and 180 cubic yards (138 m^3) of woodchips. A 12-inch (30.5 cm) layer of cured compost is placed on the pile to achieve insulation and odor control. The perforated pipe is attached to a 1/3 HP motor which pulls air down into the pile for the first two weeks of the composting process,



Plant Layout

A GRIT REMOVAL FACILITY
B PRIMARY SEDIMENTATION TANKS
C AERATION TANKS
D PRIMARY SLUDGE HOLDING TANKS
E CONTROL BUILDING
F SEPTIC WASTE HOLDING TANK
G PUMP BUILDING
H CHLORINE CONTACT TANKS
I HYDROPNEUMATIC TANK
J CLARIFIER NO. 1
K CLARIFIER NO. 2
L WASTE ACTIVATED SLUDGE HOLDING TANKS
M COMPOSTING PAD
N COMPOST & WOOD CHIP STORAGE BINS
O SLUDGE PROCESSING BUILDING

Figure 2
Process diagram of the Durham, NH wastewater treatment facility.

then blows air up and out of the pile for the final 7 to 10 days (see Figure 3). This aeration scheme is designed to build up the temperatures during the first two weeks, and then help facilitate the drying process during the final week to ten days of the aeration period. The blower is operated for 5 minutes per half hour.

Once the active composting period is completed, the pile is dismantled and the compost is transferred to the curing area where it cures for another 30 days. Although the piles are no longer aerated, degradation continues to occur and pile temperatures remain at a moderate level. This helps to increase stabilization as well as provide additional heat contact with potential pathogen survivors. Once the compost has cured, it is screened on a Lindig LR 100 rotary screen with a 0.25 in. (6.4 mm) mesh which serves to separate the woodchips from the compost. The finished compost drops into a storage bin and the recycled woodchips are either returned to the dewatering area by conveyor belt for reuse or dropped into a storage bin for later reuse. The finished compost is stored in the outdoor concrete storage bins until its use is needed by the town or private citizens for soil amendment or land reclamation purposes.

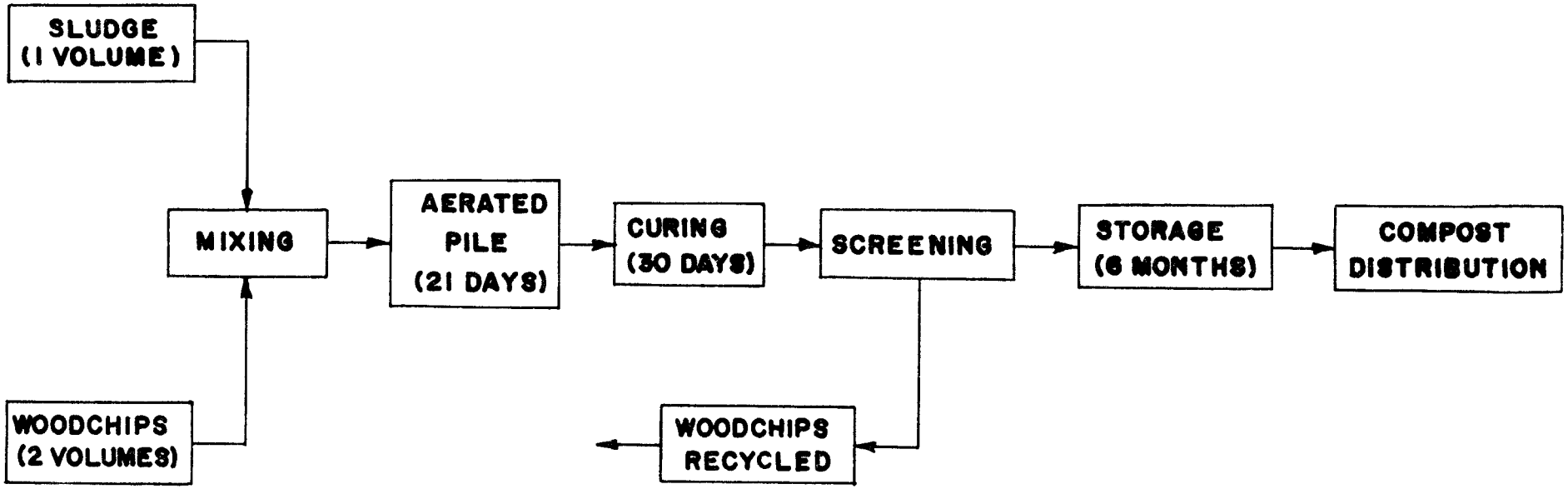


Figure 3
Flow diagram for the Durham composting operation.

CHAPTER 4

LITERATURE REVIEW

Principles of Composting

Composting is a biological process whereby the organic components of solid wastes are decomposed under controlled conditions to maximize the degree of stabilization. Controlled conditions may include the use of a reactor container for composting, or, more simply, the formation of the material into a pile or windrow.

Composting can be classified into various categories according to characteristics of the systems employed. Golueke (38) lists three classifications based on oxygen, temperature and methodology. These include: 1) aerobic or anaerobic composting, 2) mesophilic or thermophilic composting, and 3) mechanized or non-mechanized composting. In the first category, composting operations may be operated with or without air provided. Aerobic systems are maintained by turning the material at periodic intervals, or by forcing air into the pile with blowers. The rate of decomposition tends to be more rapid in an aerobic system than in an anerobic one, odor production is lower, and temperature elevation is sufficient to aid in pathogen destruction. Loss of nitrogen through the volatilization of ammonia due to high temperatures and alkaline conditions, however, is one disadvantage of an aerobic composting system.

The temperature within a mass of actively composting material follows a natural succession from the mesophilic range (i.e. approximately 10.0 to 50.0°C) to the thermophilic range (greater than 50°C) unless externally controlled to remain within a specific range. This temperature rise is the result of intensive microbial activity (32). Systems classified as thermophilic or mesophilic operate under temperatures in these ranges only.

In a mechanized composting system, temperature, pH, moisture, and oxygen may be controlled externally to insure optimum conditions during the process. In a non-mechanized system, however, the process normally must proceed without these controls.

The success or failure of any composting system ultimately depends upon the microbial population of the material (38). Operational parameters, then, must be selected to optimize conditions within the composting environment which will insure the greatest degree of microbial activity and subsequent decomposition.

A variety of microorganisms are involved in the composting process, including bacteria, actinomycetes, and fungi. Viruses, protozoans, and helminths can also exist in compost material and pose a potential public health hazard. A succession of microbial types generally occurs during the process as the composting material changes chemically and physically, and as the temperature changes. Bacteria are responsible for the initial decomposition of complex organic molecules, i.e. carbohydrates, proteins, and simple sugars. Actinomycetes and fungi are present at later stages when the more resistant organic molecules, such as cellulose and lignin, remain.

Within a composting system, certain factors are necessary to insure effective solids stabilization. Nutrient requirements necessary for microbial activity must be present in assimilable forms within the compost material. In addition to the major constituents for growth, i.e. carbon, nitrogen, phosphorus, and potassium, requirements for micronutrients must be met, including constituents for enzyme synthesis. A suitable energy source must also be present. Golueke (38) sums up these conditions in his statement, "...the more abundant the elements of nutritional significance in a substrate to microbes, the greater will be the number of microorganisms supported by it, and hence more extensively and rapidly will it be composted".

The most important nutrient balance in composting is the carbon-to-nitrogen ratio (C:N). The optimum ratio for most types of waste is 25 to 30:1 (38). A value greater than this will effectively decrease biological activity, taking several generations of organisms to reduce the carbon. Alternately, a C:N ratio less than the optimum could result in the production of toxic amounts of ammonia, due to excess nitrogen. This will be discussed in more detail later.

Four major variables extrinsic to the microorganisms are important in the composting process. Temperature, moisture content, pH, and aeration or oxygen availability affect the effectiveness of the process.

Temperature

The optimum temperature for a composting system is, at best, a compromise between the optimum temperatures of all organisms involved. Since the temperatures theoretically follow a succession from mesophilic to thermophilic, the activities of the different organisms peak while the temperature is within the optimum range specific for that microbe. Once the temperature has reached the thermophilic range, the species diversity tends to decrease. With this, the rate of decomposition of the organic matter decreases and the temperature drops to a more moderate level (55°C). Mass recolonization by mesophiles can then occur and the onset of nitrification may signal that treatment is near completion. Eventually, the species diversity lost during periods of elevated temperatures is reestablished with the appearance of forest litter species such as insects, mites, beetles, roundworms, and earthworms (32).

The concept that there are two distinct phases in composting was described by Atchley and Clark (2). The first phase, known as the mesophilic stage, is denoted by an abundance of available nutrients and ambient temperatures (10-25°C). The mesophilic organisms are highly active and cause an increase in the temper-

ature of the compost pile. This rise in temperature causes cessation of the mesophilic stage, and onset of the second thermophilic stage occurs. The thermophilic stage is characterized by temperatures higher than 50-55°C. During the thermophilic stage, there are two phenomena which occur. A high or peak temperature in the range of 70-75°C occurs which indicates the high metabolic activity of the microorganisms. This coincides with a decrease in pH which is caused by production of large amounts of carbon dioxide and organic acids resulting from the high metabolic rate.

MacGregor et al. (63) noted that rational composting process control involves the interrelated factors of heat output, temperature, ventilation, and water removal. The heat is released microbially as the organic material is biodegraded, causing a rise in temperature. High temperature eventually limits microbial activity in the compost. Ventilation supplies oxygen and removes heat and water, mainly through vaporization of water. Fundamentally, there are two kinds of composting systems: those that are and those that are not temperature self-limiting. The self-limiting system reaches inhibitive temperatures which debilitate the microbial community, supressing decomposition, heat output, and water removal. Non-self-limiting temperatures (< 60°C) support a robust community, promoting decomposition, heat output and water removal.

MacGregor et al. (63) further note that soon after organic material is assembled into a self-insulating mass, the temperature starts to increase as metabolic heat accumulates. At first, mesophilic growth is stimulated by the higher temperatures, but, as inhibitive levels are reached, this leads to a self-limiting condition. Because the elevated temperature now induces thermophilic growth, the pattern is repeated in a second, hotter stage. At peak

thermophilic temperatures, the metabolic activity is relatively slight. The system is prone to self-limitation via the excessive accumulation of heat. In the thermophilic range, activity is greatest at 52-60°C, and a steep decline starts above this upper boundary. The concept is also espoused by Jeris and Regan (54).

Typical temperatures recorded during the composting of raw sludge at Beltsville, MD, are shown in Figure 4 (102). Temperatures in the pile increased rapidly into the thermophilic range of 80°C or higher. Temperatures began to decrease after about 16 to 18 days, indicating that the sludge had been stabilized and transformed into compost. Similar results have been reported for composting of sludge at Bangor, Maine (66), Los Angeles (48), Pistoia, Italy (16) and elsewhere. Maximum temperature is usually reached in 6 to 8 days (20,23,48), even under cold weather conditions (66). Temperatures greater than 55°C can be expected for over 8 days using the Beltsville process, as shown in Table 1 (20).

Table 1

The Number of Days that the Maximum Temperature in a Compost Pile Would Exceed 55, 60 or 65°C at 95, 99 and 99.9% Confidence Levels (20)

Temperature	Confidence Level		
	95%	99%	99.9%
	(Number of days)		
55°C	10	8.6	8.4
60°C	6.4	5.6	4.9
65°C	3.3	2.8	2.4

In a recent paper, Haug (46) discussed the principles of sludge composting. The objectives of composting traditionally have been to convert putrescible organics biologically to a stabilized form and to destroy pathogens. With sludge composting, a third objective of drying the wet cake is desirable.

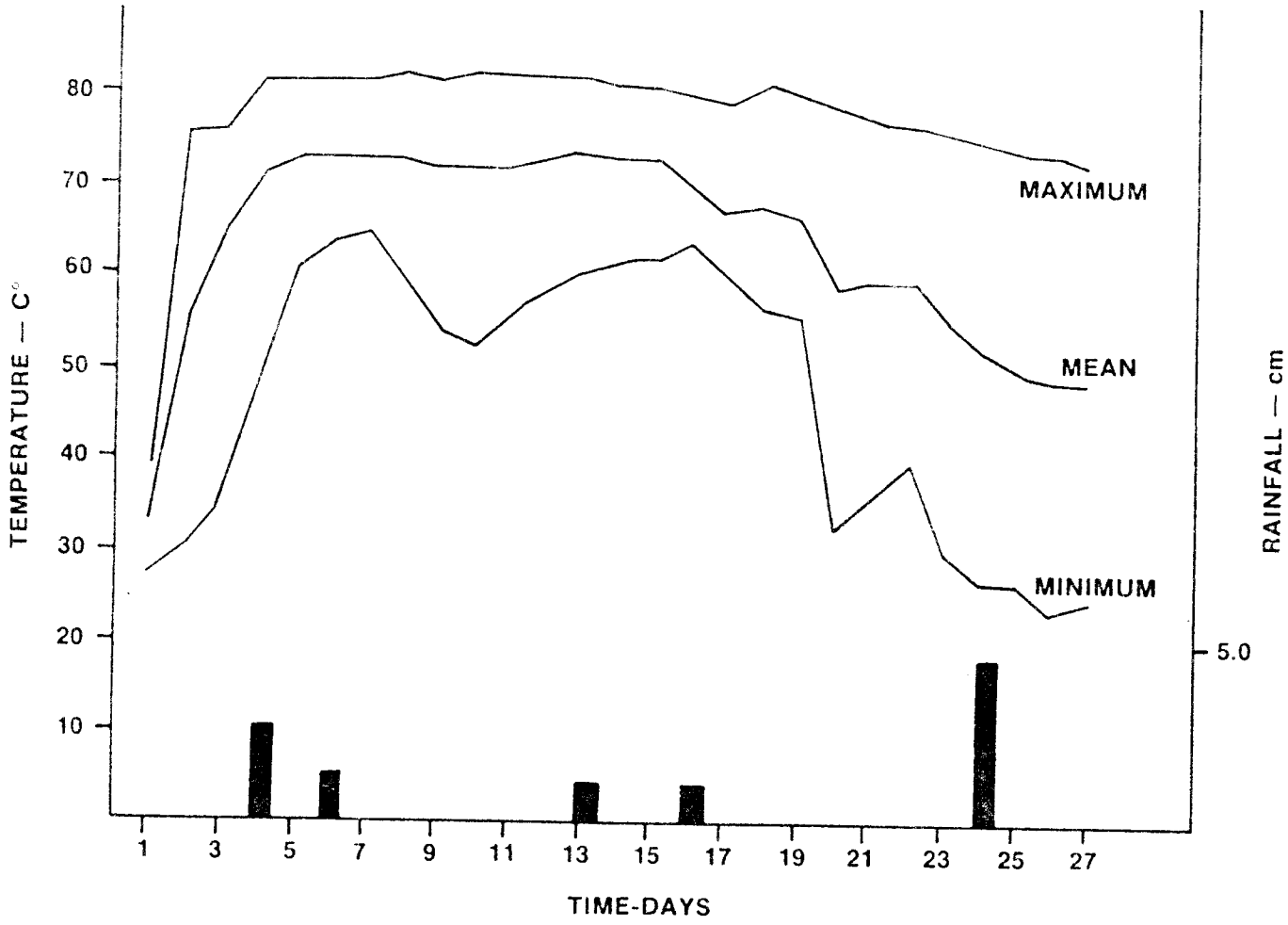


Figure 4
Typical temperatures recorded during composting at the Bettsville composting facility. Bars at bottom indicate rainfall events (102).

Drying reduces the cost of subsequent handling and increases the attractiveness of the composted product for use.

The aerobic composting process results in the generation of carbon dioxide, water and heat. The loss of weight from conversion of volatile solids to gases and from the evaporation of moisture substantially reduces the weight and volume of the composted product.

The high temperature reached in a properly designed and controlled aerobic composting process should exceed the thermal death point of most pathogens. Since moist heat is more lethal to microorganisms than dry heat (46,50), pasteurization can be achieved at a lower temperature and earlier in the process than would be possible in the dry state. If excessive moisture is present, though, temperature elevation will be less for a given quantity of heat released. On the other hand, low moisture content can decrease the rate of microbial activity and thus reduce the rate of microbial heat evolution. Moisture contents less than 45-50 percent can be rate-limiting, and bacterial metabolism generally ceases below 10-15 percent moisture.

Haug (46,50), further points out that the air requirement for drying is significantly greater than the air requirement for biological oxidation and is influenced largely by the cake solids content and exit air temperature. Only at cake solids approaching 30-40 percent and exit air temperatures of 70°C do the requirements for drying and biological oxidation become reasonably equivalent. At cake solids of 20 percent, the air requirement for drying can be as much as 10-30 times that for biological oxidation. Obviously, if too much air is supplied, the composting material will be cooled, exit air temperatures will drop, and air requirements for drying will increase. Achieving both drying and composting requires control between energy release as a result of biological oxidation and heat demands for drying.

Haug (46), concludes that in the aerated pile system, energy will be continually expended to heat air mechanically drawn into the pile. Under equilibrium conditions, compost temperatures will rise to a point where energy inputs are balanced by outputs. However, maximum obtainable temperatures are limited to about 75-80°C because the rates of biological activity, and hence heat evolution, begin to decrease above about 55°C.

Finstein (28,29,30,31,32,89) who advocates low temperature composting, states that there is little information on the optimal temperature for the various composting objectives. Disinfection is presumably fastest at the highest temperature attainable, but this may not be favorable for the decomposition of putrescible materials, bulk reduction, narrowing of the C/N ratio and other objectives.

In a study of forced aeration composting done by the U.S. EPA (95), it was noted that the weather can have an effect on composting operations. Generally, cold weather has little effect on composting itself; the piles can perform well in very cold weather if they are insulated properly, as has been substantiated by Epstein (20,23) and by Mosher and Anderson (66). Most cold weather problems relate to materials handling equipment, especially with screening. The unscreened compost may pick up moisture and make the fine particles stick together.

Moisture Content

The moisture content for optimum growth in a composting systems is 45 to 50 percent (27,45,46,47,48,82,97). The maximum amount of water allowable depends on the extent to which the interstitial spaces can be filled with water and yet leave sufficient space for the oxygen requirements of the microbes.

The minimum allowable moisture content is a function of physiological needs of the organisms. The ideal maximum amount to meet these microbial demands is 100 percent, however oxygen transfer would be impossible. The minimum amount for growth is 12 percent. Overall, the moisture content should not be allowed to drop below 45 to 50 percent.

In addition to the function of water in growth, it also has a role in the destruction of organisms (27,70). Most pathogens are destroyed at temperatures ranging from 50 to 60°C. This destruction is apparently enhanced if the moisture content is sufficient, since moist heat is more lethal than dry heat.

The higher the moisture content of the organic material, the greater is the need to maintain a large void volume to assure adequate aeration. Both size and quantity of the bulking agent must be controlled to maintain porosity throughout the pile and assure adequate air flow without excessive blower headloss. In the aerated pile composting system, woodchips or other bulking agents serve to absorb some moisture from the sludge and maintain the structural integrity and porosity of the pile. In general, the quantity of bulking agent is determined by the need for structural support and porosity and not by requirements for moisture control.

Aeration

Oyxgen is a fundamental requirement for an aerobic composting system. The availability of oxygen to the organisms is crucial to the process. This largely depends on the degree of pore or interstitial space of the material through which the oxygen is transferred to the microbes. If the oxygen cannot penetrate the compost mass because of little pore space, anaerobic pockets will develop and aerobic organisms will be succeeded by anaerobes. A bulking

agent such as woodchips is often used to adjust the pore space of a compost material and increase the oxygen availability to the microbes. The oxygen required to decompose compost material is influenced by such factors as temperature, moisture, size of the bacterial population and availability of nutrients, and is difficult to quantify for a given composting system.

For proper air movement to occur, the materials to be composted must be structurally arranged so that air passages exist in the material to replenish the oxygen required for respiration of aerobic microorganisms (52). This can be accomplished by mixing the sludge with a bulking agent (woodchips, peanut hulls, etc.) which provides the structure for increasing the air space. Unless the sludge particles are physically kept apart with a bulking agent, they will combine to form a bigger mass of sludge, thereby causing a reduction in free pore space.

Air must also be supplied in order to remove carbon dioxide and free ammonia released as byproducts of composting, to maintain a desirable thermal environment to ensure pathogen destruction and biological activity, and to dry the compost by removing water from it (52).

In general, oxygen concentrations in the gas within the compost pile should be maintained between 5 and 15 percent (97). Operating data indicates that the oxygen level in a compost pile decreases as temperature increases. Temperatures are generally highest when oxygen values range from 10 to 13 percent. Oxygen levels generally range between 5 and 12 percent (23). In most cases, the oxygen consumption rate in the compost, as measured by manometric procedures, is greatest within the first day, and then declines linearly (72).

De Bertoldi et al. (16) evaluated ventilation of the compost pile by turning, forced aeration and vacuum aeration. They found that forced aeration resulted in the greatest amount of moisture removal, although differences

between the three systems were not large until after 20 days of aeration. Compost temperature increases were the same for forced and vacuum ventilation systems for the first 10 days of composting, but the forced ventilation piles cooled off much more quickly beyond this point. Higgins (51) has stated that forced aeration systems encounter significantly less airflow resistance than vacuum induced aeration systems, resulting in more air delivery at less power and a more uniform distribution of air.

pH

The pH of the compost mass is less crucial to the process than the other factors because a broad permissible range (pH 5.5 to 8.0) exists in which organisms can grow. The optimum range for bacteria is between 6.0 and 7.5, and for fungi, it is between 5.5 and 8.0. Little can or should be done to control the pH in a composting system. According to Golueke (38), acid formers may initially metabolize polysaccharides and cellulose to form organic acids and lower the pH. Organisms growing in anaerobic pockets may also contribute to this drop. As organisms capable of metabolizing the organic acids appear, the pH may rise to 8.0 or 9.0. Loss of organic acids through volatilization and release of ammonia through mineralization of organic nitrogen may also raise this pH (32).

Summary

Golueke (38) characterized the composting process by suggesting six principle features: 1) a rise and fall in temperature; 2) the uptake of oxygen; 3) a change in appearance and odor of the material, i.e. the compost

darkens and has an 'earthy odor'; 4) the C:N ratio decreases; 5) the pH drops initially followed by an increase; and 6) ammonia is produced. The patterns and characteristics that describe composting will vary to some degree with each system. Gray et al. (43) cites four stages that characterize composting. These include, mesophilic (temperatures from ambient to 40°C), thermophilic (45 to 75°C), cooling, and maturing.

The two major objectives of any composting operation are stabilization of putrescible materials and destruction of pathogenic or disease-causing organisms. Theoretically, a final drop in temperature with no subsequent increase signals an end to the process. If the decomposition of the material is not complete, the temperature may rise when conditions again become favorable for microbial activity. It is difficult, then, to determine when the material is stable and safe for land application. At present there is no satisfactory or consistent criteria to determine the degree of stabilization. Another complicating factor exists in deciding how much stabilization of the material can safely occur in the soil once the material is applied to the land. Complete decomposition to CO_2, water, and inorganic ash by composting would render the matter inert, and would not enrich the soil. The acceptable degree of stabilization, then, may be the point at which only the more resistant organic forms remain undecomposed. Golueke (39) has stated that he does not feel that establishing a standard for the degree of stabilization is highly probable given the variability of raw material and operational conditions in compost systems. At present, he also states, the final drop in temperature and aesthetics are the most reliable standards.

Pathogen Destruction During Sludge Composting

Although composting presents an economical and efficient solution to the sludge disposal problem, there is a potential threat to public health associated with the production and use of the compost because of the wide variety of human pathogenic organisms contained in sludge. These pathogens can be classified into the following groups, with typical examples shown (8,46,90):

Bacteria
- *Salmonella sp.*
- *Shigella sp.*
- *Mycobacterium tuberculosis*
- *Vibrio cholera*

Protozoa
- *Entamoeba histolytica*
- *Giardia lamblia*
- *Naegleria fowleri*

Fungi
- *Aspergillus fumigatus*
- *Nocardia asteroides*

Enteric Viruses
- Poliovirus
- Enteroviruses
- Echoviruses
- Hepatitus A virus

Helminths
- *Ascaris lumbricoides*
- *Toxocara canis*
- *Taenia saginata*
- *Trichuris trichiura*

Destruction of pathogens and parasites occurs during composting as a result of the high temperatures attained (especially in the presence of sufficient moisture), antibiotic production among the organisms, competition, depletion of nutrients, and time (36,39). Unless conditions favorable for growth recur, pathogens can be virtually eliminated. The problem remains that if residual populations exist, and conditions do become favorable, regrowth may occur and pose a potential public health threat.

Table 2

Effectiveness of Sludge Disinfection Processes (88)

Disinfection Process	Removal or Inactivation			
	Indicator Organisms	Pathogenic Bacteria (*Salmonella*)	Viruses	Parasites (*Ascaris lumbricoides*)
Long-Term Anaerobic Storage (6 mo)				
Laboratory batch test at 4°C	F+	E	P	P
Laboratory batch test at 20°C	E	E	E	P
Temperature (Heat)-Time Processes				
Anaerobic digestion (35°C)	F	F	P+	P
Anaerobic digestion (52°C)	G	E	G	P
Aerobic digestion	F	P+	U	U
Aerobic digestion (60°C)	G	E	Est E	Est E
Composting (> 60°C)	G+	E	G+	E
Pasteurization (70°C, ½ to 1 hr.)	G	E	E	E
Pasteurization (70°C, 1 to 2 hr.)	E	E	E	E
Heat treatment (195°C)	E	E	E	E
Heat drying	E	E	E	E
Chemical Treatment				
Lime treatment (pH > 12)	E	E	Est E	P
Heavy chlorination (~1500 mg/l)	Est E	Est E	Est E	Est P
Ionizing Radiation				
Gamma irradiation (300-400 krad)	G+	E	F	E
Gamma irradiation (300-400 krad, 55°C)	E	E	E	E
High-energy electron irradiation (1000 krad)	E	E	G+	E

Key
U = Unknown
P = Poor (less than 1 log reduction)
F = Fair (1 to 3 logs reduction)
G = Good (more than 3 logs reduction)
E = Excellent (below detectable levels for pathogenic organisms analyses)
Est = Estimated

Bacteria

Data on the survival of pathogens in composted sludges are limited to a few indicator organisms in a few composting systems. Significant reductions in pathogen numbers have been noted in some composting systems. The two predominant mechanisms of pathogen kill are thermal kill and antibiotic activity. It has been proposed that both are necessary for the greatest possible reduction (37). Sivinski (84) has reported the following D-values (the time required per $\log_{10}$ reduction in population at 60°C) for destruction of pathogens by heat: Adenovirus - 0.15 minutes, Ascaris ova - 1.3 minutes, Poliovirus - 1.5 minutes, Staphylococci - 3.3 minutes, Salmonella - 7.5 minutes. Shell and Boyd (83) reported the following thermal death points: Salmonella newport - 30 minutes at 60°C, Candida albicans - 60 minutes at 70°C, Ascaris lumbricoides - 60 minutes at 60°C, and poliovirus - 30 minutes at 50°C. These values indicate that both temperature and residence time within the pile should be sufficient for pathogen inactivation. However, a temperature gradient exists within the pile with the highest temperatures in the middle. Temperatures at the outer edges may often only be slightly above ambient. These lower temperatures may allow for pathogens to survive in portions of the pile. In addition, shielding of microbes by compost particles and coating of organisms by protective organic substances may increase pathogen survival (70).

Stern and Farrell (88) have compared the effectiveness of various sludge disinfection processes and found that composting rates good to excellent for removal or inactivation of indicator organisms, pathogenic bacteria (Salmonella), viruses and parasites (Ascaris lumbricoides) if the composting temperature is greater than 60°C. This comparision is shown in Table 2.

In most studies performed on composting systems, pathogens have been shown to be destroyed, but destruction is often incomplete. Burge and Cramer (7) found that Salmonella destruction was complete in windrows within 15 days, but that fecal coliforms still survived. They also found that coliform concentrations were greatest near the surfaces of the pile (10^4-10^5/g), and that regrowth of both Salmonella and coliforms occurred during curing. Kawata et al. (57) also reported high concentrations of total and fecal coliforms taken at the surface and subsurface of a compost pile. Later, Burge, et al. (8) repeated these experiments using forced aeration and found complete destruction of fecal coliforms.

Passman (70) has noted that pathogenic bacteria can be virtually eliminated during composting if proper environmental conditions are maintained, but that even when populations are greatly reduced, a sufficient population may persist to repopulate the compost. These pathogens could then be transported to soils where they could be passed on to the general public.

In an early study performed by Reeves (74), a limited survey was made on the isolation of pathogenic intestinal bacteria including coliforms, Salmonella and Shigella from compost. Reeves' study was performed on sewage sludge and sawdust in a windrow composting system with manual turning of the material to provide aeration. Because of the ease with which he isolated Salmonella and Shigella genera from the finished compost, he concluded there are dangers involved in the possible dissemination of disease through use of composted sewage sludge. However, he emphasized the fact that his work was preliminary.

A study by Krige (60) refuted the conclusions drawn by Reeves and proposed that composted material, including sewage sludge, was safe from a public health standpoint. Krige surveyed matured compost from several municipalities. The initial composting materials varied from nightsoil and household refuse to

abattoir waste, and in most cases the material was composted in windrows turned manually at least once during the composting process. He performed analyses only on the final compost material to determine the numbers of E. coli, Salmonella, and Shigella, the presence of M. tuberculosis and an examination of Ascaris eggs. Although Krige concluded that the composts produced under controlled conditions were safe, his results were based on a one-time sampling schedule. He also reported that a statistical analysis was not possible and that the data illustrated the complexity and irregularity of highly active biological systems. He also stated that no conclusions could be drawn from the E. coli counts.

In a different approach to the study of pathogen survival during composting, Wiley and Westerberg (101) inoculated fresh composting material entering a mechanized aerobic composting apparatus with selected organisms and assayed the finished product for these same organisms. The microorganisms chosen for this study included Salmonella newport, Ascaris lumbricoides, Candida albicans, and Poliovirus type I. In analyzing the final material, they concluded that the time-temperature conditions of this composting process were adequate to destroy all indicator organisms studied.

Shell and Boyd (83) also investigated the survival of Salmonella newport, Candida albicans, Ascaris lumbricoides, and Poliovirus type I during a fully mechanized and completely enclosed composting system. By seeding these organisms into the dewatered sewage sludge, they were able to monitor the die-off patterns during the process. Reductions in all of the seeded organisms were noted.

In more recent work by Cooper and Golueke (9), a composting system consisting of municipal refuse and dewatered, digested sludge was analyzed for the survival of enteric bacteria and viruses. Cooper and Goluke attest to the fact that many believe that a "...well-managed compost process is practically ipso facto

a guarantee that the compost product will be free of pathogens". This premise, they state, is based more on faith than fact and its support is generally found in the comparision between high temperatures reached within a composting mass, and the values in tables for thermal death points of pathogens. They report that the number of studies whose purpose was to assess pathogen survival (or destruction) is actually relatively small. This same conclusion had been reached much earlier by Wiley (100).

The composting system that Cooper and Golueke (9) studied was a windrow process which employed manual turning at varying intervals. Total coliform, fecal coliform, and fecal streptococci were monitored. The results indicate a substantial overall reduction in the numbers of these organisms with time, but approximately 1000 fecal coliforms per gram dry weight of compost were still surviving after 25 days of composting. The authors concluded that temperature was not the sole bactericidal agent in the process. The reasons stated for the reduction in numbers of these organisms included the average length of exposure to lethal temperatures, the relative volumes of material actually exposed, the intervals between exposure to these temperatures, and physical conditions (especially moisture). The key point stressed by the authors was that "...at no point in time was every last particle in the pile exposed to lethal temperatures". The authors estimate approximately 25 percent of the compost was at temperatures characteristic of the top 15 cm (6.0 in.) of the pile, which for the most part were lower than 50°C.

Another important observation made in this study was the mitigating effect of low moisture content on high temperatures. Moist heat is more destructive to bacteria than dry heat, as previously mentioned. It must also be noted that thermal death points, used by many to support the belief that high temperatures alone indicate pathogen destruction, are predicated upon exposure of the organisms in a saturated environment.

In a report by Epstein et al. (23) the effects of composting raw wastewater sludge by forced aeration on the survival of total coliforms, fecal coliforms, and Salmonella were studied. They also monitored the temperature and oxygen within the pile. The bacterial analyses were performed on the initial sludge and again at the end of the composting period. Samples were removed and analyzed from five sites within the pile. The results indicate that forced aeration composting is efficient in destroying these organisms.

Burge et al. (8) evaluated the destruction of coliforms, Salmonella, f_2 bacteriophage, and parasitic ova in both windrow composting and forced aeration composting. In their study, windrow composting proved to be less effective. It was also noted that although further destruction can occur during curing, the possibility for regrowth of coliforms and Salmonella in the exterior of the curing piles does exist. Any contamination of the finished product can result in rapid growth of Salmonella and coliforms. Further work by Burge (7) has shown that Salmonella and other organisms can grow rapidly in composted sewage sludge.

Passman (70) has stated that data on pathogen persistence in composting is limited. He also stated that all pathogens are destroyed by heat, but other factors in any composting system can enhance or diminish the lethal effect of heat. Such factors include shielding of microbes by compost particles, aggregates, adsorption of microbes to particles, and coating of organisms with protective organic substances, each one increasing the chance of survival of the organisms.

Burge et al. (8) found that total and fecal coliforms and Salmonella were completely destroyed during the first ten days of composting chemically precipitated raw sludge by forced aeration.

Satriana (81) reported that a mechanical composter achieving a temperature of 140°F (60°C) was capable of reducing pathogens in the compost by 99.99 percent. All Salmonella newport, Candida albicans, Ascaris lumbricoides and Poliovirus Type 1 were destroyed or inactivated within 3 days, even when they were seeded into the compost pile in large numbers.

Fungi

Several species of fungi have been found to populate compost, a few of which can cause pneumonia or bronchial asthma (27,35,55,65,67,71). Aspergillus fumigatus is one of the most prevalent fungi on earth and is commonly found in municipal sludge compost. Millner, et al. (64) monitored A. fumigatus at a forced aeration compost plant and found minimal destruction during composting.

Aspergillus fumigatus is an opportunistic fungal pathogen of the human lung. While seldom eliciting a response in healthy humans, its spores can act as powerful allergens in sensitized individuals. In hosts previously compromised by lung infection or injury, chronic pulmonary disease, depressed immune response, or general debilitation, the organism can cause aspergillosis. The organism germinates in the lung and the hyphae invade contiguous tissues directly (59,65). Health risks to treatment plant workers can be minimized by screening individuals for any predisposing individuals and by requiring operators to wear dust filtering masks (71,97).

A. fumigatus is found in large numbers in woodchips and sludge at compost plants and is able to survive temperatures which do not rise about 60°C. Compost stored for one to four months after screening often has many A. fumigatus (65). Counts may drop to insignificant levels after 6 months of stockpiling, though (67).

A. fumigatus needs ample supplies of carbon for growth. High densities of these organisms are often found in compost because of the relatively high temperatures which promote growth and because of the large amount of decomposing organic matter. They are also found in lawn clippings, decaying vegetation on farms, and in woodchips (67).

Other fungi, mesophilic and thermophilic, have also been detected at compost facilities (15,70). These fungi play a vital role in the biodegradation process. In the initial phase of composting, both mesophilic and thermophilic fungi are fairly active, but as the temperature rises all fungi tend to disappear. When the temperature begins to drop (to 50-55°C) they resume their activity, first the thermophilic and then the mesophilic. During the phase of temperature decline, the rate of transformation of cellulose and pectin is at its peak (15).

Protozoa

There appears to be little or no data concerning survival of pathogenic protozoans during composting. Assumptions are that protozoans do not survive composting, but no field experiments have been performed to substantiate this (70).

Helminths

Large numbers of parasites can be found in wastewater sluges, since little parasite egg destruction occurs during standard sludge treatment processes. This is particularly true in warmer climates where parasites are more prevalent (61,70,75,90). Ascaris is widely regarded as an indicator organism

for monitoring for helminth survival since the Ascaris ova are known to be extremely resistant. Temperature is the primary factor contributing to helminth ova inactivation during composting, although they are also susceptible to dessication. Only a few studies have reported on parasite inactivation during sludge composting, but in general they indicate essentially complete destruction of the ova if temperatures exceed 60°C (60,70,90,101). Taffell (90) concludes that it is unlikely that parasite infections will result from use of compost. Passman (70) has proposed using Ascaris survival as the best overall indicator of the effectiveness of composting as a thermal disinfection process.

Viruses

Viruses are obligate intracellular parasites, meaning that they cannot replicate outside of a host cell. However, they can persist for extended periods outside their host. Little work has been done to determine the degree of viral inactivation during composting. Researchers with the Los Angeles County Sanitation District have recovered viruses from composted sludge (70). Burge, et al. (8) seeded sludge with the bacteriophage F-2 and found that this persisted more than 70 days in compost windrows, but was inactivated within 14 days in forced-aeration piles. Kawata, et al. (57) reported that 50 days composting time was needed for total inactivation of f_2 bacterial virus in a windrow composting system.

Cooper and Golueke (10) evaluated virus survival in windrows of a digested sludge-municipal refuse mix. They found a sharp decrease in the number of polioviruses, with only 1.6 percent of those at time zero recovered after 48 hours of composting.

Regrowth

If pathogens should survive the composting process, there is the potential for regrowth to occur when temperatures drop to those more conducive to growth. Growth of pathogenic organisms in compost can occur only for certain bacteria and for fungi, since other pathogens of concern are parasitic and cannot grow outside of a host (46,50,90).

Apparent regrowth of coliforms and Salmonella has been observed by a number of investigators. Researchers in Los Angeles County noted the regrowth of coliform and Salmonella in curing piles moistened by rain. They also reported that the method of dewatering affected the efficiency of pathogen destruction during composting (78). Regrowth of Salmonella was also detected in forced aeration composting during a demonstration project by Energy Resources Company, Inc. in Boston (78). Several months after curing, Salmonella was found to have increased from nondetectable at the end of composting to up to 300 MPN/gram.

Passman (70) emphasized that although pathogenic bacteria can be virtually eliminated during composting, a sufficient residual population may remain which could increase in number once conditions become favorable. Regrowth is not unlikely and the bacteria could be transported to the soil.

Factors affecting bacterial survival in soils include: the genetic and physiological characteristics of the bacterium, the physiocochemical characteristics of the soil, atmospheric conditions (e.g., moisture, temperature and exposure to sunlight), the mode of application to the soil, biological interactions among microbes in the compost and compost-soil environments, and host-parasite relationships. This survival period may range from several hours to years (41,70). Table 3 presents typical survival times of animal pathogens in the soil and on plants (38,40).

Table 3

Survival Times of Animal Pathogens in the Soil and on Plants (38)

Organisms	Medium	Survival Time (days)
Ascaris ova	soil	up to 7 years
	vegetables	27-35
Salmonella typhosa	soil	29-70
	vegetables	31
Cholera vibrio	spinach, lettuce	22-23
	nonacid vegetables	2
Endamoeba histolytica	soil	8
	vegetables	3
Coliforms	grass	14
	tomatoes	35
Hookworm larvae	soil	6 weeks
Leptospira	soil	15-43
Poliovirus	polluted water	20
Salmonella typhosa	radishes	53
	soil	74
Shigella	tomatoes	2-7
Tubercle bacilli	soil	6 months
Typhoid bacilli	soil	7-40

Pathogen survival after land application of compost is most likely in the soil below the top 5 cm of soil. Field conditions such as sunlight, dessication, freezing, heat, and freeze/thaw cycles are effective at reducing survival times in the upper layer (96).

Compost Disinfection Criteria

The U.S. Environmental Protection Agency now considers sewage sludge composting to be an acceptable method for stabilizing and decreasing the pathogen content of sewage sludge (96,97). There are two sets of time/temperature combinations in the "Criteria for the Classification of Solid Waste Disposal Facilities and Practices". The first provides for a "significant" reduction of pathogens. This requires that the compost temperature must exceed 40°C for at least 5 days and 55°C for at least 4 hours during that period. However, the end-use of a compost that has only undergone "significant" reduction of pathogens is restricted as to its use. These restrictions include a required 18-month interval between land application and the growing of crops for human consumption, except for those crops which do not come in contact with the compost (citrus fruits, corn, etc.). In contrast, the second time/temperature combination, which provides for "further" reduction of pathogens, requires that the temperature in an aerated pile must be at least 55°C continuously for 3 days in the coolest part of the pile, and that the temperature in the center of a turned windrow must be at least 55°C for at least 15 of the 21-30 day composting period. If these criteria are met, then waiting periods and access restrictions are not necessary.

The Fate of Nutrients During Composting

A number of inorganic nutrients are required for biological systems, including composting, to maintain the cellular functions. The nutrient that has received the most attention in composting systems is nitrogen, and in particular, the carbon/nitrogen (C/N) ratio (45). During active aerobic growth, living organisms use about 25 to 35 units of carbon for every unit of nitrogen (42), so a C/N ratio of about 30 should be optimum for composting. If excess carbon is available (a higher C/N ratio), rapid cell growth will cause a depletion of available nitrogen and a temporary slowdown in cellular growth. As cells begin to die, their stored nitrogen again becomes available to living cells and the system is brought back into balance. The result, though, is a slower than optimum growth rate, a loss in heat output, and a subsequent reduction in effectiveness of pathogen destruction. Low C/N ratios result in rapid composting, accompanied by an increasing loss of excess nitrogen from ammonia volatilization. This loss of nitrogen from the final product reduces the compost's value as a soil conditioner (20).

Characteristics of a typical digested sludge are shown in Table 4 (9). As can be seen, the C/N ratio of sludge is often quite low. One way of adjusting the C/N ratio upward is to use an organic bulking agent such as woodchips or sawdust which can serve as a supplemental carbon source as well as a bulking agent. However, it should be noted that the C/N ratio of the sludge:woodchip mix may be misleading if the supplemental carbon is in a form making it less available. The carbon contained in coarse woodchips is not highly reactive and the effective C/N ratio would be lower than for the same woodchips ground into sawdust (97).

Table 4

Characteristics of a Typical Digested Sewage Sludge (9)

Parameter	Concentration
Total Solids	19.0%
Volatile Solids (dry wt)	44.6 - 48.4%
C	242,000 mg/kg
NH_4-N	5,960 mg/kg
TKN-N	24,500 mg/kg
PO_4-P	12,000 mg/kg
Na	1,000 mg/kg
C/N	10

During composting, the nitrogen content generally decreases during the course of the process, mainly because of ammonia volatilization. De Bertoldi et al. (16) found that nitrogen loss was far greater with turning and suction methods of compost aeration than with blowing (18 percent, 11 percent and 5 percent, respectively). They reported that this is consistent with the fact that the blowing system was also characterized by the lowest initial pH and temperature, factors which strongly influence ammonia volatilization. Regardless of the aeration system used, autotrophic nitrification appeared to be absent in the early stages of composting. Nitrification was not detected until the completion of 20 days of composting. The researchers attributed this inhibition to the high temperature and high levels of ammonia present in the compost during the early stages of composting, both of which have been shown to inhibit the growth of nitrifiers.

Although a nitrogen loss usually was observed during the first phases of composting, a partial recovery later took place, due to the activity of nitrogen-fixing bacteria (15). Many species of these bacteria have been isolated during composting, mostly during the mesophilic phases (15,16).

Figure 5 shows the development of the main bacterial population in a compost system (16). Ammonia-producing and proteolytic bacteria increase considerably reaching numbers greater than 10^6 cells/g dry wt. Aerobic nitrogen-fixers tend to increase their activity in the beginning, but then decrease considerably due to the adverse effects of temperature and increase in ammonia. Later in the compost cycle, when the compost has become stabilized and temperatures begin to decrease, the ammonia-producing and proteolytic bacteria populations begin to decrease while the nitrogen-fixing bacteria population begins to increase again.

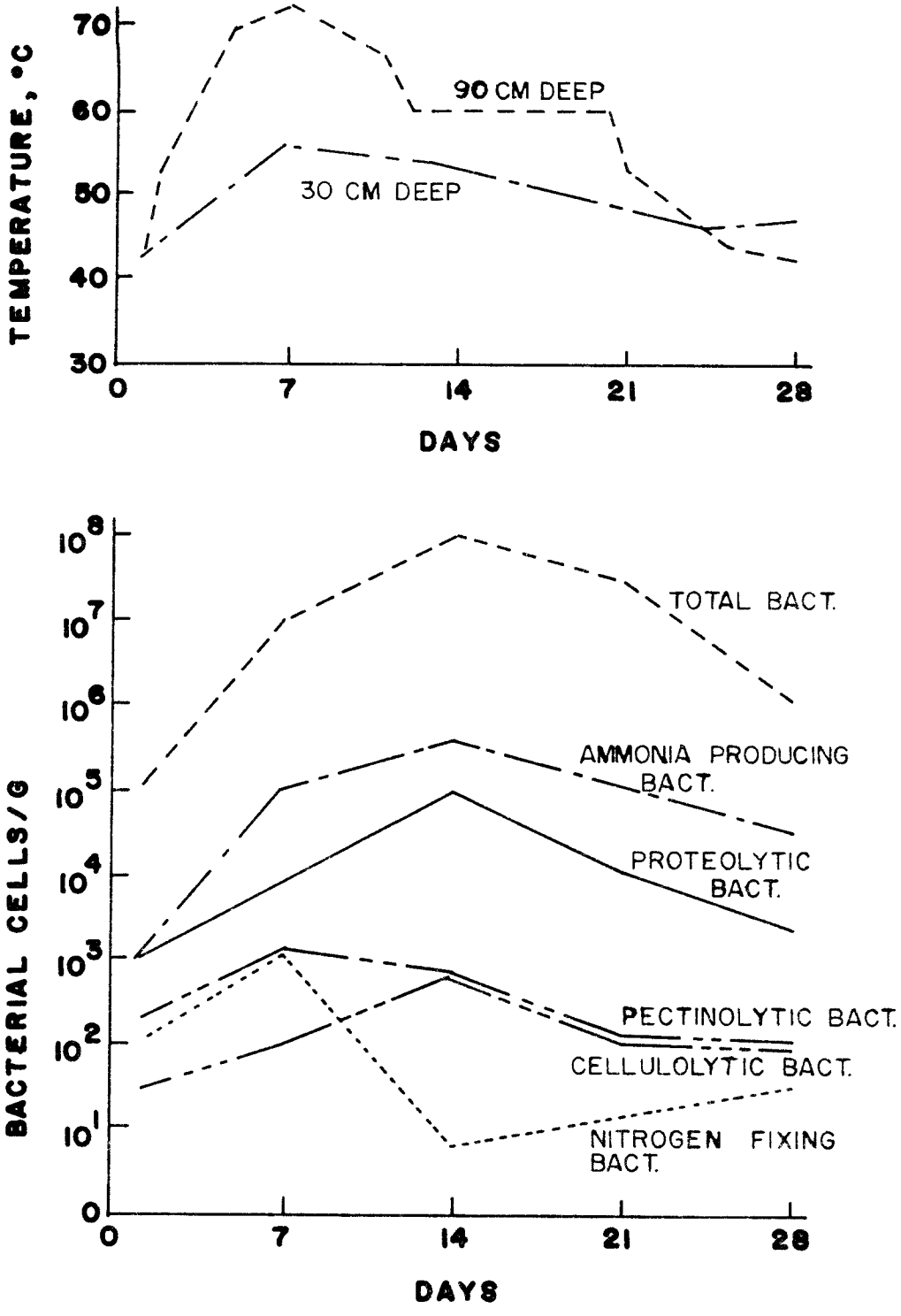


Figure 5
Development of the main bacterial populations
in a composting system (16).

Applying the finished compost product to the land as a soil amendment or for land reclamation makes good sense in that it fulfills two objectives. First, the problem of sludge handling and disposal for the community is solved. Second, a beneficial product is obtained which, if marketed, may not only help defer the cost of the sludge disposal, but may result in a net profit to the community. In any event, the idea of recycling the sludge back to the land through the compost process has been researched prominately of late and a brief review of the current literature will now be presented.

Goldstein (36), feels that composting should be practiced not merely for the sake of composting, but rather for the good it can do. The full realization of this good awaits the applications of the product to the land. The nutrients which are returned to the land include both the macro-and micro-nutrients. The macronutrients are nitrogen, phosphorus, and potassium (see Table 5). Among the micronutrients returned to the land are iron, magnesium, calcium, manganese, zinc and boron. Among the many benefits obtained when compost is applied to the land are: 1) conservation of some plant nutrients, 2) improvement of the soil, 3) transformation of an unsafe waste to a harmless and useful product, and 4) upgrading of despoiled land.

Parr, Epstein and Wilson (69) pointed out that sludges can be applied to land as liquids, partially dewatered materials, or as heat and/or air dried products. There are, however, a number of problems with land application that must be considered, including the presence of pathogens, odors, special equipment requirements, lack of public acceptance, runoff, high cost of land, excessive amounts of heavy metals and industrial organic chemicals. Composting of the sewage sludge may alleviate most of the potential problems mentioned here because it usually provides acceptable pathogen reduction and effective stabilization, and the final product is in a form which is easy to handle, transport and store.

Table 5

Plant Nutrients in Compost and Sludge (% dry weight) (12)

Material	pH	N	P	K	Ca	Mg
Durham, NH Compost	7.8	1.0	0.18	0.19	2.6	0.20
Durham, NH Sludge	6.8	3.1	0.34	0.09	1.4	0.10
Somersworth, NH Compost	7.5	1.1	0.35	0.19	3.0	0.20
Somersworth, NH Sludge	7.1	3.4	0.71	0.29	6.8	0.30
Rollingsford, NH Sludge	6.9	5.3	1.28	0.53	1.3	0.13
Millorganite	-	5.8	1.12	0.49	0.3	0.02

Most of the nitrogen in sewage sludge compost is in the organic form and must be mineralized to inorganic ammonium or nitrate before it becomes available for crops. Fifteen to twenty percent of the organic nitrogen will become available during the first cropping period following application according to Epstein (18). Sludge compost can be considered as a slow release nitrogen-fertilizer. The addition of sludge compost to soils is known to improve soil physical properties as evidenced by increased water content, increased water retention, enhanced aggregation, increased soil aeration, greater permeability, increased water infiltration, and decreased surface crusting.

Nitrogen loss in the end product is usually less than 10 percent according to Shell (86). Some nitrogen is usually lost as ammonia due to high pH values which may occur (> 8.3). Total nitrogen may be too high at the onset, which could favor ammonification and ammonia volatilization. Also, anaerobic pockets which are invariably present favor denitrification, thus driving off the nitrates.

Total nitrogen in sludge compost ranges from less than 0.1 percent to 17.6 percent, with a median of 3.3 percent. Ammonia generally ranges between 6 to 7 percent. Epstein (18) found that when applying compost to soil, irrespective of the rate of material applied, the percentage of added nitrogen mineralized remained essentially constant. Composting stabilizes the sludge to a great extent since little ammonia nitrogen is present beyond the first 7 to 10 days of incubation.

A significant part of the nitrate nitrogen can be recycled through organic compounds. Since appreciable quantities of nitrate are formed over long periods of time, it is probable that the mineralization-immobilization-denitrification transformations continue as long as the energy supply is sufficient. When the energy supply has been depleted, the recycling of nitrate nitrogen will be minimized.

Tester et al. (92,93), recently presented data on the decomposition of sewage sludge compost in soil. Because the transformations which occur in compost after it has been added to the soil are expected to be similar to the transformations which occur in the active composting process, (which was the area of interest for this study), a brief discussion of their studies will be presented.

Tester (92) reported on the decomposition of compost and compost amended soils and the mineralization of compost nitrogen with time. Compost was applied to a sandy and a loamy soil sample. The decomposition rate of readily available compost carbon appeared to be largely independent of the properties of the amended soils. Mineralization of compost nitrogen varied among the amended soils and laboratory sand. The laboratory sand-compost mixture exhibited a rapid decrease in ammonium nitrogen followed by a rapid increase in nitrate nitrogen, which is indicative of nitrification. Nitrate levels peaked by day 14 of the 60 day study, and then declined to very low levels. It was concluded that immobilization was primarily responsible for the nitrate decline. The C/N ratio of the compost was 17:1. Denitrification could have been a factor in the declining nitrate nitrogen levels, but care was taken to maintain the water regimes near 0.33 bar moisture percentage. This was considered optimum for nitrification.

In compost-amended loamy sand samples, initial ammonification was followed by nitrification resulting in approximately 6 percent of the compost nitrogen being mineralized to nitrates in 54 days.

Mixing the sewage sludge with the two soils resulted in increased water-holding capacities and pH's. Two major processes probably occur which govern the mineralization rates which occurred in the samples.

Phosphorus transformations were also studied (91). It was found that two processes are involved in phosphorus mineralization. One process is the chemosorption and precipitation reactions involving phosphorus in the soil and compost. The other process is the mineralization of organic phosphorus in the compost and soil. In strongly acidic to neutral systems, iron and aluminum minerals are predominantly involved in the adsorption reactions. In neutral to alkaline systems, calcium minerals are involved. When organic matter, such as compost, is applied to soils, mineralization of the organic phosphorus occurs and extractable levels may increase. Therefore, both mineralization and immobilization occur simultaneously, with the extractable phosphorus levels equaling the net or sum of both processes. Total phosphorous concentration in the compost added to soil in these studies was found to be 1.5 percent. Rapid phosphorus mineralization was observed in the compost-sand mixtures and appeared to be related to the high carbon dioxide evolution rates. The amount of extractable phosphorus was not linear with respect to the level of compost applied, thus precipitation reactions may be involved. Rapid net mineralization occurred, followed by immobilization.

To summarize the work by Tester, three fractions of compost were mixed with a loamy soil and a sandy soil at a rate of 89.6 metric tons/hectare and incubated at 25°C. Rates of mineralization and decomposition were determined by monitoring carbon dioxide and ammonia evolution and by measuring changes in the organic and inorganic fractions of carbon, nitrogen and phosphorus with time. The levels of ammonium nitrogen in all mixtures decreased during the incubation, with subsequent increases in nitrate nitrogen, indicating that nitrification was occuring. The quantity of compost mineralized was inversely related to the C/N ratio of the fractions. It was observed that soils with larger C/N ratios resulted in lower quantities of mineralized nitrogen. The

results presented here seem to indicate that removing the woody materials used for the bulking agent during composting of sewage sludge results in a lower C/N ratio and a higher nitrogen mineralization rate, and consequently, more value as a fertilizer.

Bhoyar et al. (3), conducted a study concerning the effect of temperature on mineralization of nitrogen during aerobic composting. Although the composting involved cotton dust and municipal refuse, it is felt that the results would have some similarities to sewage sludge composting. Laboratory studies on composting of cotton dust and refuse showed that maximum ammonification occurred in the temperature range of 60 to 70°C, and maximum nitrification occurred in the range of 30 to 50°C. At temperatures of 60 to 70°C, the rate of nitrification was low. These are essentially identical to the conclusions presented by De Bertoli et al. (16) for nitrification during wastewater sludge composting.

During aerobic composting, it is known that one-third of the carbon utilized by organisms combines with nitrogen in the living cells, while the remaining two-thirds is respired as carbon dioxide. Living organisms normally utilize 30 parts of carbon for every part of nitrogen. As the cells die and decay, the released nitrogen is utilized by other organisms, along with carbon, to produce cell protoplasm. Thus, the nitrogen gets successfully recycled while the carbon content goes on being reduced.

CHAPTER 5

EXPERIMENTAL METHODS

The research on pathogen survival during forced aeration, static pile composting of wastewater sludges was carried out in several stages. In addition, a detailed study of the fate of nutrients during composting was also conducted. The procedures used to carry out these studies are described below. More detailed descriptions of this research may be found elsewhere (26,34,105).

Full-Scale Composting of Primary Sludge

The compost piles monitored in this portion of the study were located at the pilot-scale forced aeration facility on Beech Hill, adjacent to Route 4 in Durham, New Hampshire. At that time (1979-1981) the town of Durham was composting only raw primary wastewater sludge while they awaited completion of their new secondary wastewater treatment plant.

Vacuum filtered raw primary sludge was trucked to the site, mixed with woodchips at a 3:1 woodchip:sludge ratio using a front end loader, and formed into a pile on top of a woodchip layer laid on the bare soil at the site. A top layer of woodchips (2.0 to 2.5 cm thick) was used as an insulating blanket. The resulting piles were approximately 18.3 meters (60 feet) long, 4.5 meters (15 feet) wide, and 30 meters (10 feet) high (see Figure 6). During composting, suction was applied to the pile for 10 to 14 days, after which the fan was reversed and air was blown into the pile for 7 to 12 days. The piles were then allowed to cure for 4 weeks before screening.

Samples and data were collected regularly from four sites within the compost piles during complete composting periods, ie., active composting for approximately three weeks and subsequent curing for approximately four weeks.

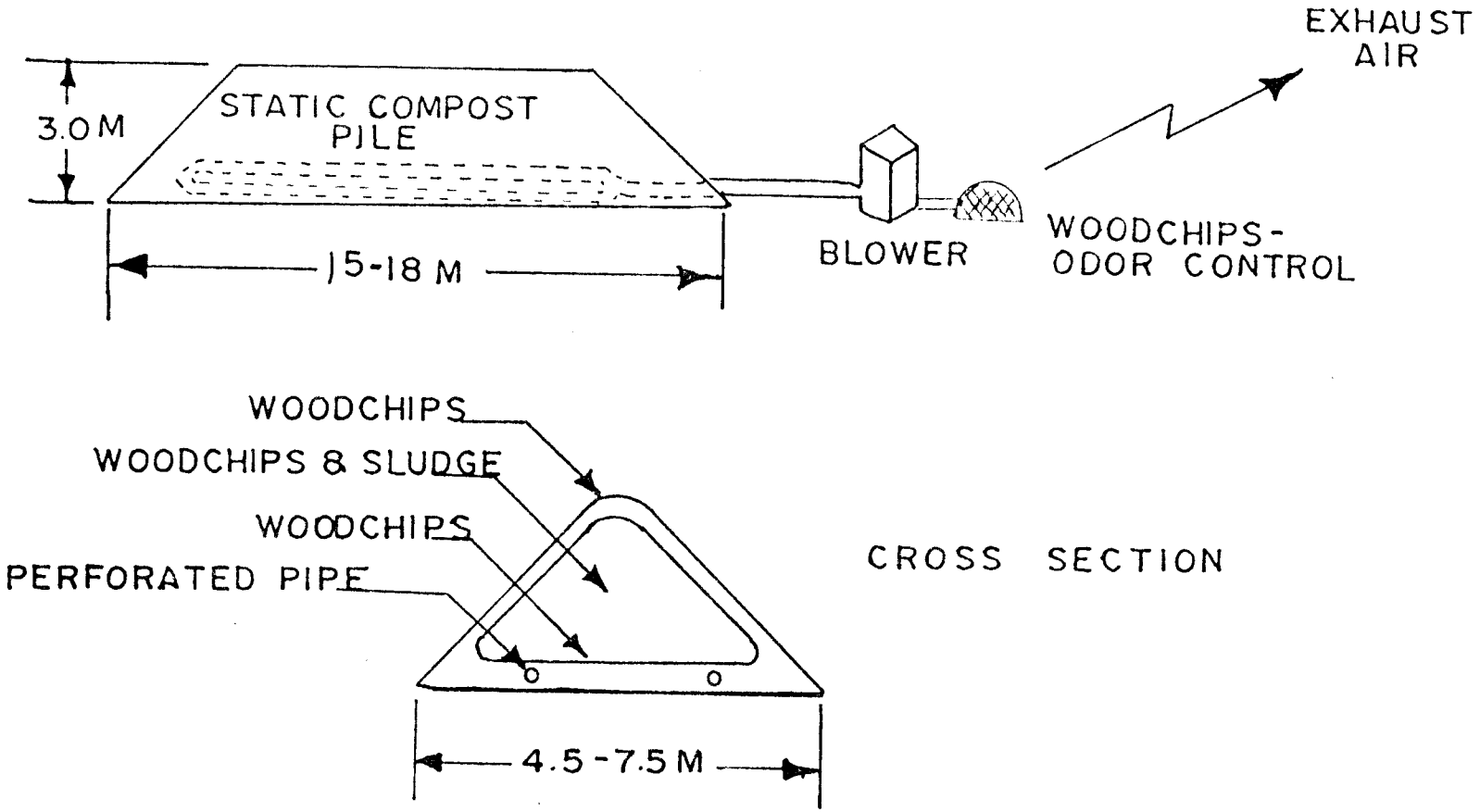


Figure 6
Typical static compost pile with forced aeration.

Figure 7 indicates the relative positions of the four sites chosen for monitoring. Sites 1 and 2 were located on either end of the pile. Samples from these sites were extracted from the outer edges of the pile. Sites 3 and 4 were located at one half the total length of the pile. These samples were extracted from the interior of the pile. The compost samples removed from sites 1 and 2 were extracted with a flame-sterilized garden spade, while a 1.2 meter (46 inch) soil auger was used to extract samples from sites 3 and 4. Site 3 was located 0.5 to 0.6 meters (1.5 to 2.0 feet) within the pile entering with the auger positioned 1.2 meters (4.0 feet) above and parallel to the base. Samples from site 4 were removed 0.8 to 0.9 meters (2.5 to 3.0 feet) within the pile entering with the auger positioned perpendicular to the base on top of the pile. The tools utilized in removing the samples were either swabbed with 95 percent ethanol and ignited, or flamed with a propane torch to minimize contamination between sample sites.

Once extracted, the samples were screened on a sterilized 6.35 mm (0.25 in) mesh screen and placed in pre-sterilized Whirlpack bags for transport. The screening effectively removed larger woodchips, rocks and twigs. The remaining compost material was similar in particle size to the material screened on a 19 mm (0.75 in) mesh screen at the end of the full-scale composting process. The time between sampling and processing of the samples never exceeded one hour and therefore no sample preservation was necessary.

The temperature of the compost mass at each of the four sites was measured at the time of sampling. A YSI #403 Thermistor Probe enclosed within a 2.4 m (8.0 ft) long pointed metal tube and a YSI Telethermometer, Model 42SC were used to measure this variable. The compost sample for biological and chemical analyses was removed before the probe was inserted into the pile in a location adjacent to the point of sample extraction.

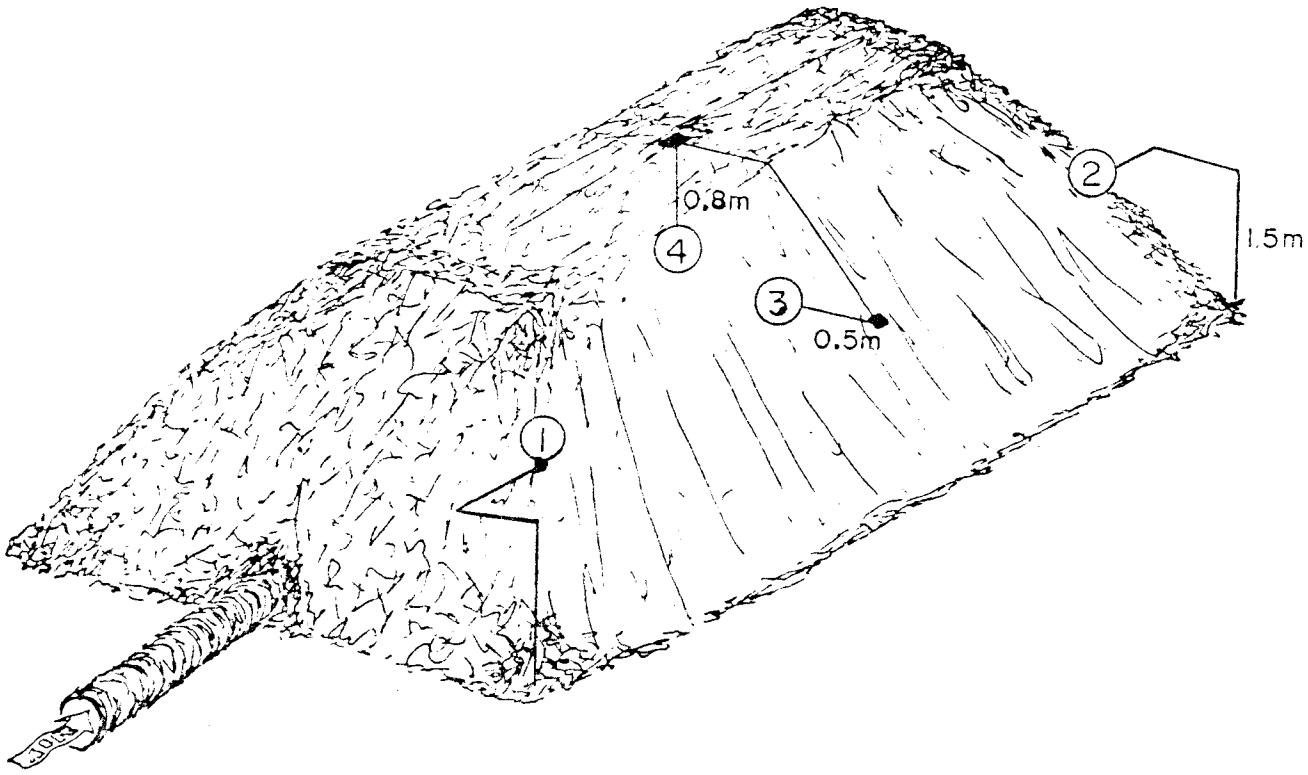


Figure 7
Position of sampling sites within the compost pile.

Extracting of the samples and measurement of the temperature completed the activities performed at the compost pile. The analyses performed at the laboratory included: 1) physical and chemical parameters and 2) microbiological parameters. In the first category pH, moisture content and the carbon: hydrogen:nitrogen ratio were measured. The second category included the detection and enumeration of fecal coliform, fecal streptococcus, Salmonella, Shigella, and Aspergillus fumigatus and analysis for the presence of aerobic and anaerobic thermophiles. Analytical procedures used will be described later.

Full-Scale Composting of Primary/Secondary Sludge

This research was conducted utilizing the automated composting facilities constructed at the Durham, NH, wastewater treatment plant. This facility is described in detail in Chapter 3 of this report. The composting sludge consisted of approximately 50 percent primary and 50 percent secondary sludge which had been dewatered to approximately 20 percent solids on a vacuum filter. The piles were aerated in the suction mode for 5 minutes per half hour for the first two weeks, and by blowing for the final 7 to 10 days of active composting.

Samples were obtained throughout the complete composting cycles of several compost piles. Shallow samples were extracted from a site about 1-1.5 feet into the pile, while deep samples were obtained about 3-4 feet into the pile.

The compost samples removed from the shallow site were extracted using a flame-sterilized garden trowel. The deep sample was extracted using a flame-sterilized shovel to obtain the sample and a sterile garden trowel to place the sample into a sterile plastic Whirl-pac bag for transport back to the laboratory.

These samples were analyzed for moisture content; volatile solids content; pH; C:N ratio; concentrations of organic nitrogen, ammonia nitrogen, nitrate nitrogen, and orthophosphate; total and fecal coliform counts; total and fecal streptococcal counts; Salmonella and Aspergillus fumigatus. In addition, temperature and oxygen content in the piles was monitored at the time of sampling, as described previously.

Pilot-Scale Composting of Primary/Secondary Sludge

In order to more closely control environmental conditions within the composting mass, several smaller compost piles were constructed at the plant to predetermined specifications especially for this research.

Two environmental parameters (aeration rate and sludge:woodchip ratio) were alternately varied in order to ascertain their individual effect, if any, on pathogen destruction and the mineral transformations which occur during composting. Each experiment was run in replicate.

The first experimental parameter investigated was aeration method. Three experimental piles were constructed on the concrete pad of the compost facility. The piles were approximately 1/10 the size of the larger plant piles, cone shaped with a base diameter of approximately 6 feet (1.8 m) and a height of approximately 5 feet (1.5 m). The piles consisted of four front end loader buckets-full of sludge-woodchip mix and two buckets-full of cover layer. Finished, cured compost was used for the cover layer.

The first two piles were aerated off of one blower in a manner similar to the plant full-scale piles. The same aeration rate of 400 scfm (0.19 m^3/s) for 5 minutes per half hour was used for both piles. These were essentially control piles in that they mimicked the plant piles in everything but size. The third pile was non-aerated or "anaerobic".

The second aeration experimental run was similar to the first in size and placement of the piles. However, the first pile was connected to two adjacent blowers and received twice the air (800 scfm or 0.38 m^3/s) that the control pile received (400 scfm or 0.19 m^3/s). The second pile was the control pile and received air from one blower only. The third pile was non-aerated. The blowers were operated at 400 scfm for 5 minutes per half hour. All other conditions of the piles were held constant. All piles had a woodchip:sludge ratio of 3:1, and initial moisture content in all piles was approximately 60 percent.

The second experimental parameter investigated was woodchip:sludge ratio. Three small scale piles were again set up as described previously. All piles were aerated in the same manner, each with one loop fed from the same blower. Aeration rates were the same for all piles (400 scfm with the blower operating 5 min/½ hour).

Woodchip:sludge ratios were varied by the operator as the components entered the pugmill. The first pile consisted of a 3:1 ratio of woodchips: sludge. The second pile was 2:1, and the third pile was 1:1. Each pile consisted of 4 buckets-full of woodchip-sludge mix from the front end loader and two buckets-full of cured compost for the cover layer. The void ratio of the 3:1 pile was calculated to be 62 percent void space by volume, the 2:1 pile was 40 percent void space, and the 1:1 pile was 30 percent void space. The void space was measured by water displacement of air in a known "undisturbed" volume of compost sample. Two identical runs as described above were conducted.

Samples were extracted from all experimental piles in the same manner. Samples were taken on day 1, and then approximately one week apart for four consecutive weeks. One sample was taken from each pile per sampling day. The samples were extracted from the center side of the pile approximately 2.5 feet

(0.8 m) into the pile. A shovel was used to extract the sample and a sterile flamed garden trowel was used to transfer the sample to sterile plastic Whirl-pac bags for transport to the laboratory. All samples were analyzed immediately upon arrival at the laboratory, or were kept under refrigeration between tests.

Three sets of parameters were routinely monitored. These included physical, chemical, and biological measurements. Physical parameters measured were temperature, oxygen content, moisture content, and volatile solids content. Chemical parameters measured were pH, C:N ratio, organic-nitrogen concentration, ammonia-nitrogen concentration, nitrate-nitrogen concentration, and ortho-phosphate concentration. The biological measurements were total and fecal coliform bacterial counts.

Analytical Procedures

Physical and Chemical Parameters

The temperature of the compost mass was measured approximately daily. A YSI #403 Thermister Probe enclosed within an 8.0 foot (2.4 m) long pointed metal tube and a YSI Telethermometer Model 42 S C were used to measure temperature. The probe was inserted from the top of the pile straight down approximately 4 feet (1.2 m) and allowed to equilibrate for 5 minutes before the temperature was read.

The oxygen content of the compost pile was measured at the time of weekly sampling with an IBC #210-002 oxygen sensor encased in a 10 foot (3.1 m) metal lead tube with open holes around the tip. This sensor was attached to an IBC single sensor oxygen meter. A Dynapump Model 12 portable vacuum pump was used

to draw a vacuum to pull air from the pile past the sensing unit. The probe was inserted into the center side of each pile and the vacuum pump turned on. Once the reading was stabilized, the measurement was recorded.

The moisture content of the compost material was measured by drying a known amount of sample at 103°C to a constant weight; this took approximately 3 days. The change in weight of the material was used to calculate the percent moisture.

The volatile solids content of the compost was measured by igniting a known amount of dried sample at 550°C for 30 minutes. The change in weight of the material was used to calculate percent volatile solids.

To determine the pH of the material, 10 grams of sample were suspended in 60 ml of Nanopure water. The pH was measured while the compost/water suspension was stirred on a magnetic stirrer. A one-to-one dilution is generally used to measure the pH of soil solutions. To correct for the discrepancy in the one-to-six dilution used in these analyses, a 10 gram sample of compost was suspended in 10 ml of laboratory pure water and the pH was recorded. Further water was added to adjust the dilution to the original one-to-six ratio and again the pH was recorded. A correction factor was determined from repeated trials of this exercise and used to adjust the original pH values.

The carbon:hydrogen:nitrogen (CNH) ratio was measured with a Hewlett-Packard F and M CHN Analyzer, Model 185. Samples from the initial and final stages of the composting process were analyzed to determine the overall change in the carbon:nitrogen (C:N) ratio. Sample residues from the moisture analysis test were used here. Prior to analysis, the samples were ground to a fine power with a mortar and pestle. Theoretical C:N ratios in the compost were calculated based on the percent carbon and nitrogen present from the CHN analysis.

Nitrate nitrogen concentration changes over time were determined by weekly analysis of nitrate nitrogen in the compost samples. The Brucine-Sulfanilic Acid colorimetric method as described in Standard Methods (1) was used for nitrate nitrogen analysis. One gram of compost was brought up to 100 ml with Nanopure water. The solution was stirred for 5 - 10 minutes to ensure solubilization of nitrates present in the sample and then 10 ml of the supernatent was transferred to a large test tube. Samples were run in duplicate. The test tubes were placed in a cool water bath and 2 ml sodium chloride solution was added. The tubes were mixed by hand and then 10 ml sulfuric acid solution was added. Again the tubes were mixed by hand and allowed to cool. 0.5 ml brucine-sulfanilic acid reagent was then added to each tube, the tubes were mixed by hand and incubated in a hot water bath (approximately 95°C) for 20 minutes. After the tubes were cooled, they were read at 410 nm on a spectrophotometer. Blanks and standards were read and the concentration of nitrate nitrogen was determined from the standard curve. Calculations were made to correct for dilutions made and for dry weight. Nitraten nitrogen was reported in ppm NO_3-N (dry weight basis).

Ammonia nitrogen was also measured weekly. The ammonia nitrogen concentration of the compost sample was determined using the ammonia distillation as in Standard Methods (1). Ten grams of compost sample were added to 100 ml Nanopure water in a Kjeldahl flask and then an additional 200 ml water was added for a final volume of approximately 300 ml. 25 ml of borate buffer was added and then the sample was distilled into 50 ml of indicating boric acid solution. 200 ml of distillate was collected and subsequently titrated with 0.02 N sulfuric acid. The appropriate calculation was done, and dilution and dry weight corrections were made. Ammonia nitrogen was reported as ppm NH_4-N (dry weight basis).

Organic nitrogen concentrations were also measured weekly. The total Kjeldahl nitrogen method as in Standard Methods (1), was employed to determine organic nitrogen. One gram of sample and 300 ml Nanopure water were added to a Kjeldahl distillation flask, together with 50 ml digestion reagent. The sample was then heated and digested as directed in Standard Methods. Subsequently, 50 ml sodium hydroxide-sodium thiosulfate reagent was added and the sample distilled into 50 ml boric acid indicating solution, collecting 200 ml distillate. This was subsequently titrated with 0.02 N sulfuric acid and calculations were made as above. Organic nitrogen was taken as the difference between total Kjeldahl nitrogen and ammonia nitrogen. Organic nitrogen was reported as ppm organic nitrogen (dry weight basis).

Orthophosphate concentration determinations were made on the first and last sampling day of the run, in an effort to assess the change in orthophosphate which was occurring during the composting period. The compost was digested using the presulfate digestion method prior to analysis to release the bound orthophosphate (1). 0.1 grams of compost was digested and then filtered. The filtrate volume was then brought up to 50 ml with Nanopure water and analyzed by the Ascorbic Acid method as in Standard Methods. Eight ml of the combined reagent was added to each sample, blank and standard, and each was incubated in the dark for 20 minutes. Color development was read at 880 nm on the spectrophotometer. A standard curve was made and sample concentrations determined from the curve. Calculations for dilution and dry weight corrections were made. The concentration of orthophosphate was reported as ppm phosphate (dry weight basis). All samples were run in duplicate.

Microbiological Parameters

The Most Probable Number (MPN) procedure was used to detect and enumerate fecal coliforms and fecal streptococci (1,4). The MPN procedure was modified by bringing a 50-g sample of compost up to approximately 100 ml with buffered dilution water (see Table 6) to yield an approximate one-to-one (w/v) dilution. From this suspension, successive dilutions were made from 10^{-1} through 10^{-8} in quadruplicate.

Sterile Lauryl Sulfate or Lauryl Tryptose Broth (Difco) with Durham tubes was inoculated in triplicate with 10, 1, and 0.1 ml from each dilution. The media inoculated with 10 ml were prepared double strength to allow for the dilution factor of the sample. After 48 h, those tubes showing growth with gas collected in the Durham tubes were presumed to have coliforms present. These results were used to calculate total coliforms from a standard MPN table. The positive tubes were subcultured into EC Broth (Difco), with Durham tubes to confirm the presence of fecal coliforms. The EC tubes were incubated for 24 h in a water bath at 44.5°C. Those tubes showing growth and gas at the end of the incubation period were used to calculate the fecal coliform count from the MPN table. Both total and fecal coliforms were expressed as MPN/g of sample, wet weight.

Analysis for streptococci was carried out in a similar fashion. The initial dilutions were prepared identically to those used for coliform counts. Presumptive tests were carried out in Azide Dextrose Broth (Difco) for 48 h. Those tubes showing growth at this point were presumed to have streptococci present, and streaked onto KF Streptococcal Agar (Difco) and incubated for 48-96 h. Transfers showing bright red colonies were confirmed fecal streptococci. Both total and fecal streptococci were determined using a standard MPN table and expressed as MPN/g of sample, wet weight.

Table 6

Formulation for Buffered Dilution Water

Stock solution:	
KH_2PO_4	34.0 g
Distilled water	500.0 ml

Adjust pH to 7.2 with 1N NaOH, and dilute to 1 liter with distilled water.

Working solution:

1.25 ml stock solution/1 liter distilled water.

Aspergillus fumigatus was detected and enumerated using a modification of the procedure prescribed by Millner et al. (64) by suspending 25 g of sample in 125 ml of sterile 0.01% Tween 80. Dilutions through 10^{-4} were prepared from this mixture in 9.0 ml of sterile 0.01% Tween 80. Littman Oxgall Agar (Difco: 50 mg/l streptomycin, 10 mg/l penicillin) were inoculated in duplicate with 0.1 ml from the 10^{-2} through 10^{-4} dilutions. The inocula were spread with a bent glass rod and the plates were incubated for 72 h at 44°C. Any samples expected to show very low concentrations of A. fumigatus were plated directly from the initial 1:6 dilution or from the subsequent 10^{-1} dilution.

Aspergillus-like colonies were counted, then confirmed as A. fumigatus by pressing a piece of clear Scotch tape to the colony and sticking the tape to a microscope slide. The picked colony was examined under low power for typical A. fumigatus morphology according to the descriptions of Raper and Fennell (73).

Minimum number of salmonellae present was estimated by the method of Pevear (unpublished data) (see Figure 8). Three 1000-ml volumes of Brillant Green Milk (BGM; see Table 7) per sample were prepared. The three flasks were inoculated with 100, 10 and 1 g of sample and incubated for 18-24 h. A 100-ml aliquot was removed from one flask before adding the 100 g sample to more closely approximate a 10^{-1} dilution. The flasks inoculated with 100 and 10 g were shaken at 100 RPM during incubation since microbial growth and activity would cause the formation of a solid curd if the flasks were not kept in motion. This was not a problem with the 1 g sample. Controls included 100 ml of BGM inoculated directly with S. heidelberg, and an uninoculated volume of BGM. After 24 h, 1 ml from each flask was added to 9 ml Tetrathionate Broth Base (Difco) with 2% iodine solution. After 24 h, each tube was streaked onto XLD Agar (Difco) which was then incubated for 24-48 h. At the end of the

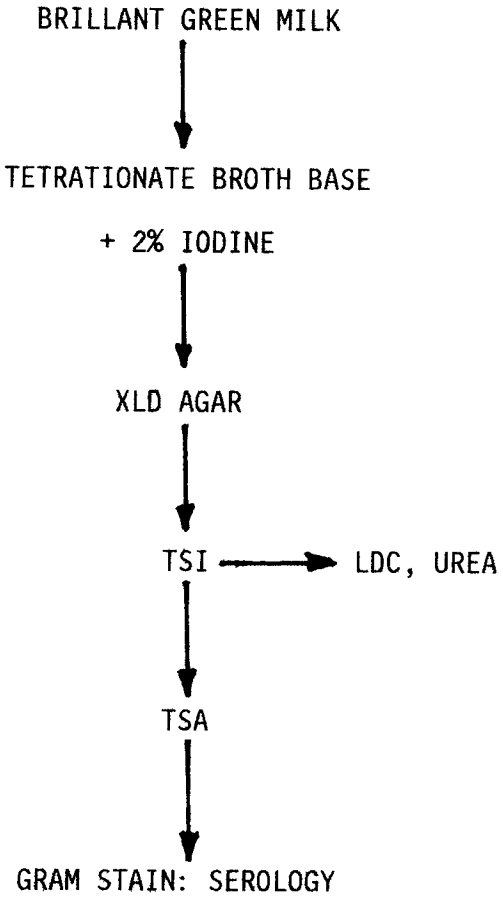


Figure 8. Flow chart of testing procedure for presence of salmonellae.

Table 7

Formulation for Brillant Green Milk (BGM)

non-fat dry milk	100 g
distilled water	1000 ml

Stir to dissolve. Autoclave 10 minutes. Cool to room temperature. Add 2 ml 1% brillant green/1000 ml.

incubation, typical S. heidelberg colonies were subcultured onto Triple Sugar Iron Agar slants (TSI; Difco) for 18-24 h. At this point, Proteus mirabilis (ATCC 9240) was added to the testing procedure as a negative control. Those isolates showing typical salmonellae reaction on TSI were transferred to Lysine Decarboxylase Broth (LDC; Difco) and Urea Agar slants (Difco) and incubated for 24 h. Those isolates showing LDC and urease patterns identical to S. heidelberg were presumed to be salmonellae and were stored on TSI slants prior to confirmation by serological testing.

Serological testing consisted of first streaking out the isolate from the TSI storage slant onto Trypticase Soy Agar (TSA) to confirm purity. The isolates were Gram stained, then tested by rapid slide agglutination with Salmonella Polyvalent-O Antiserum (Difso) and Salmonella H Antisera (Spicer-Edwards Set; Difco).

Salmonella Survival in Compost

Salmonella counts in the compost were monitored throughout the research. In addition, separate studies were performed to determine recovery limits from the compost and from compost woodchips, to assess the survival of salmonellae during the six-month holding period recommended by many regulatory authorities before use, and to determine the survival rate after incorporation of compost into soil.

Recovery Limits from Compost

Studies were performed to determine the lower limits of detection of Salmonella in compost. Compost samples were taken from active piles at a one foot depth by use of a flame sterilized garden trowel.

Aliquots of 5.0 g, 25.0 g and 50.0 g of the compost samples were weighed out and added to 50.0 ml, 250.0 ml and 500 ml of rehydrated, non-fat milk, respectively, to pre-enrich the samples. A control flask with approximately 1.0×10^9 S. heidelberg organisms in 50.0 g of compost was also passed through the process. Aqueous crystal violet was added to each milk sample (16 ml per ℓ of milk), and then the pre-enrichment cultures were incubated at 35°C for 25 ± 2 hrs.

A thick, matted curd usually formed at the milk's surface. This was blended back into the sample using a blender and a sterile knife to cut the mat. Enrichment cultures were then prepared by adding 1.0 ml aliquots of each pre-enrichment broth in duplicate to 9.0 ml dulcitol selenite broth tubes and tetrathionate broth tubes. These tubes were incubated at 35°C for 24 hrs.

Isolation was done by streaking a 3 mm loopful of each enrichment broth onto xylose lysine deoxycholate agar and brillant green agar plates in duplicate. These plates were also incubated for 24 hrs at 35°C. Biochemical testing of typical Salmonella colonies was performed using:

a) Triple sugar iron slants

b) Urea agar slants

c) Lysine decarboxylase broth

d) Tryptophane broth

e) Malonate broth

f) Phenylalanine deaminase broth

g) Phenol red ducitol broth

The minimum detectable detection limits for Salmonella heidelberg in curing compost was determined by developing a seed culture in trypticase soy broth, enumerating the concentrations of S. heidelberg present, preparing dilutions containing 10^5 through 10^1 organisms per ml, adding 1.0 ml of each

dilution to 50.0 g of compost, incubating for 1.0 hr. at room temperature, and identifying and enumerating S. heidelberg present as described previously.

Recovery of Salmonella from Seeded Compost Wood Chips

An experiment was performed to determine how long S. heidelberg could survive on compost woodchips placed in either a relatively nutrient-rich greenhouse soil environment (C:N = 59:1) or a nutrient-poor clay soil environment (C:N = 11:1). To do this, compost chips were seeded with S. heidelberg at a concentration of approximately 10^6 organisms per 100 g of chips. The chips were then mixed with a "good" soil and a "poor" at a ratio of 1:4 (chips:soil). The samples were layered in containers with a soil base overlain by a layer of chip/soil mix. Samples of each were taken over a 25 day period from containers incubated at room temperature and watered once weekly. The samples were inoculated into tetrathionate broth, incubated at 35°C for 24 hr, plated onto xylose lysine deoxycholate agar and again incubated for 24 hr at 35°C.

Survival of Salmonella in Compost During the Holding Period

Field studies were designed primarily to assess the survival of salmonellae during the six-month holding period recommended by the New Hampshire State Water Supply and Pollution Control Commission (34). The field site was a holding bin at the Durham wastewater treatment plant. Nine 30-gallon trash bags holding either 3 kg of freshly screened compost or 1.5 kg of freshly screened compost and 1.5 kg of garden soil were inoculated with either approximately 10^4 cfu Salmonella heidelberg per g of sample, or left uninoculated as

controls. An uninoculated bag with 3 kg of soil alone was also included as a control. Each sample bag was inserted into another bag and partially buried in a pile of freshly screened compost. Bags were left open to maintain aerobic conditions. The interbag space was filled with Iodophore disinfectant (Agway) to prevent environmental contamination in the event of a leak from the sample bag (Figure 8).

At the time of seeding, and then at 24 h, 1 week, 3 weeks, and then monthly through 6 months, samples of approximately 200 grams were taken with a flamed trowel and carried to the laboratory in sterile plastic Whirl-Pak bags. Samples were processed immediately and kept under refrigeration between tests. For the final sample, the bags were retrieved from the pile and brought back to the laboratory intact. A sample was also take each time from the pile to run as an additional control.

At the final testing, two field samples were "fed" by saturating them with a 10% glucose solution, then incubated overnight prior to testing in an effort to assess regrowth potential.

Depending upon the sample, analyses were run for salmonellae, fecal coliforms, fecal streptococci, Aspergillus fumigatus, pH, and percent moisture.

Effect of Soil on Salmonella Survival

Bench scale studies were designed primarily to determine in what way, if any, the amount of soil combined with the finished compost affects the survival of salmonellae. Simultaneously, the relationship of soil quality and temperature to the compost/soil ratio was determined.

Compost and soil were mixed in ratios of 9:1, 8:2, 7:3, 6:4, and 5:5 compost to soil by weight and seeded with approximately 10^4 cfu S. heidelberg/g

mixture. The soil was either nonsterilized nutrient-rich greenhouse soil (C:N = 59:1) or a nutrient-poor clay soil (C:N = 11:1). The mixtures were incubated at either 10°C, or room temperature. A seeded sample of finished compost without soil was included in each study.

Tests for salmonella, pH, and percent moisture were done at the time of seeding, 48 h, 7, 14, 21, and 28 days, except where otherwise indicated. Most Probable Number (MPN) assays for fecal coliforms and fecal streptococci were done at the first and last sampling.

Comparison of Fecal Indicators in Compost with Levels in the Community

Because of the lack of guidelines indicating what level of pathogens in compost is harmful, a study was performed in which food samples were collected from local markets and food vendors and analyzed for pathogens. These samples were analyzed for fecal coliforms, fecal streptococci, salmonella, shigella, and for the presence of aerobic and anaerobic thermophiles, and the results compared with those for fresh sludge, fresh woodchips, recycled woodchips, compost during various stages of the composting period, sifted compost and compost-amended soil.

Compost Parasite Enumeration

A research program was carried out to assess the effectiveness of microscopal methods for detecting Giardia and Ascaris in compost.

Giardia and Ascaris stool samples from active cases of giardiasis and ascariasis were obtained from the NH Department of Health, and their contents of cysts and eggs determined by quantitative microscopy. These known samples

were then used to seed compost and the detection limits of the microscope technique, with and without supplementary flotation separatory techniques, were established.

Enumeration of Anaerobic Bacteria in Compost

A new and innovative technique was developed for quantitating the numbers and kinds of anaerobic bacteria present in composting materials. The procedure consisted of digging three feet into a compost pile and centering a three foot diameter metal pipe into the hole, after which the compost floor at the bottom of the pipe is seared with a propane torch. The pipe is then continuously flushed with CO_2. An auger is used to bore a foot deeper through the seared layer and the auger's contents are transferred under the CO_2 shield into a sealed glass container, which is returned to the laboratory and analyzed in an anaerobic chamber. The methodology was checked by opening containers of a sensitive oxidation-reduction dye indicator, resuzurin, in the area of sampling operations and observing for changes indicating oxidizing conditions.

CHAPTER 6

RESULTS

Physical-Chemical Operating Data

Primary Sludge Composting

Both primary and combined primary/second wastewater sludges were composted during the course of this research. Primary sludge compost piles were monitored for temperature, pH, moisture content and C:N ratio. The piles were sampled throughout the composting cycle from both shallow (1-1.5 ft deep) and deep (3-4 ft deep) sites. A summary of the results of this sampling is shown in Table 8. The temperature data is plotted in Figures 9 through 11.

As can be seen, temperatures in the deep samples were in the thermophilic range throughout, and were about 20°C higher than in the shallow samples which were normally only in the mesophilic range. It is also apparent that ambient air temperature had little or no effect on temperatures in the middle of the compost pile.

Primary/Secondary Sludge Composting

During monitoring of the full-scale primary/secondary compost piles, much more detailed analyses were performed. The results were virtually identical to the findings for primary sludge composting, although the mixed piles took longer to reach their thermophilic peak. Tables 9 and 10 present the analytical results obtained on samples taken from two separate compost piles. Figure 12 is a plot of internal temperatures for one of these piles.

Temperature in the shallow samples peaked around day 10 at 35-40°C, and in the deep samples at 70-80°C. Bacterial pathogen indicators showed a marked

Table 8

Physical and Chemical Data from Composting of Primary Sludge

Day	Ambient Temperature (°C)	Shallow Samples Temperature (°C)	Shallow Samples Moisture (%)	Shallow Samples pH	Deep Samples Temperature (°C)	Deep Samples Moisture (%)	Deep Samples pH
1	22	52.5	42.8	8.2	76.5	43.1	8.2
5	22	61.2	37.0	7.9	76.0	31.2	8.0
9	26	55.2	38.8	7.8	71.0	35.4	8.0
13	24	50.2	33.0	7.5	66.1	37.6	7.8
19	23	66.2	35.7	7.9	75.5	36.0	8.1
22	21	50.0	32.4	8.2	71.6	39.5	8.3
26	16	48.7	41.6	8.0	64.7	42.3	7.9
30	13	51.8	41.8	8.1	65.8	38.7	8.1
34	17	52.0	43.4	8.1	65.2	33.2	8.2
37	20	53.7	40.2	7.7	66.9	40.3	7.8
50	20	57.4	41.6	7.6	71.5	41.7	7.7
			Pile II				
1	16	62.7	38.7	8.2	73.7	44.5	8.3
4	15	50.0	39.4	8.4	72.0	45.1	8.6
7	9	53.3	35.9	8.5	75.3	43.8	8.7
10	2	42.0	37.1	8.4	64.0	45.1	8.5
13	3	41.5	41.8	8.6	68.0	46.7	8.5
16	5	44.8	41.4	8.3	68.2	50.0	8.6
19	12	45.7	37.0	8.6	66.2	41.0	8.9
22	18	43.0	37.8	8.0	55.2	39.8	8.3
28	6	39.8	40.4	8.3	53.0	46.2	8.3
31	5	39.0	37.2	8.6	56.3	45.8	8.4
37	6	38.0	40.0	8.2	67.7	51.5	8.2
			Pile III				
0		51			84		
7		56			83		
14		51			87		
21		66			84		
28		47			85		

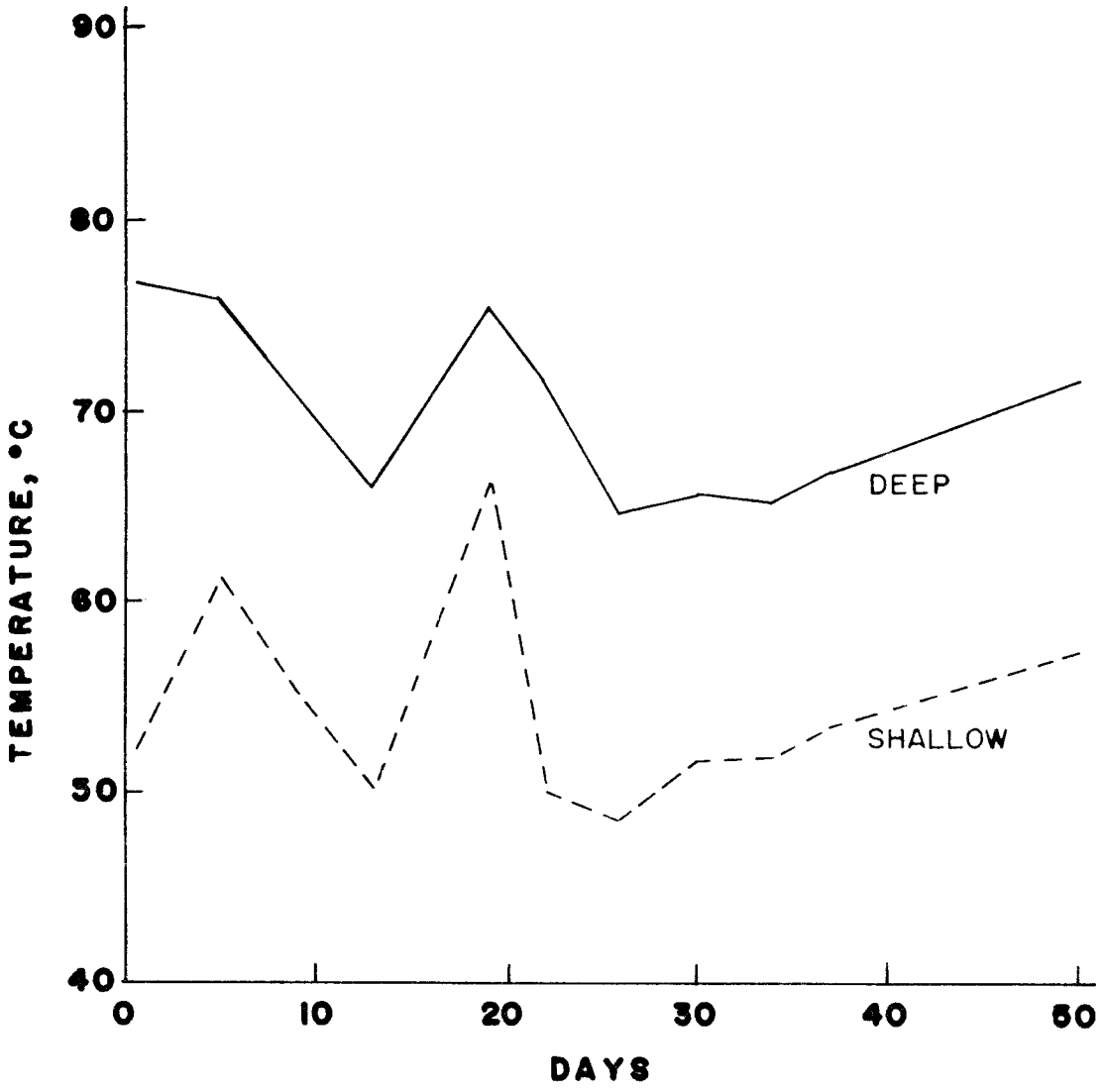


Figure 9
Temperatures recorded during composting of primary sludge-Pile I.

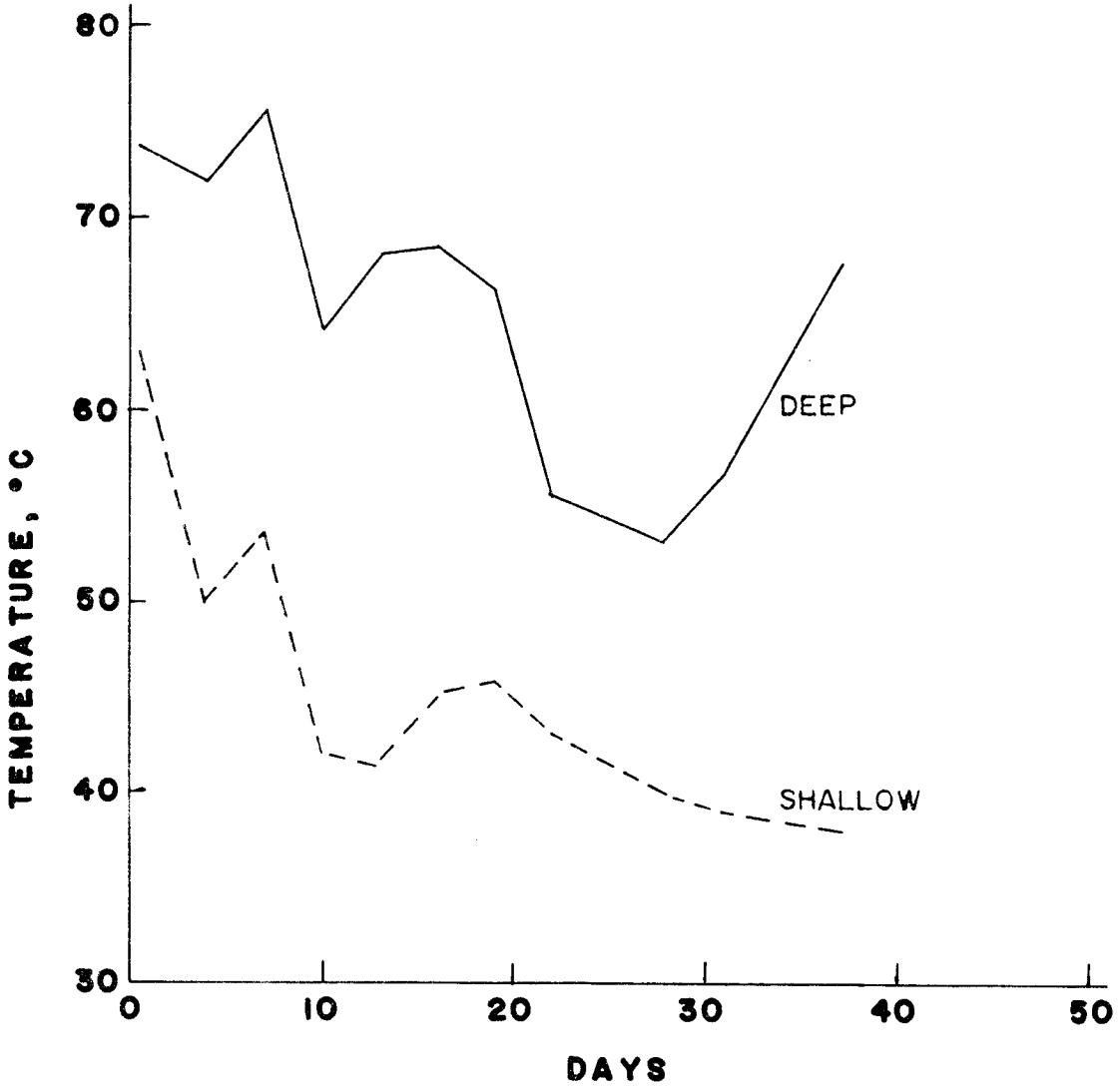


Figure 10
Temperatures recorded during composting of primary sludge-Pile II.

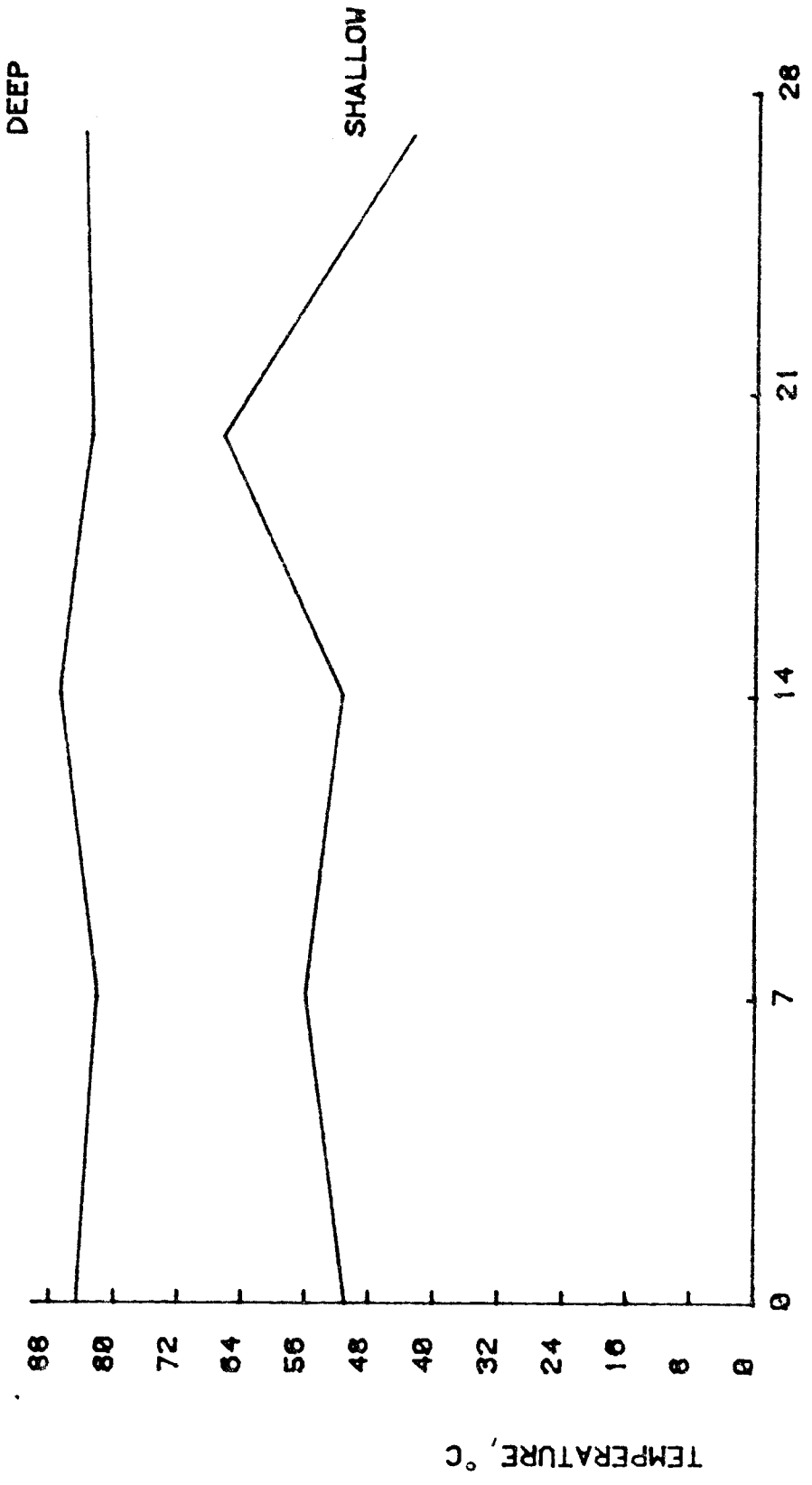


Figure 11
Temperatures recorded during composting of primary sludge-Pile III.

Table 9

Physical and Chemical Data from Composting of Primary/Secondary Sludge - Pile #1

Parameter	Shallow Sample Day		Deep Sample Day	
	0	28	0	28
pH	6.51	7.33	6.88	8.36
Temperature °C	26	22	26	51
Moisture, %	53	55	63	54
Carbon, %	23.66	25.89	32.48	24.66
Hydrogen, %	2.2	1.37	2.67	1.12
Nitrogen, %	1.91	1.73	1.64	1.45
Volatile Solids, %	53	49	40	44
Total N (ppm)	89	87	1635	1102
Organic-N (ppm)	5980	6625	16610	7297
Nitrate-N (ppm)	440	445	313	217
C:N Ratio	12:1	15:1	20:1	17:1
Coliforms	4.8×10^3	4.8×10^3	1.86×10^3	0

Parameter	Sample Depth	Day					
		0	7	14	16	21	28
Temperature	Shallow	26	36	39	-	32	22
	Deep	26	70	77	74	61	51
pH	Shallow	6.51	6.44	7.34	-	7.31	7.33
	Deep	6.88	7.84	8.21	-	8.22	8.36
% Moisture	Shallow	53.65	61.92	65.29	-	54.63	54
	Deep	62.81	54.78	56.65	-	55.78	55
% Volatile Solids	Shallow	53.29	52.98	50.61	-	40	49
	Deep	40.72	67.02	62.34	-	43.73	44

Table 10

Physical and Chemical Data from Composting of Primary/Secondary Sludge - Pile #2

Parameter	Day 0	7	14	23
		Shallow Sample		
pH	7.31	6.75	6.2	6.9
Moisture, %	50	57	32	57
Carbon, %	16.35	26.0	22.48	14.65
Hydrogen, %	1.23	1.72	1.66	0.89
Nitrogen, %	1.21	1.36	1.29	1.13
Volatile Solids, %	35	38	36	36
Total N	9950	11250	-	5000
Ammonia-N (ppm)	146	651	-	78
Organic-N (ppm)	9576	9181	7165	4452
Nitrate-N (ppm)	830	1676	497	535
Orthophosphate (ppm)	6400	8139	2377	4651
Temperature °C	26	36	29	23
C:N Ratio	14:1	20:1	17:1	13:1
Coliforms	4.8×10^2	-	-	4.8×10^2
		Deep Sample		
pH	5.96	5.58	8.4	8.0
Moisture, %	70	72	63	70
Carbon, %	39.75	35.32	34.53	32.03
Hydrogen, %	4.54	3.74	4.16	4.17
Nitrogen, %	2.65	1.97	2.27	1.97
Volatile Solids, %	85	73	74	70
Total N	27000	30000	-	22000
Ammonia-N (ppm)	2133	12267	-	3780
Organic-N (ppm)	23700	18816	18086	18000
Nitrate-N (ppm)	1933	3060	1167	466
Orthophosphate (ppm)	15053	23017	1459	5000
Temperature °C	26	50	49	39
C:N Ratio	15:1	19:1	16:1	17:1
Coliforms	4.8×10^6	-	-	0

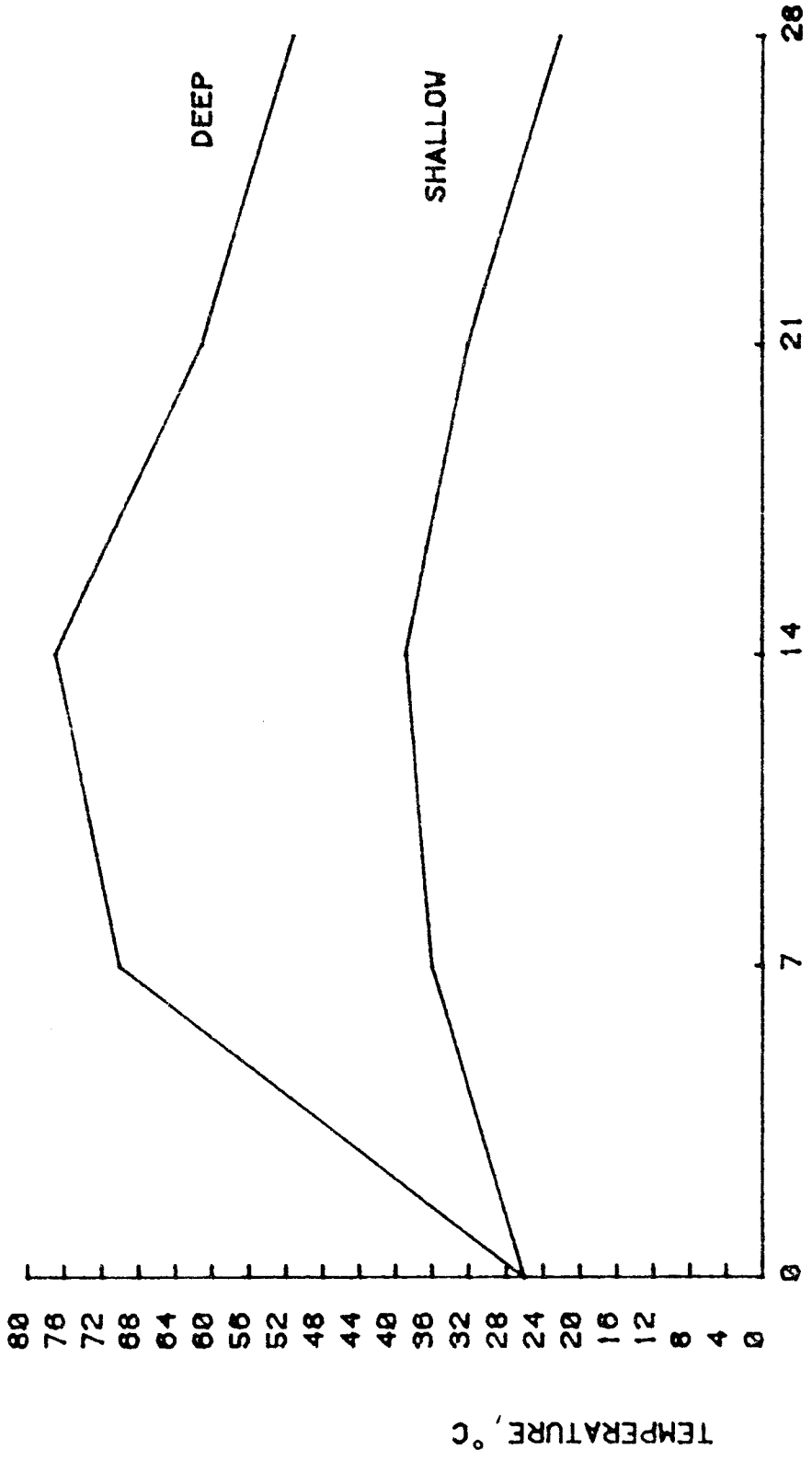


Figure 12
Temperatures recorded during composting of primary/secondary sludge.

decrease in the deep samples and a slight decrease in the shallow samples (due to lower temperatures at the exterior of the compost pile). This is consistent with what has been reported in the literature. Moisture content and volatile solids concentrations showed a slight decrease over the composting period at both deep and shallow sites. C:N ratio seemed to remain fairly constant. pH was seen to decrease slightly in the shallow samples and increase slightly in the deep samples.

Pathogen Survival

Primary Sludge Composting

During the early part of this research, work was done to determine the rate of pathogen kill while composting primary sludge and the factors affecting pasteurization. It was found that the presumptive pathogen kill, based on the kill of the indicator organisms (fecal coliform and fecal streptococcus), was achieved when the deep section of the pile maintained thermophilic temperatures. This can be seen in Figures 13 through 15 which plot the indicator organism counts for shallow and deep locations within the three primary sludge compost piles monitored. Temperature profiles show that in the shallow layers the high temperatures achieved are not always sufficient to achieve complete indicator organism kill.

The primary sludge compost piles were also monitored for the presence of aerobic and anaerobic thermophiles. Carefully taken samples from below two feet into the compost pile yielded only thermophilic bacteria, at levels greater than 10^7 per gram, after the second week of composting. These were shown to all be either aerobic or facultative anaerobic organisms. No obligate anaerobes were isolated. About half of the isolates produced spores typical of the family Bacillaceae.

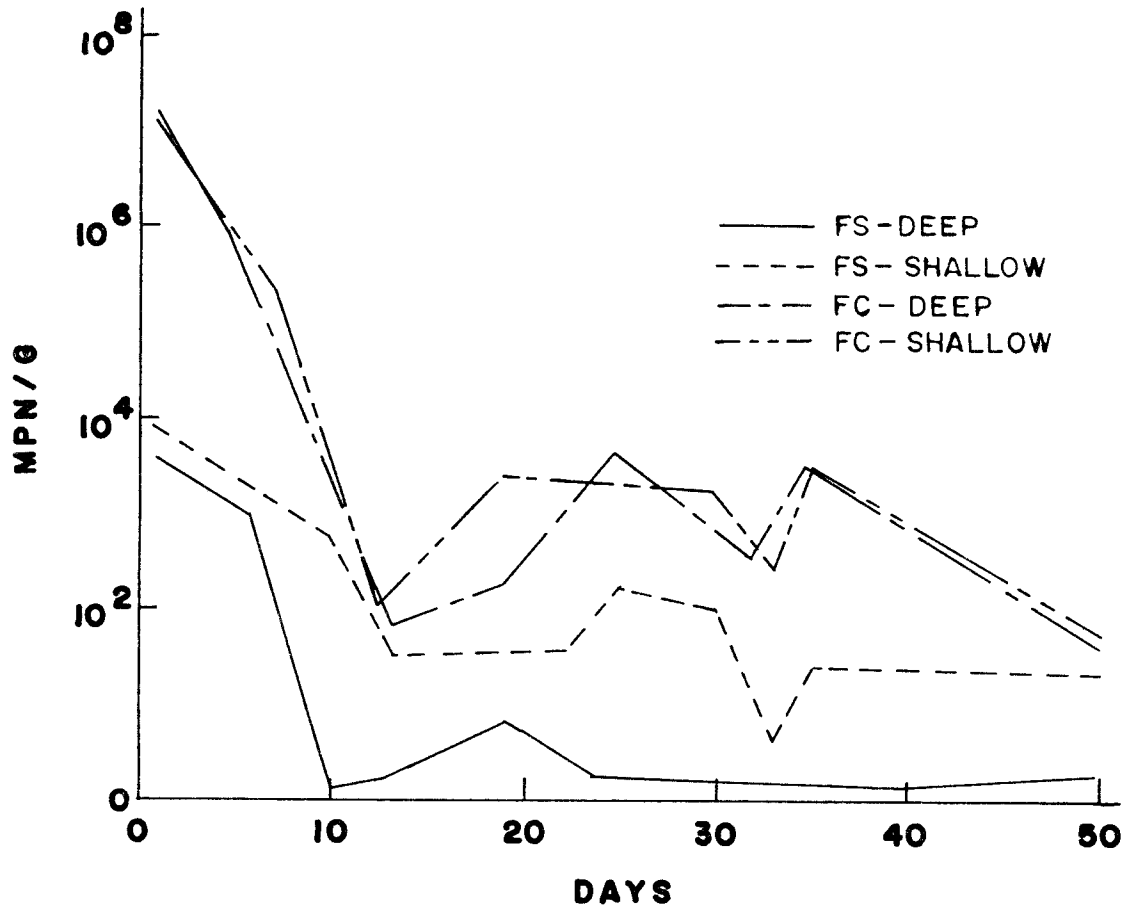


Figure 13
Fecal coliforms (FC) and fecal streptococci (FS) present during composting of primary sludge-Pile I.

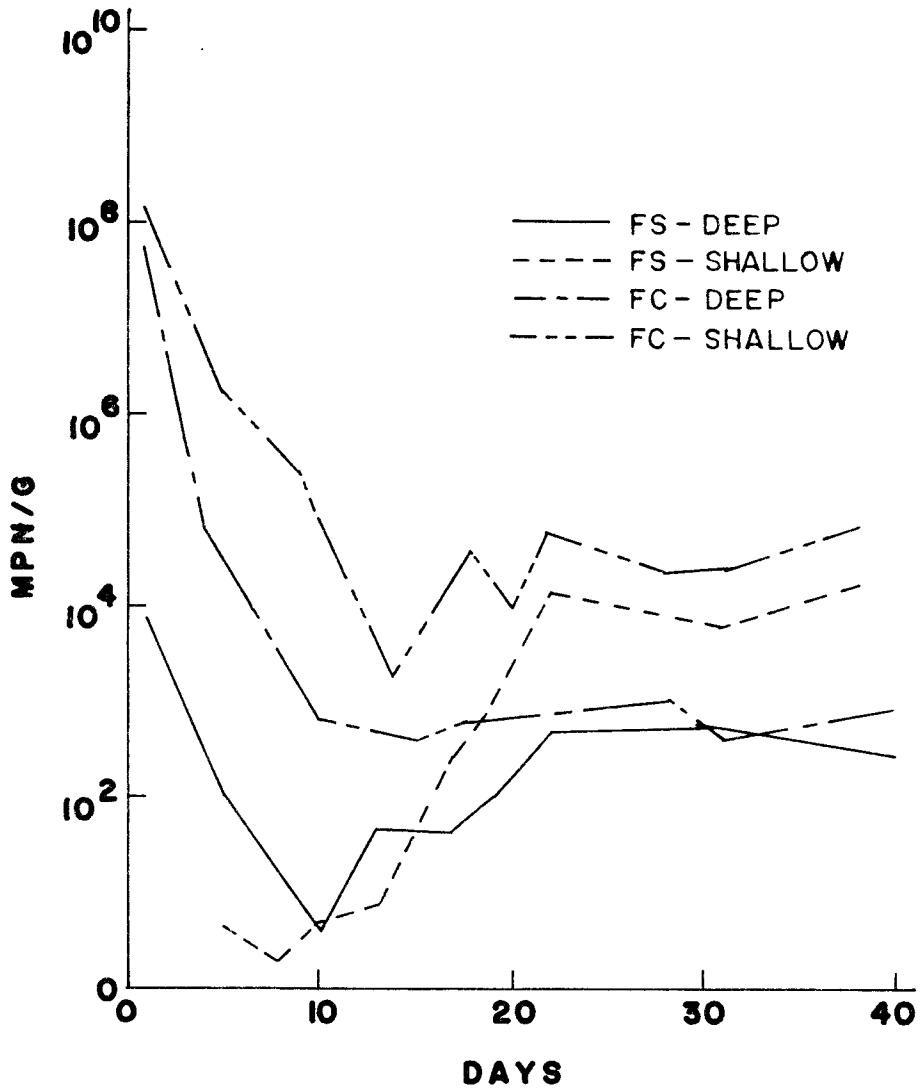


Figure 14
Fecal coliforms (FC) and fecal streptococci (FS) present during composting of primary sludge-Pile II.

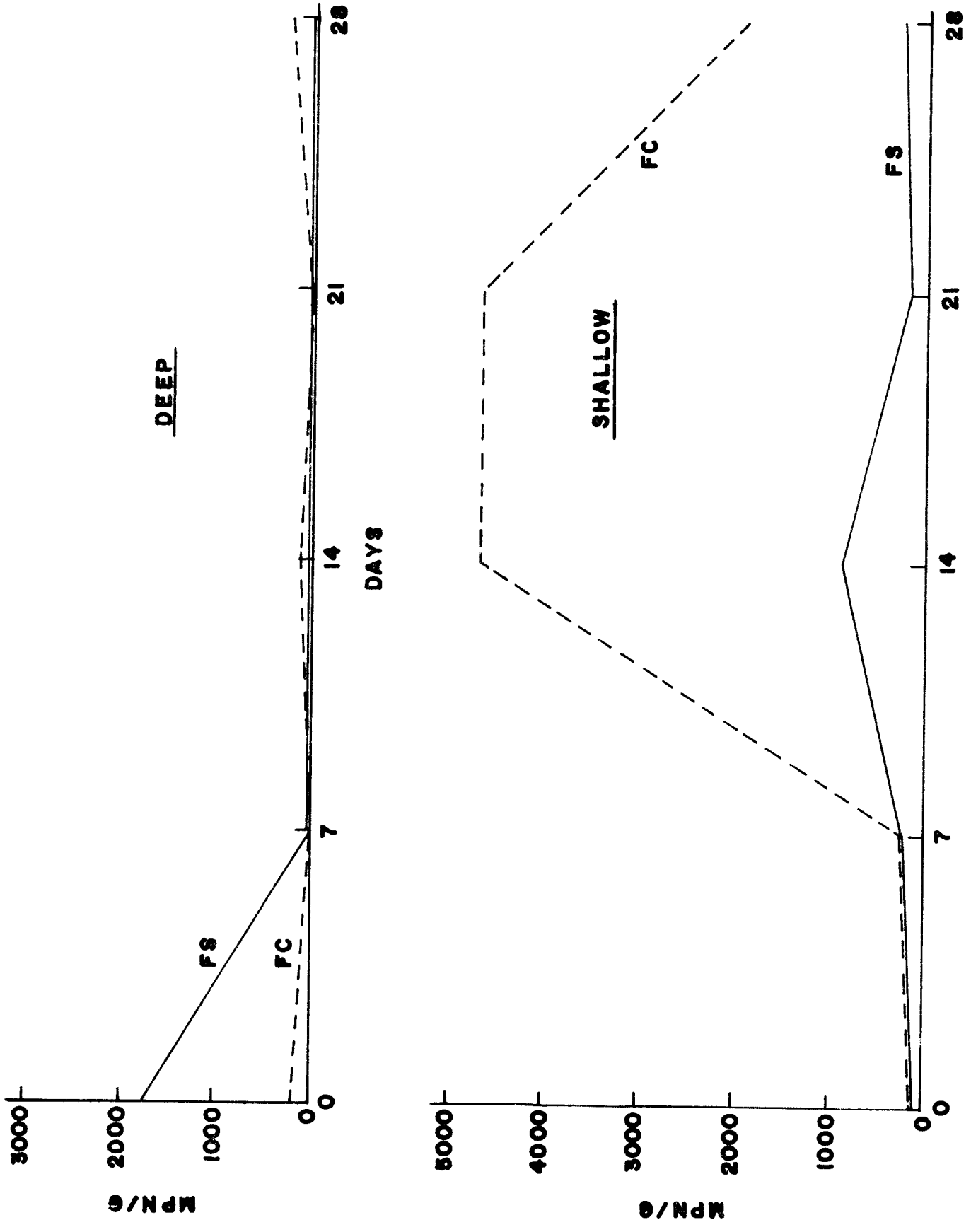


Figure 15
Fecal coliforms (FC) and fecal streptococci (FS) present during composting of primary sludge-Pile III.

Studies were also performed to assess the effectiveness of analytical methods for detecting Giardia and Ascaris in compost. Known quantities of cysts of these parasites were seeded into compost samples, after which the detection limits of microscopal techniques, with and without supplementary flotation separation, were established.

Using a standard analytical volume of 0.02 ml of material for microscopic analysis, it was found that a Giardia sample requires about 30 minutes of time per sample for counting and that for a single sample of this volume, the compost must contain 1.5×10^4 cysts per g for reliable detection. At this level of presence, for a compost made of three parts chips and 1 part sludge, and assuming that 100 percent of the Giardia cysts shed into the wastewater system will reside in the sludge, then there must be at least 5-6 active cases per 1000 population to ensure detectability with a single examination using this sample size (i.e. 0.02 ml). (Clearly, if only 10 percent of the Giardia cysts end up in the sludge, then 50-60 cases per 1000 would be required, and so on, so that the 5-6 case estimate represents a minimum, not a maximum, number.) Doubling the sample volume will halve the number of cases necessary for detection, e.g.

0.04 ml	-	1 hr working time	-	2 to 3 cases per 1000
0.08 ml	-	2 hr working time	-	1 to 2 cases per 1000
0.16 ml	-	4 hr working time	-	0.5 to 1 cases per 1000

and so forth.

Ascaris eggs are present in much lower numbers in infected human stool than are Giardia cysts, 8×10^3 eggs per g stool versus 9×10^5 cysts per g, for Giardia. Consequently, although the examination of a 0.02 ml sample requires an examination time of only ten minutes because of the larger size of the eggs, this is counterbalanced by their much lower numbers. The same calculations used for Giardia show that over 600 active cases per 1000 popula-

tion would be required for their reliable detection by examination of 0.02 ml of sample (again this is a minimum number).

Although Giardia may possibly be detectable with about an hour of working time in samples from compost made from wastes of a population with 2-3 active cases per 1000, Ascaris detection would require over 100 working hours if the population from which the compost was derived had only 2-3 cases per 1000. For Ascaris detection, it is suggested that it is more economical, and more assured, to estimate their presence in the pile from community health records showing the incidence of the disease.

The survival of a fungal species was also monitored during the course of primary sludge composting, Aspergillus fumigatus is a known respiratory allergen surviving well in many environments. Because of its ubiquity in nature, accurate measurement was difficult since contamination can be widespread during any plating or culturing operation. Other difficulties in detecting and enumerating A. fumigatus occurred when extracting the species from the compost and transferring the material to make subsequent dilutions. Once the spores or conidia have been released, they can grow to form colonies on the agar. It was not unusual to find greater numbers of colonies on plates of lower dilutions because of this. Contamination of the agar plates with bacterial species can and did occur despite the presence of antibiotics. This often made accurate counting difficult, if not impossible.

The A. fumigatus data collected for the primary sludge compost (Table 11) must be analyzed with these limitations in mind. The numbers of A. fumigatus (CFU/gram) generally decreased during the composting period, but the amount of reduction was not large. Significant numbers of A. fumigatus were present throughout the composting periods, particularly in the cooler shallow samples.

Table 11

Aspergillus fumigatus in Primary Sludge Compost

Pile	Day	*Aspergillus fumigatus*, log CFU/g	
		Shallow Sample	Deep Sample
1	1	3.55	3.92
	5	3.95	2.75
	9	3.85	2.19
	13	3.31	2.64
	19	2.90	3.08
	22	3.05	2.23
	26	2.34	1.30
	30	ND	3.43
	34	ND	0.00
	37	ND	2.73
	50	2.67	2.70
2	1	3.13	2.00
	4	2.75	2.90
	7	3.58	2.84
	10	2.21	1.95
	13	2.93	1.26
	16	3.34	1.54
	19	3.31	0.30
	22	3.35	2.16
	28	2.75	1.75
	31	2.93	1.84
	37	3.60	2.53

Table 12

Pathogens in Secondary Sludge Compost Piles (shallow/deep samples)

Organism	Day 0	7	14	21	28
Total Coliforms[a]	$\frac{4.8 \times 10^3}{1.86 \times 10^3}$	$\frac{4.8 \times 10^3}{0}$	$\frac{4.8 \times 10^2}{0}$	$\frac{1.86 \times 10^3}{0}$	$\frac{4.8 \times 10^3}{0}$
Fecal Coliforms[a]	$\frac{0}{0}$	$\frac{1.4 \times 10^2}{0}$	$\frac{1.86 \times 10^2}{0}$	$\frac{1.86 \times 10^2}{0}$	$\frac{80}{0}$
Total Streptococci[a]	$\frac{1.86 \times 10^5}{1.86 \times 10^4}$	$\frac{4.8 \times 10^3}{4.8 \times 10^3}$	$\frac{4.8 \times 10^4}{18}$	$\frac{4.8 \times 10^4}{4.8 \times 10^2}$	$\frac{4.8 \times 10^3}{9.2 \times 10^3}$
Fecal Streptococci[a]	$\frac{1.86 \times 10^3}{0}$	$\frac{4.8 \times 10^2}{0}$	$\frac{86}{0}$	$\frac{1.86 \times 10^2}{0}$	$\frac{4.8 \times 10^2}{8}$
Salmonellae	$\frac{0}{ND}$	$\frac{0}{ND}$	$\frac{0}{ND}$	$\frac{ND}{ND}$	$\frac{ND}{ND}$
Aspergillus Fumigatus[b]	$\frac{2.4 \times 10^5}{0}$	$\frac{7 \times 10^4}{0}$	$\frac{2.35 \times 10^5}{0}$	$\frac{1.1 \times 10^6}{0}$	$\frac{1.7 \times 10^6}{0}$
Temperature, °C	$\frac{ND}{ND}$	$\frac{36}{70}$	$\frac{39}{77}$	$\frac{32}{61}$	$\frac{22}{51}$

[a] Most probable number per gram

[b] CFU/g

ND = not done

Primary/Secondary Sludge Composting

The second phase of the project consisted of monitoring compost piles of mixed primary and secondary sludges. The results were virtually identical to the findings on primary sludge composting, although the mixed piles took longer to reach their thermophilic peak. Because Durham constructs extended piles, the mixed sludge could have sat on the composting pad for 2 to 3 weeks before it was forcibly aerated. Under these conditions, pasteurization often occurred from the microbial heat generated while the material was being held on the pad pending completion of the pile and start of aeration. Day 0 in these studies refers to the day on which aeration was initiated.

Growth in the shallow layers of the secondary piles paralleled that of the primary piles. The temperatures remained low enough to support a fluctuating population of both fecal coliforms and fecal streptococci, while the temperatures in the deep samples were prohibitive to any significant growth of either (Figure 16).

Other pathogenic organisms were also monitored in one of the primary/secondary sludge compost piles. The results of these analyses are shown in Table 12. As can be seen, temperatures of the shallow samples were only slightly above ambient and allowed for the survival of Aspergillus fumigatus, as well as fecal coliforms and fecal streptococci. However, no salmonellae could be recovered from any of the samples.

Pathogen Survival on Woodchips

Studies were performed to determine the limits of detection of Salmonella heidelberg seeded onto wood chips which had been recovered from a cured compost

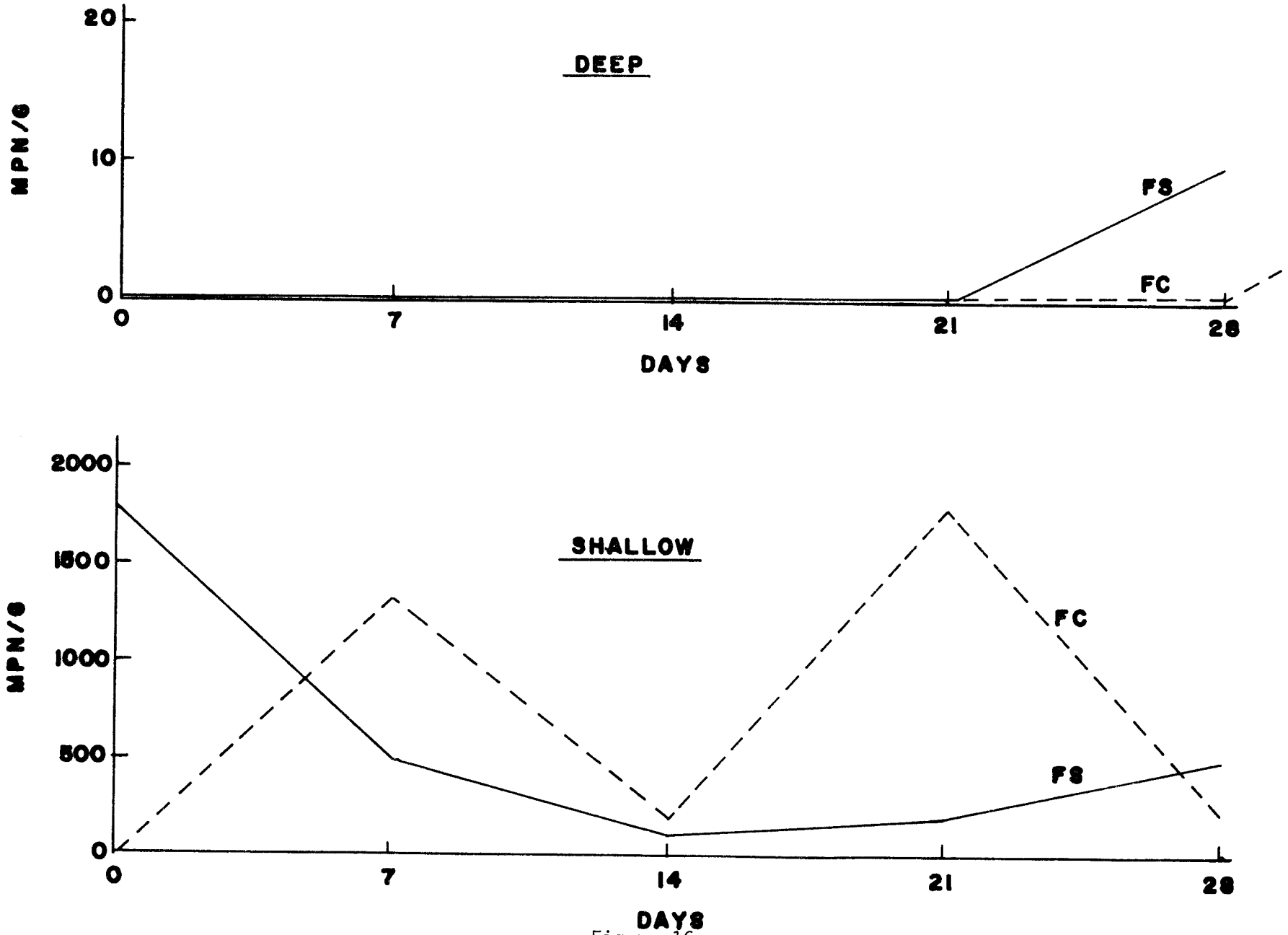


Figure 16
Fecal coliforms (FC) and fecal streptococci (FS) present during composting of primary/secondary sludge.

pile. Using the methodology described in Chapter 5, it was determined that the minimum detectable concentration is 13 cfu/g. Using this same recovery technique, recovered wood chips were seeded with S. heidelberg. These were then both layered and mixed with rich and poor soil. By the seventh day, there was a 3-5 log reduction in salmonellae population. By two weeks, no salmonellae could be recovered at all, indicating that salmonellae survival times on woodchips is relatively short.

Pathogen Survival in Compost Augmented Soil

During the course of this project, there were two ongoing field studies. The study which monitored indicator organisms at compost amended sites in Durham showed the fecal coliforms and fecal streptococci virtually gone during cold weather after 18 months from amendment. Regrowth occurred during the warm summer months. After 2 years, the fecal coliforms failed to regrow to any significant levels and could be considered gone. The fecal streptococci counts appeared to stabilize after the same period, but at a much higher level than the fecal coliforms (Table 13).

A more strictly controlled field experiment was conducted over the course of a year. Wood chips sifted from the Durham piles were either layered or mixed with lawn soil on a small farm in Durham, As in the amended soil study, regrowth occurred in spiked samples during the hot summer months, but the regrowth organisms never reached the original concentrations. During most of the year the counts were 0 cfu/g, or nearly so (Table 14).

Table 13

Survival of Fecal Coliforms and Fecal Streptococci in Amended Soil

Site	Date	Elapsed[a] Time	Fecal[b] Coliforms	Fecal[b] Streptococci
Warm Weather Samples				
1	7/80	3-4 years	8	2.2×10^3
2	7/80	3 years	8	4.8×10^3
3	7/80	2 years	3.0×10^2	8.6×10^2
4	7/80	1 year	4.6×10^2	48
5	7/80	3-4 months	4.0×10^2	1.9×10^2
Cold Weather Samples				
1	10/81	4-5 years	0	0
2	10/81	4 years	0	8
3	10/81	3 years	8	0
4	10/81	2 years	0	8
5	10/81	18 months	0	0

[a] Time elapsed since soil amendment.

[b] Most Probable Number per gram, wet weight.

Table 14

Survival of Fecal Coliforms and Fecal Streptococci on Wood Chips Mixed and Layered with Lawn Soil

Date	Elapsed Time	Fecal[b] Coliforms		Fecal[b] Streptococci	
9/29	0	0[c]		30[c]	
		2.8×10^3[d]		4.8×10^3[d]	
		Mixed	Layered	Mixed	Layered
10/6	7 days	0	8×10^3	4.8×10^2	4.8×10^3
10/15	16 days	30	4.8×10^2	46	4.8×10^3
11/13	45 days	1.9×10^2	86	6	86
3/25	6 months	18	86	0	8
4/21	7 months	86	1.9×10^2	0	4.6×10^2
5/19	8 months	14	30	3.0×10^2	8
6/23	9 months	0	1.9×10^2	1.4×10^3	4.6×10^2
7/22	10 months	1.9×10^2	1.9×10^2	4.9×10^2	1.9×10^3
10/7	13 months	0	0	18	46

[a] Time elapsed since addition of chips.

[b] Most Probable Number per gram wet weight.

[c] Before addition of chips.

[d] Recovered chips before mixing with soil.

Pathogen Survival During Compost Curing

Based on the results from these studies, another research project was designed to appraise the survival of a primary enteric pathogen, S. heidelberg, and of the fungus Aspergillus fumigatus in the finished screened product from the composting of a primary/secondary sludge. This was done by incubating bagged samples of screened compost which had been seeded with S. heidelberg in the curing piles and monitoring for the organisms specified above, as well as for bacterial indicator organisms. Some of the samples were also mixed with soil before incubation.

Table 15 shows the fate of fecal coliforms, fecal streptococci, and salmonellae in the finished compost during the curing stage. In each case, no salmonellae were detectable by three weeks after initiation of the curing stage. There was no indication of regrowth over the remaining five months of the sampling period. Fecal coliforms and fecal streptococci were undectable at the end of the six month period.

Table 16 shows that, even after saturation with 10% glucose, there was no detectable regrowth of salmonellae. There was regrowth of total coliforms, fecal coliforms, total streptococci, and fecal streptococci, however. The fecal streptococci recovered the least dramatically.

Aspergillus fumigatus maintained a relatively constant population over the six month testing period, as can be seen in Table 17.

Percent moisture and pH as measured in the field samples are listed in Table 18. Moisture ranged from 47 percent to 74 percent in the bagged compost samples, and from 31 percent to 57 percent in the bagged compost/soil mixtures. By 2 months, the bagged samples leveled off at their saturation points and remained saturated throughout the remainder of the sampling time due to heavy rainfall during the early part of the field studies.

Table 15

Survival of Fecal Coliforms, Fecal Streptococci, and Salmonellae in Compost During the Curing Stage

Sampling Day	Fecal[a] Coliforms	Fecal[a] Streptococci	Salmonellae[b]
Compost Seeded with S. heidelberg			
0	4.8×10^3	1.8×10^3	13
1 week	42	46	13
3 weeks	22	4.8×10^2	<0.13
6 months	0	0	<0.13
Compost and Soil Seeded with S. heidelberg			
0	8.6×10^2	4.8×10^4	13
1 week	8.6×10^2	46	13
3 weeks	46	4.8×10^2	<0.13
6 months	0	0	<0.13

[a] Most Probable Number per g, wet weight.

[b] Minimum number per g, wet weight.

Table 16

Regrowth of Fecal Coliforms, Fecal Streptococci, and Salmonellae in Samples Supplemented with 10% Glucose at 6 Months

Total[a] Coliforms	Fecal[a] Coliforms	Total[a] Streptococci	Fecal[a] Streptococci	Salmonellae[b]
Compost Seeded with S. heidelberg				
9.2×10^4	4.6×10^2	4.8×10^4	8	0
Compost and Soil Seeded with S. heidelberg				
1.9×10^5	4.8×10^3	4.8×10^4	46	0

[a] Most Probable Number per g, wet weight

[b] Minimum Number per g, wet weight.

Table 17

Survival of *Aspergillus fumigatus* in Compost During the Curing Stage (cfu/g, wet weight)

Sample Day	Site					
	Compost	Compost/Soil	Compost Seeded with S. heidelberg	Compost/Soil Seeded with S. heidelberg	Soil	Loose Compost
0	2.5×10^4	7×10^4	1.4×10^5	7.0×10^4	0	3.5×10^4
1 week	2.75×10^4	8×10^4	7.75×10^4	5.25×10^4	0	3.75×10^4
3 weeks	1.6×10^5	1.5×10^5	1.25×10^5	8.5×10^4	-	2.75×10^4
2 months	1.2×10^5	7.2×10^4	1.65×10^5	5.0×10^4	-	6.0×10^4
3 months	1.85×10^5	8.25×10^4	7.5×10^4	4.0×10^4	0	3.0×10^4
6 months	1.75×10^5	1.6×10^5	9.5×10^4	1.75×10^5	0	5.0×10^4

Table 18

Percent Moisture and pH in Compost
During the Curing Stage

Sample Day	Site											
	Compost		Compost/Soil		Compost Seeded with S. heidelberg		Compost/Soil Seeded with S. heidelberg		Soil		Loose Compost	
	% Moisture	pH	% Moisture	pH	% Moisture	pH	% Moisture	pH	% Moisture	pH	% Moisture	
0	49.2%	7.3	31.4%	7.2	47.4%	7.2	31.2%	7.2	14.5%	6.0	49.2%	
1 day	58.6%	7.2	38.4%	7.2	53.5%	7.2	39.1%	7.2	ND	ND	ND	
1 week	66.4%	7.6	48.6%	7.3	53.0%	7.2	47.8%	7.3	18.9%	6.3	52.8%	
3 weeks	67.4%	7.6	57.2%	7.4	61.2%	7.5	45.0%	7.2	21.2%	5.9	45.0%	
2 months	68.8%	7.4	58.9%	7.5	70.1%	7.7	51.0%	7.3	32.5%	5.8	57.8%	
3 months	74.7%	7.1	49.4%	7.2	71.4%	7.4	51.0%	7.3	32.7%	7.0	57.7%	
4 months	70.0%	7.2	53.0%	7.4	70.0%	7.7	53.0%	7.3	32.0%	6.3	ND	
6 months	73.0%	7.0	52.3%	6.2	73.2%	6.3	54.0%	6.7	32.0%	6.0	ND	

ND = not done

Bench studies were designed to assess the effect of several varying conditions on salmonellae survival. Therefore, the results are presented in relation to each of these variables.

Table 19 presents salmonellae survival in relation to differing soil and temperature conditions. In each case there appears to be no predictable effect based on either soil type or temperature. Tables 20 through 23 show the percent moisture and pH under different soil and temperature conditions. Percent moisture decreased under virtually all conditions, but most dramatically at 10°C. There was no significant variation in pH under any conditions.

Table 24 shows the fecal coliform and fecal streptococci counts in relation to salmonellae counts at the initiation and completion of sampling. Except for one outlying value, the fecal coliforms and fecal streptococci range from 0-18 MPN/g, wet weight. The salmonellae counts vary independently of the indicator counts. Table 25 presents this same information but in relation to the moisture levels. When viewed in this respect, the salmonellae counts decrease as the moisture levels fall. It must be kept in mind, however, that decreases in salmonellae are undetectable until the count falls below 13 cfu/g.

Significance of Pathogen Levels in Compost

In order to determine the significance of pathogen levels determined to be present in compost, a study was performed in which these bacterial fecal indicator concentrations were compared with the levels of those organisms in selected areas of the community, particularly in food items. Table 26 summarizes representative analyses or cumulative averages of the results obtained from samples from several stages of the composting cycle, amended soils, and

Table 19

Effect of Differing Soil and Temperature Conditions on Bench Scale Salmonellae Survival[a]

Conditions	Sample Day	% Compost					
		100	90	80	70	60	50
Poor soil at room temperature	0	13	13	13	13	13	13
	2	13	13	13	13	13	13
	7	13	13	13	13	13	13
	14	13	13	13	13	13	13
	21	13	13	13	13	13	13
	28	13	13	13	13	13	13
Poor soil at at 10°C	0	13	13	13	13	13	13
	2	13	13	13	13	13	13
	7	1.3	13	13	13	<13	13
	14	-	13	13	13	13	13
	21	13	-	-	-	-	-
	24	-	13	1.3	0.13	1.3	1.3
	28	<1.3	-	-	-	-	-
Good soil at room temperature	0	13	13	13	13	13	13
	2	13	13	13	13	13	13
	7	13	13	13	13	13	13
	14	13	13	13	13	13	13
	21	13	1.3	13	13	13	13
	28	13	13	1.3	1.3	13	13
Good soil at 10°C	0	13	13	13	13	13	13
	2	13	13	13	13	13	13
	7	1.3	13	13	13	<13	13
	14	-	13	13	1.3	1.3	13
	21	13	13	13	13	13	13
	28	<1.3	0.13	0.13	0	0.13	0.13

[a] Minimum number/gram, wet weight.

Table 20

Percent Moisture and pH in Bench Scale
Good Soil/Compost Mixtures at 10°C

Percent Compost	Sample Day	Salmonellae[a]	Percent Moisture	pH
100	0	13	57.2	6.8
	2	13	55.0	6.8
	7	1.3	57.6	6.6
	14	ND	35.1	6.7
	21	13	14.8	6.7
	28	0.13	8.6	6.6
90	0	13	56.0	6.8
	2	13	49.1	6.8
	7	13	47.2	6.7
	14	13	30.5	6.9
	21	13	14.7	6.8
	28	0.13	6.4	6.7
80	0	13	53.7	6.7
	2	13	48.0	6.9
	7	13	43.2	6.8
	14	13	32.5	6.9
	21	13	13.0	6.9
	28	0.13	4.2	6.9
70	0	13	49.0	6.9
	2	13	47.9	6.8
	7	13	40.0	6.9
	14	1.3	32.2	6.9
	21	13	9.9	6.9
	28	0	2.6	6.9
60	0	13	ND	6.9
	2	13	42.8	6.8
	7	1.3	19.5	7.1
	14	1.3	13.9	7.1
	21	13	6.2	6.8
	28	0.13	2.8	6.8
50	0	13	39.6	6.9
	2	13	39.4	6.9
	7	13	22.3	7.1
	14	13	10.8	7.1
	21	13	7.9	6.9
	28	0.13	3.8	6.9

[a] Minimum Number/gram, wet weight

ND = not done

Table 21

Percent Moisture and pH in Bench Scale
Good Soil/Compost Mixtures at 20°C

Percent Compost	Sample Day	Salmonellae[a]	Percent Moisture	pH
100	0	13	55.5	6.1
	2	13	56.9	6.4
	7	13	56.1	6.7
	14	13	ND	ND
	21	13	47.9	6.9
	28	13	49.1	6.8
90	0	13	59.7	7.1
	2	13	56.3	7.1
	7	13	50.8	7.1
	14	13	56.8	7.0
	21	1.3	52.3	7.2
	28	13	54.8	7.0
80	0	13	49.0	6.9
	2	13	55.2	7.0
	7	13	53.0	6.9
	14	13	54.2	7.0
	21	13	52.7	7.1
	28	1.3	54.4	6.9
70	0	13	45.6	6.9
	2	13	45.2	7.0
	7	13	43.7	6.9
	14	13	45.1	7.2
	21	13	41.3	7.1
	28	1.3	45.4	6.9
60	0	13	44.7	7.1
	2	13	43.2	6.8
	7	13	36.8	6.9
	14	13	33.1	7.0
	21	13	38.0	6.9
	28	13	40.2	7.0
50	0	13	43.0	7.2
	2	13	37.1	7.0
	7	13	38.1	7.0
	14	13	31.3	6.7
	21	13	25.5	7.1
	28	13	27.0	7.0

[a] Minimum Number/gram, wet weight

ND = not done

Table 22

Percent Moisture and pH in Bench Scale
Poor Soil/Compost Mixtures at 10°C

Percent Compost	Sample Day	Salmonellae[a]	Percent Moisture	pH
100	0	13	57.2	6.8
	2	13	55.0	6.8
	7	1.3	47.6	6.6
	14	ND	35.1	6.7
	21	13	14.8	6.7
	28	0.13	8.6	6.6
90	0	13	46.0	6.2
	2	13	41.8	6.6
	7	13	37.2	6.8
	14	13	32.0	6.2
	24	13	10.7	6.7
80	0	13	44.8	6.2
	2	13	41.1	6.5
	7	13	29.6	6.9
	14	13	12.5	5.6
	24	1.3	7.2	6.8
70	0	13	39.7	6.2
	2	13	35.5	6.5
	7	13	12.4	6.8
	14	13	8.9	5.7
	24	0.13	3.7	6.9
60	0	13	31.6	6.4
	2	13	24.1	6.5
	7	1.3	12.5	6.8
	14	13	8.1	5.8
	24	1.3	4.1	7.0
50	0	13	29.3	6.5
	2	13	22.5	6.6
	7	13	8.4	7.0
	14	13	5.7	6.1
	24	1.3	2.6	7.0

[a] Minimum Number/gram, wet weight

ND = not done

Table 23

Percent Moisture and pH in Bench Scale
Poor Soil/Compost Mixtures at 20°C

Percent Compost	Sample Day	Salmonellae[a]	Percent Moisture	pH
100	0	13	55.5	6.1
	2	13	56.9	6.4
	7	13	56.1	6.7
	14	13	ND	ND
	21	13	47.9	6.9
	28	13	49.1	6.8
90	0	13	47.9	6.3
	2	13	54.1	6.4
	7	13	50.6	6.7
	14	13	54.3	6.8
	21	13	45.4	6.5
	28	13	36.6	6.7
80	0	13	42.8	6.3
	2	13	48.2	6.4
	7	13	44.7	6.8
	14	13	44.3	6.7
	21	13	38.0	6.7
	28	13	33.6	6.8
70	0	13	38.3	6.3
	2	13	41.6	6.4
	7	13	38.4	6.8
	14	13	40.2	6.7
	21	13	34.0	7.0
	28	13	23.5	6.9
60	0	13	37.1	6.2
	2	13	38.6	6.4
	7	13	35.8	6.8
	14	13	35.4	6.9
	21	13	32.3	6.9
	28	13	36.2	7.1
50	0	13	27.8	6.1
	2	13	30.4	6.3
	7	13	31.7	6.9
	14	13	29.9	6.8
	21	13	19.0	7.0
	28	13	16.2	6.8

[a] Minimum Number/gram, wet weight

ND = not done

Table 24

Fecal Coliform and Fecal Streptococci Counts
In Relation to Salmonellae Counts in
Bench-Scale Studies

Percent Compost	Sample Day	Soil/Temp. Conditions	Salmonellae[a]	FC[b]	FS[b]
100	0	Room Temp.	13	0	0
	28		13	0	0
	0	10°C	13	0	0
	28		0.13	0	0
90	0	Good/RT	13	0	6
	28		13	0	0
	0	Poor/RT	13	0	0
	28		13	0	0
	0	Good/10°C	13	0	0
	28		0.13	0	0
	0	Poor/10°C	13	0	0
	28		13	0	0
80	0	Good/RT	13	14	0
	28		1.3	0	6
	0	Poor/RT	13	0	0
	28		13	0	1
	0	Good/10°C	13	0	6
	28		0.13	0	0
	0	Poor/10°C	13	0	8
	24		1.3	0	0
70	0	Good/RT	13	0	6
	28		1.3	0	0
	0	Poor/RT	13	0	0
	28		13	0	0
	0	Good/10°C	13	0	14
	28		0	0	0
	0	Poor/10°C	13	0	14
	24		0.13	0	0
60	0	Good/RT	13	0	6
	28		13	0	0
	0	Poor/RT	13	0	0
	28		13	0	0
	0	Good/10°C	13	0	6
	28		0.13	0	0
	0	Poor/10°C	13	0	8
	24		1.3	0	0
50	0	Good/RT	13	0	6
	28		13	0	0
	0	Poor/RT	13	0	4.8×10^3
	28		13	0	0
	0	Good/10°C	13	0	18
	28		0.13	0	0
	0	Poor/10°C	13	0	0
	24		1.3	0	0

[a] Minimum Number/gram, wet weight

[b] Most Probable Number/gram, wet weight

Table 25

Fecal Coliforms (FC), Fecal Streptococci (FS), Salmonellae (SAL) and Percent Moisture Data from First and Last Day of Bench-Scale Studies

Percent Compost	Room Temp/Good Soil				Room Temp/Poor Soil			
	FC[a]	FS[a]	SAL[b]	%HOH	FC[a]	FS[a]	SAL[b]	%HOH
90	0	0	13	59.7	0	0	13	47.9
	0	0	13	54.8	0	0	13	36.6
80	14	1	13	49.0	0	0	13	42.8
	0	6	1.3	54.4	0	0	13	33.6
70	0	6	13	45.6	0	0	13	38.3
	46	0	1.3	45.4	0	0	13	23.5
60	0	6	13	44.7	0	0	13	37.1
	0	0	13	40.2	0	0	13	36.2
50	0	6	13	43.0	0	4.8×10^3	13	27.8
	0	0	13	27.0	0	0	13	16.2
	10°C/Good Soil				10°C/Poor Soil			
90	0	6	13	56.0	0	0	13	46.0
	0	0	0.13	6.4	0	0	13	10.7
80	0	6	13	53.7	0	8	13	44.8
	0	0	0.13	4.2	0	0	1.3	7.2
70	0	14	13	49.0	0	14	13	39.7
	0	0	0	2.6	0	0	1.3	3.7
60	0	6	13	42.8	0	8	13	31.6
	0	0	0.13	2.8	0	0	1.3	4.1
50	0	18	13	39.6	0	0	13	29.3
	0	0	0.13	3.8	0	0	1.3	2.6
100	0	0	13	57.2	0	0	13	47.9
	0	0	0.13	8.6	0	0	13	36.6

[a] Most Probable Number/gram, wet weight

[b] Minimum Number/gram, wet weight

Table 26

Summarized Counts of Fecal Coliforms and Fecal Streptococci from Composting Operations and Foodstuffs Vended at a Local Restaurant

Sample	Bacterial Count (colony forming units per g)	
	Fecal coliforms	Fecal streptococci
collected sludge[a]	4.8×10^5	4.8×10^6
chips, new[a]	46	ND
chips, recycled[a]	5.6×10^4	4.8×10^2
compost pile[b]		
6 in depth	$1.8 \times 10^3 \pm 1.9 \times 10^3$	210 ± 320
4 ft depth	7.2 ± 7.0	320 ± 760
sifted compost[a]	19 ± 26	73 ± 130
amended soil[c]		
3-4 yr	8	2.2×10^3
3 yr	8	4.8×10^3
2 yr	300	860
1 yr	460	48
3-4 mo.	400	186
Foodstuffs[a]		
chicken salad	4.8×10^3	8.6×10^3
potato salad	1.9×10^3	4.2×10^3
tossed salad	4.2×10^3	88
egg salad	1.5×10^3	240
cole slaw	3.0×10^3	4.8×10^3

[a] Single sampling

[b] Average of 2 mo. sampling

[c] Lapsed time since addition of compost to soil.

ND = not done

from a heavily patronized area restaurant. It should be pointed out that food from another restaurant, two supermarkets and a local ceterer were also analyzed and were better from a fecal indicator standpoint than the one shown in the table.

It can be seen that the sifted compost was lower in bacterial indicator content than the food items retailed by at least one major restaurant in the area. The community level of fecal coliforms and fecal streptococci may serve as a useful yardstick of the microbial safety of the finished compost.

It is also worth noting from Table 26 that the recycled woodchips are the major residual reservoir of enteric bacteria in the composting process.

Effect of Aeration Rate on Composting

The effect of aeration rate on composting was evaluated by varying the aeration rate of pilot-scale compost piles. The results from the first variable aeration rate study, in which aerated (400 scfm) and nonaerated piles were compared, are presented in Table 27. Figures 17 and 18 depict the measured changes in internal pile temperature and volatile solids content, respectively. It can be noted that the two piles mimicked each other, except that the temperatures were consistently lower in the nonaerated pile and the moisture content was lower in the aerated pile. Temperatures peaked on day 7 at 64°C in the aerated pile, and at 40°C in the nonaerated pile.

In the second aeration experiment, pilot-scale compost piles were aerated at rates of 0 scfm, 400 scfm and 800 scfm. The results of this study are shown in Table 28. Again, temperature and volatile solids data are plotted in Figures 19 and 20, respectively. Similar trends to that described for the first experiment were observed. The 400 scfm pile showed the greatest and

Table 27

A Comparison of Aerated and Nonaerated Composting

Parameter	Day 0	7	12	19	28
			Aerated		
pH	6.33	7.69	7.56	6.93	6.53
Temperature °C	26	36	29	25	17
Moisture, %	72.5	56	60	60	62
Carbon, %	31.5	-	29.67	-	31.4
Hydrogen, %	3.04	-	1.26	-	1.57
Nitrogen, %	1.55	-	1.93	-	1.83
Volatile Solids, %	76	60	66	62	50
Total N (ppm)	18,400		21,670		14,000
Ammonia-N (ppm)	1,178	-	72	-	242
Organic-N (ppm)	17,600	-	11,690	-	14,300
Nitrate-N (ppm)	270	-	659	-	592
Orthophosphate (ppm)	6,250	-	4,230	-	7,368
Heat Content (Kcal/gm)	4.5	-	3.92	-	2.82
C:N Ratio	20:1	-	16:1	-	17:1
			Nonaerated		
pH	6.33	7.54	7.95	7.49	6.66
Temperature °C	26	64	37	45	42
Moisture, %	72.58	72.5	67.6	59.5	59
Carbon, %	31.5	-	27.49	-	33.15
Hydrogen, %	3.04	-	1.60	-	1.51
Nitrogen, %	1.55	-	1.83	-	2.02
Volatile solids, %	76.8	76	68	71	48
Total N (ppm)	18,400	-	19,000	-	19,000
Ammonia-N (ppm)	1,178	-	2,000	-	471
Organic-N (ppm)	17,600	-	17,300	-	13,600
Nitrate-N (ppm)	270	-	550	-	397
Orthophosphate (ppm)	6,250	-	5,156	-	6,829
Heat Contnet (Kcal/gm)	4.5	-	3.67	-	2.68
C:N Ratio	20:1	-	15:1	-	16.5:1

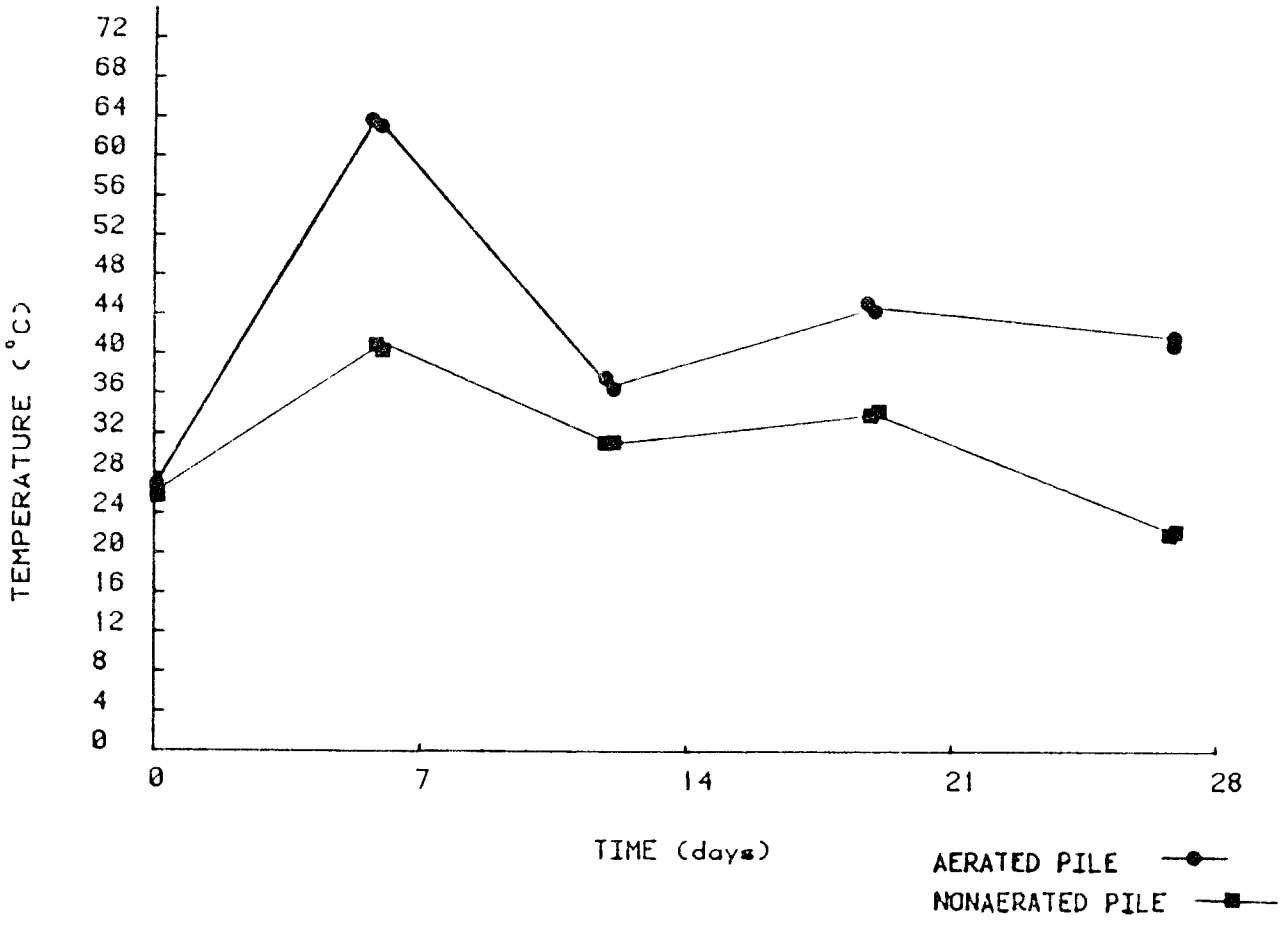


Figure 17
Compost pile temperatures under aerated and nonaerated conditions.

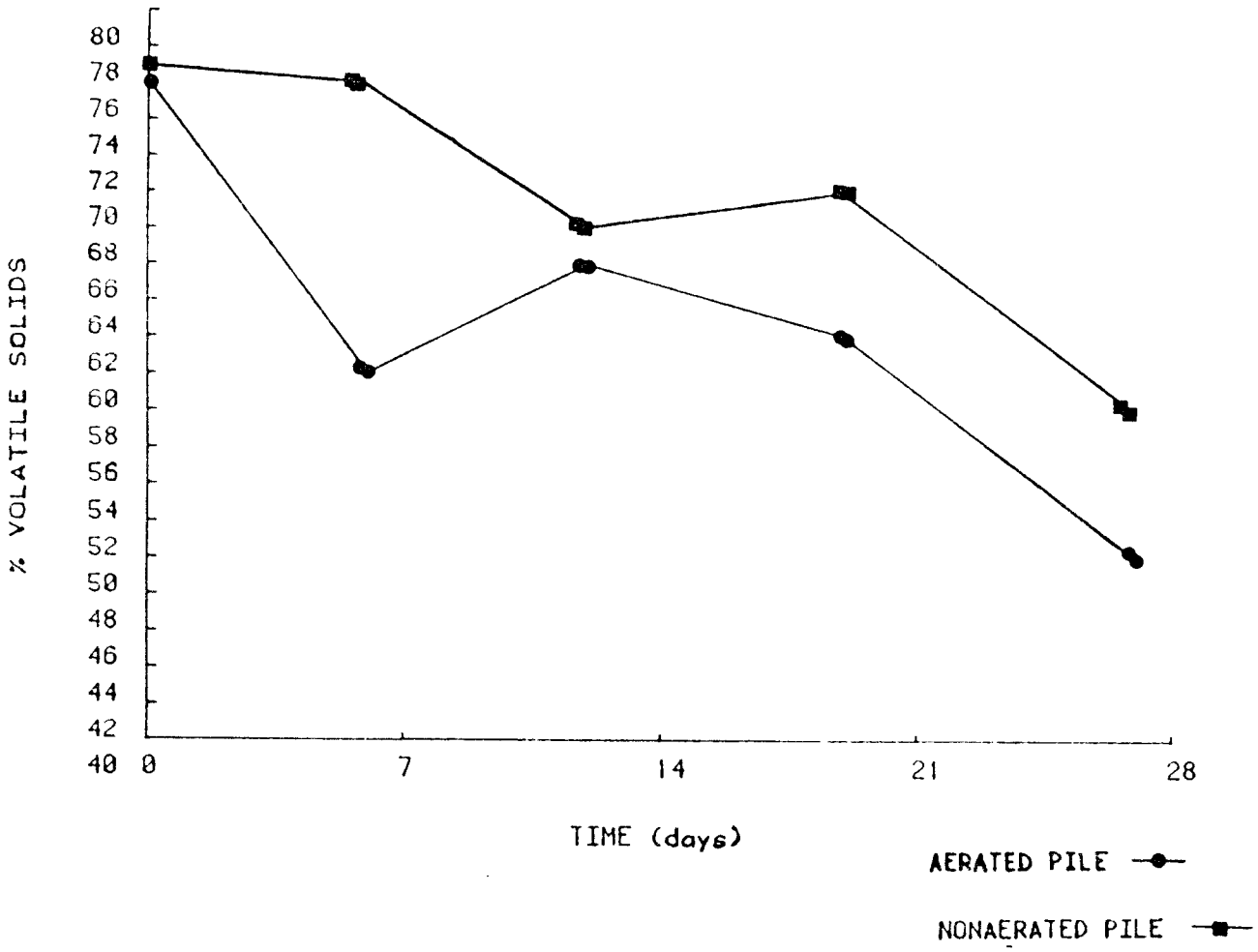


Figure 18
Compost pile volatile solids content under aerated and nonaerated conditions.

Table 28

The Effect of Aeration Rate on Sludge Composting

Parameter	Day 0	7	14	21	29
	400 scfm aeration rate				
pH	7.2	7.23	6.43	5.9	6.8
Temperature °C	20	45	67	63	47
Moisture, %	71.9	72	53.9	58	46
Carbon, %	42.8	36.7	28.6	37.9	30.8
Hydrogen, %	4.8	4.2	3.1	3.8	3.1
Nitrogen, %	1.9	1.7	1.9	2.3	2.5
Volatile Solids, %	78.98	68.7	70	68	68
Total N (ppm)	15,000	13,400	11,500	11,600	11,400
Ammonia-N (ppm)	35	285	91	35	72
Organic-N (ppm)	14,660	12,539	11,339	11,400	11,390
Nitrate-N (ppm)	300	480	448	180	90
C:N Ratio	23:1	22:1	15:1	16:5	12:3
Orthophosphate (ppm)	$11,701_6$	$\bar{4}$	-	-	5740
Coliforms (MPN/g)	2.2×10^{6}	3×10^{4}	-	86	0
	800 scfm aeration rate				
pH	7.2	7.0	6.5	6.3	6.7
Temperature, °C	20	40	49	27	42
Moisture, %	71.9	69	42	48	38
Carbon, %	42.8	36.5	34.4	26.9	34.0
Hydrogen, %	4.8	4.4	3.2	2.9	4.2
Nitrogen, %	1.9	1.7	2.9	1.9	2.6
Volatile Solids, %	78.98	71.4	68	64	59
Total N (ppm)	15,000	14,000	12,000	12,100	12,100
Ammonia-N (ppm)	35	350	136	42	9
Organic-N (ppm)	14,660	12,539	12,027	12,115	12,109
Nitrate-N (ppm)	300	640	217	226	148
C:N Ratio	23:1	21:1	12:1	14:1	13:1
Orthophosphate (ppm)	$11,071_5$	-	-	-	1048_5
Coliforms (MPN/g)	1.86×10^{5}	4.8×10^{6}	-	2.2×10^{6}	4.2×10^{5}

Table 28 (cont.)

	nonaerated				
pH	7.2	6.6	6.7	6.4	6.7
Temperature, °C	20	25	28	55	42
Moisture, %	71.9	60	58	65	60
Carbon, %	42.8	28.9	32.6	38.9	32.6
Hydrogen, %	4.8	3.0	3.4	3.9	2.9
Nitrogen, %	1.9	1.7	1.8	2.3	2.7
Volatile Solids, %	78.98	74.4	70	71	70
Total N	15,000	14,000	13,000	13,000	7,750
Ammonia-N (ppm)	35	140	404	24	70
Organic-N (ppm)	14,660	13,170	12,533	12,800	12,690
Nitrate-N (ppm)	300	350	238	240	200
C:N Ratio	23:1	17:1	18:1	17:1	12:1
Orthophosphate (ppm)	11,071	-	-	-	7,750
Coliforms (MPN/g)	80	4.8×10^6	-	1.5×10^5	2.2×10^8

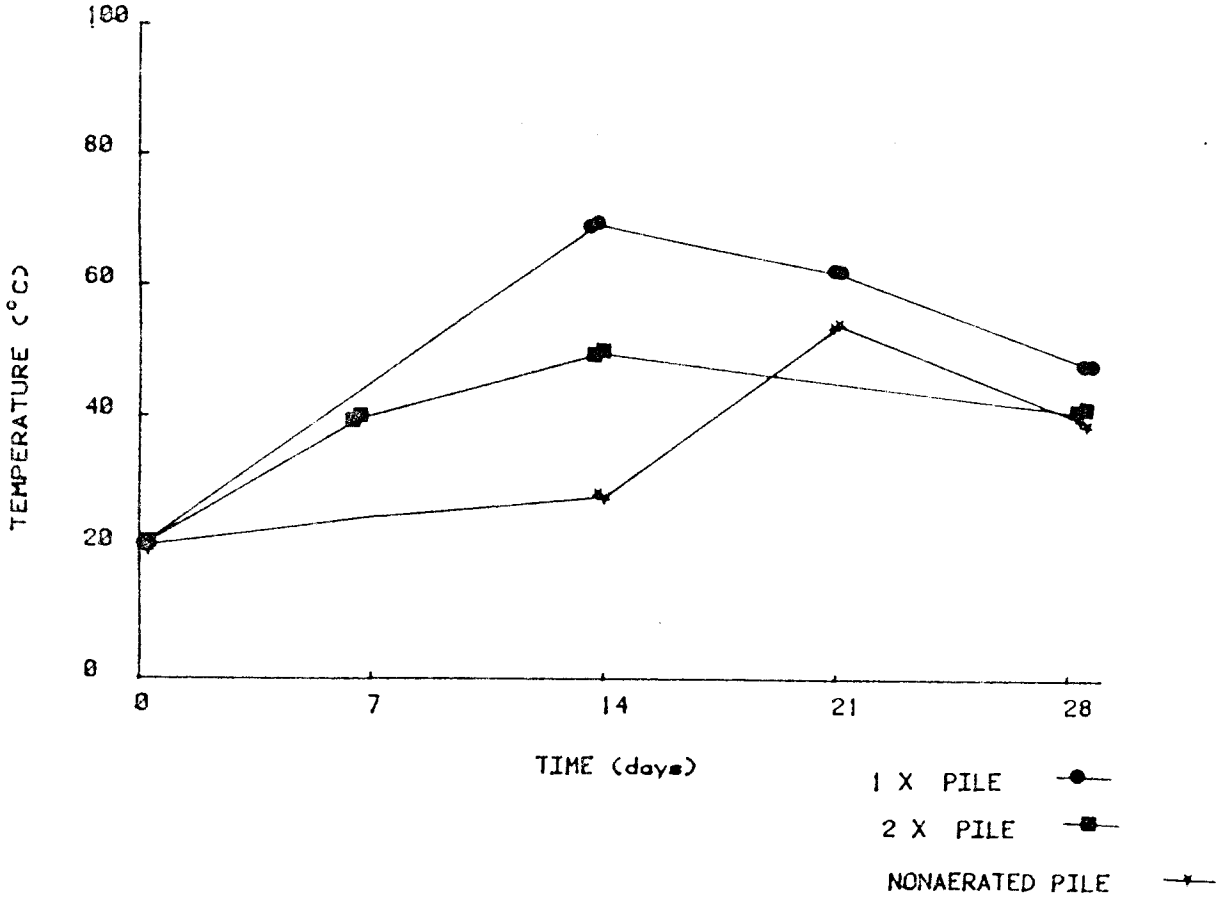


Figure 19
Effect of aeration rate on compost pile temperature.

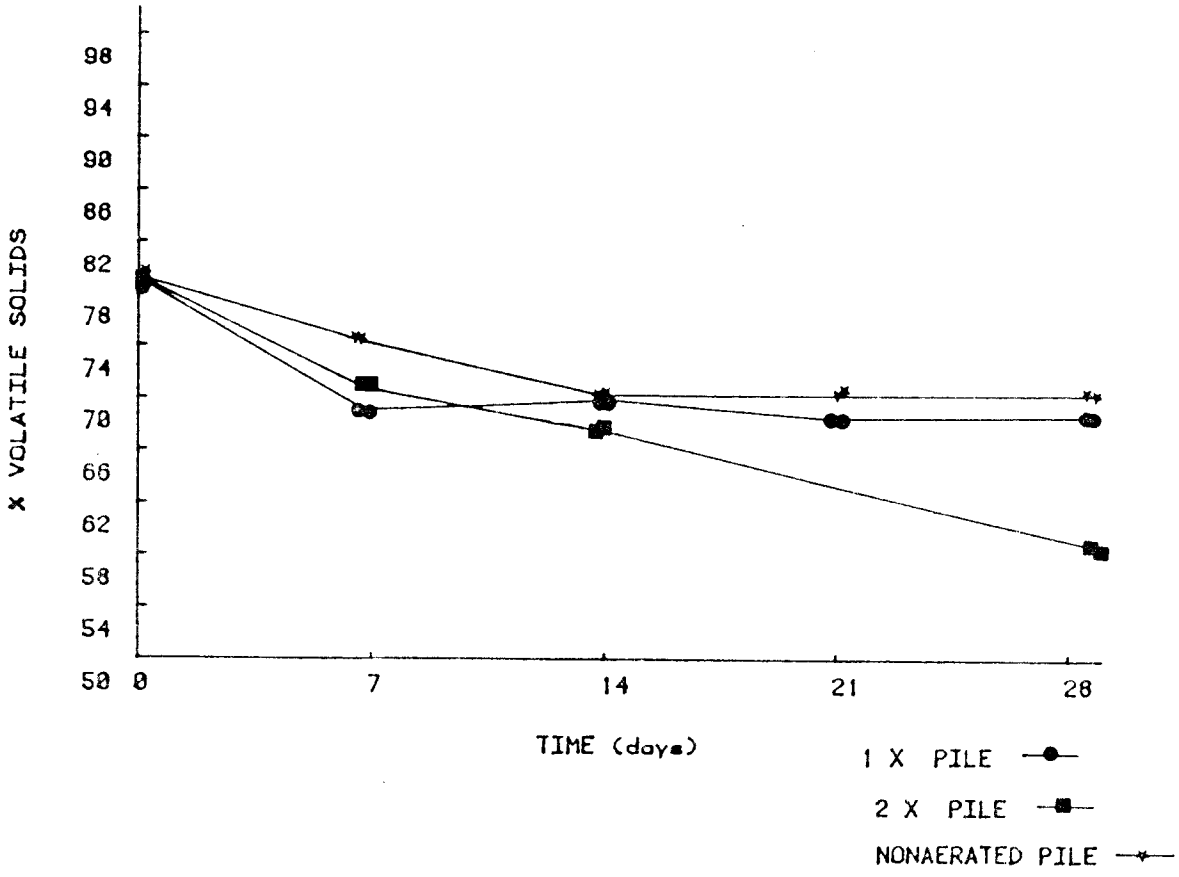


Figure 20
Effect of aeration rate on compost pile volatile solids content.

fastest rise in temperature, peaking at 67°C around day 14. The 800 scfm pile peaked at 49°C, and the nonaerated pile peaked at 55°C on day 21. This seems to indicate that the 800 scfm pile had an excess air flow which resulted in cooling of the compost mass. The nonaerated pile may have had microaerophilic or even anaerobic conditions which resulted in slower metabolism of organics. Little drying or volatile solids reduction occurred in the nonaerated pile, while the greatest reduction occurred in the 800 scfm pile. This is reasonable since the 800 scfm pile had the greatest air flow for drying and a lower temperature which would favor volatile solids reduction by encouraging microbial degradation or organics.

Effect of Woodchip:Sludge Ratio on Composting

The woodchip:sludge ratio experiment dealt with changing the woodchip:sludge ratio in such a way as to optimize the composting by obtaining a satisfactory product while using the least amount of woodchips. Since woodchip expense is considerable in this operation, a reduction in woodchip use would represent an economic savings.

The results of these experiments are presented in Tables 29 and 30 and in Figure 21. Both runs, which were duplicates of each other, exhibited similar results and, therefore, the data from the two runs has been combined on the figure. Temperature was highest in the 3:1 woodchip:sludge ratio pile, peaking at 70-74°C around day 12. The 2:1 pile peaked at 55-60°C, and the 1:1 pile peaked at 40°C, which seems to indicate that the void ratio was not large enough to have proper air transfer up through the pile, and microaerophilic or anaerobic conditions were present. This resulted in less heat generation and accumulation and a lower temperature.

Table 29

The Effect of Woodchip:Sludge Ratio on Sludge Composting - Run #1

Parameter	Day 0	7	19	26
	1:1 Ratio			
Coliforms (MPN/g)	4.8×10^6	2.2×10^6	8.2×10^2	8.6×10^2
pH	6.4	7.14	7.31	7.5
Temperature, °C	20	21	46	26
Moisture, %	67	70	69	70
Carbon, %	23.34	22.41	41.92	34.37
Hydrogen, %	2.58	1.87	5.18	3.19
Nitrogen, %	1.86	1.78	2.4	2.48
Volatile Solids, %	70	67	55	69
Total N (ppm)	23,000	24,000	24,000	20,000
Ammonia-N (ppm)	373	2,613	4,561	1,628
Organic-N (ppm)	22,608	21,000	23,483	18,700
Nitrate-N (ppm)	740	900	970	785
C:N Ratio	13:1	13:1	17:1	14:1
Orthophosphate (ppm)	7,826	4,666	2,000	7,142
Oxygen, %	-	4	8.5	14
Void Space, % (volume)	31	-	-	-
	2:1 Ratio			
Coliforms (MPN/g)	4.8×10^6	86	86	1.86×10^2
pH	6.4	7.78	7.86	7.1
Temperature, °C	20	27	62	26
Moisture, %	67	73	73	73
Carbon, %	23.34	32.98	23.57	29.03
Hydrogen, %	2.58	3.81	2.29	3.25
Nitrogen, %	1.86	2.64	1.78	2.71
Volatile Solids, %	70	72	72	72
Total N (ppm)	23,000	19,000	20,000	21,000
Ammonia-N (ppm)	373	2,985	3,940	1,252
Organic-N (ppm)	22,608	16,696	21,840	20,118
Nitrate-N (ppm)	740	740	800	650
C:N Ratio	13:1	13:1	13.8:1	11:1
Orthophosphate (ppm)	7,826	6,666	-	5,926
Oxygen, %	-	3	9	17
Void Space, % (volume)	39	-	-	-

Table 29 (Cont.)

Parameter	Day 0	7	19	26
	3:1 Ratio			
Coliforms (MPN/g)	4.8×10^6	30	30	1.86×10^3
pH	6.4	7.82	7.14	7.0
Temperature, °C	20	63	39	25
Moisture, %	67	67	70	67
Carbon, %	23.34	24.85	27.98	31.93
Hydrogen, %	2.58	2.4	2.66	2.88
Nitrogen, %	1.86	1.55	2.02	2.02
Volatile Solids, %	70	70	70	66
Total N (ppm)	23,000	19,000	2,000	14,000
Ammonia-N (ppm)	373	2,485	1,625	1,252
Organic-N (ppm)	22,608	16,969	19,600	13,580
Nitrate-N (ppm)	740	820	750	490
C:N Ratio	13:1	16:1	14:1	16:1
Orthophosphate (ppm)	7,826	7,878	-	4,750
Oxygen %	-	16	21	20
Void Space, % (volume)	62			

Table 30

The Effect of Woodchip:Sludge Ratio on Sludge Composting - Run #2

Parameter	Day 0	7	12	19	28
	1:1 Ratio				
Coliforms (MPN/g)	80	2.2×10^6	3×10^4	86	4.8×10^6
pH	6.7	6.26	6.26	7.3	6.6
Temperature, °C	20	20	20	19	24
Moisture, %	81	80	77	79	72
Carbon, %	27.94	37.32	24.41	29.37	30.74
Hydrogen, %	3.22	4.65	3.5	3.67	3.32
Nitrogen, %	1.83	3.37	1.9	2.42	3.12
Volatile Solids, %	75	77	77	66	70
Total N (ppm)	35,000	34,000	27,000	28,000	26,000
Ammonia-N (ppm)	3,063	3,757	917	546	528
Organic-N (ppm)	32,010	30,050	26,204	27,719	24,671
Nitrate-N (ppm)	342	450	217	190	196
C:N Ratio	16:1	13:1	12:1	12:1	10:1
Orthophosphate (ppm)	12,631	-	11,304	6,666	5,357
Oxygen, %	-	-	13	-	-
	2:1 Ratio				
Coliforms (MPN/g)	80	1.86×10^5	4.8×10^6	2.2	2.2
pH	6.7	7.01	7.45	7.1	7.0
Temperature, °C	20	44	55	57	57
Moisture, %	81	71	70	70	71
Carbon, %	27.94	21.31	37.66	23.41	40.44
Hydrogen, %	3.22	1.79	4.23	1.85	4.78
Nitrogen, %	1.83	1.61	2.12	1.85	3.44
Volatile Solids, %	75	75	76	75	75
Total N (ppm)	35,000	16,000	17,000	13,000	16,000
Ammonia-N (ppm)	3,063	2,210	4,290	460	400
Organic-N (ppm)	32,010	13,913	13,583	12,940	15,476
Nitrate-N (ppm)	342	620	233	300	172
C:N Ratio	16:1	13:1	19:1	13:1	12:1
Orthophosphate (ppm)	12,631	-	4,137	5,833	4,482
Oxygen, %	-	-	10	-	-

Table 30 (Cont.)

Parameter	Day 0	8	13	20	32
	3:1 Ratio				
Coliforms (MPN/g)	80	4.8×10^6	2.2	2.2	0
pH	6.7	6.93	6.77	5.9	5.6
Temperature, °C	20	64	74	58	47
Moisture, %	81	69	73	70	66
Carbon, %	27.94	31.36	29.15	31.69	30.51
Hydrogen, %	3.22	3.67	2.74	2.74	3.39
Nitrogen, %	1.83	3.00	2.05	2.6	2.16
Volatile Solids, %	75	76	77	72	70
Total N (ppm)	35,000	12,000	-	14,000	14,000
Ammonia-N (ppm)	3,063	290	-	140	25
Organic-N (ppm)	32,010	11,832	-	13,966	13,738
Nitrate-N (ppm)	342	387	111	216	103
C:N Ratio	16:1	11:1	15:1	11:9	14:1
Orthophosphate (ppm)	12,631	-	5,172	4,666	4,411
Oxygen, %	-	-	17	-	-

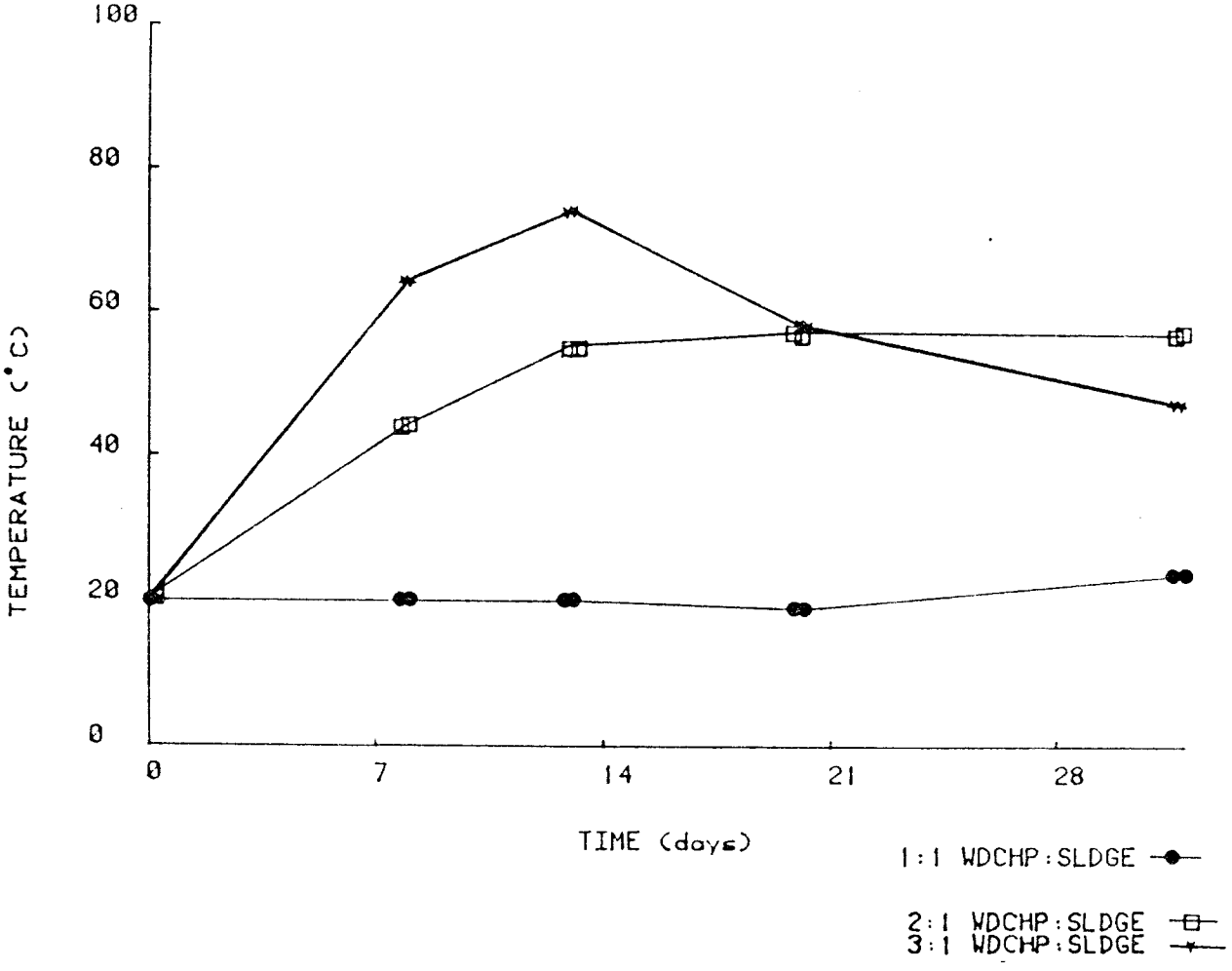


Figure 21
Effect of woodchip: sludge ratio on compost pile temperature.

Moisture content, pH, volatile solids content and C:N ratio were similar in all three piles over time for both runs. The second run, however, showed a greater moisture content reduction in the 3:1 pile than in the 2:1 and 1:1 piles.

Bacterial indicator kill occurred similarly in the 3:1 and 2:1 piles due to the high temperatures attained there. A decrease in coliforms was noted in the 1:1 pile, but due to the lower temperature, the bacterial population was able to survive the composting process.

Oxygen levels in the 1:1 pile ran around 4 to 8 percent over the composting period. In the 2:1 pile oxygen content averaged 10 percent, and in the 3:1 pile it was 16 percent. This indicates that the 1:1 pile could indeed be considered to be oxygen deficient, having oxygen levels generally less than 5 percent. The 2:1 and 3:1 piles were considered optimal for composting, considering the oxygen levels present.

The Fate of Nutrients During Sludge Composting

Nutrient balance studies were performed both on the full-scale primary/secondary compost piles and on the pilot-scale compost piles used for the aeration rate and woodchip:sludge ratio experiments. The full-scale piles were monitored to serve as controls, to ascertain the ranges of nutrients present in the compost, and to characterize the background levels and expected changes over time. The pilot-scale compost piles were monitored to determine the effects of varied operating conditions on nutrient mineralization or mobilization.

Nutrient data for the full-scale piles is shown in Table 9. Figure 22 shows the trends observed in nitrogen transformations during composting of sewage sludge. This figure presents averaged data for the two full-scale

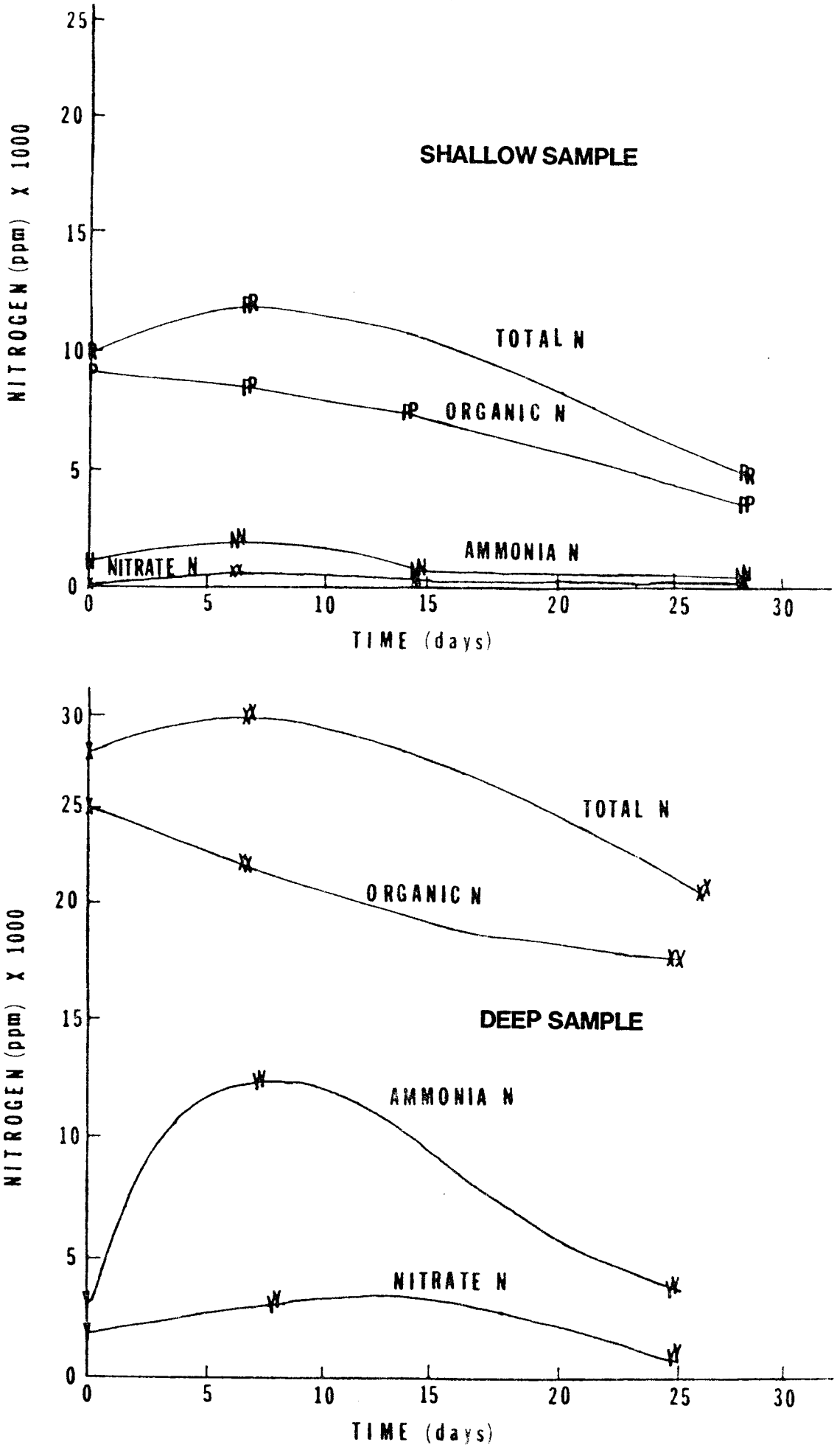


Figure 22
Nitrogen transformations during composting of primary/secondary sludge.

piles studied. It can be noted that organic nitrogen decreased over time, while ammonia nitrogen initially increased sharply until a peak was reached at approximately day 7 - 10. The ammonia nitrogen concentration then began to decline, accompanied by an increase in nitrate-nirogen concentration. The nitrate nitrogen peak occurred on approximately day 14, followed by a decrease. Similar trends were seen to occur in both shallow and deep samples, (approximately 12 inches and 3-4 feet, respectively), except the concentrations and magnitude of changes in the shallow samples were less.

The results from the first variable aeration rate experimental piles, in which aerated and nonaerated piles were compared, are presented in Table 27. The aerated pile showed a greater decrease in organic nitrogen (Figure 23) and a greater increase in nitrate nitrogen (Figure 24) accumulation over time. The non-aerated pile showed a greater accumulation of ammonia nitrogen over time (Figure 25) which indicates that nitrification, which is an aerobic process, did not occur in the nonaerated pile to the extent that it did in the aerated pile. This seems to indicate that the aerated pile conditions favored nitrogen mineralization.

The nutrient monitoring results from the second variable aeration experiment are presented in Table 28 and Figures 26 through 29. Similar trends to that above are observed here. Nitrogen mineralization was greatest in the pile aerated at 400 scfm. This is indicated by the greatest net decrease in organic nitrogen and the greatest accumulation over time of nitrate nitrogen. The nonaerated pile exhibited the greatest accumulation of ammonia nitrogen.

Results from the woodchip:sludge ratio experiments (Tables 29 and 30) indicate that the 3:1 pile provided for the greatest nitrogen mineralization (Figures 30 through 33). This pile exhibited the greatest total reduction in organic nitrogen and greatest nitrate nitrogen accumulation over the composting

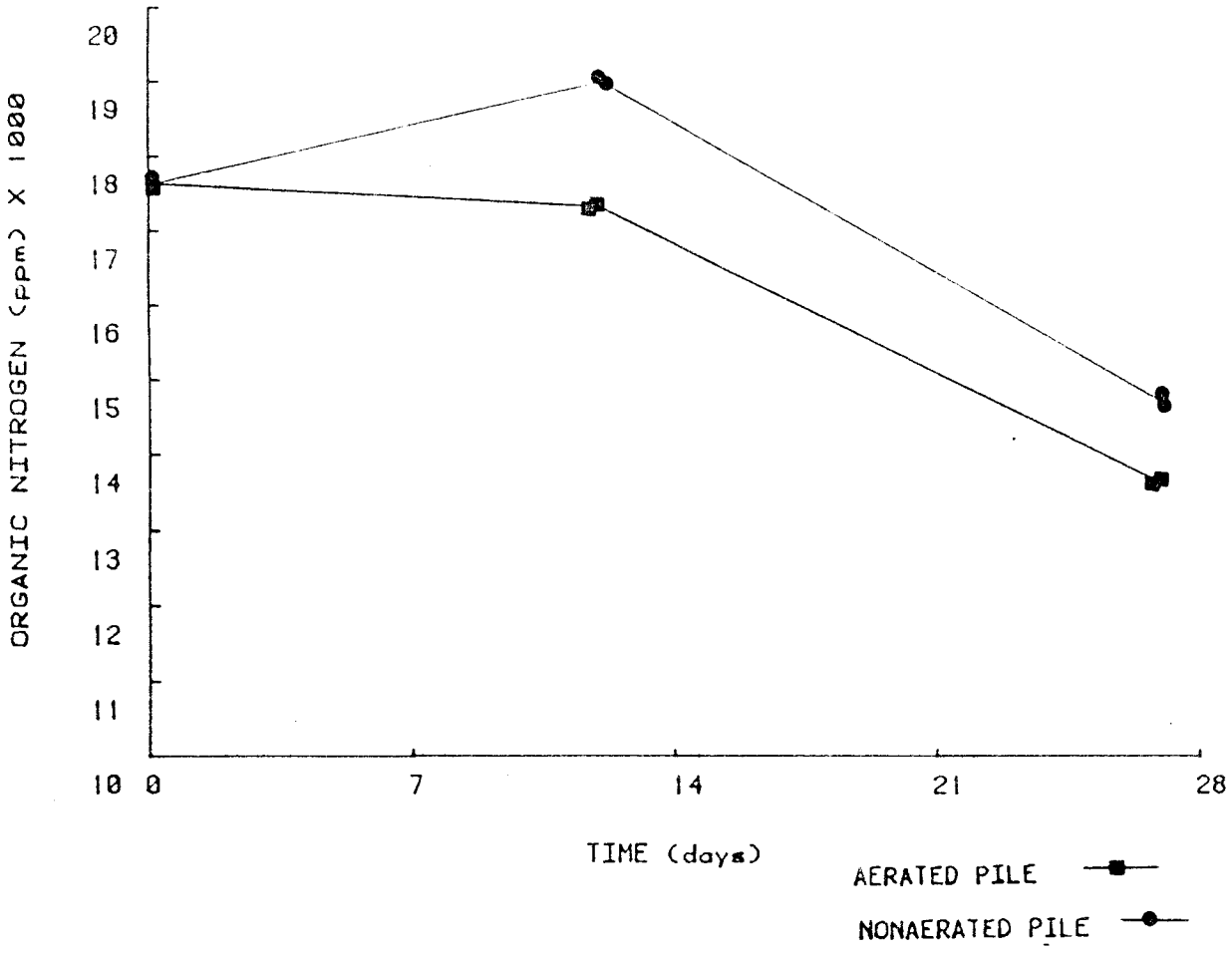


Figure 23
Changes in organic nitrogen content of compost in aerated and nonaerated piles.

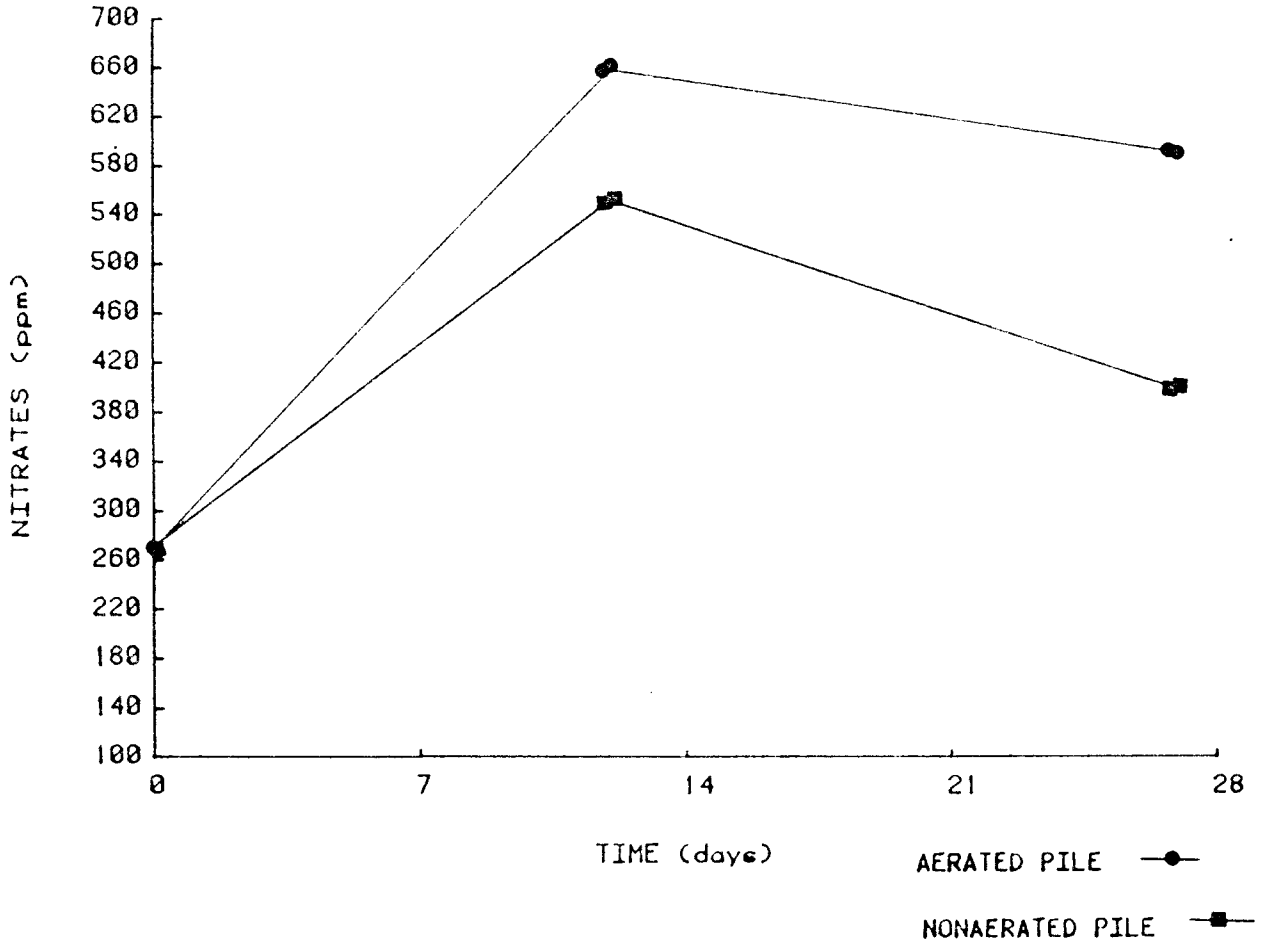


Figure 24
Changes in nitrate nitrogen content of compost in aerated and nonaerated piles.

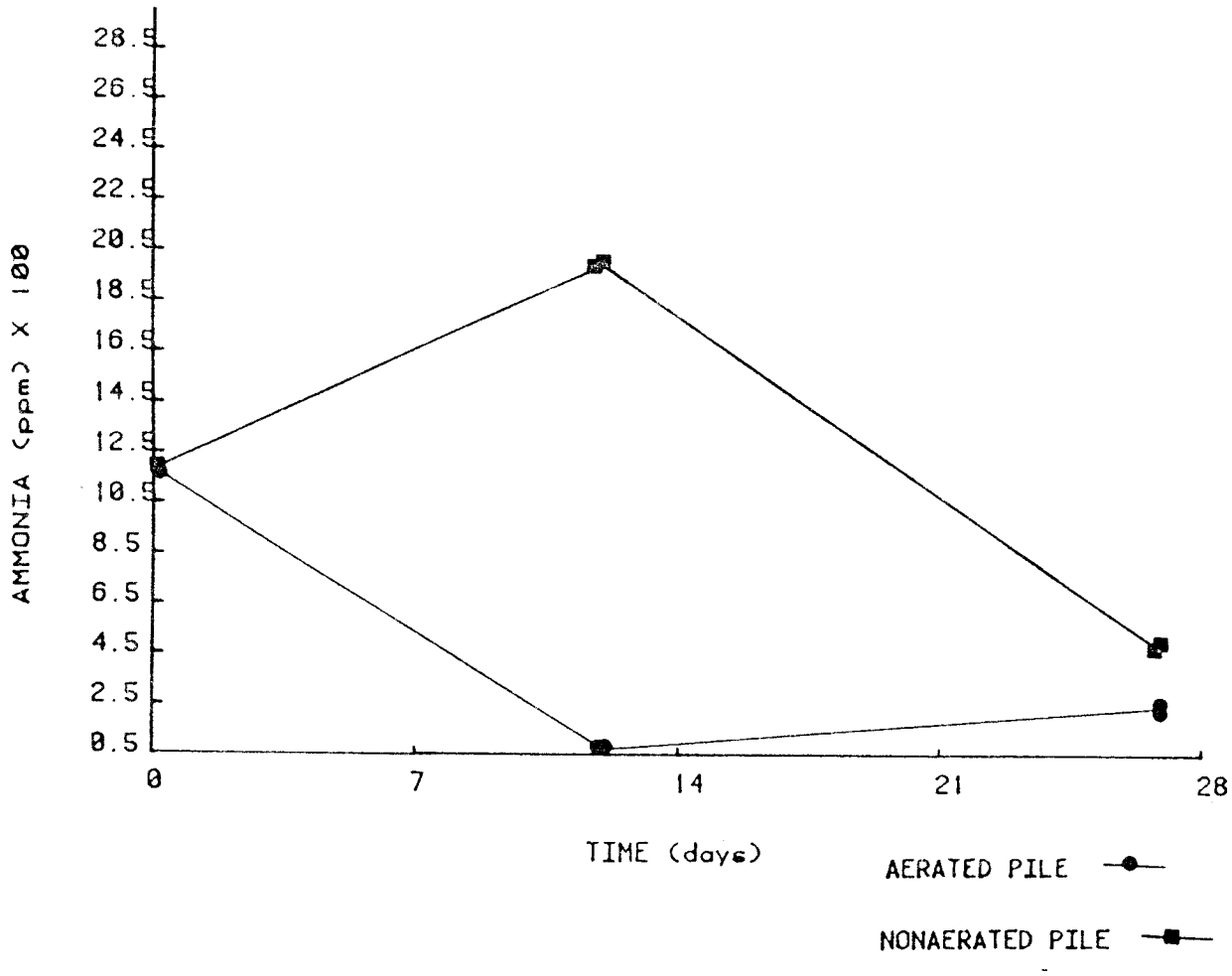


Figure 25
Changes in ammonia nitrogen content of compost in aerated and nonaerated piles.

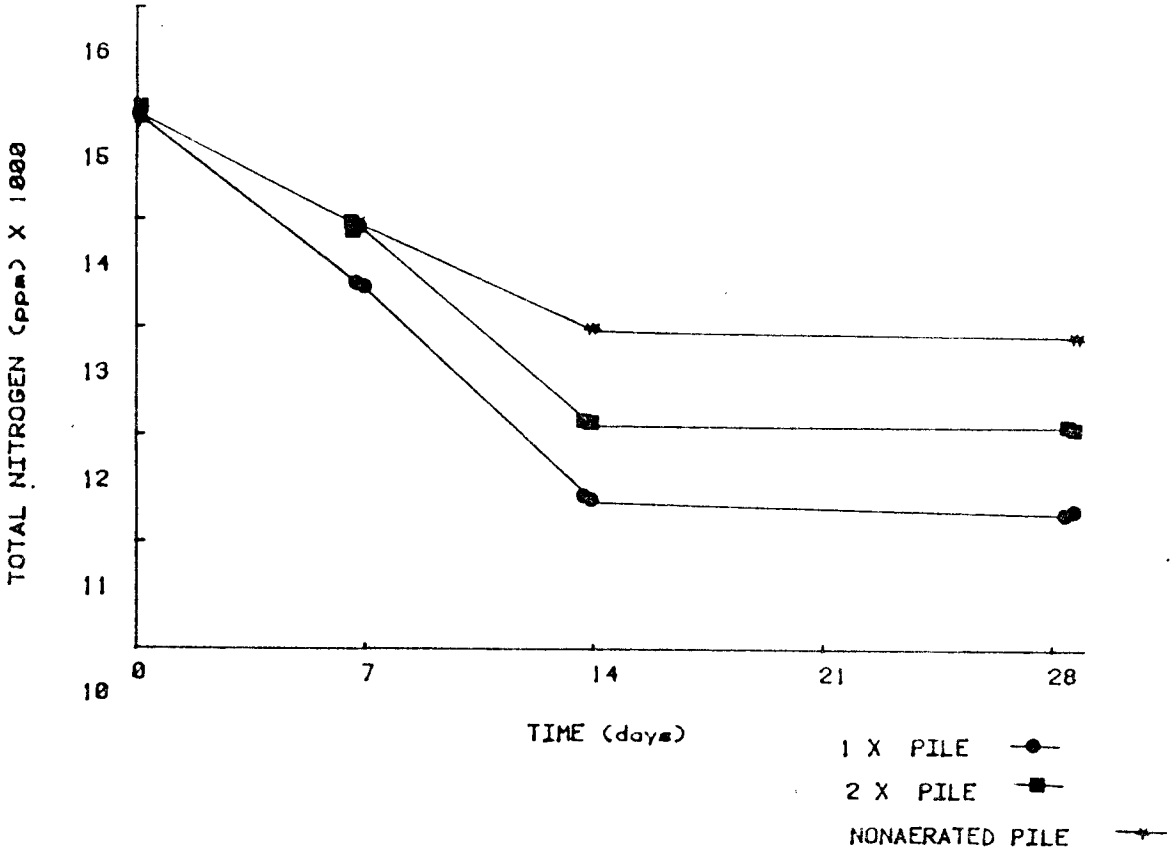


Figure 26
Effect of aeration rate on total nitrogen in compost.

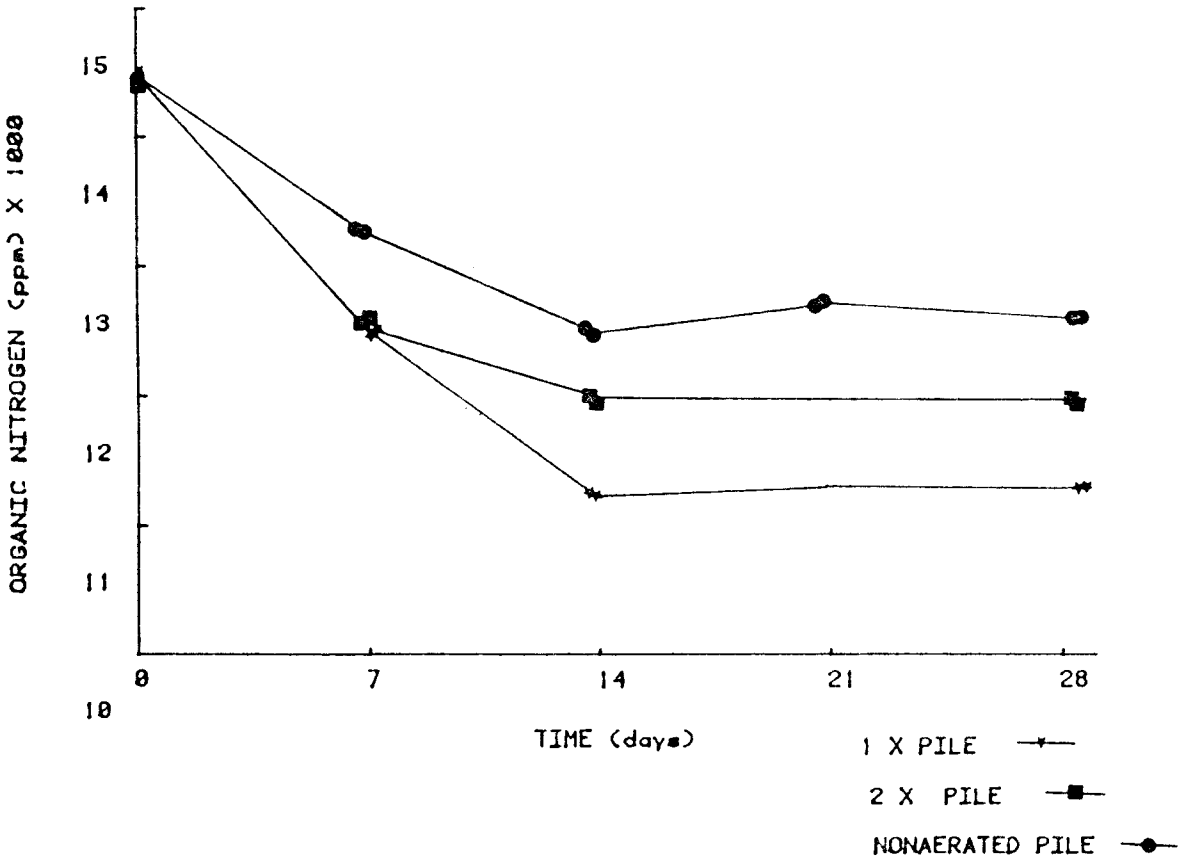


Figure 27
Effect of aeration rate on organic nitrogen in compost.

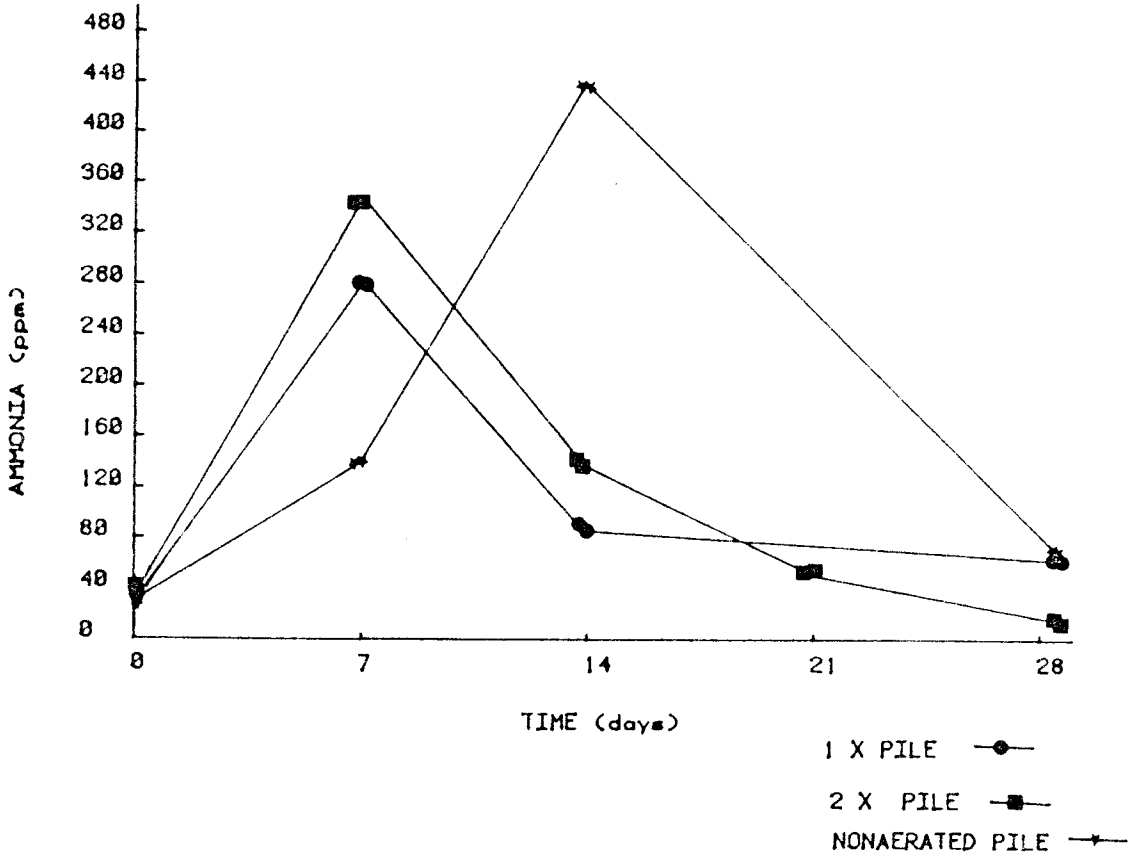


Figure 28
Effect of aeration rate on ammonia nitrogen in compost.

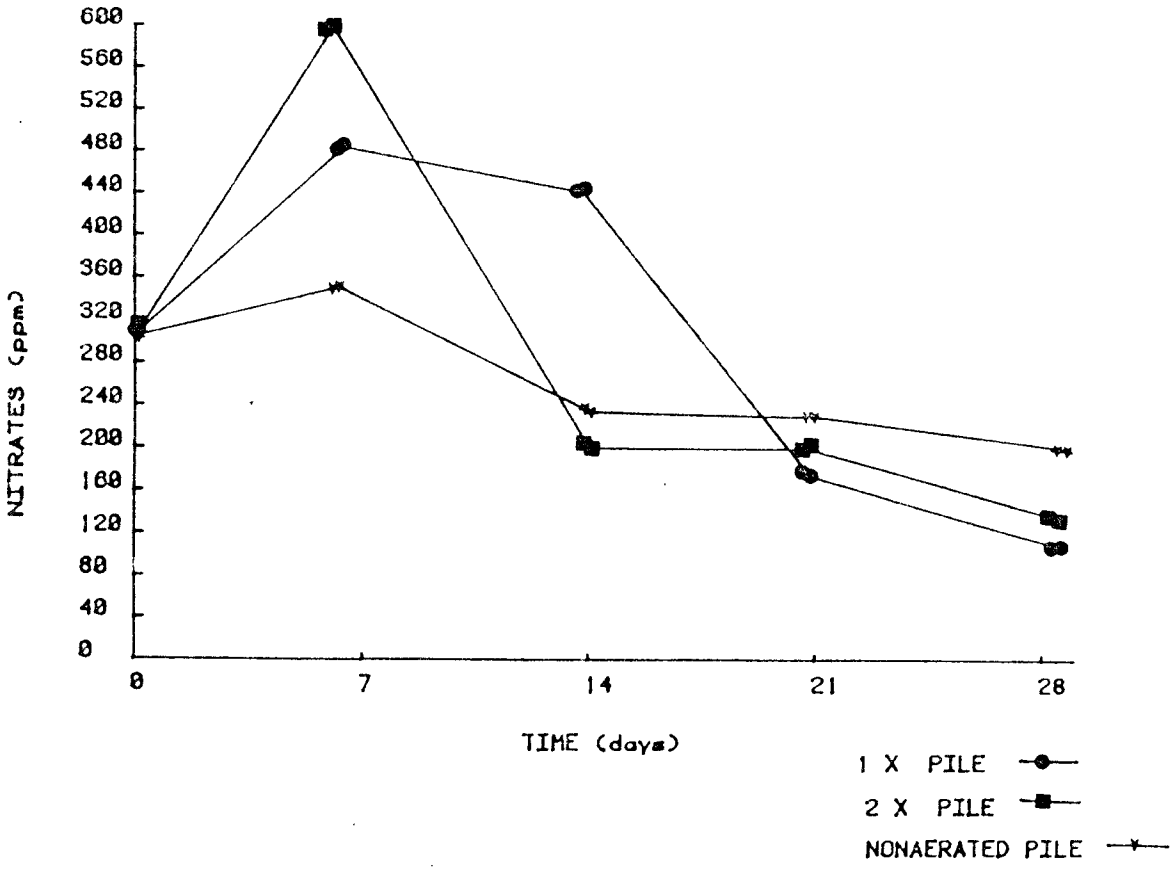


Figure 29
Effect of aeration rate on nitrate nitrogen in compost.

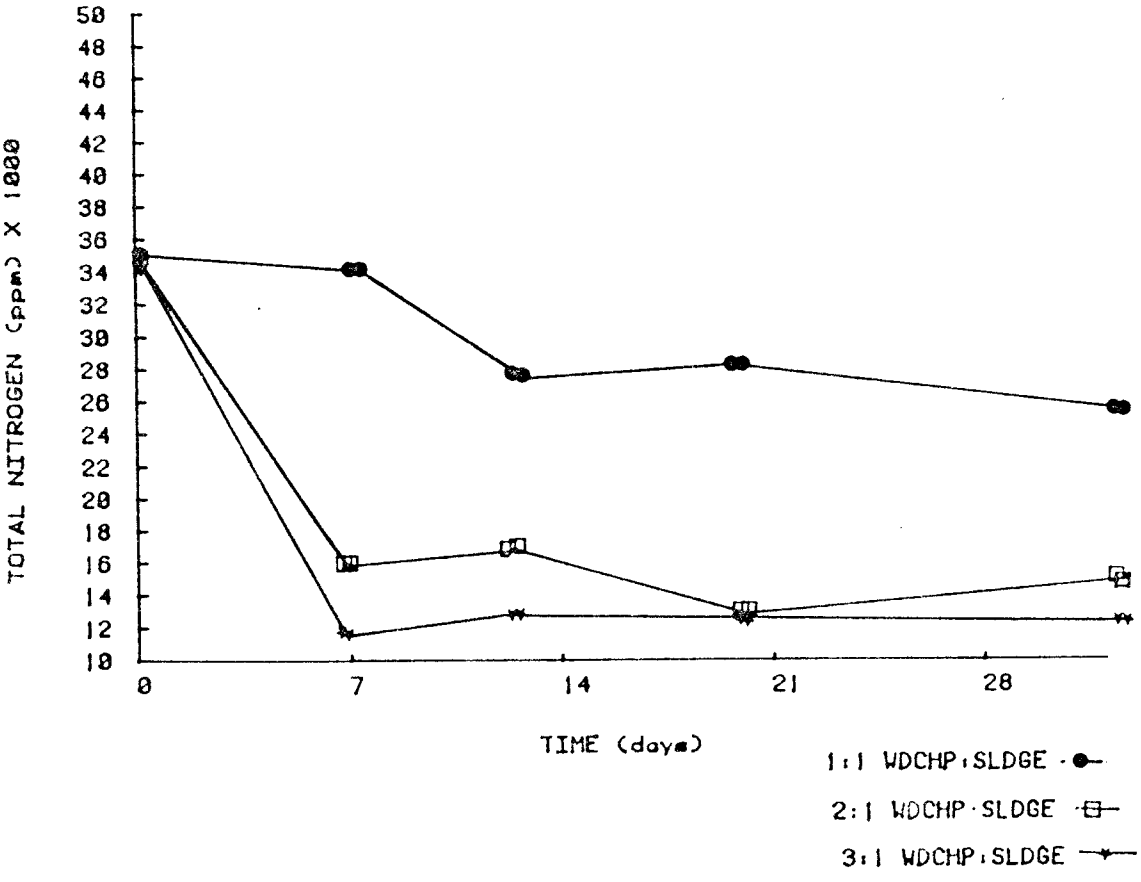


Figure 30
Effect of woodchip: sludge ratio on total nitrogen in compost.

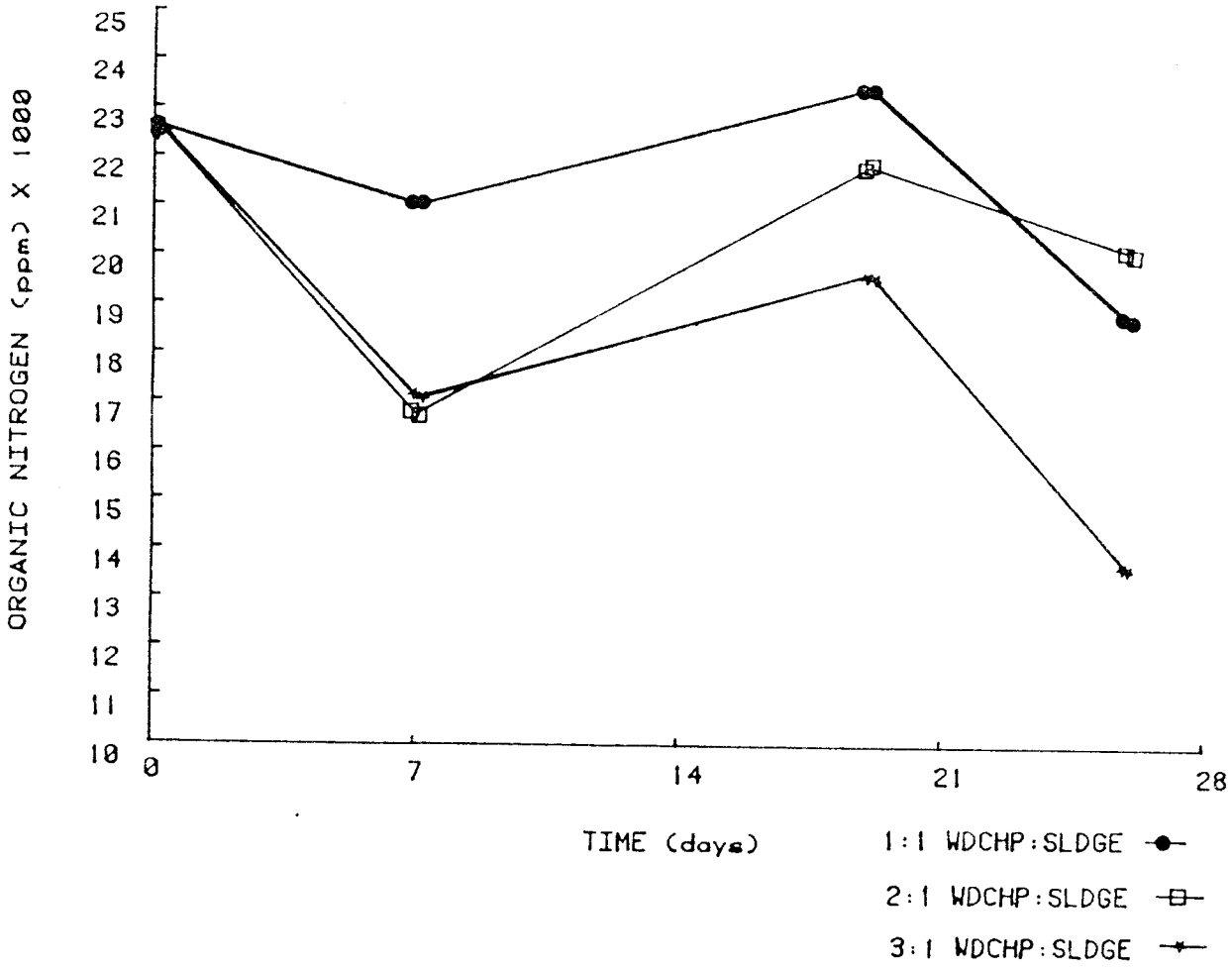


Figure 31
Effect of woodchip: sludge ratio on organic nitrogen in compost.

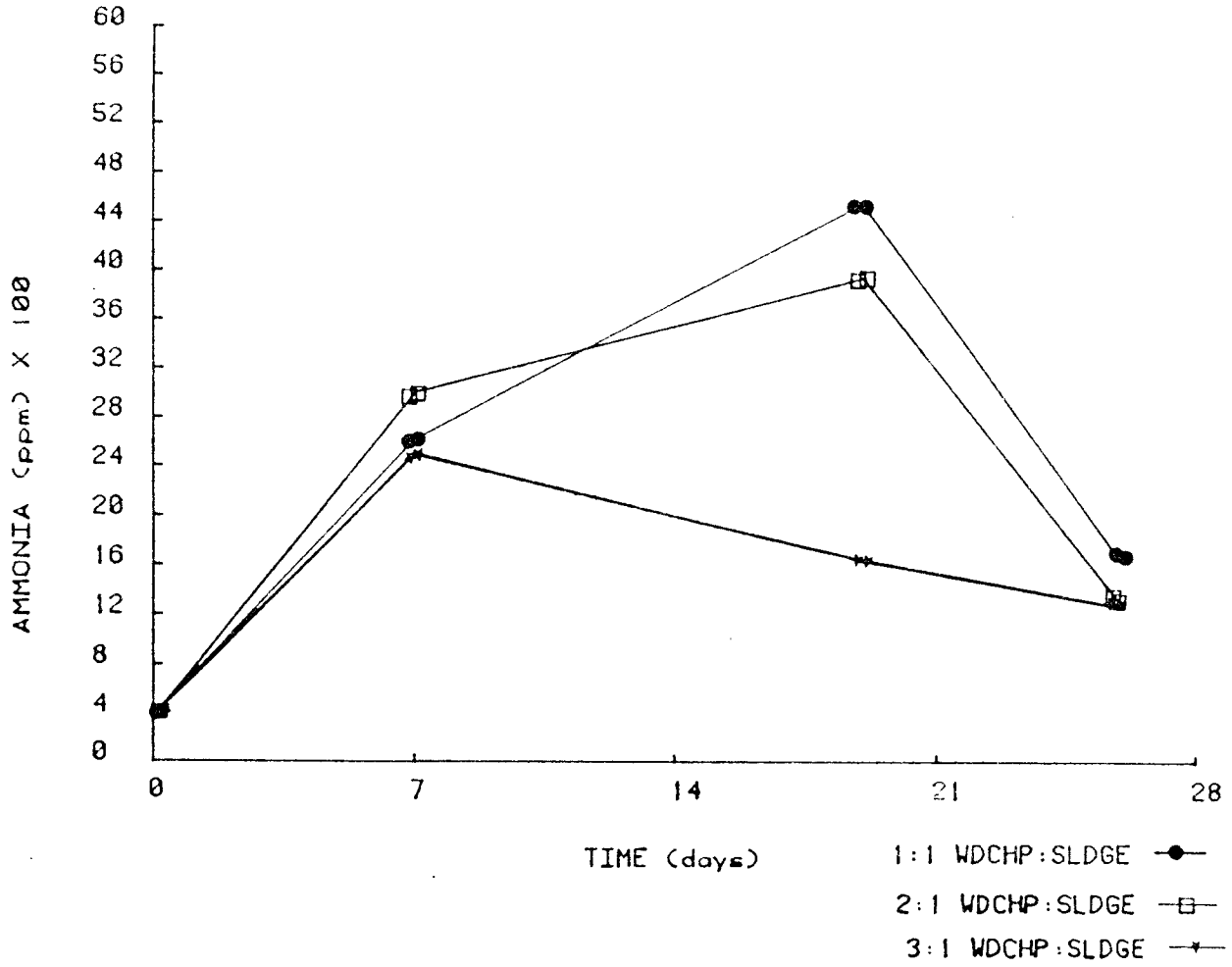


Figure 32
Effect of woodchip: sludge ratio on ammonia nitrogen in compost.

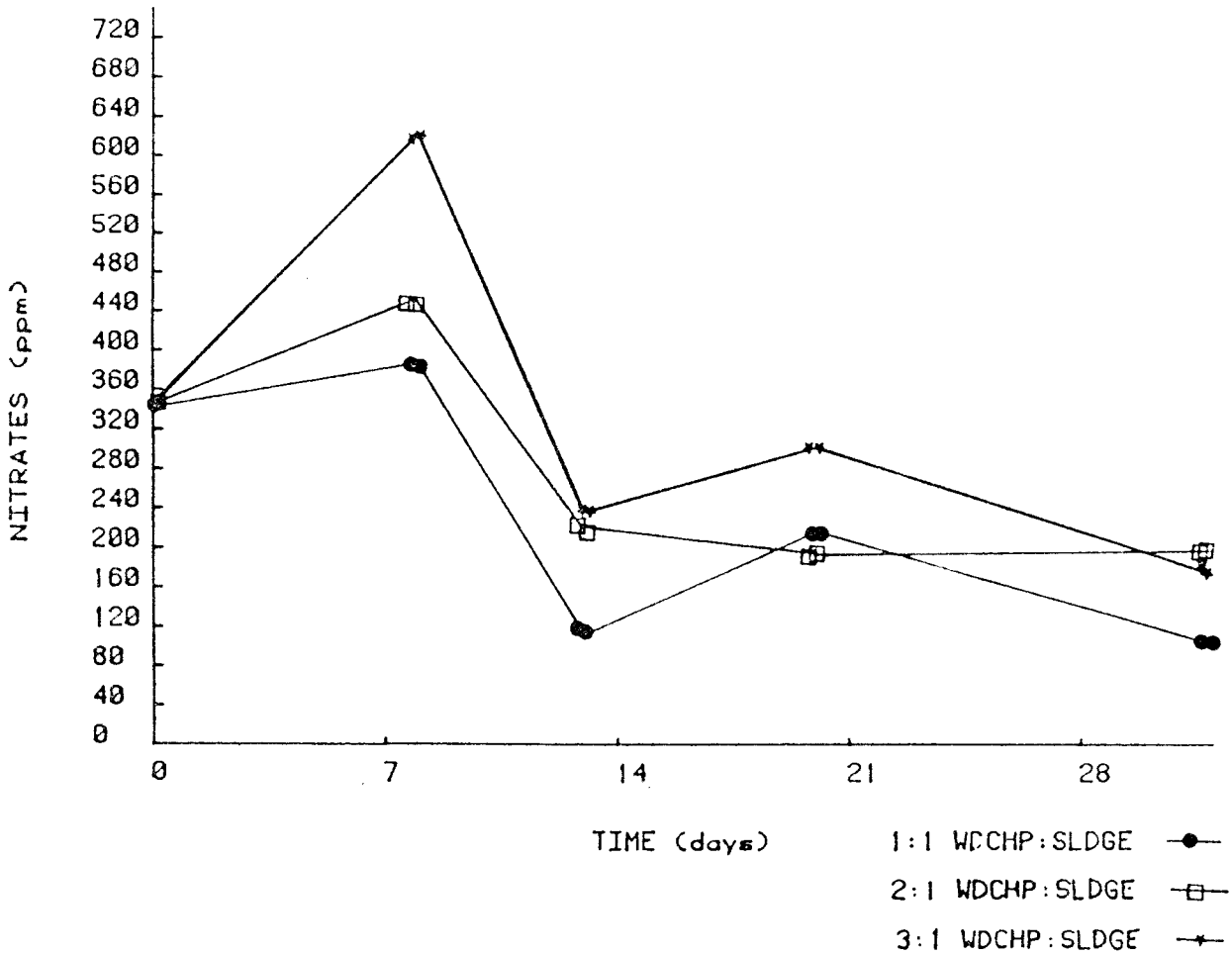


Figure 33
Effect of woodchip: sludge ratio on nitrate nitrogen in compost.

period. The 2:1 pile showed similar but slightly lower results. The 1:1 pile showed the greatest ammonia nitrogen accumulation and the least nitrate nitrogen accumulation. This is consistent with the lack of oxygen present, since nitrification is an aerobic process.

CHAPTER 7

DISCUSSION OF RESULTS

Pathogen Survival in Compost

Analyzing the survival of pathogenic organisms and the factors which affect their survival during forced aeration composting is very complex. It is difficult to deal with the compost mass as an entity since it is actually composed of an infinite number of microenvironments. The activities of the organisms involved in composting occur in these microenvironments and oftentimes measurements taken in the bulk of the compost mass do not represent the conditions of these smaller habitats. With these limitations, it is difficult to firmly establish exactly what is occurring during the process and why. However, an overall view is possible, and some conclusions concerning the operation of sludge compost piles and survival of pathogens can be made.

Some consistent patterns are noted in the growth of the organisms enumerated. The two predominant factors suggested in the literature for the destruction and regrowth of pathogens are temperature and antibiotic activity (36,38,101). An analysis of antibiotic activity was not included in this study, but the temperature of the compost mass at both shallow and deep locations was measured.

During the first part of this research, work was performed to determine the rate of pathogen kill in composting primary sludge and the parameters affecting pasteurization. It was found that the presumptive pathogen kill, based on the kill of the indicator organisms, fecal coliforms and fecal streptococci, was achieved when the deep section of the pile maintained thermophilic temperatures (Figures 13 through 15). Temperature profiles showed that in the deep center of the pile the temperatures reached a thermophilic peak of approximately 85°C. However, the sides and shallow areas of the pile maintained

temperatures below or barely into the thermophilic range. Although the shallow areas occasionally did reach a thermophilic peak of 65°C, this high temperature was not maintained long enough to achieve kill.

The pathogen indicator counts shown in Figures 13 and 14 may be inflated because of contamination from shallower samples during sampling. The sampling technique was modified after these studies were completed and the new technique, which prevented any chance of contamination, was used thereafter. Consequently, the results from the third primary sludge compost pile, shown in Figure 15, are probably more representative of what is actually occurring. This figure indicates substantially greater reductions in fecal coliforms and fecal streptococci in the deep section of the pile where temperatures are highest. As can be seen, though, even at these very high temperatures a small number of indicator organisms still survive. The high temperatures recorded suggest that most pathogenic organisms should have been eliminated. However, as several other investigators have noted (9,10,70,100), high temperatures alone do not necessarily guarantee destruction of pathogens. Both fecal coliforms and fecal streptococci were detected in the Durham compost despite lethal temperatures. It is highly probable that the temperatures measured did not represent those temperatures to which the organisms were exposed. Clumping or aggregation of the material is one way by which the organisms could be protected from lethal temperatures. It is possible that within the samples extracted for analysis, the organisms were protected from the surrounding temperatures by these clumps or aggregates of compost, as is suggested by Passman (70). Passman also notes that many other factors can diminish the lethal effect of high temperatures.

There is a definite relationship between the temperatures measured and the patterns of fecal coliform and fecal streptococcus survival. Decreases in

counts of both organisms occurred when the temperature measurements remained high, i.e. greater than 50°C. Once the temperatures dropped below this level, the decreases in numbers of organisms either declined, or in some cases, the numbers of organisms increased.

Results from monitoring of mixed primary/secondary sludge compost piles were virtually identical to the findings for primary sludge composting, although the mixed piles took longer to reach their thermophilic peak. Because Durham constructs extended piles, the mixed sludge could have sat on the composting pad for 2-3 weeks before it was forcibly aerated. Under these conditions, pasteurization often occurred from the microbial heat generated while the material was being held on the pad pending completion of the pile.

Growth in the shallow layers of the secondary piles paralleled that of the primary piles. The temperatures remained low enough in the shallow layers to support a fluctuating population of both fecal coliforms and fecal streptococci, while the temperatures in the deep samples were prohibitive to any significant growth of these organisms (Figure 16). Coliform counts in the shallow samples actually increased, due to regrowth, as the pile began to cool down.

Analyses for the fungus Aspergillus fumigatus show that, although counts decreased at high temperatures, the decrease was not substantial and regrowth occurred when the compost temperatures dropped back into the mesophilic range (see Tables 11, 12 and 17).

The pH of the compost material does not appear to affect the fate of the organisms to a noticeable degree. Compost pH is directly affected by the composition of the sludge and woodchips, temperature, the organisms present and their mode of growth, and a myriad of other factors. However, in general the pH fluctuations with time and from location to location within a given pile were relatively minor and had no effect on pathogen survival.

Compost moisture content may have an effect on the survival of organisms during composting. The presence of water in the interstitial spaces of the compost actually has a dual function. Ironically, although water is necessary for organisms to reproduce and in doing so stabilize the compost material, it is also a factor in their destruction. Moist heat is more lethal than dry heat to those organisms exposed to it. Therefore, with lethal temperatures but relatively low moisture levels, increases in the levels of some organisms may occur.

In general, moisture contents did not change appreciably during these composting studies, although it did appear that higher temperatures resulted in lower moisture contents, probably due to a greater degree of evaporation at the higher temperatures. Moisture content is also affected by ambient conditions, including temperature, precipitation and wind. This is especially true for the outer edges of a pile. The small differences between moisture contents in these piles suggests that the effects of these ambient conditions may balance out by the differences in evaporation. It should be noted here than the Durham Wastewater Treatment Plant was using an organic polymer for sludge thickening during this study and this seemed to result in less drying than when lime and ferric chloride were used later. This polymer seemed to have a high affinity for water holding.

Pathogen survival studies were also conducted using the woodchips from the compost operation. These chips were shown to be free of the pathogen Salmonella heidelberg, but when the organism was seeded onto used woodchips it was able to survive for up to two weeks. A 3-5 log reduction in S. heidelberg occurred during the first week.

Pathogen Survival in Compost During Curing

The counts of the indicator organisms in the finished compost raised the question of the ability of an overt, enteric pathogen to survive on this substrate. The New Hampshire Water Supply and Pollution Control Commission has recommended a six-month holding period to insure product safety before distribution of the compost to the public (33). From our experience with the indicator organisms, we expected that this arbitrary holding period was longer than necessary. Consequently, a study was designed to appraise the survival of Salmonella heidelberg in the finished screened product from the composting of primary/secondary sludge, and to determine the effect, if any, of the addition of varying amounts of soil to the curing compost. Secondary objectives included enumeration of indicator organisms and correlation of their survival with that of the salmonellae, and estimation of survival of naturally occurring Aspergillus fumigatus in screened compost. A strong positive correlation between indicator organism destruction and loss of salmonellae would provide an easily performed test for the quality and safety of the finished product. A. fumigatus has been recovered from all phases of the composting operation in Durham except, possibly, the thermophilic centers of the piles. However, the fate of this organism over time had not been studied in the finished compost.

The results of the curing stage studies performed show seeded salmonellae to be undetectable after the third week of curing, and the indicator organisms below detectable limits by the end of the 6 month testing period (Table 15).

The glucose saturation experiments were designed to determine if the salmonellae, fecal coliforms, and fecal streptococci were all killed or only appeared to be so because of limits of detection in the initial tests. Table

16 suggests that there was an undetected population of the indicator organisms in the compost at the end of the testing period, but not of salmonellae. This test also suggests that even if the finished compost is put under presumably ideal conditions, the salmonellae do not regrow.

Table 15 shows that both curing stage samples had initial populations of indicator organisms of 10^2 - 10^4 organisms per g. It is reasonable to assume that these high numbers of indigenous organisms in the field samples, and possibly other native organisms which were not counted, were detrimental to the survival of the salmonellae. Klein and Casida (58) found approximately 10^7 cells/g in sandy soil. This concentration increased to 10^9 cells/g when the soil was supplemented with 0.10 percent glucose. Since the finished compost is relatively rich in organic nutrients (C:N=16:1), the 10^9 estimate for Klein and Casida's supplemented soil probably approaches a minimum total count in the finished compost. Studies done at the Sandia Laboratory showed that coliforms effectively inhibited growth of salmonellae (79). This conclusion was more rigidly tested in a subsequent study at the same laboratory (80). They found that S. montevideo and E. coli grew rapidly both in sterile compost in separate systems and when inoculated simultaneously at the same concentrations. However, if the compost had been saturated with this particular strain of E. coli prior to the salmonellae inoculation, inhibition of the salmonellae growth was effective. S. typhimurium grew well in the sterile compost, but poorly in the compost saturated with a mixed coliform culture, which was more effective in competing with salmonellae than the pure E. coli strain. The E. coli-saturated compost showed a normalized S. typhimurium population of 10^2, versus 10^4 in the sterile compost. The S. typhimurium grew to 10^4 in the sterile compost, but only to 10^1 in compost saturated with mixed coliforms.

A related study by Yeager and Ward (104) done with raw sludges showed that seeded S. typhimurium grew in the presence of indigenous organisms in both raw and dewatered sludges, but failed to reach the population densities which had been attained in sterilized raw and dewatered sludges. In natural sludges, the salmonellae dropped below detectable limits in a few days, but there was little decline in the population in previously sterilized sludges.

The analogy to the curing stage situation is clear. The screened compost was already highly populated with coliforms (Table 15). This coliform population was certainly a mixed one, accounting for the parallel results in the field experiments and the Sandia Laboratory studies.

The nature of the competition was not discernible in this study, but the Sandia Laboratory report assumes the competition to be at the nutrient level (81). Since salmonellae is a member of the Enterobacteriaceae, as are E. coli and the coliforms in general, one would expect their nutritional needs to be similar. These similarities would account for the competition for nutrients, but not for the consistent success of E. coli at the expense of salmonellae. The explanation is probably at a more subtle level than simple nutrient competition. It may lie in the utilization of available nutrients. If the coliforms in general, and E. coli in particular, can subsist on lower levels of a given nutrient, transport nutrients into the cell more efficiently, or derive more energy from nutrients via alternative pathways, they may have a competitive edge over the salmonellae. The salmonellae are not known to survive as well as the other coliforms under identical conditions. The easy detection of coliforms as indicators of fecal pollution is an example of this. Unless salmonellae pollution has been recent, localized and massive, salmonellae itself will die off and escape detection leaving the surviving coliforms as indicators of its present.

Klein and Casida (58) investigated a related situation in which E. coli die-out in normal soil was related to nutrient availability and normal soil flora. They concluded that the organism died out in the soil as a result of its high maintenance energy requirement in relation to that of the soil flora. The E. coli could not reduce its metabolic rate to meet the low organic carbon availability in the soil. A similar effect has been observed in seawater where organic matter levels were sufficient to maintain native marine organisms, but not E. coli (6). If E. coli, which is more tolerant environmentally than salmonellae, is unable to reduce its metabolic rate under limited nutrient conditions, one would expect to see salmonellae die-out even more quickly under the same conditions. This is assuming that the environmental fragility of salmonellae is directly related to a high metabolic demand.

Thus, carbon/nitrogen ratios can often be a determining factor in micro-organism survival in soils. Russ and Yanko (78) determined that composted sludges with C:N ratios of approximately 15:1 or lower did not support regrowth of salmonellae. The theoretical C:N ratios in this study ranged from a low of 15:1 in the poor soil/compost mixtures mixed at a ratio of 1:1 to a high of 22:1 in good soil/compost mixtures mixed at a rate of 1:1. These values fall into the range capable of supporting salmonellae growth, suggesting that competition from the coliforms, rather than a nutrient limitation in the compost, had a major effect on salmonellae survival.

The compost did not constitute a suitable growth medium for A. fumigatus which had survived in the mesophilic area of the piles either. Combined with a lack of thermophilic temperatures in the finished compost to destroy the spores, it is not surprising that a relatively constant population of 10^4 - 10^5 cfu/g, wet weight, was maintained throughout the study. These findings are supported by Millner et al. (65) who found A. fumigatus ubiquitous and

relatively constant in all sub-thermophilic phases of the composting operation.

Monitoring of several composting sites in the State of Maine found no significant public health hazard from either background or transient operation related aerospore concentrations. Only those workers engaged in onsite activities associated with elevated aerospore counts, e.g. screening or wood chip manipulation, would be at any inhalation risk. This additional health risk to workers could be minimized by screening individuals for any predisposing conditions, and by requiring operators to wear dust filtering masks (71).

From these curing stage results, one would reasonably expect to see the same declining population patterns in a bench scale set-up. It was assumed from the difference in salmonellae populations at 1 week in the field (Table 15) that the addition of soil, by its quantity and/or its quality, had a detrimental effect on salmonellae survival. This, however, was not the case. Neither the quality nor the quantity of soil seemed to have a consistent or predictable effect on the salmonellae population (Table 19). Likewise, there was no consistent effect attributable solely to temperature. The controlled variables whose effects were measured showed only negligible effects. This conclusion is in contrast to the results of the field studies. The difference between the two studies appears to lie with the initial population of fecal coliforms and fecal streptococci in the samples. Table 15 shows that both curing stage samples had initial populations of indicator organisms of 10^2 - 10^4 organisms per g. Table 24 shows, with one exception, indicator counts in the bench samples were less than 20 organisms per g.

In the absence of significant coliform competition (Table 24), moisture may account for the salmonellae die-off seen in the bench scale studies. Russ and Yanko (78), in their work on the effect of moisture content on long-term

survival of salmonellae in sludge, found that a moisture content of 20 percent was required for salmonellae survival. Yeager and Ward (104) found a similar effect in sludges in that a minimum of 15 percent moisture was required for regrowth of bacterial isolates in sludge. Approximately 86 percent of the samples in this research fall above this 20 percent criterion. Slightly over 70 percent of the samples with less than 13 organisms per g have moisture levels below 10 percent.

Bacterial survival has often been measured as a function of time in dried soil. Viable counts of Pseudomonas declined by a factor of 100 within a month of inoculation (76). Arthrobacter under similar conditions showed a 50 percent initial decrease, then remained viable for at least six months (5). Azotobacter was found to remain viable for as long as 13 years (98). It would appear that the cysts of Azotobacter allow it to retain viability (87), while the vegetative cells of Pseudomonas and Arthrobacter are more susceptible to elimination. Although Arthrobacter does not possess any obvious resting structure, it is hypothesized that the rod-to-coccus conversions of the organism may confer upon it some resistance to desiccation over that of the more conventional vegetative cell, e.g. Pseudomonas.

Salmonellae possess no specific dormant structure nor do they undergo the extreme morphological changes of Arthrobacter. In this respect, then, they are analogous to the Pseudomonas in the above-mentioned study. It is not surprising then that we see a rapid elimination of salmonellae under desiccation conditions.

Variations in pH appeared to have little effect on survival in this study. Most organisms can tolerate a pH range of 3-4 units around their optimum, although rapid growth is restricted outside a range of one unit or less (14).

Pathogen Survival in Compost Amended Soils

During the course of this project, there were two ongoing field studies. The study which monitored indicator organisms at compost amended sites in Durham showed the fecal coliforms and fecal streptococci virtually gone during cold weather after 18 months from amendment. Regrowth occurred during the warm summer months. After 2 years, the fecal coliforms failed to regrow to any significant levels and could be considered gone. The fecal streptococci appeared to stabilize after the same period, but at a much higher level than the fecal coliforms (Table 13).

A more strictly controlled field experiment was conducted over the course of a year. Woodchips sifted from the Durham piles were either layered or mixed with lawn soil on a small farm in Durham. As in the amended soil study, spiking regrowth occurred during the hot summer months, but the regrown organisms never reached the original concentrations. During most of the year, the counts were 0 cfu/g, or nearly so (Table 14).

The Fate of Nutrients During Sludge Composting

Two full-scale primary/secondary sludge compost piles were monitored to characterize the concentrations of the various nitrogen forms present, and the magnitude of changes which occur during composting. Subsequent to this, two environmental parameters were alternately varied in pilot-scale composting piles in an effort to ascertain their individual effects on the composting process, and more specifically, their effect on the mineralization of nitrogen. The parameters studied were variable aeration rate and woodchip:sludge ratio. In addition, the carbon:nitrogen ratio was determined during composting of primary sludge.

The generally accepted optimum C:N ratio is 25:1, which insures that carbon and nitrogen are present in adequate proportions for growth and decomposition of the wastes (38). The ratio measured for Durham raw sludge averaged 15.8:1. (Raw sludge is often as low as 11:1.) Woodchips were added to adjust the ratio to approximately 25:1 by increasing the carbon supply, a common practice in sludge composting. However, the carbon supply in woodchips is not readily degradable by most organisms in the compost system. The carbon: nitrogen measurements presented in this report, which were made without the woodchips, may therefore be more indicative of what the actual C:N ratio available to the organisms is.

The average C:N ratio at the onset of primary sludge compost averaged 15.0:1 and at the finish, 12.5:1. This decrease was the result of degradation of the carbonaceous matter both biologically and chemically.

Evaluation of the full-scale primary/secondary sludge compost piles showed that the trends which occur in wastewater treatment and in nature for nitrogen mineralization also occur during the composting process. This agrees with the findings of Tester's work (91,92) on N-mineralization in soil-compost amendments. There is a net reduction of total nitrogen in the system, as can be seen in Figure 22. This occurs via mineralization of organic nitrogen, subsequent volatilization of ammonia, and denitrification. Ammonia volatilization is favored by a pH above 7.0, and high temperature. Denitrification is favored by anaerobic or microaerophilic pockets which undoubtedly exist in the nonhomogenous mixture. Due to the nature of the mixing, masses of unmixed material occur which may exhibit anaerobic pockets in which denitrification could occur.

Total nitrogen in the deep samples is seen to increase initially and then decrease. This may have been due to the activity of nitrogen-fixing bacteria

which have been shown to be present in compost, particularly during the mesophilic stages (15,16). Nitrogen-fixers generally increase their activity in the early stages of composting, decrease their activity when the temperatures rise into the thermophilic range, and then increase it again when the temperature drops.

The large concentration of organic nitrogen which initially occurs is seen to decrease over time as ammonia nitrogen concentration increases (see Figure 22). Once the ammonia nitrogen is formed, it is either consumed by nitrifying bacteria and converted to nitrite and then nitrate, or it is volatilized, depending on the environmental conditions existing in the pile. The ammonia nitrogen concentration decreases and nitrates begin to accumulate in the pile. The nitrates may be leached from the system, denitrified, or immobilized (taken back up by bacterial cells).

These results are in agreement with DeBertoldi, et al. (15,16) who found that ammonia-producing and proteolytic bacteria increase considerably in numbers and that nitrogen content generally decreases during the course of composting because of ammonia volatilization. They also reported that autotrophic nitrification was minimal at high compost temperatures and when high ammonia concentrations were present, but that nitrification increased later in the compost cycle.

Pilot-scale compost piles were used to ascertain the effects of aeration rate on nutrient transformations. Considering nitrogen mineralization, the pile aerated at 400 scfm showed the greatest decrease in organic nitrogen and total nitrogen. This indicates that these aeration conditions favored the microbial nitrogen transformations and volatilization which occur in waste treatment. The high temperature and pH (between 6.5-7.0) seemed to favor nitrogen volatilization. The nonaerated pile favored ammonia accumulation due

to the low oxygen concentrations present. The pile aerated at 800 scfm favored nitrate accumulation since nitrification is an aerobic process and there was a high oxygen concentration present. The slightly lower temperatures would also favor nitrification.

In the woodchip:sludge ratio experiments, the greatest reductions in organic nitrogen and total nitrogen occurred in the 3:1 pile. This indicated that nitrogen mineralization and volatilization were favored due to the aerobic conditions, moderately high temperatures and pH above 7.0. Greatest ammonia accumulation occurred in the 1:1 pile, again showing the less aerobic conditions. Greatest nitrate accumulation occurred in the 3:1 pile showing that the highly aerobic conditions (by virtue of greater void space) favored nitrification.

CHAPTER 8

CONCLUSIONS

The objectives of this research were listed in Chapter 2. The conclusions reached can be summarized as follows:

1. Temperatures achieved within the composting mass were generally within the thermophilic range (up to 70-80°C), but the outer edges of the pile seldom rose above mesophilic temperatures (35-50°C). All organisms isolated from the deep sections of the piles were shown to be aerobic or facultative anaerobic thermophilic bacteria. No obligate anaerobes were detected.
2. In general, pathogen kill, based on enumeration of fecal indicator organisms and of selected pathogens, was achieved in the deep sections of the piles, but not necessarily in the shallow areas where temperatures did not reach the thermophilic range. On the order of 10^2 fecal coliforms and fecal streptococci per gram of compost were still present at the end of the compost period in the shallow samples. None were present in the deep samples.
3. For perspective, these levels of pathogens in compost were compared with the naturally occurring level in the general community. It was found that commercially sold food products may have fecal indicator counts higher than what is present in finished compost, even from the outer layers of the compost pile.
4. Aspergillus fumigatus was detected at all stages of the composting cycle. Their counts decreased only slightly during composting, and regrowth usually occurred when compost temperatures dropped back in the mesophilic range.

5. It was determined that the lower detection limits for Giardia cysts and Ascaris eggs in compost is that contributed by a population containing 5-6 active cases or 600 active cases for 1000 population, respectively. It is suggested that it would be more economical and more accurate to estimate the presence of these parasites in compost from community health records showing the incidence of the disease.
6. Salmonellae and Shigella were never detected in finished compost. It would appear that elimination of salmonellae in finished screened compost is due primarily to competition from native organisms. Lacking this competition, severe desiccation can achieve similar levels of reduction in salmonellae numbers. If a composting operation is run properly, the finished product should be dry enough to desiccate any surviving salmonellae. If the product is not below the suggested 20 percent moisture, and if salmonellae have survived the composting operation, it is likely that other organisms have survived as well. This surviving population would provide the competition necessary to eliminate the salmonellae.
7. There appears to be no practical correlation between coliform counts and salmonellae survival. Likewise, soil quality, soil quantity, temperature, and pH have only negligible effects.
8. Fecal coliforms and fecal streptococci in compost added to soil can survive for periods up to two years. Their numbers decrease to non-detectable during cold weather, but they may exhibit regrowth in warmer months. The fecal streptococci detected may be contributed by insects in the soil, rather than by the compost.
9. Although there may be an initial increase in nitrogen in the compost due to nitrogen fixation, overall there is a net loss of nitrogen during the

composting process. This occurs via mineralization of organic nitrogen, subsequent volatilization of ammonia, and denitrification.

10. Pathogen and indicator organism reductions during compost curing may be due to a lack of essential nutrients. Addition of glucose to compost which had been curing for 6 months resulted in rapid regrowth, indicating that the organisms were still there in small numbers and were only lacking a suitable carbon source for growth.
11. Experiments using various woodchip:sludge ratios indicated that a 3:1 ratio resulted in the greatest degree of drying and volatile solids removal and the greatest pathogen indicator reductions.
12. The six month holding period recommended by the State of New Hampshire is much longer than is necessary to insure a safe product. Two months, three at the outside, would be a long enough period to allow adequate public health precautions while making the product practical in an area with a limited growing season.

CHAPTER 9

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