12-1986

Static pile composting of dairy waste solids for use as animal bedding

Barry L. Emerton

To the Graduate Council:

I am submitting herewith a thesis written by Barry L. Emerton entitled "Static pile composting of dairy waste solids for use as animal bedding." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.

C. Roland Mote, Major Professor

We have read this thesis and recommend its acceptance:

Bobby L. Bledsoe, Dan L. McLemore

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

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Vice Provost
and Dean of the Graduate School

STATIC PILE COMPOSTING OF DAIRY WASTE SOLIDS FOR USE AS ANIMAL BEDDING

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Barry L. Emerton

December 1986

DEDICATION

In honor of Mr. and Mrs. Carl Copeland

and

In memory of Mr. and Mrs. Joseph Emerton

my Grandparents

ACKNOWLEDGEMENTS

The author wishes to express his gratitude and appreciation to the following:

The Department of Agricultural Engineering and its Head, Dr. Houston Luttrell, for accepting me into the Agricultural Mechanization Program and making departmental resources available for this research;

Dr. C. Roland Mote for his instruction, guidance, and support while serving as Major Professor;

Dr. Bobby L. Bledsoe and Dr. Dan L. McLemore for serving as Graduate Committee Members;

Mr. Henry Dowlen and the staff at the Dairy Experiment Station for their technical assistance and acquisition of data during this study;

Mrs. Janice Allison and the staff at the Water Quality and Waste Management Laboratory for their assistance in the microbiological examinations;

Dr. William L. Sanders and John Schneider, Agricultural Experiment Station Statisticians, for their assistance in the statistical analysis;

Mr. Fritz Mucke and fellow graduate students for their technical assistance and support throughout this study;

And finally, my parents, Mr. and Mrs. Howard Emerton, and Sheila for their patience and support throughout the past two years.

ABSTRACT

A series of thirteen (13) static compost piles were constructed during the period of June, 1985 to March, 1986 at the University of Tennessee Dairy Experiment Station near Lewisburg, Tennessee. The study was performed to investigate the relationship among various compost process parameters (e.g., method of aeration, pile size, and time) and the moisture content and coliform bacteria population in composted dairy waste intended for use as bedding in free stalls.

Both natural and forced aeration methods were employed to supply oxygen to the piles of manure solids. The natural aeration method consisted of nothing more than aging the manure solids in an unconfined pile. The forced aeration method employed a fan to force air into a perforated plenum located underneath the compost pile. The forced aeration system was controlled by either a cycle time switch or a temperature set point controller sensing pile temperature.

Temperatures of the compost mass were monitored daily at three (3) levels within each pile. Samples from three (3) levels were analyzed for moisture content and total coliform bacteria populations on a weekly basis. A heterotrophic plate count - spread plate method was used to enumerate the total coliform bacteria.

Results of the temperature study suggest that the fan had an impact on the composting process such that the piles with the fan reached a higher internal temperature than the piles without the

fan. Further, the time to reach maximum temperature was lower for the piles with the fan than for the piles without the fan. However, piles without the fan were able to achieve temperatures generally considered adequate for good composting.

The compost piles of dairy waste solids dried very slowly. There were no differences in drying rates between the two (2) aeration methods or between the two (2) pile sizes.

No consistent trends or patterns were demonstrated by the total coliform populations through time with regard to treatment or level within the pile. Observations suggest that in many piles the population first declined but started rebuilding at some latter point during the process.

It was anticipated that the total coliform population would decline as the temperature in the pile exceeded their normal living conditions. However, even after several weeks of temperatures above 60°C, total coliform populations of a magnitude similar to those at time zero were found in many samples.

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1.0 INTRODUCTION

Dairymen are faced with the problems of waste management and the increasing cost and declining availability of bedding materials. In most areas, traditional bedding materials, such as sawdust and wood shavings, are becoming scarce and high in price due to more competitive uses for the material. The other problem exists because the current trend in dairying towards larger, more confined herds results in increased quantities of manure to be handled and disposed of.

Recently, a system has been developed whereby solids removed from dairy manure are used as bedding material. Bishop et al. (1980a) found that many dairymen are composting dairy waste solids from two weeks to several months and using them as bedding in free stalls.

Bedding is used primarily for the purposes of keeping animals clean and comfortable. A desirable material is one that is wet enough so the material is not easily swept away, and dry enough so that it doesn't stick to the animals. It is also desirable that the material not promote the development of mastitis or other health problems.

As shown in the following literature review, there is no clear understanding of the degree and/or method of processing necessary for converting solids separated from dairy cow manure into suitable bedding material. However, the natural microbiological stabilization

process known as composting offers several attractive benefits. The purpose of this project was to investigate the relationship among various compost process parameters and the quality of the resulting composted dairy manure solids.

2.0 REVIEW OF LITERATURE

2.1 DAIRY WASTE SOLIDS AS BEDDING

The general trend in dairy management has been toward more confined herds and an elimination of large pasture areas. The sizes of dairy production systems have also continually increased. This is shown in both the number of animals milked and in the quantity of milk produced by each cow. This move toward confinement and larger herds has accentuated the problems of waste management and availability of animal bedding materials.

Many dairymen are composting dairy waste solids from two (2) weeks to several months and using this material as free stall bedding instead of straw, sawdust, or wood shavings (Bishop et al., 1980a). Carroll and Jasper (1978) found that recycled composted dairy waste solids make good free stall bedding material with the provision that it be dried before use.

Keys et al. (1976) experimented with the acceptability of dewatered manure solids (29% dry mass), dehydrated manure solids (90% dry mass), and sawdust (81% dry mass) as bedding material for dairy cattle. The cattle were allowed free choice of the three (3) materials in free stall housing. In tests held in both summer and winter, they found that the dewatered manure solids were used significantly less than the other treatments. The reason was not apparent. However, the cows probably preferred the dehydrated manure solids as bedding due to the lower moisture content (Keys et al., 1976).

Carroll and Jasper (1978) separated the solid and liquid fractions of a manure slurry and composted the solids for several months. Aeration was provided naturally. After the composting period, the material was spread into a corral for drying. After several months of drying, the composted material was repiled and used as bedding in free stalls. Carroll and Jasper claimed this material had coliform counts of zero if completely composted.

Janzen et al. (1982) conducted a series of experiments utilizing crushed limestone, composted dairy waste solids (DWS), and a 50:50 mixture (by volume) of limestone:DWS as bedding material in free stalls. They found that the limestone treatment resulted in lower bacteria counts in the bedding, teat swabs, and milk. The DWS and the 50:50 mixture treatments showed no significant difference in bacteria counts. Janzen concluded that the pH of each treatment appeared to have a significant impact on the counts of potential mastitis pathogens. The significantly higher pH of the limestone treatment may be one of the contributing factors to decreased bacteria counts in that treatment (Janzen et al., 1982).

Carroll (1977) believed that "next to the milking machine, bedding materials are the environment portion that have a major influence on the type of bacterial infections that are found in the udder."

Bishop et al. (1980a), in an effort to separate the effect of bedding type from any possible seasonal variations, conducted separate trials during each of the four seasons of the year. Before composting, samples of dairy waste solids (DWS) had higher bacteria

counts than samples of sawdust, wood shavings, and straw. However, after composting, bacteria counts in the DWS had decreased to a level below that of the straw but remained above the sawdust and shavings. After approximately 14 days of use in the free stalls, the bacterial counts of the DWS had risen to a point comparable to those before composting. This could indicate that the type of bedding may not be an indication of the number of microorganisms present (Bishop et al., 1982).

Bishop et al. (1980a) concluded that "even though bedding material may affect the numbers of bacteria on the teat surface, it does not mean the udder itself is infected". They further added that there appeared to be no direct relationship between bedding material and udder infection.

Several authors claim success using fresh, non-composted, dairy waste solids as bedding material (Elam, 1971; Dale and Swanson, 1975). Dale and Swanson tested a system called the Total Recycle Unit (TRU), developed by Babson Brothers Company, Oak Brook, Illinois. The solids moved through the separator unit and were washed to remove mucous and dissolved solids. The material was approximately 70% moisture as it came from the unit. They found that even though the bacteria counts were positive, no animal illness had been attributed to the bedding in two years' use. Counts of Klebsiellae and Salmonellae had always been negative.

2.2 COMPOSTING

Toth and Gold (1971) define composting as being a process involving conversion of organic matter into humus by thermophilic microorganisms under optimum moisture and aeration conditions. Through this process, carbon dioxide gas is evolved and internal pile temperatures may reach 68 to 77°C.

Several factors influence the type and rate of decomposition during composting. Willson and Hummel (1972) recognized aeration rate and structure as being important factors in decomposition of dairy waste solids. Carroll and Jasper (1978) indicated that temperature, moisture, degree of aeration, and the nature of the material were important factors in composting dairy waste solids. It has also been found that pathogen destruction is important if composted material is to be used as bedding (Carroll and Jasper, 1978; Janzen et al., 1982; Bishop et al., 1981).

2.2.1 Structure and Aeration

Aeration provides oxygen for the aerobic decomposition process. The structure of the compost material controls the diffusion of this oxygen through the mass (Willson and Hummel, 1972). The structure of the mass is influenced by such factors as moisture content, degree of settling, and the amount and type of bedding material initially mixed with the raw manure (Willson and Hummel, 1972). As settling occurs, some of the air passages are blocked and aeration is inhibited.

Willson et al. (1980) indicated that aeration provides three main functions for the composting process: (1) Aeration provides oxygen for the development of thermophilic microorganisms which ensure rapid decomposition and stabilization of the organic material, (2) aeration provides for lowering the moisture content of materials that may have been too high initially, and (3) aeration removes excess heat generated by the microorganisms. Willson et al. (1980) add that proper control of the aeration rate is essential since a rate which is too high can lead to excessive heat loss, cooling of the pile, and incomplete stabilization. A rate which is too low can slow decomposition or prohibit it altogether.

In composting, aerobic conditions must be attained by movement of air into the compost mass. Several processes have been developed to provide aeration to the composting material. These processes provide oxygen through natural aeration, pile turning, and forced aeration.

2.2.1.1 Natural Aeration

Miller et al. (1982) and Willson and Hummel (1972) suggest that the static compost pile or windrow is aerated primarily through convective air movements. The rate of aeration is proportional to the difference between the ambient temperatures and the interal pile temperatures. The temperature differential between the pile and the ambient air establishes a convective updraft through the pile. As the internal temperature rises at the beginning of the compost process, the aeration rate increases due to cooler outside air

entering the pile. Later, as the composting process slows, cooling of the mass reduces the aeration rate. Willson and Hummel (1972) add that for a windrow or pile of a given permeability, the aeration rate can be controlled by varying the size and shape of the mass.

2.2.1.2 Pile Turning

An essential factor in establishing and maintaining an aerobic environment inside the compost pile is an ample supply of oxygen at all times. Mechanical turning or mixing is a method employed to incorporate oxygen into the compost mass. Thorough mixing causes weed seeds, fly larve, and pathogenic organisms which could survive near the cooler surface to be exposed to lethal temperatures common to the interior of the pile (Merkel, 1981).

While composting sludge at Johnson City, Tennessee, Stone and Wiles (1975) stated that the minimum number of turnings which resulted in satisfactory compost was once per week for the entire pile life. It was also noted that the best decomposition was obtained by turning the pile twice each week.

Poincelot (1972; 1974) indicated the schedule of turning should be based on oxygen demand; however, in practice turning frequency is based upon temperature and moisture content. Merkel (1981) indicated that if the piles are turned too frequently, heat will be removed faster than it is produced. Thus, the temperature will be lowered below the thermophilic range and the process will become temperature limited.

When the capital expenditures for a front-end loader plus the cost of labor for the operator are considered, forced aeration is an alternative to pile turning which should be evaluated (Martin et al., 1972).

2.2.1.3 Forced Aeration

Forced aeration can be accomplished by mechanically forcing air either into or out through the pile. Forcing air into the pile (vacuum-induced aeration) is referred to as the Beltsville Aerated Pile Method (Willson et al., 1980). Forcing air out through the compost mass (forced-pressure aeration) is referred to as the Rutger's Composting Process (Finstein et al., 1983).

2.2.1.3.1 Vacuum-Induced Aeration. Willson et al. (1980) maintained aerobic composting conditions using a vacuum-induced aeration system. The objective of this aeration scheme was to maintain oxygen levels in the air inside the compost mass from 5 to 15%. The desired level was maintained by drawing air through the pile intermittently.

In the vacuum-induced mode, a blower forms a vacuum inside the pile, forcing air to enter the compost pile from the outside. The air is pulled through the pile into a four-inch nominal diameter perforated pipe located beneath the material. This air is then discharged into an odor filter pile where malodorous gases are absorbed. An in-line centrifugal flow fan proved to be an efficient

mechanism for developing necessary pressures to move air through the compost mass (Willson et al, 1980).

The blowers are controlled by use of a time clock set to operate the motor for four (4) minutes out of twenty (20) when servicing 45.4 metric tons (50 tons) of sludge. Willson et al. (1980) noted that exact aeration rates depend on pile shape and the amount of material to be composted, however, an aeration rate of 15.4 m^3 per hour per metric ton (500 ft^3 per hour per ton) of sludge (DW) should maintain the oxygen level between 5 and 15%.

2.2.1.3.2 **Forced-Pressure Aeration.** Finstein et al. (1983) and MacGregor et al. (1981) studied the effects of static pile aeration via the Rutgers Composting Process. They devised a practical means of controlling the pile temperature in field scale studies of composting municipal sewage sludge. The process consisted of a temperature feedback control system in association with forced-pressure aeration in static piles.

The composting system was basically very similar to the Beltsville piles except air was blown into the duct work by six (6) blowers and exhausted through the pile.

Finstein et al. (1983) and MacGregor et al. (1981) proposed to maintain the temperature of the composting mass at less than 60°C. At the onset of composting, the purpose of Finstein's system was to promote a rapid temperature ascent. During this start-up period, oxygen is needed for heat generation through aerobic respiration. Adding oxygen by aeration conflicts with the need to minimize

heat removal during the initial temperature ascent. Finstein et al. (1983) stated, "the compromise was to actuate the blower, by timer, on a schedule to provide an adequate oxygen level, 5% oxygen. When the temperature reaches a preset level, sensed by a thermistor in the pile, the purpose of ventilation changes to that of matching heat removal to heat output, such that pile temperature is poised at a biologically favorable level (<60°C)."

Higgins (1982;1984b) compared the forced-pressure mode to the vacuum-induced mode through design calculations and field scale tests. He found that the forced-pressure mode encountered significantly less airflow resistance than the vacuum-induced mode. He noted that elimination of the odor filter pile eliminated half the total resistance in either system. He further added that not only can more air be delivered for less power, but a more uniform distribution of air is obtained through the forced-pressured mode.

DeBertoldi et al. (1984) performed tests comparing the vacuum-induced, the forced-pressure, and the pile turning methods of aerating compost piles. DeBertoldi noted that of the three (3) systems tested, the forced-pressure aeration system linked to a temperature feedback control provided for the most rapid composting. It produced the best end-product in terms of a lower moisture content and achieved a higher degree of stabilization (DeBertoldi et al., 1984).

Higgins (1984a) developed an airflow control valve and condensate drain that allows switching back and forth between the vacuum-induced and forced-pressure methods of static pile aeration.

The valve and drain are interconnected to the same fan. Higgins indicated that being able to switch systems during composting takes advantage of the desirable features of both airflow systems while eliminating most of the undesirable features of each (Higgins, 1984a).

It is important to note that the material in both the Beltsville Aerated piles and the piles composted by the Rutger's Process was capped with a layer of stable material (Golueke, 1982; Willson et al., 1980; Stone and Wiles, 1975). This layer, consisting of aged compost or sawdust, provided an insulation value to the composting material and ensured the continuation of the high temperature zone throughout the composting mass (Golueke, 1982).

The Beltsville piles were covered with 30 cm (12 in) of aged compost. This covering was designed to prevent odors from escaping to the atmosphere and provide insulation for better heat maintenance (Willson et al., 1980).

Stone and Wiles (1975) experimented with covering the compost pile with a blanket of previously composted material or plastic sheeting. Stone noted that it was apparent that covering piles from day zero had an adverse effect on the internal pile temperatures, with no significant advantage gained for surface temperatures. It appeared that the optimum time to cover a pile to achieve thermal kill of pathogens on the surface was after the composting mass had reached its maximum temperature (Stone and Wiles, 1975).

2.2.2 Moisture

Moisture content is critical to the biological stabilization of compost material. Water concentrations in the composting mass serve a very important function in the rapid decomposition of the organic matter (Toth and Gold, 1971). A large amount of heat is generated during decomposition, and unless sufficient moisture is present, the pile will dry out before stabilization is complete. Too much water should also be avoided since this tends to restrict pore space and produce anaerobic conditions (Toth and Gold, 1971).

If the compost material is to be placed in static piles, the question arises as to the optimal moisture content for aerobic stabilization to begin. Haug (1980) proposed "moisture levels be high enough to assure adequate rates of biological stabilization, yet not so high that void spaces are eliminated, thus reducing the rate of oxygen transfer and in turn the rate of biological activity". In reviews of earlier literature, Merkel (1981) cited Golueke et al. (1954) as finding that moisture contents above 60% cause compaction of the material and fill the void spaces with water, thus reducing the amount of air present. Also, if the moisture content is below 50%, high temperatures destroy the microorganisms, seriously curtailing the stabilization process.

Willson et al. (1980) working with the Beltsville Aerated Pile, recommended the maximum moisture content for consistently good composting activity was about 60% wet basis. Haug (1980) found the importance of proper moisture control was highlighted in work by Senn (1971) on the composting of dairy manure. Senn found that at

moisture contents of 66%, composting temperatures rose to about 55°C but no higher. At moisture contents of 61%, the temperatures rose to greater than 75°C. Whereas, in manure at 60% moisture, the temperature quickly rose to above 75°C and remained for several days. Senn (1971) concluded that 60% moisture was adequate for composting dairy manure.

In studies of dairy waste solids used as bedding, Bishop et al. (1980a) experimented with manure having an initial moisture content of 72 to 74% before composting. Conversely, in studies with sewage sludge, Stone and Wiles (1975) suggested that piles be kept at 50 to 60% moisture at least until the twenty-eighth day. This range is also confirmed in studies by Poincelot (1972; 1974).

2.2.3 Temperature

Carroll and Jasper (1978) have determined that the internal pile temperature is an important indicator of the progress of the stabilization process from beginning to end. Willson et al. (1980) stated that temperatures in the compost pile revealed more about the composting progress than any other single measurement. They further noted that the temperature readings should be taken from several locations in the composting mass. Continuous monitoring of temperature is not necessary, but remote sensing of temperature may be more cost effective than sending out an operator to take measurements (Willson et al., 1980).

Merkel (1981) observed that the temperature in both aerobic and anaerobic composting gradually rises to well within the thermophilic range (>40°C) due to excess heat generated by microbial activity. Both mesophilic and thermophilic organisms are present during the composting process (Willson et al., 1980). The mesophilic organisms appear to be active between temperatures of 20 and 35°C. As temperatures rise into the 45 to 60°C range, thermophilic organisms dominate the composting process.

It has been suggested that the composting process produces a typical temperature profile within the compost mass (U.S. EPA, 1971; Willson et al., 1980). The temperature ascent begins soon after the compost material is piled. Temperatures rapidly increase into the thermophilic range, often as high as 80°C. Temperatures of 66 to 71°C are easily reached and maintained for about ten (10) days (U.S. EPA, 1971). Willson et al. (1980) noted that temperatures begin to decrease after about 16 to 18 days, thus indicating that the microorganisms had used up the organic constituents and the composting mass had been transformed into a stable humus.

Poincelot (1972) recognized a "considerable spacial temperature variation" between the center of the composting mass and the surface in both large and small piles. He noted that the temperature gradient lessened as the size of the mass increased. Poincelot (1972;1974) stated that "since heat loss is proportional to volume, the larger pile, having a smaller surface area to volume ratio loses relatively less heat."

Stone and Wiles (1975) also observed that temperatures varied with depth in the compost mass. The temperature variations were more pronounced early in the composting process. They further added that ambient weather conditions appeared to have little if any effect on the compost pile's internal temperatures. Surface temperatures, however, varied considerably during the process depending upon season and weather conditions (Stone and Wiles, 1975).

Researchers composting various organic materials have experienced similar temperatures within the compost mass. Bishop et al. (1980a; 1980b) composted dairy waste solids at 72 to 74% moisture. They noted that the pile temperatures rapidly increased the first four (4) days, then slowed down, and peaked at about 71°C. Carroll and Jasper (1978) experienced temperatures as high as 75°C while composting dairy waste solids.

While composting sewage sludge through the Beltsville Aerated Pile process, Epstein et al. (1976) observed the temperatures throughout the compost mass were in the thermophilic range of 40 to 60°C. The temperatures increased rapidly and peaked at 78°C in the center of the pile. Even in the peripherial areas, the temperature exceeded 60°C at some point in time. The temperatures were lowest (30 to 46°C) at a position 40 cm (16 in) from ground level and 30 cm (12 in) from the surface. The temperatures began to decline after 14 days of composting (Epstein et al., 1976).

Poincelot (1972) suggested that the temperature should not exceed 70°C for any great length of time. Above 70°C "thermal kill" of the microorganisms occurred, resulting in a slowdown in

stabilization. Finstein et al. (1983) designed and developed a temperature feedback control mechanism to limit the internal pile temperature to less than 60°C to avoid this thermal limitation. Willson et al. (1980) indicated that if the majority of the temperature readings indicated a temperature above 80°C, the aeration rate could be increased to remove moisture and thus reduce the decomposition rate.

2.2.4 Temperature - Pathogen Level Relationships

Willson et al. (1980) suggested that the temperature of the compost mass had a profound effect on the growth and activity of microorganisms. They noted that temperature determines the rate at which composting occurs and is an excellent indicator of the extent of pathogen destruction or survival.

Golueke (1982; 1984) found it necessary to treat time as well as temperature as an essential factor in the destruction of pathogens. Golueke stated that "pathogens do not die off instantaneously -- some time interval is required, however brief it may be". He suggested that destruction of pathogens is accomplished by exposing them to the five (5) agents and mechanisms of destruction, namely, heat, competition, antibiosis, destruction of nutrients, and time (Golueke, 1982; 1984). Golueke noted that for satisfactory pathogen destruction, all pathogens must be exposed to the lethal conditions either simultaneously or successively. Also, sufficient time must be allowed for these agents to exert their full effects (Golueke, 1984).

Haug (1980) also suggested that thermal inactivation of pathogens is a time-temperature relationship. He noted that equal success in pathogen destruction can be achieved with a high temperature for a short period of time or a lower temperature for a longer duration.

Destruction of human and animal pathogens by composting has been reported (Wiley and Westerberg, 1969; Willson et al., 1980; Poincelot, 1974; Carroll and Jasper, 1978; Burge et al., 1978; Epstein et al., 1976; Lounsbury and Miller, 1984; U.S. EPA, 1971; Stone and Wiles, 1975).

In sludge composting studies at Johnson City, Tennessee, Stone and Wiles (1975) proposed that an inverse relationship exists between total coliforms in the compost mass and compost mass temperatures. They noted that a temperature range of 49 to 55°C would significantly reduce the coliform populations, often to a level undetectible by the Most Probable Numbers Method. However, a temperature decrease in the later stages of composting allowed reestablishment of a significant number of coliforms. Stone and Wiles further stated that for proper processing, all the compost material must be exposed to temperatures of 50 to 55°C for at least seven (7) days.

While investigating the thermal tolerance of pathogenic organisms, Willson et al. (1980) concluded that if temperatures exceed 55°C for several days, pathogens levels rapidly diminish. They further stated that most pathogens would be destroyed if all areas of the pile reached 60°C.

In composting studies of municipal sludge, the U.S. EPA (1981) proposed that the attainment and maintenance of a 55°C temperature for a period of three (3) days should eliminate all pathogens in the compost mass.

Epstein et al. (1976) observed that the Beltsville Aerated Pile process resulted in the reduction of fecal and total coliform populations. They added that the highest survival area was in the lower corner (foot) of the compost mass. This area also had the lowest temperatures of any area. Survival of microorganisms in this area is believed to be the result of a lack of insulation (Epstein et al., 1976).

Work by Carroll and Jasper (1978) on composting dairy manure solids indicated that coliforms such as Escherichia coli, Klebsiella, and Enterbacter failed to survive a temperature of 60°C for thirty (30) minutes. They further added that if complete stabilization has occurred, this material would have coliform populations of zero.

Wiley and Westerberg (1969) concluded that all pathogens were destroyed when temperatures in sewage sludge compost remained at 60 to 70°C for three (3) days. Their test for total coliforms indicated an increase initially; however, the counts were reduced to undetectable levels by the tenth day of composting. Bishop et al. (1980b) disagreed with Wiley and Westerberg by stating that "our data do not agree with that of Wiley and Westerberg since all organisms remained viable to some extent even after four (4) days of exposure". Bishop found that composting dairy waste solids at

temperatures above 60°C for four (4) days failed to kill the organisms.

Bramley and Neave (1975) indicated that in dairy herds with previous mastitis problems, new infections could be reduced if coliform counts in bedding are maintained below 10^6/g wet weight. They note that higher counts have been associated with mastitis infection.

2.3 SUMMARY

Previous investigators have concluded that composting dairy waste solids can improve their quality with respect to use as bedding material (Carroll and Jasper, 1978). Others feel that it is not necessary to compost the dairy waste solids (Elam, 1971; Dale and Swanson, 1975). Still others believe there is no direct relationship between bedding material and udder infection (Bishop et al., 1980a).

Studies suggest that the composting mass be maintained at 50 - 60% moisture until the 28th day of composting (Stone and Wiles, 1975) and that composting is inhibited or restricted if moisture content in the mass is above 60% (Golueke, 1954; Willson et al., 1980). However, dairy waste solids have been successfully composted at moisture contents above 72% (Bishop, 1980a).

Pathogen levels may be important for dairy waste solids that are to be used as bedding material. Destruction of pathogenic bacteria by the composting process has been reported (Wiley and Westerberg, 1969; Willson et al., 1980; Poincelot, 1974; Carroll and Jasper, 1978; Burge et al., 1978; Epstein et al., 1976; Lounsbury and

Miller, 1984; U.S. EPA, 1971; Stone and Wiles, 1975). Additional research has shown pathogen destruction with reestablishment of populations in the later stages of composting (Stone and Wiles, 1975).

Temperature within the compost mass has been shown to be an excellent indicator of the extent of pathogen destruction. Research has shown that time as well as temperature should be considered as a key factor in the destruction of pathogenic bacteria (Golueke, 1982). Some have found that temperatures of 50 to 55°C maintained for seven (7) days are essential for pathogen destruction (Stone and Wiles, 1975). Others have shown that pathogens have been destroyed with temperatures of 60 to 70°C for three (3) days (Wiley and Westerberg, 1969). However, similar research has noted survival of pathogens after exposure to temperatures above 60°C for four (4) consecutive days (Bishop et al., 1980b).

An essential factor in establishing and maintaining an aerobic environment inside the compost pile is an ample supply of oxygen at all times. Miller et al. (1982) and Willson and Hummel (1972) suggested that the static compost pile or windrow is aerated primarily through naturally occurring convective air movements. Willson et al. (1980) note that if this rate of aeration is too low, the composting process can be slowed or prohibited altogether.

Several mechanical methods have been developed to accelerate the aeration of the compost mass and thus speedup the composting process itself. One such method is to manually turn or mix the composting material with a front-end loader. Stone and Wiles (1975)

found that the best decomposition was obtained by turning the compost pile twice each week. Finstein et al. (1983) and Willson et al. (1980) suggested that the capital expenditures for equipment and labor associated with pile turning could be cut if a forced aeration technique is used. Willson et al. (1980) maintained aerobic composting conditions using a vacuum-induced aeration system. Finstein et al. (1983) and MacGregor et al. (1981) maintained the temperature of the composting mass below 60°C with a forced-pressure aeration system coupled with a temperature feedback control.

The body of available knowledge thus far fails to provide a clear indication on at least two (2) points related to using the composting process to convert dairy waste solids into bedding. There is conflicting information on changes in the various quality parameters that can be expected. There is also a lack of a clear understanding about the optimum composting process operating criteria. Further research aimed at helping to understand the appropriate role for composting in the production of bedding from dairy waste solids appears to be justified.

3.0 OBJECTIVES

The overall purpose of this study was to investigate the relationship among various compost process parameters (e.g., method of aeration, compost pile size, and time) and the moisture content and coliform bacteria population in the composted dairy waste solids. The specific objectives were:

1. To construct a series of large and small compost piles from dairy waste solids, and to aerate some of the large piles with forced air from a fan;

2. To regularly observe the temperature at several levels within each pile, and collect samples for laboratory determination of moisture content and total coliform population; and

3. To compare the observed temperature, moisture content and total coliform population data from the various compost piles.

4.0 EXPERIMENTAL MATERIALS AND PROCEDURES

4.1 SYSTEM DESCRIPTION

Dairy manure solids obtained by separating the solid and liquid fractions of a manure slurry were stacked in two (2) size piles with a rectangular base and allowed to compost for as long as 120 days. Both natural and forced aeration methods were employed to supply oxygen to the piles of manure solids. Temperatures at various levels within each pile were monitored. Samples from various levels within each pile were analyzed for moisture content and total coliform populations.

4.1.1 Compost Materials

The dairy waste solids used in this experiment were separated from a dairy manure slurry by a DeLaval Lisep separator unit installed at The University of Tennessee Dairy Experiment Station near Lewisburg, Tennessee. The manure was collected in a central pit and then pumped as a slurry to the separation facility. The slurry consisted primarily of manure deposited in the loafing area along with used bedding material and wastewater from the milking facility.

The centrifugal separator split the solid and liquid fractions of the manure slurry. The liquid fraction flowed into a lagoon located approximately 100 m (109 yards) away. The solids accumulated in stacks in either of two storage sheds attached to the separation facility. From there, the solids were transported with tractor and front-end loader to the composting site. The composting site was

formerly a loafing area for the cattle. It was located between the separation facility and the lagoon. Figure 4.1 depicts the general layout of the composting facilities at the Dairy Experiment Station.

4.1.2 Compost Piles

A series of static compost piles were constructed during the period of June, 1985 to March, 1986. The piles were classified according to the pile size and method of aeration.

4.1.2.1 Pile Size

The dimensions for the base of the compost piles were arbitrarily selected with an eye toward optimizing the number of piles that could be built from the limited supply of manure solids. A rectangular base with dimensions of 1.8 m (6 ft) by 2.7 m (9 ft) was selected for all piles. Each pile had an approximately triangular cross section. The dairy waste solids were stacked to a height of 1.2 m (4 ft) in the large piles, and 0.9 m (3 ft) in the small piles.

4.1.2.2 Method of Aeration

A natural aeration method and a forced aeration method were studied. The natural aeration method consisted of nothing more than aging the manure solids in an unconfined pile. This type pile is primarily aerated through naturally occuring convective air movements. The forced aeration method employed a fan to force air

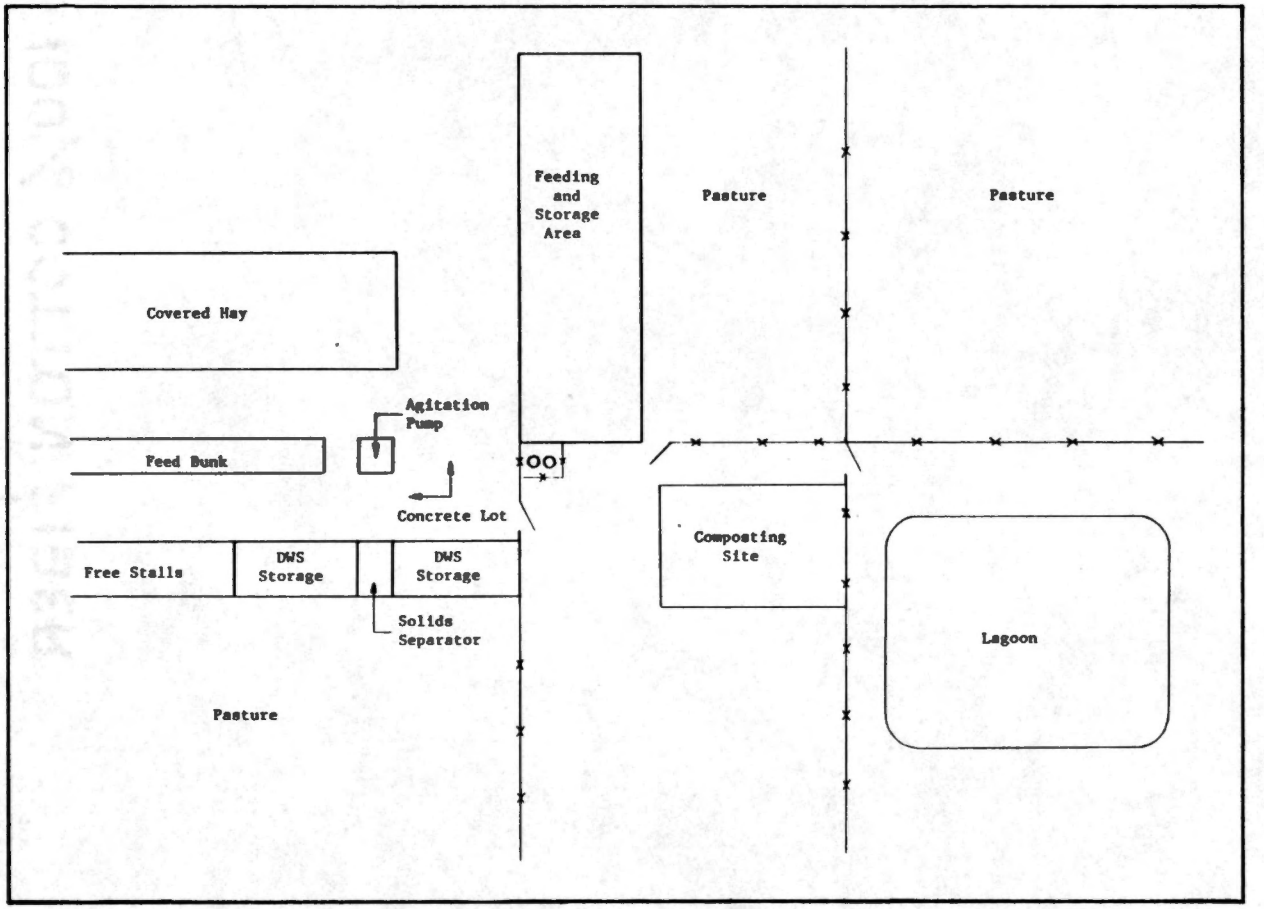


Figure 4.1. General location of the facilities at the Dairy Experiment Station near Lewisburg, Tennessee. Not to scale.

into a perforated plenum located underneath the compost pile. The pressure inside the plenum forced air up through the composting manure solids.

The ventilation system for the forced aeration method consisted of a blower (Dayton Model No. 6K845, W. W. Grainger, Inc., Chicago, IL) connected through 4-inch nominal diameter PVC pipe to the air distribution plenum located beneath the pile of manure. The plenum was a 0.9 m (3 ft) by 1.2 m (4 ft) by 20 cm (8 in) wooden chamber covered with a wire mesh and open to the soil on the bottom. An 11 cm (4.5 in) diameter hole was cut in the center of the 0.9 m (3 ft) end to receive the blower duct. The air flow rate was controlled with a damper located in the pipe near the fan unit. The damper was constructed from a 4-inch nominal diameter PVC tee with a screw-in cap. Various size holes were drilled in the cap as needed to control the air flow rate. The blower unit was housed within a cover structure. Figure 4.2 shows the blower assembly with the damper unit.

The forced aeration system was controlled by either a cycle time switch or a temperature set point controller sensing pile temperature. The temperature control system was designed to maintain the temperature of a selected position in the pile at or below an established set point. For this project, the selected position was 30 cm (12 in) above the plenum and the set point was 46°C.

A temperature controller (Omega Model No. E924-J12-A20, Omega Engineering, Inc., Stamford, CT) with an adjustable set point received a signal from a thermocouple located in the compost pile at

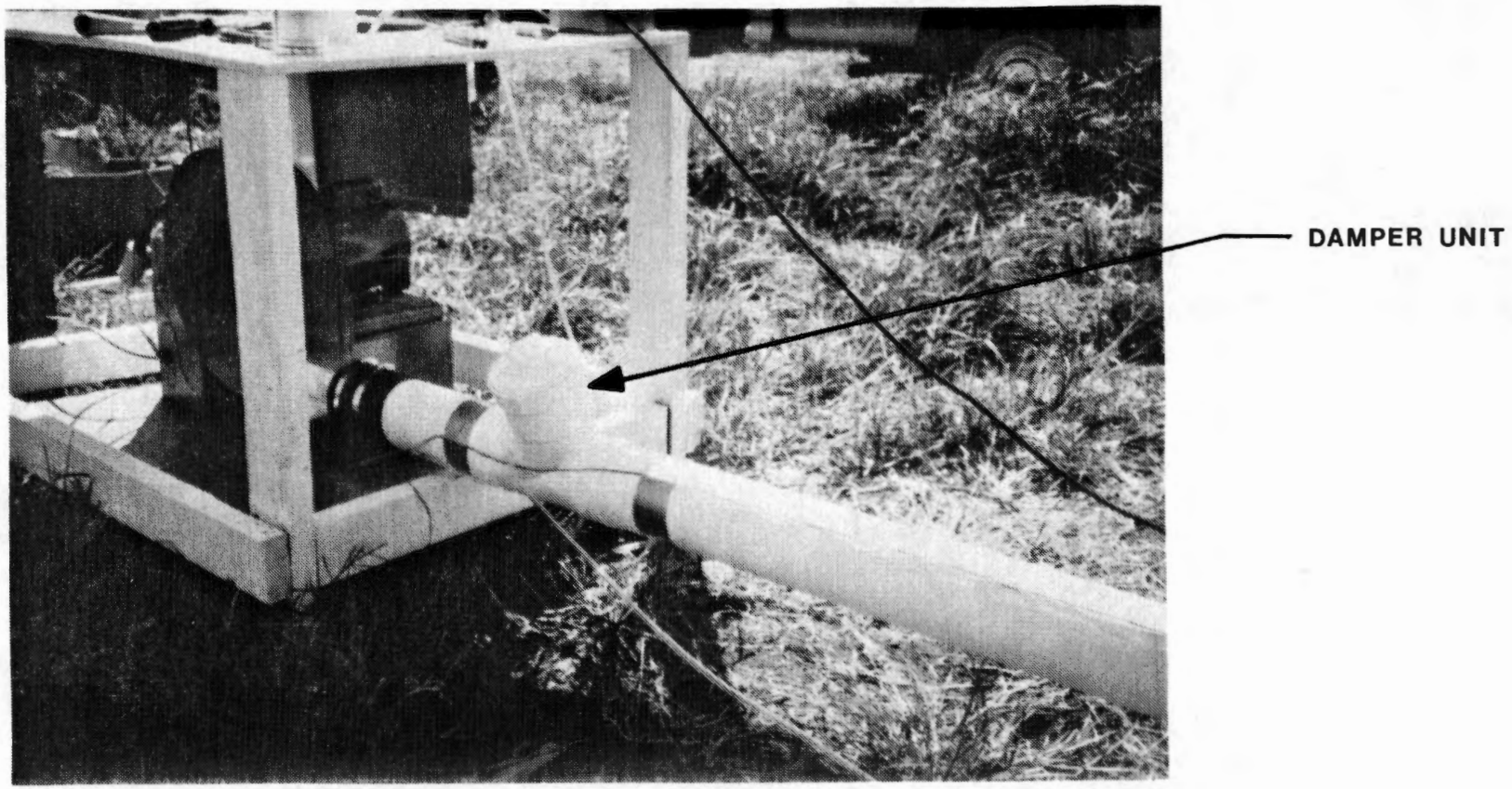


Figure 4.2. Blower assembly with damper unit constructed from a 4-inch PVC tee and screw-in PVC plug.

the selected position. If this signal indicated a temperature greater than the set point, the blower unit was directly activated by the temperature controller. The blower unit continually ran until the pile cooled to the set point temperature. If the signal indicated that the temperature was less than the set point, control of the blower was turned over to a 30-minute cycle timer. This timer operated the blower 30 seconds every 15 minutes until the temperature exceeded the set point. An elapsed time indicator recorded the time that the blower operated. The flow chart of blower control is presented in Figure 4.3.

The temperature controller, cycle timer, and elapsed time indicator were housed in a weatherproof metal control box located near the blower unit.

4.2 CONSTRUCTION OF THE PILES

Construction of the compost piles consisted of simply stacking the manure solids within a 1.8 m (6 ft) by 2.7 m (9 ft) rectangular base until the desired height was achieved. The only difference between the forced aeration and natural aeration piles was the addition of a surface blanket of sawdust and a ventilation system to the forced aeration pile.

4.2.1 Natural Aeration Pile

A 1.8 m (6 ft) by 2.7 m (9 ft) rectangular area was staked as a base for the pile. A 2.4 m (8 ft) stack pole was set in the center of the staked base for measurements during construction. The pole

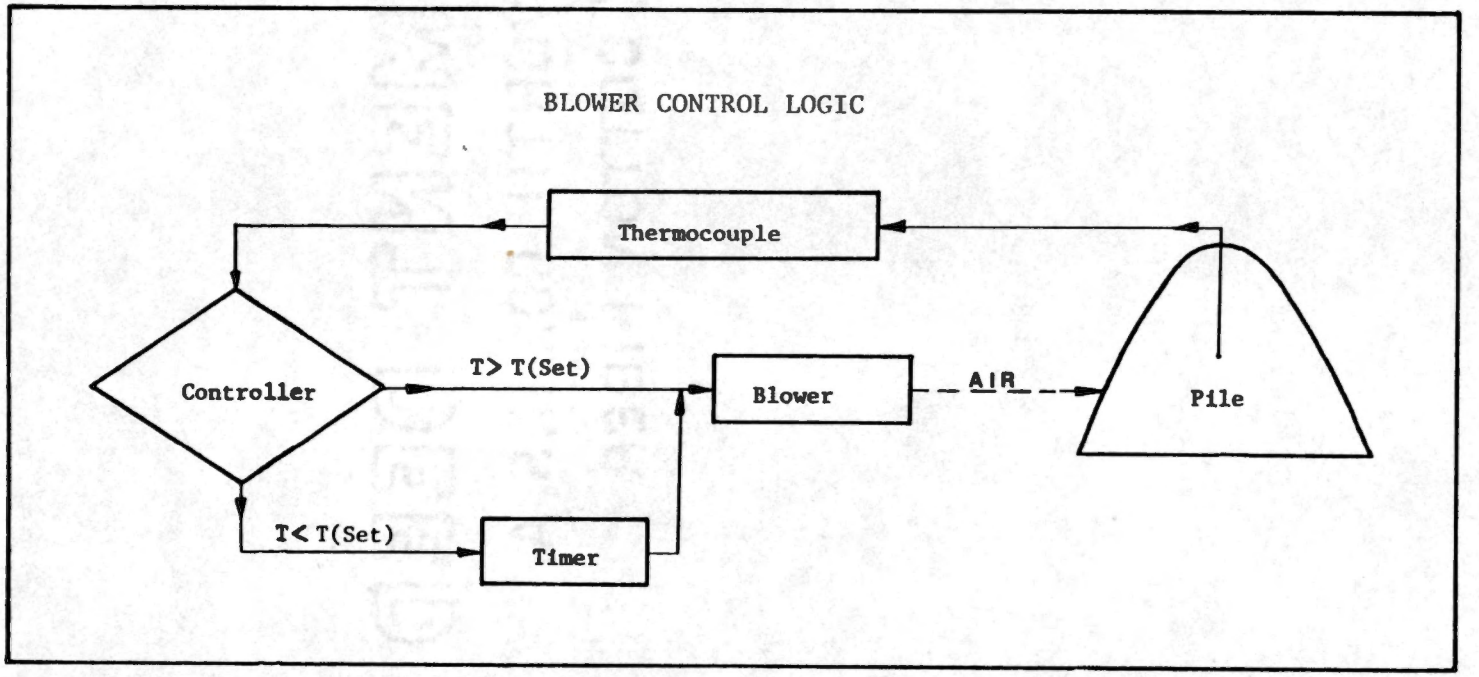


Figure 4.3. Flow chart of the blower control logic. (Adapted from Finstein, 1980:349).

was scaled in feet, zero being ground level. Manure solids were transported from the separation facility to the composting site with a front-end loader. The solids were dumped within the staked base and spread evenly with hand tools. The manure solids were stacked in 30 cm (12 in) lifts to the desired height. When the solids reached each 30 cm (12 in) increment, as marked on the stack pole, a Chromel-Alumel (Type K) thermocouple was inserted. Also, at each 30 cm (12 in) level, a length of 1.5-inch nominal diameter CPVC pipe was placed horizontally in the pile for use as a sampling tube. The pipe was approximately 1.5 m (4.5 ft) long and extended approximately 0.8 m (2.5 ft) beyond the face of the compost pile. The sampling tube was capped on the outside end with a rubber stopper. Figure 4.4 shows both the large and small naturally aerated piles as they were constructed.

During pile construction, numerous samples were removed from the loader buckets of manure solids and placed in a sterile container. These samples represented time zero samples for the piles constructed on that day. The samples in this container were thoroughly mixed and a portion removed for analysis at the lab.

4.2.2 Forced Aeration Pile

The forced aeration piles were constructed in much the same manner as the naturally aerated piles except a mechanical ventilation system was installed. The forced aeration piles consisted of manure solids stacked upon a rectangular wooden box used as an air plenum. This box was constructed of treated pine and had an open dimension of

Figure 4.4. Large and small naturally aerated piles as they were constructed. Large pile is on the left; small pile is on the right.

0.91 m (36 in) by 1.22 m (48 in). The box stood 20 cm (8 in) high. The top of the plenum was covered with a wire mesh. An 11 cm (4.5 in) diameter hole was cut into the center of one 0.91 m (36 in) end to receive the blower duct. A stack pole was set near the box and scaled in feet, zero being at the top of the plenum.

A 1.8 m (6 ft) by 2.7 m (9 ft) base was staked around the plenum. The remaining area around the plenum inside this base was filled with previously composted solids or sawdust to the top of the plenum. A 2.5 cm (1 in) blanket of loose straw was placed over the wire mesh to keep it from becoming clogged as solids were stacked. The plenum was then connected to the blower unit with 4-inch nominal diameter PVC sewer and drain pipe. Figure 4.5 shows the plenum located within the base of the forced aeration pile.

Manure solids were stacked upon the base in 30 cm (12 in) increments. As in the naturally aerated piles, sampling tubes and thermocouples were placed at each 30 cm (12 in) increment. The thermocouple lead wire from the blower control unit was installed at a position 30 cm (12 in) above the plenum. A wooden block with several turns of thermocouple wire around it served to hold the thermocouple in position inside the pile.

After all the solids were placed on the pile and the thermocouples and sample tubes were in position, the entire forced aeration pile was covered with an approximately 5 cm (2 in) thick layer of sawdust. The intent of the sawdust blanket was to eliminate a surface layer of manure solids that did not reside in the

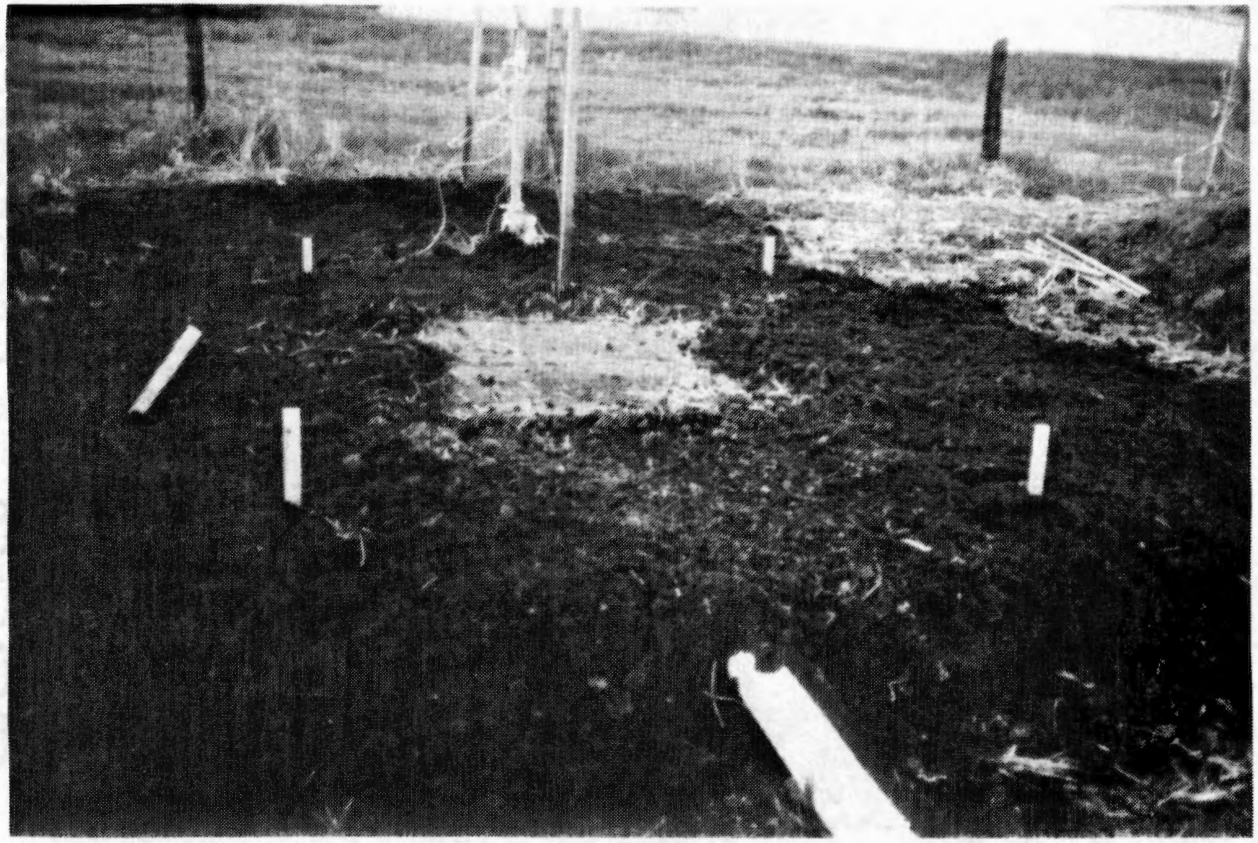


Figure 4.5. Air plenum located within the base of the forced aeration piles.

composting environment on the interior of the pile. Figure 4.6 shows the forced aeration pile as it was constructed.

Soon after the pile was completed, arrangments were made to begin forced aeration. Power was supplied to the fan in order to determine the air flow rate. Static pressure measurements were taken with an inclined manometer reading 0-15 cm (0-6 in) of water (Dwyer Instruments, Inc., Michigan City, IN). The air flow velocity was measured with a hot wire anemometer (TSI Model No. 1610-12, Thermo-Systems, Inc., St. Paul, MN). The static pressure and air flow velocity were measured in the duct approximately 4.6 m (15 ft) from the fan.

An air flow rate was then calculated using a calibration curve supplied with the anemometer. The damper was adjusted accordingly and a new flow rate determined. This trial and error procedure continued until a desirable air flow rate was attained.

4.3 SAMPLE COLLECTION

The piles were designed and constructed so as to provide a means of monitoring the performance parameters of temperature, moisture content, and total coliform bacteria population.

4.3.1 Temperature

As discussed earlier, thermocouples were placed at specific intervals within the pile during construction. A single thermocouple was placed at each 30 cm (12 in) increment in height in the pile.

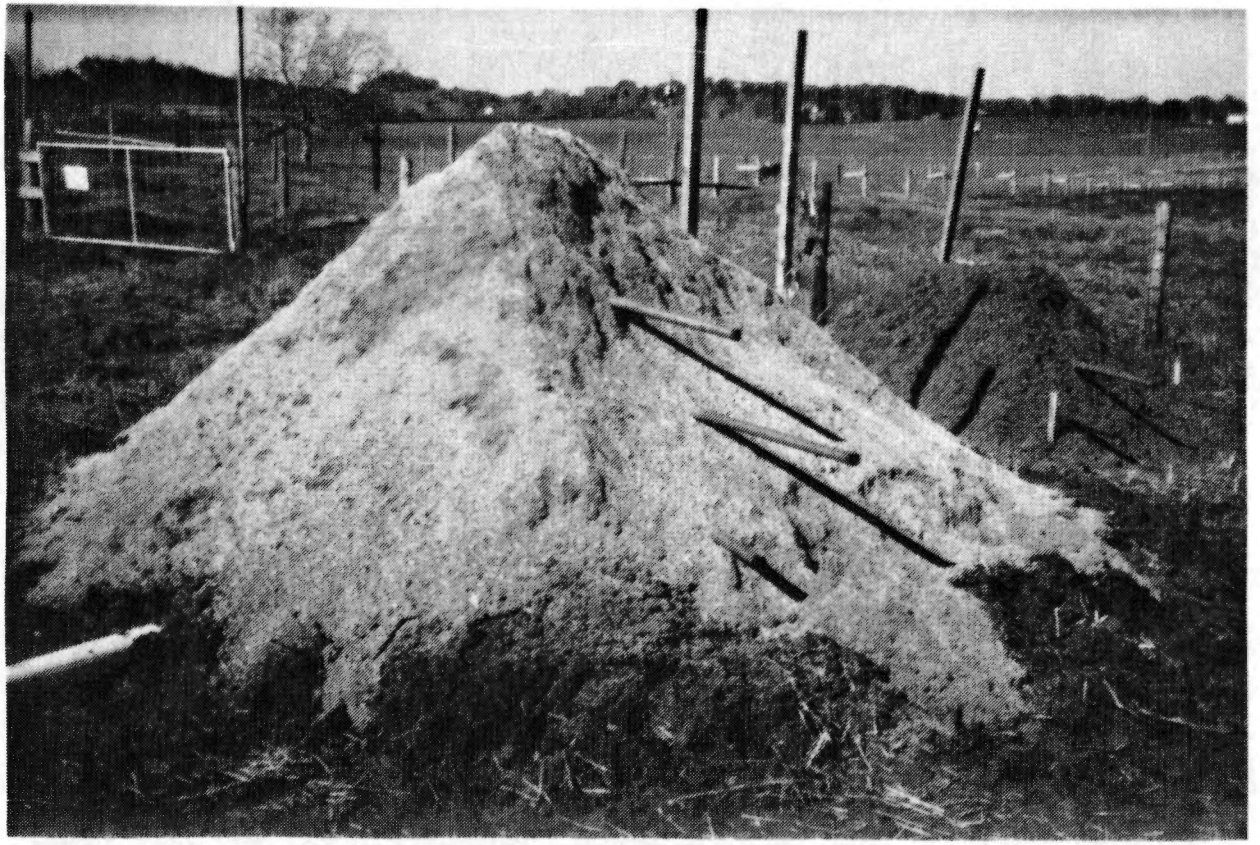


Figure 4.6. The forced aertion pile as it was constructed.

Temperatures were monitored daily by the staff of the dairy experiment station. A hand-held thermocouple thermometer readout device (Digi-Sense Model No. 8529, Cole-Parmer Instrument Co., Chicago, IL) was used to read the temperature of each level in all piles. These values were recorded on a data sheet. The data sheet contained sections to list other relevent information such as the date, the time readings were made, fan operation time, and any special observations. These data sheets were mailed to the Agricultural Engineering Department in Knoxville weekly. For the five-day period, just after piles were constructed, this information was transferred by telephone between Lewisburg and Knoxville daily. This permitted a means of monitoring performance and detecting problems early in the pile's life.

Daily observations of temperature continued throughout the life of the pile. There were some circumstances, such as inclement weather, which interrupted daily observations.

4.3.2 Moisture and Coliforms

During construction of the piles, sampling tubes were placed at 30 cm (12 in) intervals within each pile. The sampling tubes were installed so as to provide a means of withdrawing a sample of the composting material without disturbing the overall pile structure. These samples were used to determine the moisture contents and total coliform populations at the individual levels within the compost piles.

Approxiately once each week, samples were taken with a Penn State Forage Sampler (NASCO, Fort Atkinson, WS). An electric drill was used as a power source for the sampler. The sampler was inserted into the compost piles through each sampling tube. The electric drill was engaged and a sample was captured. The sampler was removed from the tube and disassembled. The sample was pushed out of the sampler chamber by a sterile push-rod and placed in a Whirl-Pak plastic pouch (NASCO, Fort Atkinson, WS). The pouch was marked with the pile number and sample level. The sampler was then cleaned and sterilized by an alcohol-flame technique in preparation for the next sample.

The sterilization method consisted of washing the sampler in a water bath and dipping it in alcohol. After the alcohol dip, the sampler was flamed inside and out with a butane torch. Both the sampling tool and the sample were handled in the most aseptic manner possible to avoid contamination of the samples.

The samples were packaged and transported by parcel post to the Water Quality and Waste Management Laboratory in the Agricultural Engineering Department at The University of Tennessee in Knoxville.

4.4 LABORATORY ANALYSIS

Sample transit time from Lewisburg, Tennessee to Knoxville, Tennessee was approximately two (2) days. The compost samples were processed upon arrival at the laboratory. Sampling, preparation of samples, and microbiological examinations were those approved by

Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 1985).

4.4.1 Moisture Content Determination

The compost samples were mixed well in the Whirl-Pak bags. Dry matter content of the compost materials was determined by drying 25 to 50 g of the material in a 103°C oven to a constant weight. The moisture content was calculated by dividing the weight of the moisture by the combined weight of the moisture and dried material.

4.4.2 Microbiological Examination

A test for total coliform bacteria was used as an indicator of pathogens. Even though all coliform bacteria are not necessarily pathogenic, their destruction is indicative of good composting practices (Haug, 1980). MacConkey Agar was selected as the plating medium. According to product labeling, MacConkey Agar is "a selective and differential plating medium for the isolation and differentiation of gram-negative enteric bacilli".

A heterotrophic plate count - spread plate method was performed as approved by the Standard Methods Committee in 1985 (American Public Health Association, 1985). One (1.000) gram aliquots of each wet sample were placed into 99 ml of sterile buffer diluent and blended for five (5) minutes by a Burrell wrist-action shaker to form a slurry.

One (1.00) ml of this slurry was pipeted into a 99 ml sterile buffer dilution blank (10^{-2} dilution). Ten (10.00) ml of the slurry

was pipeted into a 90 ml sterile buffer dilution blank (10^{-1} dilution). Aliquots (.01 ml) of the original slurry, the 10^{-1}, and 10^{-2} dilutions were pipeted onto MacConkey Agar, available from DIFCO Laboratories of Detroit, MI. Four (4) duplicate aliquots were plated from each dilution. The plates were incubated at 37°C for 20 hours. After incubation all colonies were counted and recorded. Total counts are given as colony forming units per dry gram of solid sample. Analytical procedures were checked by using a positive control Escherichia coli. This control of known population was plated and counted along with each group of samples during each microbiological examination.

4.5 DATA ANALYSIS

Three (3) treatments (TMT) were established based upon the aeration technique and size of pile. The treatments were:

A. FA: Forced Aeration - 1.2 m (48 in) piles

B. NAL: Natural Aeration - 1.2 m (48 in) piles

C. NAS: Natural Aeration - 0.9 m (36 in) piles

The data for temperature, moisture content, and total coliform population for the 30 cm (12 in), 60 cm (24 in), and 90 cm (36 in) levels within each pile were recorded.

The piles were allowed to compost for as long as 120 days. However, for statistical analysis, a composting period of approximately 41 days from construction was established for all piles

except 2600 and 2700. Data beyond this 41-day period were compiled but not used in the statistical analysis.

Since this was a repeated measures design, attempts were made to fit an appropriate function over time to enable characterization of the responses and test the hypothesis comparing the various treatments. Decompostion by aerobic microorganisms is a very complex and interactive process involving many environmental factors. No mathematical function was apparent to characterize such a phenomenon. A strategy to describe these responses over time via a broken line regression was chosen (Sanders, 1986).

The data for fan-run-time and pressure drop across the forced aeration piles were compiled. Fan-run-time results were sorted by pile and separated into control by the timer and control by the temperature controller.

4.5.1 Temperature Data

The observed temperature data (in degrees celsius) were plotted for each pile and depth over time (days). With inspection, some of the responses appeared to be clearly nonlinear. However, no specific mathematical function was apparent to explain the responses. A broken line regression technique with two (2) breaks was used to characterize the temperature responses over time.

Model predicted temperature (in degrees celsius) versus time (in days) was plotted for each pile level within all piles in the manner illustrated in Figure 4.7. Upon examination of the predicted

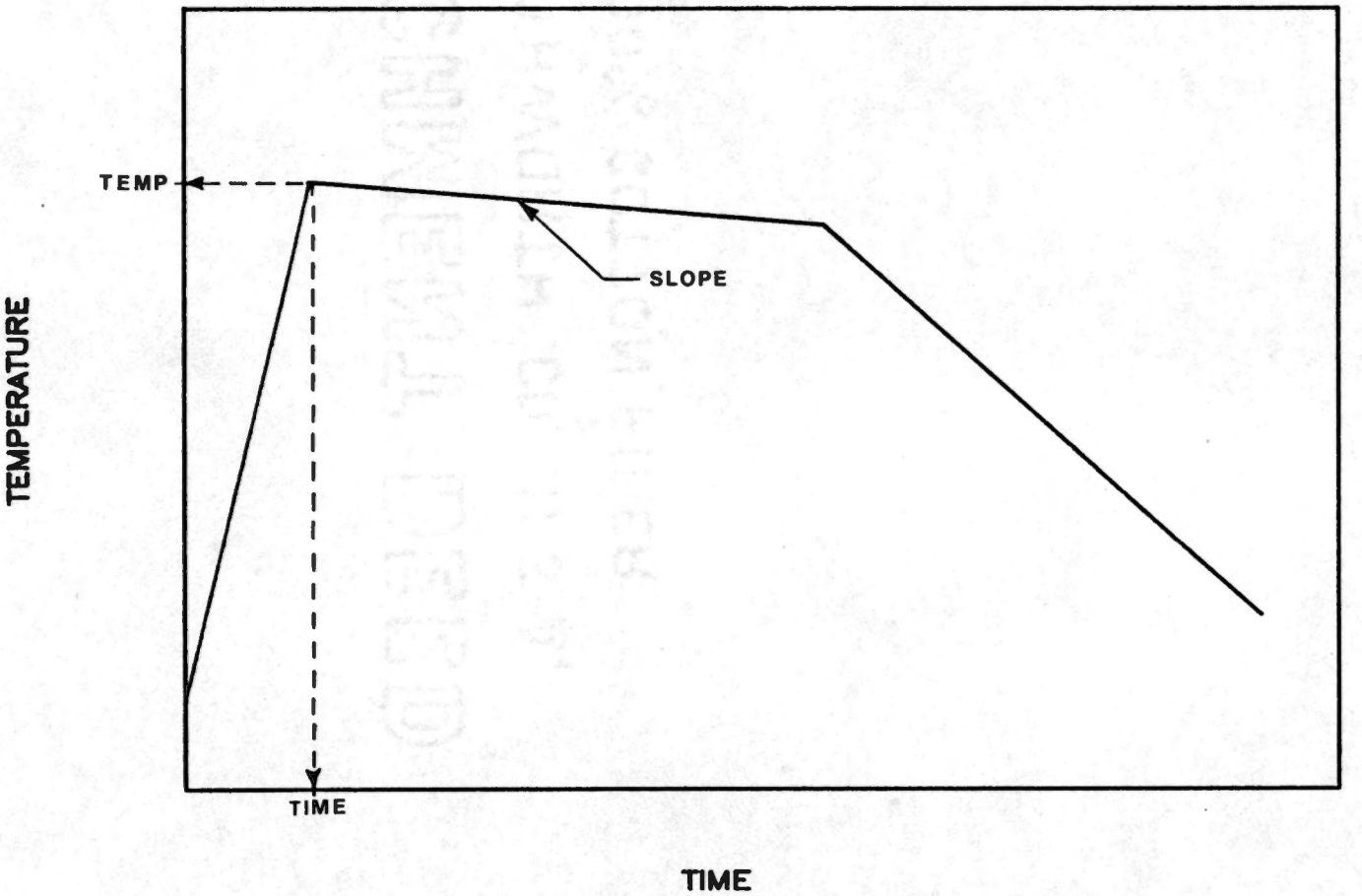


Figure 4.7. General broken line temperature responses illustrating the statistics used to compare treatments.

curves, various parameters were observed to be characteristic in each of the three (3) treatments. These parameters were:

1. Temp: Maximum temperature achieved at each level,
2. Time: Time required to reach the point of maximum temperature, and
3. Slope: Slope of the second line segment (an indication of the time that temperature remained at an elevated level).

Numeric values for these parameters were obtained from the predicted regression curves and incorporated into an analysis of variance. An example of the SAS code follows:

```
PROC  GLM;
    CLASSES  TMT  PILE  LEVEL;
MODEL TEMP TIME SLOPE  =  TMT + PILE(TMT) + LEVEL + LEVEL*TMT;
TEST  H  =  TMT  E  =  PILE(TMT);
TEST  H  =  LEVEL  LEVEL*TMT;
```

The null hypotheses for TMT PILE(TMT) LEVEL and TMT*LEVEL were achieved via the SAS code indicated above. A printout of the actual SAS code used in the broken line regressions is presented in the Appendix.

Piles 2600 and 2700 were only tested over a 12-day period due to a failure of the aeration fans on the twentieth day. The final moisture and coliform samples were taken on the twelfth day. Temperature sampling was discontinued to correspond with the final moisture and total coliform samples. Due to the short life of these piles, only one (1) break was used in the regression technique. However, all parameters were tested.

4.5.2 Moisture Data

The data for levels 30 cm (12 in), 60 cm (24 in), and 90 cm (36 in) were averaged to give a single moisture content for the pile on each observation date. The data were fit with a model using a simple linear regression technique. The slopes of the predicted lines (moisture content vs. time) were tested in an analysis of variance. An example of the SAS code follows:

```
PROC  GLM;
    CLASSES  TMT  PILE;
MODEL  SLOPE  =  TMT + PILE(TMT).
```

This test was used to determine if there was a significant difference in change of moisture content between treatments. With the exception of piles 2600 and 2700, comparisons were made over an approximate 41-day period. Piles 2600 and 2700 were tested over a 12-day period due to a failure of the aeration fans on the twentieth day. The last moisture sample was taken on the twelfth day.

4.5.3 Total Coliform Data

The data for total coliforms were handled in much the same manner as the temperature. The logarithm (base 10) of the raw data was fit with a model using a broken line regression technique with one (1) break (Sanders, 1986). Total coliform population (cfu/g) versus time (days) was plotted for each pile level within all piles. With the exception of piles 2600 and 2700, comparisons were made over an approximately 41-day period. Piles 2600 and 2700 were tested over a 12-day period due to mechanical failures. The predicted curves were used to make comparisons between treatments and across pile levels.

These curves demonstrated no consistent patterns over time. It could be observed that these curves were extremely erratic and no attempts were made to generalize the effects of time upon coliform counts. Thus, a visual examination of the predicted curves was used to evaluate the differences and similarities among the pile levels and treatments.

5.0 RESULTS AND DISCUSSION

Table 5.1 identifies the piles constructed and included in the analysis of this study. The original goal was to produce as many piles as possible during the summer, fall, and winter seasons. However, a limited supply of dairy waste solids was produced, and piles were constructed as the material became available.

Missing piles in the sequencing were constructed but not included in the results for various reasons. Piles 1100 through 1400 were constructed for testing the forced aeration system and sampling procedures, and thus were not included in the results. Pile 1700 was not included in the results since it was 90 cm (36 in) forced aeration pile and thus did not fit into the established treatments. Pile 2200 was a 60 cm (24 in) naturally aerated pile and it likewise did not fit into the established treatments.

Piles 120 cm (48 in) tall are referred to as "large piles". Similarly, piles 90 cm (36 in) tall are referred to as "small piles". Details of the results of the temperature, moisture, total coliform, and fan performance studies follow.

5.1 TEMPERATURE

Temperature of the compost mass gives an indication of the overall status of the composting process from beginning to end. The temperatures were monitored at various positions within the compost mass. For a review, in the large piles, thermocouples were placed at 30 cm (12 in), 60 cm (24 in), and 90 cm (36 in) above ground level.

TABLE 5.1

Identification of Piles Constructed at the Dairy Experiment Station During 1985 and 1986

Pile Number	Date Constructed	Date Destroyed	Aeration Status	Height (Meters)
1500	08-08-85	12-11-85	Natural	1.2
1600	09-12-85	12-11-85	Natural	1.2
1800	11-08-85	01-23-86	Forced	1.2
1900	11-08-85	01-23-86	Natural	0.9
2000	12-11-85	03-19-86	Natural	1.2
2100	12-11-85	03-19-86	Natural	0.9
2300	01-23-86	03-19-86	Forced	1.2
2400	01-23-86	03-19-86	Forced	1.2
2500	01-23-86	03-19-86	Natural	1.2
2600	03-19-86	04-07-86	Forced	1.2
2700	03-19-86	04-07-86	Forced	1.2
2800	03-19-86	05-06-86	Natural	1.2
2900	03-19-86	05-06-86	Natural	0.9

In the small piles, the thermocouples were placed at 30 cm (12 in) and 60 cm (24 in) above ground level.

As previously discussed in the data analysis section, a broken line regression technique was used to characterize the responses of temperature over time. The observed temperature data and the predicted curves for piles 1500 and 2400 are shown as an example in Figures 5.1 and 5.2.

Table 5.2 presents the results of the analysis of variance performed on the parameters of temp, time, and slope as predicted by the broken line regression technique. Two (2) contrasts were made over each of the 30 cm (12 in), 60 cm (24 in), and 90 cm (36 in) levels. One contrast was the forced aeration treatment (FA) versus the large pile natural aeration treatment (NAL). The other contrast was the large pile natural aeration treatment (NAL) versus the small pile natural aeration treatment (NAS). The probability that differences of the magnitude observed occurred solely by chance is reported as "PROB" in Table 5.2.

Results of the statistical analysis on temperature are as follows:

- The forced aeration piles reached a higher maximum temperature than the large natural aeration piles at all levels, (i.e., a higher temperature was reached in the piles with a fan);
- The maximum temperature was reached faster in the forced aeration piles than in the large natural aeration piles;

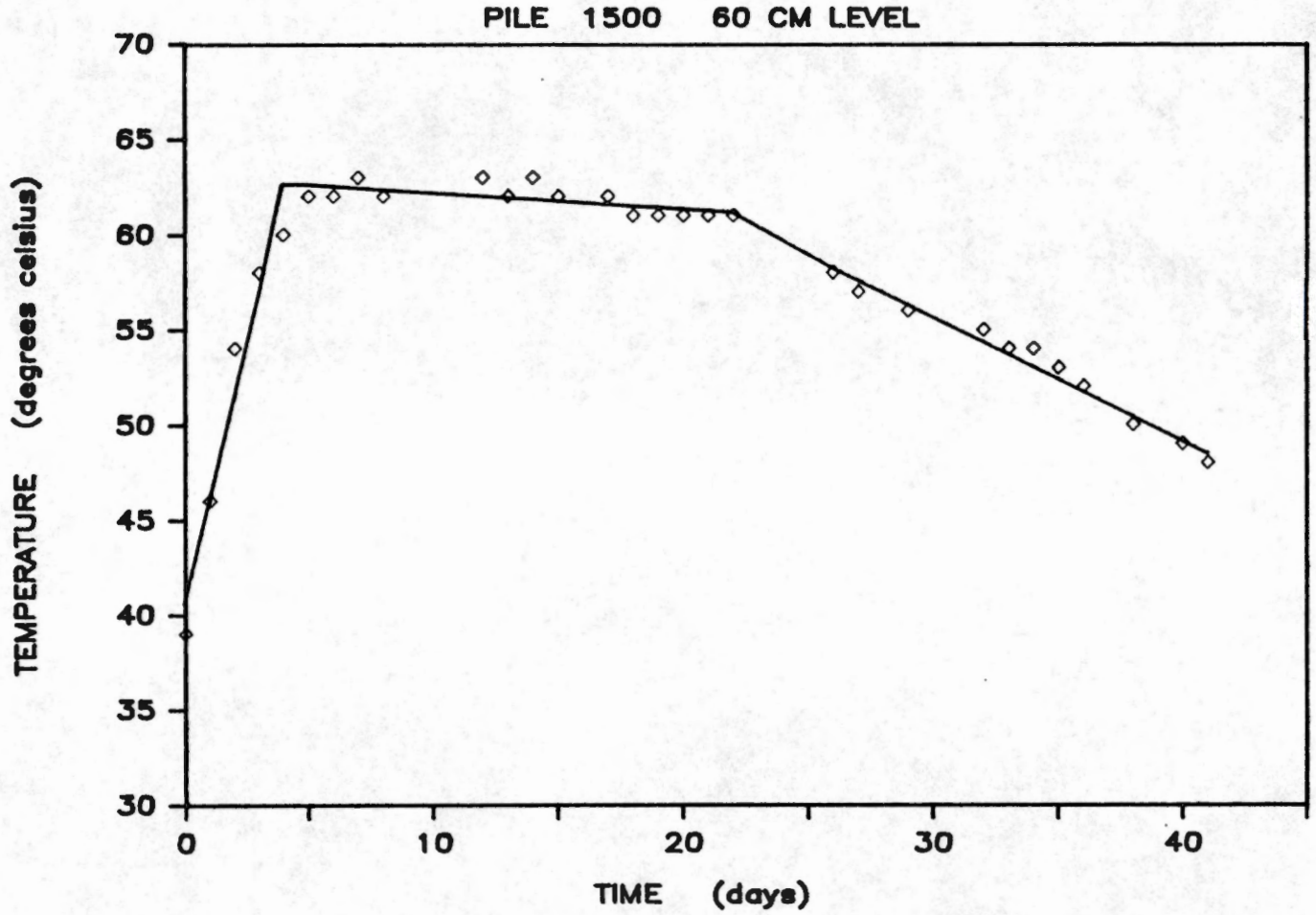


Figure 5.1. Example of the predicted temperature curves and observed data for pile 1500, 60 cm level.

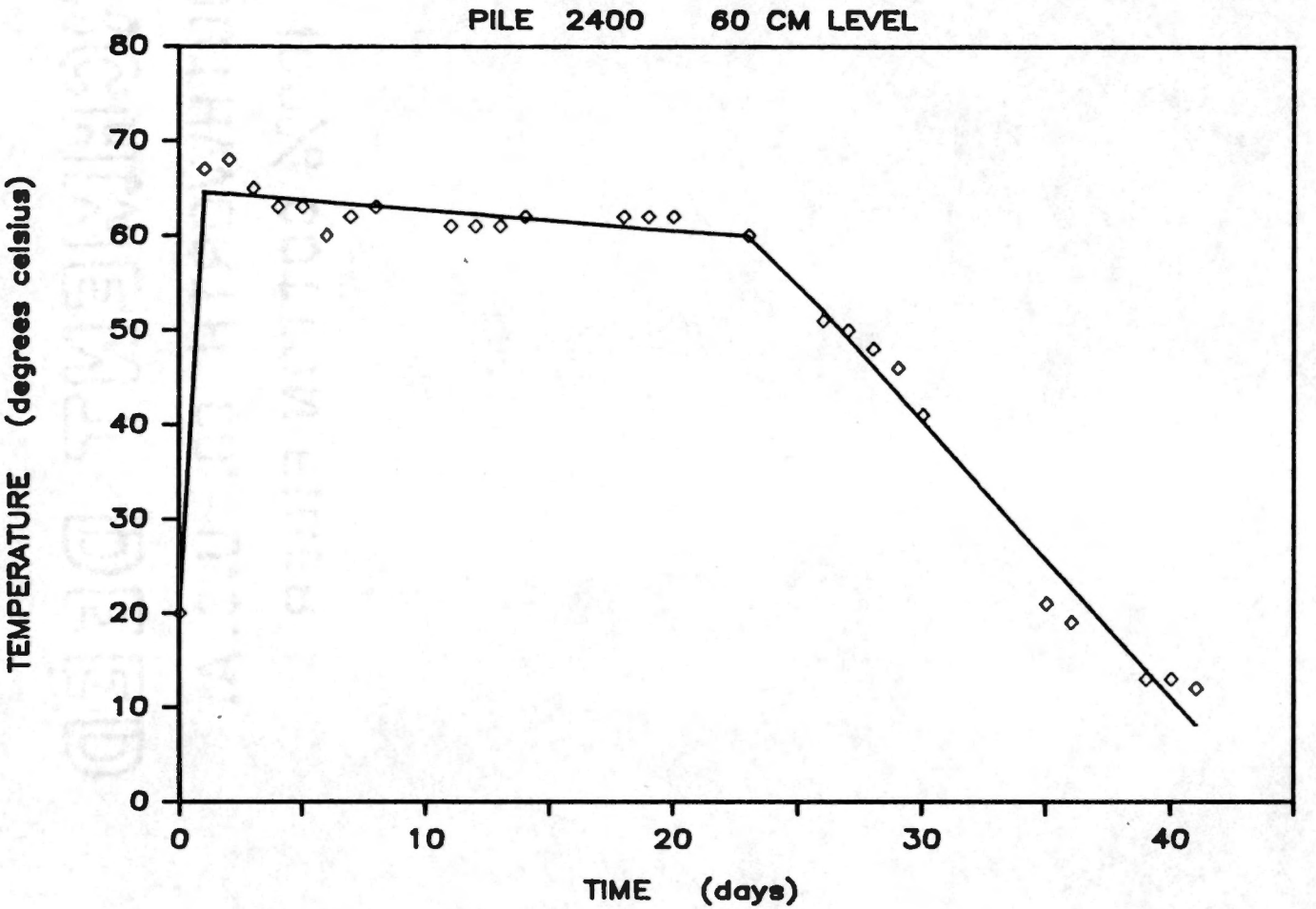


Figure 5.2. Example of the predicted temperature curves and observed data for pile 2400, 60 cm level.

TABLE 5.2

Predicted Temperature Parameter Means

Contrast	TMT[a]	Temp[b]	PROB[c]	Time[d]	PROB[c]	Slope[e]	PROB[c]
30 cm (12 in) Level							
1	FA	60.20	0.267	1.00	0.049	-0.40	0.448
	NAL	53.35		11.01		0.56	
2	NAL	53.35	0.528	11.01	0.846	0.56	0.072
	NAS	57.75		9.99		-2.26	
60 cm (24 in) Level							
1	FA	70.55	0.064	1.14	0.253	-0.53	0.039
	NAL	61.45		5.22		0.04	
2	NAL	61.45	0.380	5.22	0.059	0.04	0.629
	NAS	56.82		13.49		-0.10	
90 cm (36 in) Level[f]							
1	FA	75.25	0.009	1.40	0.321	-0.69	0.291
	NAL	64.36		1.85		-0.48	

[a] FA indicates forced aeration treatment, NAL indicates natural aeration large pile treatment, NAS indicates natural aeration small pile treatment.

[b] Mean predicted maximum temperature in the compost mass at the indicated levels in degrees celsius.

[c] Probability that differences of the magnitude observed occurred solely by chance (PR>F).

[d] Mean predicted time (days) required to reach the point of maximum temperature.

[e] Mean predicted slope of the second line segment in degrees celsius per day (gives an indication of the time that the temperature remained at an elevated level).

[f] Contrast No. 2, NAL versus NAS, could not be performed since the NAS treatment does not have a 90 cm (36 in) level.

- The temperatures remained hot longer in the large natural aeration piles than in the forced aeration piles, (i.e., the elevated temperatures presisted longer in the piles without the fan);
- At the 30 cm (12 in) level, the small natural aeration piles reached a higher maximum temperature than the large natural aeration piles;
- The small natural aeration piles reached their maximum temperature at the 30 cm (12 in) level faster than the large natural aeration piles;
- The large natural aeration piles reached a higher maximum temperature at the 60 cm (24 in) level than the small natural aeration piles, the reverse of the result at the 30 cm (12 in) level;
- The large natural aeration piles reached their maximum temperatures faster than the small natural aeration piles at the 60 cm (24 in) level;
- The temperature remained hot longer in the large natural aeration piles than in the small natural aeration piles at both the 30 cm (12 in) and 60 cm (24 in) levels.

5.2 MOISTURE

The moisture content of the material as it comes from the separator is approximately 80% on a wet weight basis. One objective of the static pile composting process was to lower the moisture

level. Reduction in moisture content through composting has been documented (Finstein, 1980; MacGregor et al. 1981).

Samples for moisture content were taken from various positions within each pile. As a review, samples were taken 30 cm (12 in), 60 cm (24 in), and 90 cm (36 in) above ground level in the large piles. Samples were taken at positions 30 cm (12 in) and 60 cm (24 in) above ground level in the small piles.

As previously discussed in the data analysis section, the moisture contents for levels 30 cm (12 in), 60 cm (24 in), and 90 cm (36 in) were averaged to give a single moisture content for the pile on each observation date. The results of the regression of averaged moisture content with time are shown in Table 5.3.

The predicted slopes show that some drying took place in all piles except pile 1900. The near zero (0) drying rate predicted for pile 1900 suggests that the moisture content was essentially constant throughout the life of the pile. With the lesser slopes found in piles 1900 and 2000, the coefficient of determination (R^2) is very poor. However, the magnitude of the coefficient of variation (CV) associated with piles 1900 and 2000 shows that there was little scatter in the data and that the actual slope was near zero (0) as predicted by the equation.

It should be pointed out that none of the piles experienced a great amount of drying. The greatest drying rate was in pile 2300, a forced aeration pile, with a slope of -0.50. Assuming that this rate remained constant over the entire composting process, it would take

TABLE 5.3

Results of the Linear Regression Performed on the Moisture Data

Aeration Status	Pile	Predicted Intercept	Predicted Slope	R^2[a]	CV[b]
Forced	1800	79.6	-0.23	0.75	3.09
Forced	2300	79.0	-0.50	0.96	3.35
Forced	2400	77.3	-0.36	0.49	11.64
Forced	2600	77.8	-0.40	0.66	3.25
Forced	2700	78.3	-0.32	0.75	2.05
Natural	1500	80.2	-0.11	0.54	2.13
Natural	1600	80.7	-0.08	0.60	1.40
Natural	2000	77.4	-0.03	0.26	1.26
Natural	2500	79.1	-0.47	0.93	3.96
Natural	2800	78.3	-0.25	0.93	1.74
Natural	1900	79.4	0.01	0.01	1.70
Natural	2100	78.4	-0.07	0.98	0.28
Natural	2900	78.1	-0.22	0.92	1.55

a R^2 indicates closeness of fit of observed data to values predicted by regression equation. An R^2 of 1.00 implies a perfect fit.

b Coefficient of variation - provides a measure of the average degree of variation, expressed as a percentage of the mean of the dependent variable.

40 days for the compost mass to dry from an initial 79% moisture to 59% moisture. However, it must be stressed that these drying rates are probably not suitable for predicting drying times in excess of 41 days, since only data for the first 41 days were used to develop the drying rates. Observations suggest that most of the actual drying occurred during the early days of the composting process, and that drying all but ceased later. The predicted drying rates are most useful for comparing treatments.

The slopes predicted by the regression technique were incorporated into an analysis of variance. The analysis of variance was used to determine if any difference existed between the three (3) treatments. A Waller-Duncan k-ratio t test was used to distinguish between the means of the treatments produced by the analysis of variance. The results of the analysis are shown in Table 5.4.

Given the sensivitity of this experiment, no differences were found between the FA and NAL treatments nor between the NAL and NAS treatments. The drying rates are low altogether, and there is no indication that a substantial amount of drying took place in the piles.

5.3 TOTAL COLIFORMS

Total coliform bacteria was used as the pathogen indicator in the compost process. Total coliform counts give an indication of the disease causing potential of the compost material. Their destruction is indicative of good composting practices (Haug, 1980).

TABLE 5.4

Results of the Statistical Analysis Performed on the Predicted Drying Rates

Treatment[a]	No. of Observations	Mean Drying Rate (% per day)	Grouping[b]
FA	5	0.362	A
NAL	5	0.188	A B
NAS	3	0.095	B

[a] FA indicates forced aeration treatment, NAL indicates natural aeration large pile treatment, NAS indicates natural aeration small pile treatment.

[b] Means with the same grouping letter are not significantly different, alpha = 0.10.

The same samples used in the moisture content studies were used in the microbiological examination. Each sample was thoroughly mixed at the lab and a portion was removed for each study.

5.3.1 Treatment Differences

The results of the broken line regression (1 break) are shown in Table 5.5. This Table shows the predicted population of total coliform bacteria for all piles and all levels within the piles tested over an approximately 41-day composting period. These predicted curves were used to make comparisons between the three (3) treatments and the levels within each pile.

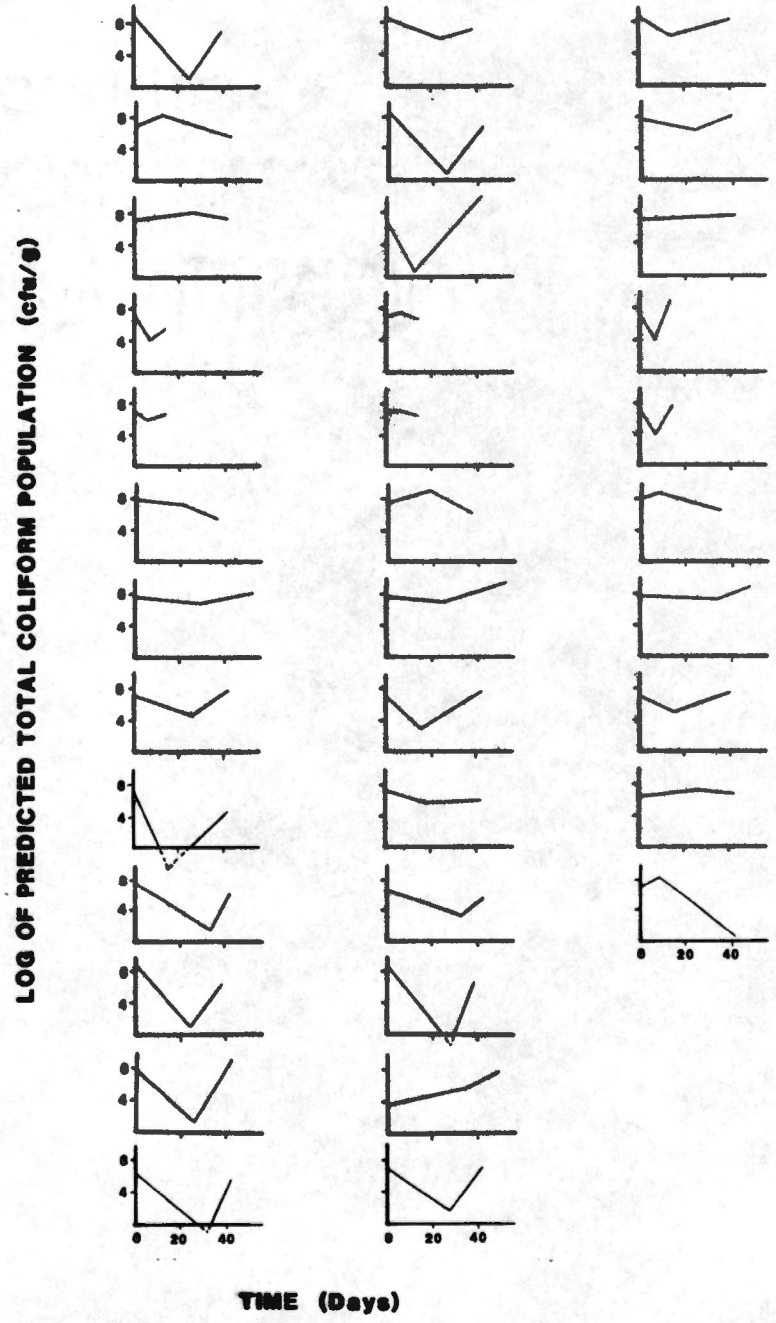
No consistent trends or patterns were demonstrated by the curves with regard to treatment or level within the pile. Many curves, however, show an upward turn in the total coliform counts, which suggests that the coliform bacteria population may start rebuilding at some point during the composting process. The predicted curve for pile 1800, a forced aeration pile, first shows a decline and then an increase in the population of organisms across all levels within the pile. However, the curve for pile 2400, also a forced aeration pile, shows an increase then a decrease for the 30 cm (12 in) level. The 60 cm (24 in) level shows a decline then an increase, and the 90 cm (36 in) level shows a steady increase in total coliform population.

These variations are much the same in the natural aeration piles. The predicted curves for all levels within pile 1600 are very similar. All levels show a decrease and a later increase in total

TABLE 5.5

Total Coliform Populations Through Time Predicted by a Broken Line Regression Technique (Sanders, 1986)

Pile	Treatment	30 cm (12 in)	60 cm (24 in)	90 cm (36 in)
1800	FA			
2300	FA			
2400	FA			
2600	FA			
2700	FA			
1500	NAL			
1600	NAL			
2000	NAL			
2500	NAL			
2800	NAL			
1900	NAS			
2100	NAS			
2900	NAS			



coliform population. However, the predicted curves for pile 2500 show very dissimilar characteristics across all pile levels. At a level of 30 cm (12 in), the slope of both line segments is very steep. A sharp decline is first noted, then a sharp increase is shown. The 60 cm (24 in) level shows a gradual decline then a leveling off in counts. At the 90 cm (36 in) level, little change in the population is predicted by the curve. Likewise, pile 2100, a small naturally aerated pile, shows a sharp decline and then an increase in population at the 30 cm (12 in) level. Conversely, the 60 cm (24 in) level shows an almost constant increase in total coliform population.

5.3.2 Population Persistence and Variability

It was anticipated that the total coliform population would decline as the temperature in the pile exceeded their normal living conditions. However, even after several weeks of temperatures above 60°C, total coliform populations of a magnitude similar to those at time zero were found in many samples. Some piles were sampled for as long as 120 days. Large populations were regularly found throughout the sample period, thus suggesting that coliform bacteria will persist in compost piles of dairy waste solids for long periods of time.

The population enumerated from samples taken at a given pile position varied a great deal from week to week. The data in Figure 5.3 illustrate both the variability and the persistence of large populations for extended periods.

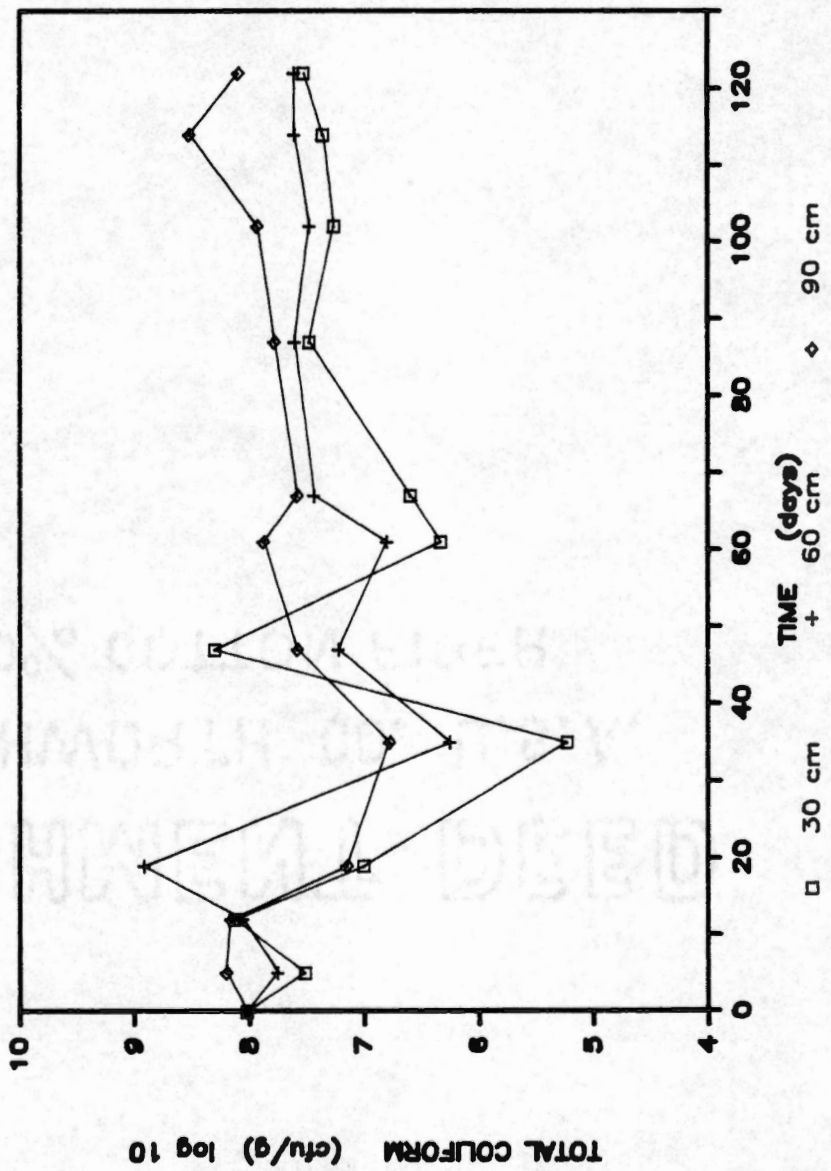


Figure 5.3. Total coliform population history for all levels in pile 1500.

Due to the variations in counts across treatments and pile levels, the techniques for sampling, shipping, storing, and culturing the samples were investigated. Nothing was found, however, to indicate that the sample handling procedures caused the variability. Since the remaining factor was the compost material itself, variations within the pile level were studied. Figure 5.4 shows the results of a test for variation within a given pile level. Several samples were taken from the same horizontal plane in the pile within centimeters of each other. The results show that samples in the naturally aerated pile ranged from approximately 10,000 to over one (1) million total coliforms per dry gram. The forced aeration pile data ranged from less than 100 to more than one (1) million total coliforms per dry gram.

Thus, this study indicates that different microenvironments exist in a given level within the pile. There are areas with high total coliform populations next to areas with lower populations. The existence of microenvironments within the pile may account for the variability in the data. The existence of different microenvironments also suggests that it will probably be very difficult to successfully reduce coliform populations by composting.

5.4 FAN PERFORMANCE

Table 5.6 shows the fan performance statistics for all forced aeration piles. Static pressure measurements were made with an inclined manometer at the times indicated in the Table. The air

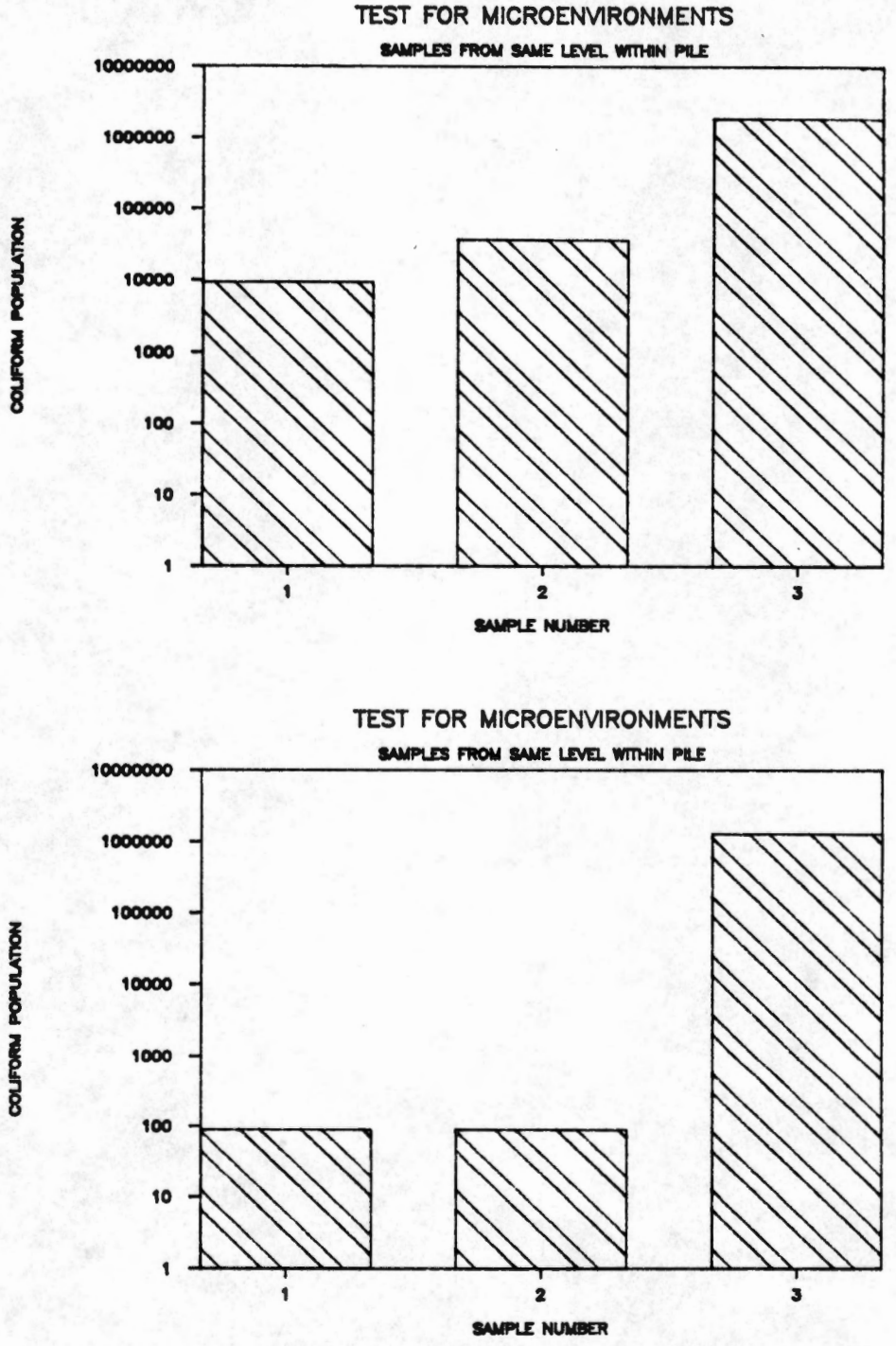


Figure 5.4. Tests for variations within a single pile level. Top plot is NAL treatment and bottom plot is FA treatment.

TABLE 5.6

Fan Performance Statistics

Pile	Time (days)	Static Pressure (cm H_2O)	(in H_2O)	Air Flow Rate (m^3/min)	(cfm)	Timer Setting
1800	0	1.27	0.50	2.13	75.3	30 s/15 min
1800	33	1.42	0.56	1.87	65.9	
2300	0	1.57	0.62	2.46	86.9	35 s/15 min
2300	54	1.50	0.59	2.99	105.7	
2400	0	1.88	0.74	2.46	86.9	35 s/15 min
2400	54	2.03	0.80	2.99	105.7	
2600	0	1.73	0.68	2.46	86.9	30 s/15 min
2700	0	2.54	1.00	2.73	96.3	30 s/15 min

flow rate was measured with a hot wire anemometer. The setting of the cycle timer is reported in fan on-time seconds per 15-minute period.

Figures 5.5, 5.6, 5.7, 5.8, and 5.9 show the plots of blower operation through time. The blower operation was separated into control by the cycle timer and control by the temperature set point controller. Percent on time was calculated by dividing the amount of time the fan had run by the elapsed time between observations. The solid line represents the percentage of time the fan actually operated. The dashed line represents the fan run time as controlled by the cycle timer. The amount of time the fan was controlled by the temperature controller is represented by the difference in the solid and dashed lines.

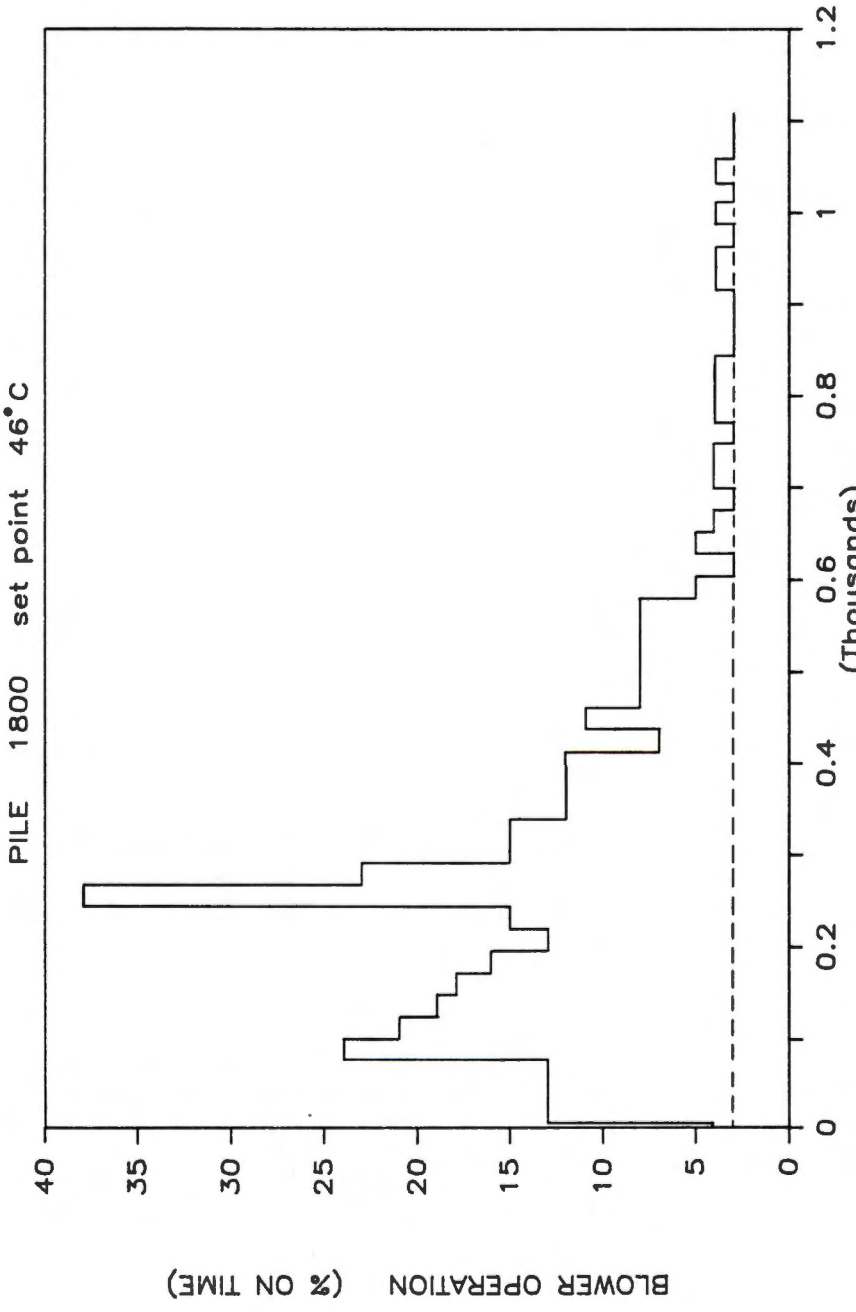


Figure 5.5. Blower operation history for pile 1800.

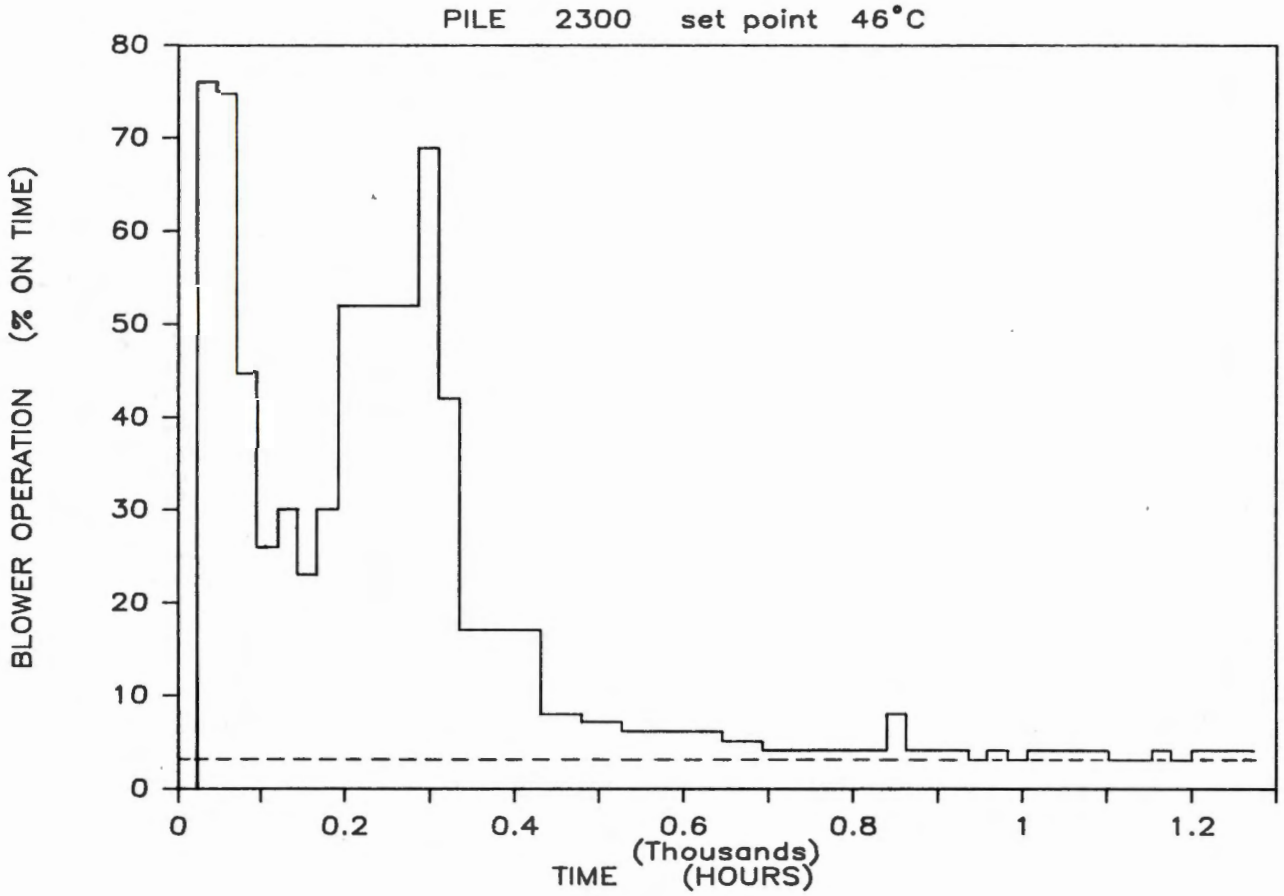


Figure 5.6. Blower operation history for pile 2300.

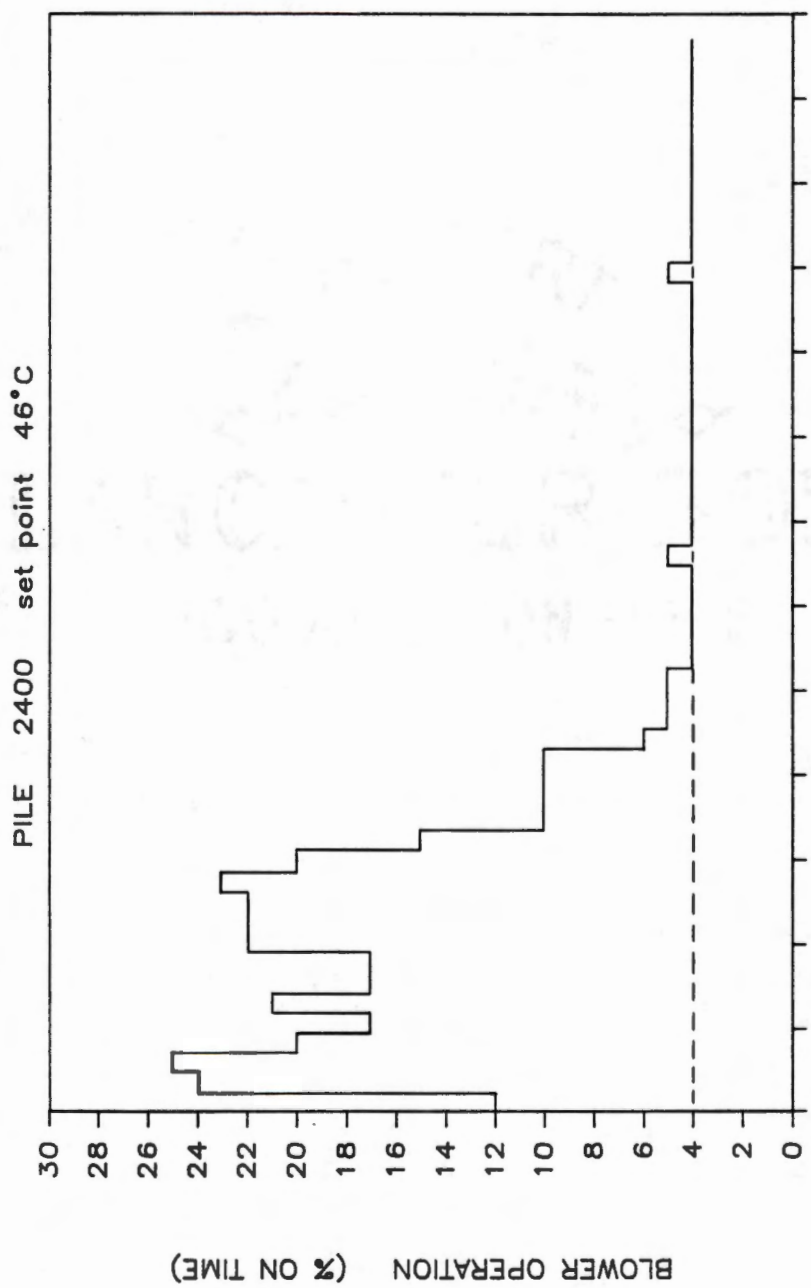


Figure 5.7. Blower operation history for pile 2400.

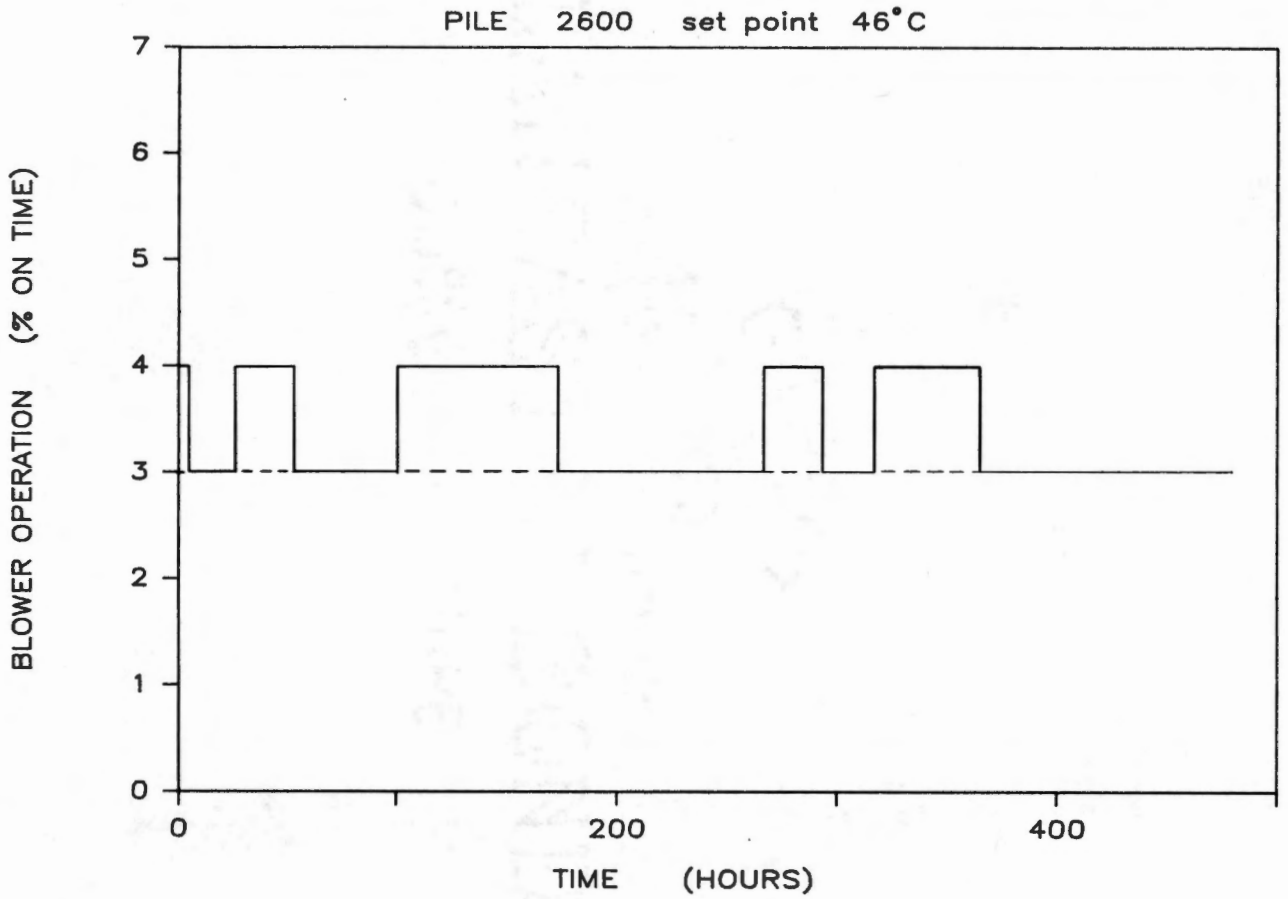


Figure 5.8. Blower operation history for pile 2600.

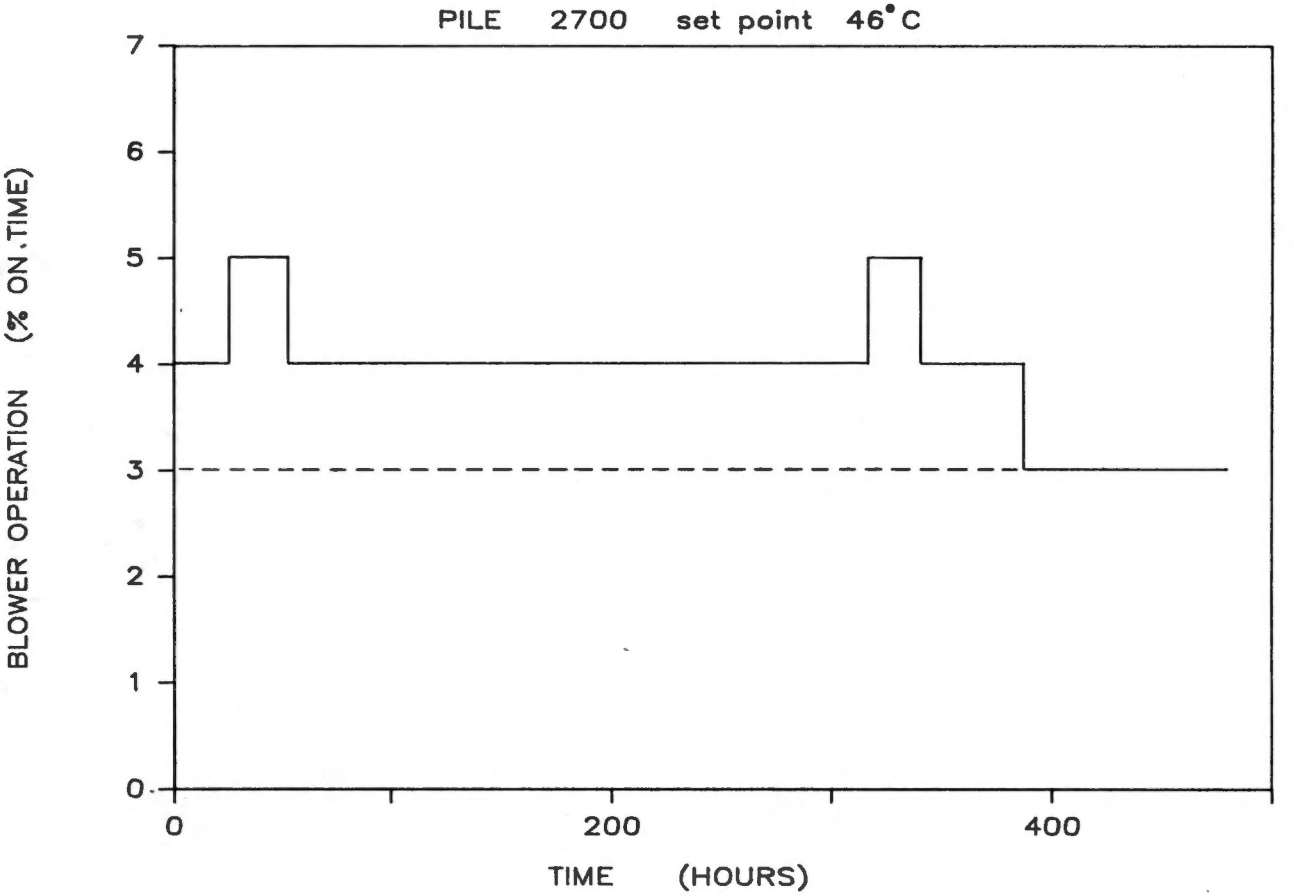


Figure 5.9. Blower operation history for pile 2700.

6.0 SUMMARY AND CONCLUSIONS

6.1 SUMMARY

A series of static compost piles were constructed during the period of June, 1985 to March, 1986. Dairy manure solids obtained by separating the solid and liquid fractions of a manure slurry were stacked into two size piles with a rectangular base and allowed to compost for as long as 120 days. Both natural and forced aeration methods were employed to supply oxygen to the piles of manure solids. Temperatures were monitored at various levels within each pile. Samples from various levels within each pile were analyzed for moisture content and total coliform populations. The piles were classified into three (3) treatments according to the pile size and method of aeration. The purpose of the study was to investigate the relationship among various compost process parameters (e.g., method of aeration, pile size, and time) and the moisture content and coliform bacteria population in the composted dairy waste solids.

6.2 CONCLUSIONS

Results of this study support the following conclusions about temperature, moisture removal, and total coliform populations in static compost piles of dairy waste solids.

6.2.1 Temperature

Forced aeration of static piles is superior to natural aeration if initial rate of temperature rise and maximum temperature

achieved is important. However, naturally aerated static piles will achieve temperatures generally considered adequate for good composting, and will maintain elevated temperatures longer than forced aeration static piles.

Both large and small naturally aerated static piles can attain internal temperatures generally considered adequate for good composting. However, the trend for positions nearer the surface to achieve higher temperatures in less time indicates that the interior of small piles will get hotter quicker than will the interior of large naturally aerated piles.

6.2.2 Moisture

Compost piles of dairy waste solids dry very slowly. It makes no difference which aeration method or pile size is used since there were no significant difference between the treatments tested.

6.2.3 Total Coliforms

Static pile composting will not eliminate coliform bacteria from dairy waste solids. Regions with large total coliform populations can be located in compost piles after as long as 120 days.

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APPENDIX

```
*THIS  PROGRAM WILL INPUT DATA, FIT THE BROKEN LINE
 REGRESSION, AND THEN PLOT THE OBSERVED AND FITTED VALUES.;

TITLE1 'HEIGHT: 12 INCHES';
     ** UAL  =  NATURALLY AERATED 48 INCH PILE;
     ** UAS  =  NATURALLY AERATED 36 INCH PILE;
     ** AER  =  MECHANICALLY AERATED 48 INCH PILE;

     ** D12  =  DEPTH OF 12 INCHES FROM GROUND LEVEL;
     ** D24  =  DEPTH OF 24 INCHES FROM GROUND LEVEL;
     ** D36  =  DEPTH OF 36 INCHES FROM GROUND LEVEL;
     ** DSUR  =  SURFACE OF THE PILE;
DATA A;
INPUT       TMT $ PILE  DAY  T12  T24  T36 TSUR;
CARDS;



RUN;

DATA _1500 _1600 _1800 _1900 _2000 _2100 _2300 _2400
     _2500 _2600 _2700 _2800 _2900;
SET A;
IF PILE = 1500 THEN OUTPUT _1500;
IF PILE = 1600 THEN OUTPUT _1600;
IF PILE = 1800 THEN OUTPUT _1800;
IF PILE = 1900 THEN OUTPUT _1900;
IF PILE = 2000 THEN OUTPUT _2000;
IF PILE = 2100 THEN OUTPUT _2100;
IF PILE = 2300 THEN OUTPUT _2300;
IF PILE = 2400 THEN OUTPUT _2400;
IF PILE = 2500 THEN OUTPUT _2500;
IF PILE = 2600 THEN OUTPUT _2600;
IF PILE = 2700 THEN OUTPUT _2700;
IF PILE = 2800 THEN OUTPUT _2800;
IF PILE = 2900 THEN OUTPUT _2900;

PROC NLIN DATA=_1500 OUTEST=PARMS1;
  PARAMETERS A=63 B1=5.4 B2=-.09 B3 = -.640 X0=4.1 X1=21.5;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 1500';

DATA PARMS1;
```

```
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA COMBO;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=COMBO;

PROC PLOT DATA=COMBO;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

PROC NLIN DATA=_1600 OUTEST=PARMS1;
  PARAMETERS A=20 B1=5.7 B2=-.35 B3 = -.640 X0=2,5,7 X1=7,10,20;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 1600';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_1800 OUTEST=PARMS1;
  PARAMETERS A=61.3 B1=21.8 B2=-.31 B3 = -4.70 X0=1.88 X1=31.67;
```

```
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 1800';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_1900 OUTEST=PARMS1;
  PARAMETERS A=20 B1=5.7 B2=-.35 B3 = -.640 X0=2,5,7 X1=7,10,20;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 1900';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
```

```
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2000 OUTEST=PARMS1;
  PARAMETERS A=20 B1=5.7 B2=-.35 B3 = -.640 X0=2,5,7 X1=7,10,20;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 2000';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2100 OUTEST=PARMS1;
  PARAMETERS A=20 B1=5.7 B2=-.35 B3 = -.640 X0=2,5,7 X1=7,10,20;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
```

```
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 2100';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2300 OUTEST=PARMS1;
  PARAMETERS A=70 B1=52 B2=-.46 B3 = -4.56 X0=.965 X1=31.86;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 2300';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1 -X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
```

```
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2400 OUTEST=PARMS1;
  PARAMETERS A=64 B1=68 B2=-.17 B3 =-2.9 X0=1 X1=23;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 2400';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2500 OUTEST=PARMS1;
  PARAMETERS A=20 B1=5.7 B2=-.35 B3 = -.640 X0=2,5,7 X1=7,10,20;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
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```
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
            +(U2*A) + B2*Z2
            +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 2500';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2600 OUTEST=PARMS1;
  PARAMETERS A=80 B1=22.7 B2=-.95 X0=1.5;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  MODEL T12 = U1*A + B1*Z1
            +(U2*A) + B2*Z2;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 Z1 Z2;
  TITLE2 'PILE 2600';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY THEN MY_PRED = C_2 + B2*DAY;

PROC PRINT DATA=TEMP;
```

```
PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2700 OUTEST=PARMS1;
  PARAMETERS A=77 B1=15 B2=-.7 X0=2;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 Z1 Z2;
  TITLE2 'PILE 2700';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY THEN MY_PRED = C_2 + B2*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2800 OUTEST=PARMS1;
  PARAMETERS A=66 B1=12 B2=-.24 X0=2;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 Z1 Z2;
  TITLE2 'PILE 2800';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
```

```
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY THEN MY_PRED = C_2 + B2*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA COMBO;
  SET COMBO TEMP;

PROC NLIN DATA=_2900 OUTEST=PARMS1;
  PARAMETERS A=66 B1=15 B2=-1.0 B3 = -.171 X0=1.65 X1=9.00;
  U1 = (DAY LE X0);
  U2 = (X0 < DAY AND DAY LE X1);
  U3 = (DAY > X1);
  Z1 = U1*(DAY-X0);
  Z2 = U2*(DAY - X0);
  Z3 = U3*(DAY - X1);
  MODEL T12 = U1*A + B1*Z1
              +(U2*A) + B2*Z2
              +U3*(A+B2*(X1-X0))+B3*Z3;
  OUTPUT OUT=NEW1 PREDICTED=YHAT RESIDUAL=RES;
         ID U1 U2 U3 Z1 Z2 Z3;
  TITLE2 'PILE 2900';

DATA PARMS1;
  SET PARMS1; IF _TYPE_ = 'FINAL';

DATA TEMP;
  IF _N_=1 THEN SET PARMS1;
  SET NEW1; DELTA_T1 = X0; DELTA_T2 = X1-X0;
  C_1 = A - B1*X0;
  C_2 = A - B2*X0;
  C_3 = A + B2*(X1-X0) - B3*X1;
  IF DAY LE X0 THEN MY_PRED = C_1 + B1*DAY;
  IF X0 < DAY AND DAY LE X1 THEN MY_PRED = C_2 + B2*DAY;
  IF DAY > X1 THEN MY_PRED = C_3 + B3*DAY;

PROC PRINT DATA=TEMP;

PROC PLOT DATA=TEMP;
  PLOT YHAT*DAY='*' T12*DAY/OVERLAY;

DATA PILE.T12;
  SET COMBO TEMP;
  Y0 = A;
  Y1 = C_2 + B2*X1;
  IF Y1 DATA CATMOD;
  INPUT GROUP HABITAT $ COUNT
```

VITA

Barry L. Emerton was born in Gainesboro, Tennessee on December 6, 1960. He was educated in the Overton County School System and graduated from Livingston Academy in 1979.

In the Fall of 1979, the author enrolled in the Agricultural Engineering Technology Program at Tennessee Technological University in Cookeville, Tennessee. He completed his Bachelor of Science Degree in December of 1983. Upon graduation, he accepted a temporary position with the USDA Farmers Home Administration in Celina, Tennessee.

In September of 1984, the author accepted a research assistantship in the Department of Agricultural Engineering at The University of Tennessee, Knoxville. He completed the requirements for a Master of Science Degree, with a major in Agricultural Mechanization, in December, 1986.

The author holds memberships in Gamma Sigma Delta and Delta Tau Alpha Honor Societies, and is an Associate Mechanization Member of the American Society of Agricultural Engineers.