AEROBIC THERMOPHILIC COMPOSTING OF PIGGERY SOLID WASTES

A thesis presented in partial fulfilment of
the requirement for the degree of
Doctor of Philosophy
in Environmental Engineering at
Massey University

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July 2001

For

My wife Rita

My children Amit, Dipak and Meena

ABSTRACT

Commercial piggery operations produce substantial quantities of solid waste requiring further treatment and disposal. Screened piggery solids contain recyclable nutrients and pathogenic organisms. Point source contribution from piggeries to surface and ground water pollution can be minimised by the application of composting process and technology. This process can serve as the treatment component of an overall waste management plan of a commercial piggery to biologically convert the putrescible to a stabilised form free of pathogenic organisms.

The rate of biochemical reaction determines the speed at which composting can proceed. Solids Retention Time (SRT) is the most important factor in determining the stability of the compost product. SRT is function of, among many other factors, the type of substrate and amendments and their corresponding reaction rate constants. In order to establish the minimum SRT, it is important to correctly derive the reaction rate constant from decomposition data. Rates of decomposition vary widely depending on the organic substrate. Although numerous guidelines are available for the design of effective composting plant, most of these guidelines or studies deal with sewage sludge or municipal solid waste. There is a complete lack of data on composting process design or reaction rates for piggery solids.

Due to these specific concerns, the main objectives of this thesis were to examine the composting process in relation to bulking material and operating conditions; analyse the disappearance of Total Organic Carbon with temperature development in order to determine first order reaction rates; and to analyse the inactivation or decay of indicator pathogens in piggery solids and sawdust composting trials and experiments.

Aerobic static pile composting of piggery solids was investigated at pilot (5 m^3) scale. Sawdust was used as the bulking agent to provide additional carbon and to increase the porosity of the substrate. Composting trials, using different substrate to bulking agent ratios

and aeration frequencies were performed. The composting mixture was placed over an aerated base in the form of a pile. Temperature development, pH, Total Nitrogen, Total Phosphorus, Total Organic Carbon, Total Solids, Volatile Solids and pathogenic indicators were monitored until the completion of the trial.

The development of temperature profiles in three layers of the pile in each trial was similar and in agreement with trials conducted by various researchers. The change in moisture levels at two sampling points within the compost heap for each trial were similar. The moisture removal results demonstrated that the moisture removal from the compost pile depends not only upon a suitable temperature range, but also on the mode of heat movement. The increase in Total Solids and decrease in the fraction of Volatile Solids during the composting period in many trials were in agreement with trends described by many authors and demonstrated the decomposition process.

The nutrient analysis showed that up to 75% of initial nitrogen was conserved in the compost while there was no significant change in phosphorus concentration. There was varying order of magnitude reduction in Streptococci numbers in different trials. Similar trends were observed for total coliform (MPN) reduction. The high temperatures of the pile for prolonged periods were expected to decrease the bacterial counts to levels lower than those observed. The high values of MPN indicate that there are certain spore formers which survive the composting process.

The decomposition curve of Total Organic Carbon was used to calculate rate constant (k) over time from the temperature development data. A medium-order, Newton-Raphson algorithm, which solved non-stiff differential equation was used to solve the reaction rate equation numerically. Two models were compared for the determination of reaction rate constant. Values of reaction rate constant varied under different operating conditions of compost piles. The best values of reaction rate constant of the order of 0.008 and 0.007 per day were obtained from trial 4 that used a 25:75 (volume basis) sawdust-waste ratio; and was aerated for 10 minuted every hour. Same trial had the lowest Mean Residence Time (MRT) of approximately 115days.

Two controlled laboratory experiments at 70 ^{0}C and 60 ^{0}C, respectively were also performed to independently verify rate constants developed from pilot trials. Laboratory experiments gave similar reaction rate constants to those mentioned above. This is beside the fact that a constant temperature profile was maintained throughout the composting period in these two experiments. The average residence time of solids under controlled conditions was not very different from MRT values obtained in the same pilot trial.

A comparison of two models showed that a simple first-order kinetic model can be used for the determination of inactivation coefficient, but using Arrhenius equation incorporating the reference temperature would provide a better thermal inactivation coefficient estimates. In trial 4, inactivation rate coefficient values were of the order of 0.394 and 0.380 per day at two sampling positions, respectively. The laboratory experiments provided inactivation rate coefficient values of the order of 61.97 and 47.34 per day, respectively. The significant difference in the reduction of indicator microorganisms between pilot trials and controlled experiments emphasises that homogeneity is critical in any composting process. It also emphasises the need for a temperature feedback aeration system.

ACKNOWLEDGEMENT

I wish to express my profound appreciation and sincere gratitude to the following people for their contribution towards the completion of this thesis.

Professor Rao Bhamidimarri, my Chief Supervisor, for his valuable guidance, help, encouragement, and patience during my studies.

Dr. Aroon Parshotam, my Supervisor, for all his encouragement and inestimable help.

Professor Gavin Wall for assisting with the trial set-up and encouragement, and Dr. Graham Manderson for his help with understanding the bugs.

Professor Ken Milne for his encouragement and support.

Messrs Denis Lepper, Steve Lepper, Earnie Hughes and Janis Webby for letting me work on their piggeries.

Mr. John Alger, Mrs. Ann-Marie Jackson, Mr. Bruce Collins, Mr. Michael Sahayam, Mr. Bob Toes, and Mr. Lance Curry for their technical and analytical help.

My friend Dr. Satish Kumar for accommodation, food, help and support.

All staff of formerly the Department of Agricultural Engineering at Massey University for their support and friendship.

The New Zealand Pork Industry Board for funding part of this research project.

Dr. Margaret Lawton, Dr. Bob Lee, Mr. Mark Cleaver, and Mr. Peter Stephens of Landcare Research for providing time and facility to complete my thesis. Dr. Jackie Aislabie, Ms.

Rhonda Fraser and Mr. Matthew Taylor for assistance with laboratory experiments.

All staff at Landcare Research Hamilton and Palmerston North offices for their help on various occasions.

Mr. David Hunter for help with graphics.

Associate Professors Alan Langdon and Janis Swan of the University of Waikato for their support.

My parents Mr. Uma Shanker Pandey and Mrs. Satyavati Pandey for their love, encouragement and offering me education with many sacrifices. My parent-in-laws Dr. Kapil Tiwari and Mrs. Basundhara Tiwari for their love, encouragement and continued help. I also thank all my family members and relatives for their love and support.

Last, but most importantly, to my wife Rita and children Amit, Dipak and Meena for their love, encouragement, inspiration, understanding, and sharing the joy and suffering of the life during these times.

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CHAPTER 1

INTRODUCTION

Animal wastes have always been used as fertilisers for crop or pasture production, but only during recent years have the risks of environmental pollution associated with their improper use been discussed. It is estimated that approximately 4.6 million tons of fresh manure is produced in New Zealand annually (Bolan, 1989).

Losses of nitrogenous compounds during decomposition of animal wastes occur either through emission of gases such as NH_3 and NO_x, or as liquid in the form of bound nitrogen, NH_4^+ and small amounts of NO_3^-. Although both are of ecological relevance, the economics should also be taken into consideration in terms of inefficient use of nitrogen.

Point sources (e.g. piggery effluent outfalls or industrial effluents) or non-point sources such as stormwater runoff and leaching and runoff from pastures and croplands can generate the nitrate pollution. Eutrophication is an increase in the amount of nutrients in the water. Since P and N are the nutrients limiting the primary production in most lakes, these nutrients are the most important in stimulating eutrophication. Nitrogen compounds can also have a number of potentially harmful effects on human and animal health. The number of justifiable complaints about odour from livestock farms have also increased in recent years.

Current treatment technologies to stabilise the animal waste include no integrated approach The land application of liquid piggery waste onto agricultural land by tanker or by sprinkler irrigation has been the popular option. The alternative widely adapted is the two-stage lagoon system. There are a number of less common alternatives that the New Zealand farmer has tried. The long ditch system (or retention ditch) has been used by a number of dairy farmers. The anaerobic digestion of waste to produce methane as a source of fuel has also been used, but it is a more technically sophisticated and expensive form of waste management and requires higher level of operation and monitoring.

Solid-liquid separation followed by treatment appears to be an option in view of the high concentrations of suspended solids, biochemical oxygen demand (BOD), and nutrients in piggery wastes. Piggery solids are fibrous in nature, and form an ideal substrate for composting. Composting is defined as the biological decomposition and stabilisation of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land. The biological decomposition of organic wastes is achieved using systems identified as windrow, static pile or in-vessel systems. The composting process in any of these is governed by the basic principles of heat and mass transfer and by biological conditions under which living microorganisms can function.

The composting has been practised for many years and numerous guidelines are available for the design of effective plants (Finstein and Morris, 1975; Epstein *et al.*, 1976; Haug, 1993; Kuter *et al.*, 1985; Finstein *et al.*, 1986a; Nakasaki *et al.*, 1987). Most of these guidelines deal with municipal solid waste or sewage sludge. There is still lack of understanding of certain parameters, which if underestimated lead to poor design. In addition to increased knowledge about parameters for proper composting process design, further information regarding the interrelationship between the composting process and the quality of the end product needs to be developed. A quantitative description of the interdependent biological and physical factors is also not available in the literature. Some studies have investigated reaction rate constants to quantify the rate of degradation of organic matter. The rate constants are then used to design a composting system to allow long enough retention time to produce compost with sufficient stability and maturity. There is, however a complete lack of information on designing piggery solid composting systems, or reaction rates for piggery solids.

The main objectives of the study presented in this thesis are to examine the composting process in relation to bulking material and operating conditions; analyse the disappearance of Total Organic Carbon with temperature development in order to determine first order reaction rates; and to analyse the inactivation or decay of indicator pathogens for a period of up to 23 days in piggery solids and sawdust composting trials.

Materials and methods used for the composting trials are presented in Chapter 3. The changes in temperature, Total Solids, Volatile Solids, Total Nitrogen, Total Phosphorus during composting, as well as reduction in the counts of indicator microorganisms were the major factors investigated in these experimental studies and these results are presented in Chapter 4.

The analysis of disappearance of Total Organic Carbon with temperature has been presented in Chapter 5. This chapter tests two models with first order reaction rates, with and without temperature effects. Rate of thermal inactivation of pathogens in the compost heap and limitations on pathogenic inactivation are also presented in Chapter 5. The performance of various variables in these composting studies is discussed in Chapter 6.

Finally, the conclusions of the research, application of research, and suggestions for future work are presented in Chapter 7.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

The pig industry has seen a steady growth in most regions of the world, including New Zealand. The FAO statistics (FAO, 1993; FAO, 1994) demonstrate such a growth in Table 2.1.

Table 2.1 Pig population (000) in various regions of the world

Region	1979-81	1991	1992	1993	1994
World	744148	862900	862388	870505	875407
Asia	368684	443759	453482	471014	482889
Europe	138616	181788	173982	170200	167983
USA	6045	54477	57684	59815	57904
Africa	10144	17588	18873	20478	21080
Canada	9548	10172	10498	10572	11200
Oceania	4216	4601	4876	473	4794

Technology for managing livestock wastes has been introduced to New Zealand much more recently than the livestock themselves. For the first century of livestock farming , waste management was rarely of public concern. The small proportion of total animal waste production that was concentrated in places like piggeries or farm dairies was usually discharged into streams and rivers without adverse comments.

It is common in New Zealand to discharge waste materials, either raw or treated, into coastal and inland waters. This is putting stress on these aquatic habitats and is also

offending the cultural and spiritual values of New Zealanders. With the steady growth of the New Zealand pig industry in recent years, piggeries have been identified as the most significant point source contributors to surface and groundwater pollution among the agriculture and livestock industry (Bhamidimarri and Pandey, 1996). There is increasing interest in the use of land for the management of various types of liquid and solid waste products. The use of land treatment systems for piggery waste management has received much more attention in recent years. Under the Resource Management Act, discharge of piggery effluent requires a resource consent from the regional authorities after assessment of the environmental effects and evaluation of the different treatment and disposal options available.

2.2 Properties of agricultural wastes

The constituents of agricultural wastes which can affect water quality include organic matter, nutrient, suspended solids, waste heat and pathogens. Manure is faecal waste and urinary excretion of animals, while animal waste commonly refers to manure with added washwater, bedding, soil, hair or spilled feed. Similarly, other agricultural wastes may also be mixture of various components. Fresh manure generally contains about 20 to 30% dry matter, which is rich in cellulose, lignin, nitrogenous compounds and minerals. Manures contain all the nutrients essential for plant growth because of its origine, directly or indirectly, from plant materials. Only small amounts of the nutrients present in livestock feed are retained by the animal, the rest is lost through excretion (Azevedo and Stout, 1974).

Animal waste is a highly variable material with its properties dependent on several factors: animal age and species, type of ration, production practices and environment (Vanderholm, 1984). The type of ration is the single most important factor influencing the characteristics of animal waste. Vanderholm (1984) illustrated the likely characteristics of raw pig manure in New Zealand piggeries and also demonstrated the effect of different rations on those characteristics. Table 2.2 contains values for waste production and characteristics of raw pig manure. Nutrient content of various animal and poultry manures, as reported in the

literature, is given in Table 2.3 (Vanderholm, 1984).

Table 2.2 Freshly voided pig manure characteristics (Vanderholm, 1984)

	Meal fed	Whey fed
Animal weight (kg)	50	50
Raw manure (kg/day) Faeces and urine	3.3	10.3
Total solids (TS, kg/day)	0.3	0.2
Volatile solids (VS, %TS)	80	60
BOD (kg/day)	0.1	0.12
COD (x BOD)	2.9	2
Total N (kg/day)	0.023	0.021
Total P ((kg/day)	0.008	-
Total K (kg/day)	0.015	-

Table 2.3 Nutrient content (g/kg dry weight basis) of animal manures

Nutrients	Cattle	Sheep	Pig	Horse
Nitrogen (N)	25-40	20-45	20-45	17-30
Phosphorus (P)	36436	36467	36499	36343
Potassium (K)	36365	20–29	15-48	15-18
Calcium (Ca)	36297	36390	36238	36369
Magnesium (Mg)	36376	36313	36220	36282
Sulphur (S)	36252	36220	36282	36219

Hydraulic flushing method of removing waste from the housing is the most popular system in New Zealand (Warburton, 1980). Due to dilution, the characteristics of flushed

wastewater vary from those given in table 2.2. Table 2.4 gives a typical range of characteristics of piggery wastewater in New Zealand.

Table 2.4 Characteristics of Piggery wastewater (Vanderholm, 1984)

Parameter	Value
TS range (mg/L)	5600-40,000
VS range (% of TS)	80
BOD range (mg/L)	2880-12,800
COD range (mg/L)	7000-32,800
Total N (mg/L) average range	 1738 1075-2500
Total P (mg/L) average range	 537 109-950
Total K (mg/L) average range	 855 760-1400

The importance of manure with regard to soil fertility and crop production has mainly been ascribed to the supply of large amounts of primary plant nutrients N, P and K. The organic matter in the manure can replenish the supply of humus and improve the physical properties of soils. Addition of manure also enhances the microbiological processes in soils.

2.2.1 Nitrogen

Nitrogen is usually associated with fertilisers and farming, but all living things including humans and animals require nitrogen for life and growth. Nitrogen in manure is of primary concern because of its role in plant growth and its impact on environmental pollution. It is estimated that about 70 to 95% off N in the feed is excreted by the animal in solid and

liquid portions of manure (Waksman, 1952; Barrow, 1961; Floate, 1970). Three major fractions of N are identified in manure; (1) inorganic N (ammonium (NH_4^+) and nitrate (NO_3-) and rapidly mineralizable N (uric acid and urea), (2) easily decomposable organic N with a low C/N ratio (proteins and amino acids), and (3) resistant slowly mineralizable organic N with a high C/N ratio (lignocellulosic fibre complex). Manures also contain easily de-composable N-free organic compounds, such as fats, fatty acids, and simple sugars (Faassen and Dijk, 1987).

2.2.2 Phosphorus

The amount of P in manure varies considerably due to variation in dry matter content and composition of animal feed and is present mainly as solid phase inorganic P (Riemsdijk *et al.*, 1987). In fresh manure the inorganic P (Pi) content ranges from 0.3 to 2.4% of dry matter, whereas the organic P (Po) ranges from less than 0.1 to 1% (Peperzak *et al.*, 1959). About 78.4% of total P in sheep manure was estimated to be in the Pi form (Floate, 1970). Faeces contribute most to the total as well as to the organic P (Gerritse and Zugec, 1977).

The main forms of Po in fresh pig slurry are inositol hexaphosphate (phytin) and adenosine triphosphate (Gerritse, 1978). A mineral species, struvite ($MgNH_4PO_4.2H_2O$) has been identified in the solid fraction of manure, and the presence off octocalcium-phosphate ($Ca_4H(PO_4)_3.3H_2O$) and dicalcium phosphate ($CaHPO_4.2H_2O$) have also been suggested (Fordham and Schwertmann, 1977a,b). Gerritse and Eksteen (1978) found that only a small fraction of the total P in manure solution is present as dissolved Po (1-2%).

2.2.3 Potassium and other nutrients

An appreciable amount of K (Table 2.3) is also present in animal manures. The K in manures is considered to be as available as its fertiliser equivalent (Tunney, 1981). Other nutrients like Ca, S and Mg, and micronutrients are also present in manure and make a valuable contribution to soil fertility.

2.2.4 Environmental concerns related to nutrients

Point sources (e.g. piggery effluent outfalls or industrial effluents) or non-point sources such as stormwater runoff and leaching and runoff from pastures and croplands can generate the nitrate pollution. Eutrophication is an increase in the amount of nutrients in the water. Since P and N are the nutrients limiting the primary production in most lakes, these nutrients are the most important in stimulating eutrophication. Most low producing oligotrophic lakes (low in nutrients) are P rather than N limited (Keeney, 1973) due to the paucity of P in the biosphere compared to N. Nitrogen can, however, be a limiting element in some ultra oligotrophic lakes (Forsberg, 1977). The productivity of coastal and eustarine ecosystem is quite often limited by N (Goldman, 1976). In many already eutrophic lakes, biotic productivity is controlled by N because the N/P ratio of pollutants from many sources are far below the ratios required for the plant growth (Cameron and Haynes, 1986). In some oligotrophic lakes where N is the limiting nutrient, the inputs from ground water, surface runoff, or precipitation may be essential to maintain biological productivity (Keeney, 1982). However, over enrichment of surface water with nutrients results in a range of changes in water quality that are generally considered undesirable.

Algae can affect surface water in a number of ways. Mats of algae can cover the entire surface of the water, clouding the water and reducing visibility. Sunlight is blocked and is unable to reach underlying plants, limiting their growth.

Fish kills are most likely to occur at night because algae use oxygen dissolved in the water instead of producing their own through photosynthesis. The accelerated life cycles of aquatic plants and organisms speed up the eutrophication process. Lake Rotorua, in the central North island of New Zealand is an example of a waterway affected by excess plant growth. Extensive work has been done to limit introduced nutrients and to restore the lake's water quality (Schipper and Schipper, 1998).

Although nitrate has the potential to upset the balance of plant life in water bodies, it is not toxic in the aquatic system. Warm-water fish endure concentrations up to 90 mg/L nitrate-nitrogen. Other forms of nitrogen, such as ammonia or nitrite, present a more serious

danger to fish, in particular trout and salmon. According to the United States Environmental Protection Agency, levels of ammonium-nitrogen in excess of 1mg/L are toxic to fish (Schipper and Schipper, 1998).

Humans are directly affected by nitrogen-related environmental concerns. Blue-green algae may release toxins into the water, which can cause skin rashes. When swallowed, the water can also can also cause digestive problems in humans and livestock. Algal blooms may make shellfish unsafe to eat during certain times of the year. Furthermore, if the water body impacted by algal bloom is a source for drinking water supplies, it may be expensive to remove odours and impurities (Schipper and Schipper, 1998).

2.2.5 Health concerns related to nutrients

Nitrogen compounds can have a number of potentially harmful effects on human and animal health. The New Zealand Department of Health has set the maximum acceptable nitrate-nitrogen concentration level for drinking water at 11.3 mg/L (NZ DoH, 1992).

Nitrate is found naturally in many foods, especially in vegetables and is relatively harmless in the levels found in foods. It is usually metabolised by the body and eliminated without causing harm. Health concerns arise when microorganisms in the digestive tract convert nitrate to nitrite. Nitrite is absorbed into the blood and can interfere with blood's ability to distribute oxygen throughout the body. If nitrite concentrations in the blood are too high, symptoms off asphyxiation appear and the victim's skin may turn blue. Infants whose formula has been prepared with nitrate contaminated drinking water are most at risk of developing this blood problem. Methaemoglobinaemia, or "blue baby syndrome" as it is commonly known can be fatal but once diagnosed the problem is easily corrected. Infants are more at risk of methaemoglobinaemia than adults. This is because their nourishment comes from liquids. Infants drink up to three times more liquid per unit weight of body mass than adults do. A baby's digestive chemistry is different from that of an adult because the baby does not eat the solid food. More nitrate-reducing bacteria may live in a baby's stomach which is less acidic than an adults stomach, increasing the chance of nitrite formation (Schipper and Schipper, 1998).

According to a 1982 review of nitrate contamination of New Zealand aquifers (Burden, 1982) no cases of methaemoglobinaemia have been reported in New Zealand. However, this could be due to the fact that methaemoglobinaemia is not classified as a notifiable disease by the New Zealand Health Department. Levels of nitrate-nitrogen above the recommended limit have been linked with an increase in the incidence of stomach cancer in adults, through the formation of carcinogenic nitrosamines (Hill *et al.*, 1973). For several decades the researchers have implied that nitrate-nitrogen may affect the cardiac function of the human (Malberg *et al.*, 1978). A relation between the high concentration of nitrate-nitrogen in drinking water and hypertension has been recorded (Morton, 1971) but other studies have failed to establish any relationship (Malberg *et al.*, 1978).

2.2.6 Odour and ammonia emission

In USA and European countries the number of justifiable complaints about odour from livestock farms have increased in recent years. In UK out of total number of premises causing complaint, over 50% were associated with the pig farms and nearly 50% of the total resulting from the spreading of slurry or manure on land (Pain *et al.*, unpublished paper). Smells can be produced almost continuously e.g. livestock housing, but the most objectionable odours are usually intermittent and arise when manure, which has been stored under anaerobic conditions, are agitated, transported or applied onto the land (Smith and Neilsen, 1983).

In addition to odours, the emission of ammonia from livestock building and from the application of slurry and manure to land is a cause of increasing concern (Voorburg, 1985). Such emissions may not only have an impact on atmospheric chemistry and acid deposition but also represent a decrease in the fertiliser value of the slurry and manure.

2.2.7 Health risks associated with aerosols from wastes

Aerosols are tiny droplets of water, especially common to high pressure system of spray irrigation and carried offsite by wind (Loehr, *et al.*, 1979a).

Aerosols can also be defined as a system of colloidal particles dispersed in gas, smoke or fog; as far as waste water treatment is concerned; aerosols can be created through various processes, especially in activated sludge, trickling filters and spray irrigation. Bacteria, viruses, parasites or chemicals may be contained in aerosols droplets, transportation of these agents in wastewater aerosols is very likely and should be considered a potential source of disease to humans.

The dispersion of aerosols in the atmosphere is caused by all surface activities where systems are not closed. Soil injection is an exception. Many agricultural activities may evolve, for example, both pathogenic and nonpathogenic microorganisms.

Aerosols vary in size ranging from about 0.01-50 μm (Loehr *et al.*, 1979b) thus making them fairly accessible to intake into the human's body. While inhalation the aerosols can enter the body, intact small aerosol particles will reach the alveoli of lungs. Larger aerosols can be cleared by the respiratory system and be swallowed-infectious hepatitis and salmonella disease, for example are transmitted through the gastrointestinal tract. Adsorption of aerosols through skin is also possible and the example of this is contact dermatitis from spraying.

Several field studies have been carried out to measure the emission and airborne spread of viable microorganisms from wastewater collection, treatment and disposal processes. These studies have shown that many types of pathogens and bacteria are emitted at every stage of wastewater treatment and are viable and carried off a considerable distance through wind. However interpretation of the results of these studies in terms of health hazard has been inconclusive, and those, who did make 'health hazard' conclusions, did so by inference. For example, the recovery of index organisms such as coliform from the air at some distance away from source and in a respirable particle size was believed to be an indication of health hazard from inhalation. Conversely, the failure to recover high concentration of microorganisms, downwind from source, was interpreted to be absence of a significant health risk from the source (Hickey and Reist, 1975).

Teltsch and Katzenelson (1978) carried out a study in which controlled experiments utilizing marker bacteria (a mutant *E. coli* resistant to the antibiotic nalidixic acid, was added to the wastewater as a marker bacterium) were carried out to evaluate quantitative relationship between enteric bacteria in the effluent used for irrigation and aerosolised bacteria detectable in the air and to evaluate the effect of some meteorological factors such as relative humidity, temperature, wind velocity and solar irradiation on bacterial dispersion in the air. Aerosolised coliform were detected when their concentration was 10^3/mL or more in the wastewater. Relative humidity and irradiation appeared to affect the viable bacteria in the air; a positive correlation was found between relative humidity and number of aerosolised bacteria. The correlation between solar irradiation and bacterial level, on the other hand, was negative. During night irrigation, up to 10 times more aerosolised bacteria were detected than with day irrigation. Wind velocity did not play an important role in the survival of aerosolised bacteria.

Katzenelson *et al.*(1976) compared the incidence of enteric communicable disease in an Agricultural Communal Settlement practising wastewater spray irrigation with partially treated non-disinfected oxidation pond effluent, and that in other Agricultural Communal Settlement practising no form of wastewater irrigation. The incidence of shigellosis salmonellosis, typhoid fever and infectious hepititis, was two to four times higher in communities practising wastewater irrigation. No significant difference was found for the incidence of streptococcal infections, tuberculosis, and laboratory-confirmed cases of influenza. Moore *et al.* (1988) identified possible adverse effects on human health from slow rate land application of wastewater. During the first irrigation period at the land treatment system, irrigation wastewater quality approximated that of a low quality primary effluent as determined by microbial and physical-chemical parameters. Seasonal level of human enteric viruses in the wastewater were highest during late summer, coinciding with the time of the substantial crop irrigation.

2.2.8 Piggery waste management alternatives

At present no integrated approach is adopted for the management of piggery wastes. The land application of liquid piggery waste onto agricultural land by tanker or by sprinkler

irrigation has been the popular option. The sprinkler systems involve hosing or flushing down the piggery or dairy yard , collecting the wash down in a sump and pumping directly through a pipeline system to a sprinkler or set of sprinklers. The sprinklers are shifted, about daily, to new positions. However, pump and sprinkler blockages, seal and bearing failure in pumps, saturation and pugging in the winter, the unpleasant odour, labour oriented task of shifting sprinklers, and the spread of weeds, have all contributed to the farmers' disenchantment with these systems (Warburton, 1980).

The alternative widely adapted is the two-stage lagoon system. The raw waste is pumped or gravity fed to the first lagoon which is usually an anaerobic lagoon. The effluent from this lagoon goes into a second more shallow aerobic lagoon. The lagoon system has the advantage of relatively low costs, low labour and minimum management requirements. Where gravity feed to the lagoons is possible, there are no pumping problems. Difficulties do exist, however, with this system. Permeable soils can give rise to sealing problems, while odours can be a nuisance. For large piggeries, inadequate land area may be available, and desludging after several years of use also pose problems for the farmers.

There are a number of less common alternatives that the New Zealand farmer has tried. The long ditch system (or retention ditch) has been used by a number of dairy farmers. This consists of a long ditch with a series of baffles or small overflow wooden or concrete dams for solid retention, followed by a long open ditch to encourage some form of natural re-aeration before the discharge. This system requires regular cleaning, can create odours, is subject to flushouts from storm water if not installed to prevent this, and is generally more susceptible to failure due to mismanagement than would be the two-stage lagoon system. The system is unsatisfactory for high strength piggery effluent.

The anaerobic digestion of waste to produce methane as a source of fuel is a more technically sophisticated and expensive form of waste management and requires higher level of operation and monitoring.

Solid-liquid separation followed by treatment appears to be an option in view of the high concentrations of suspended solids, biochemical oxygen demand (BOD), and nutrients

(refer to Table 2.2 and 2.4) in piggery wastes. Piggery solids are fibrous in nature, and form an ideal substrate for composting.

2.2.9 Waste treatment alternatives

Liquid or separated liquid and solid organic piggery waste has been directly reused in agriculture, but this practice is becoming rare with increasing public awareness of environmental problems. Many environmental concerns have been discussed in detail earlier. Due to these concerns, it is now widely accepted that for recycling of solid organic waste its organic matter must be stabilised, and for specific situations, sanitised to eliminate the risks of human and animal infection.

Current treatment technologies to stabilise the organic fraction of a solid waste include mesophilic or thermophilic aerobic and anaerobic digestion. Problems associated with these technologies are incomplete removal of pathogens in the first and high costs in maintaining thermophilic temperatures in the second case. Sanitisation of organic waste using lime or chlorine treatment is also ineffective, whereas pasteurisation and irradiation present serious post-processing contamination problems, and are expensive processes. The product of thermally dried organic solids can be stored for a long time. However, it is very expensive and since the organic solid is not biodegraded, it is prone to moisture resorption and contamination. Composting is an aerobic biological method of organic solid stabilisation. It can produce a product that is reasonably safe and aesthetically acceptable and has high utility.

2.3 Composting

Composting is defined as the biological decomposition and stabilisation of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land (Haug, 1993). In other words, composting is a controlled biooxidative process that:

1. requires a heterogeneous organic substrate in the solid state;
2. evolves by passing through a thermophilic phase; and
3. leads to production of carbon dioxide, water, minerals, and stabilised organic matter (compost) ((Zucconi *et al.*, 1985).

The basic composting process is depicted in Figure 2.1. The major factors that affect the decomposition of organic matter by microorganisms are oxygen and moisture (Epstein, 1997). Temperature is the result of microbial activity and plays a very important role in the composting process. Other important factors that could limit the composting process are nutrients and pH. Carbon and nitrogen are essential for microbial growth and activity and their presence in the composting process is of utmost importance. Carbon is the principal source of energy and nitrogen is required for cell synthesis. Most of the self-heating of organic matter is the result of microbial respiration (Finstein and Morris, 1975) raising the temperature of the mass. An increase in temperature affects the microbial population through changes in mesophilic and thermophilic organisms changing the rate of decomposition. The degradation of the volatile solids during composting also results in heat generation and a subsequent temperature increase.

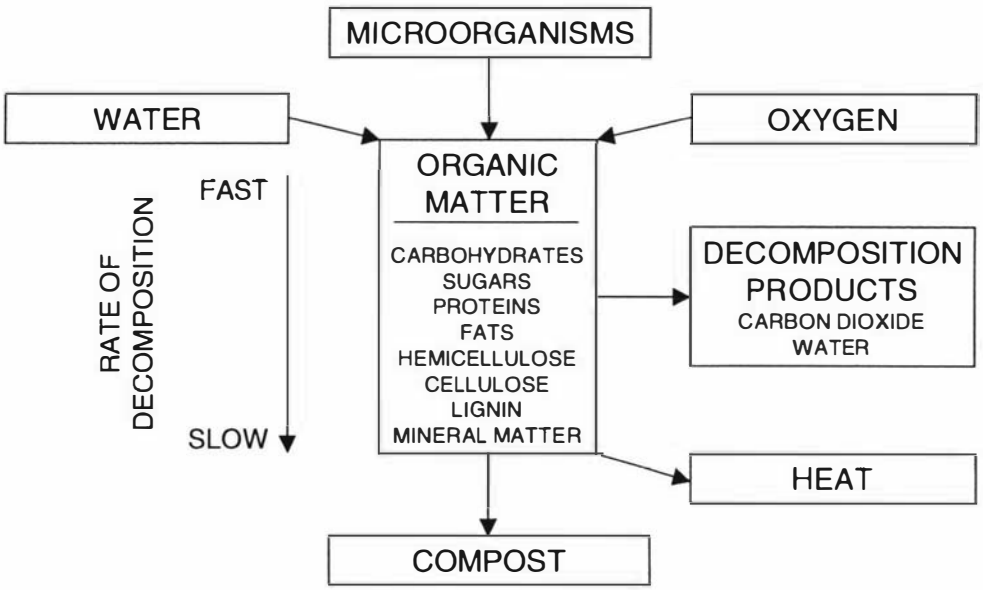


Figure 2.1 The composting process (Epstein, 1997)

Wastes treatable by composting vary from the heterogeneous organic and inorganic mixture in municipal solid waste (Deportes, *et al.*, 1998; Glenn, 1997; Goldstein *et al.*, 1996) to the more homogeneous animal manure (Singley *et al.*, 1975), crop resides, fisheries waste biomass (Martin, 1999); pulp and paper residues (Provenzano *et al.*, 1998); and primary and secondary sewage sludges (Bernal *et al.*, 1998; Golueke, 1977). During the composting process, provided enough oxygen is available, the organic materials are converted to more stable products such as humic acids and carbon dioxide and water is evolved. In general terms, the composting process can be represented by the following equation (*Finstein et al.*, 1986b).

$$\text{Fresh organic waste} + O_2 \xrightarrow{\text{microbial metabolism}} \text{stabilised organic residue} + CO_2 + H_2O + \text{Heat} \qquad (2.1)$$

The composting is therefore simply a means of converting raw organic matter into a usable humus (Gray *et al.*, 1971).

If anaerobic conditions predominate, the metabolic end products are methane, carbon dioxide and various low molecular weight organic acids. Due to their high volatility, these compounds cause a significant odour from anaerobic reactions in composting. As a consequence, the main aim of all composting systems is to avoid anaerobic reactions through adequate aeration (i.e. oxygen supply) (Finstein *et al.*, 1987a and 1987c).

Composting includes a thermophilic phase, which is useful due to its disinfective effect on pathogenic organisms present in raw material such as sewage sludge (Haug, 1993).

Composting is becoming more and more popular from the treatment-oriented perspective, in which composting serves as the treatment component of an overall waste management plan, and whose objectives are the biological conversion of putrescribe organics to a stabilised form free of pathogenic organisms. Wet substrates such as sewage sludge or

piggery solids can also be significantly dried during composting, another valuable factor from the subsequent disposal point of view. Thus composting has come into widespread use as a municipal, agricultural and industrial waste treatment process during the last several years. The beneficial or detrimental effect of the application of these composted materials on land has also been studied extensively over the past few years (Houot *et al.*, 1998; Marull *et al.*, 1997; Diazmarcote *et al.*, 1995). Of particular interest to New Zealand is that the cost of composting has bee shown to be one-third to one-half less than alternative sludge treatment methods, such as incineration (Goldstein, 1987).

2.3.1 Factors controlling composting

The composting process proceeds satisfactorily only within a well defined range of conditions. The key design features in recent composting technology are known to be a suitable microbial population, the volatility and type of material, the moisture content, the oxygen concentration, the carbon/nitrogen ratio, the temperature and the pH value. Some of these factors are discussed below.

2.3.3.1 Microbial population

Composting is a dynamic process in which the physical and chemical changes are caused by a rapid succession of a mixed microbial populations. Biological waste materials contain a large number of many different types of bacteria, fungi, mould, and other living organisms. Therefore, the microbial activity has the most significant effect on composting (Waksman, 1952).

Gotaas, 1956 concluded that more species of bacteria are involved in aerobic decomposition than in anaerobic fermentation. There is a remarkable change in the nature and abundance of the microbial population during the decomposition. Temperature and availability of nutrients probably exert the greatest influence in determining the species of organisms comprising the population at any stage.

The facultative and obligate aerobic bacteria, actinomycetes, and fungi are the most active during aerobic composting. Mesophilic bacteria are characteristically predominate at the start of the process, followed by thermophilic bacteria, and actinomycetes.

2.3.3.2 Aeration

Adequate supply of oxygen to the organisms should be maintained if composting is to proceed rapidly (Crawford, 1983). Aeration is also useful in reducing a high initial moisture content in composting materials (Gotaas, 1956).

The supply of oxygen can be increased by blowing air into the compost heap, agitating, the provision of air vents into the base of the composting mass, or by "turning" or regular mixing of compost heaps (Crawford, 1983). If, however, the rate of air flow through the compost is too great heat losses and desiccation will occur, and the rate of decomposition will be reduced (Crawford, 1983).

2.3.3.3 C/N ratio

The rate at which organic matter decomposes during composting is principally dependent upon the C/N ratio of the materials. As mentioned earlier, during composting microorganisms utilise the C as a source of energy and the N for building cell structure. Microorganisms utilise C and N at a ratio of about 30:1. Low C/N ratios in substrate result in nitrogen volatilisation in the form of ammonia (Poincelot, 1974). This is particularly true under alkaline conditions (Epstein, 1997). Anaerobic or partially aerobic conditions can result in ammonia release to the atmosphere (Knuth, 1970). The loss of N reduces the value of compost as a fertiliser. At C/N ratios exceeding 50:1, the decomposition decreases (Gotaas, 1956), because of rapid cell growth and immobilisation of N (Witter and Lopez Real, 1987a), resulting in reduced cellular growth. As cells die, their stored N becomes available to living cells (Bishop and Godfrey, 1983).

A C/N ratio of 20 has been widely accepted as optimum for composting (Gotaas, 1956). Singh (1987) reported that the decomposition of organic waste increased considerably when

the C/N ratio was narrowed down to 30 through the addition of urea-N. Witter and Lopez Real (1987a) observed excessive loss of N during the composting of manure at a lower C/N ratio.

Witter and Lopez-Real (1987b) have stated that the C/N ratio does not accurately reflect the decomposition process. Instead, the final value of the finished product in agricultural or horticultural use is an important characteristic.

2.3.3.4 Temperature

Temperature control is an important factor in aerobic composting process. High temperatures (above 50^0C) are essential for the destruction of pathogenic organisms and undesirable weed seeds. The preponderance of information on the effects of temperature on composting suggests that optimum decomposition takes place between 55 and 60^0C (Sikora and Sowers, 1985).

There has been some debate regarding the optimum temperature for decomposition of organic matter. One reason for this controversy is that different substrates or materials decompose more rapidly at different temperatures (Epstein, 1997). Bhoyar *et al.* (1979) found that greater NH_3 formation occurred during composting at temperatures between 60 and 70^0C than at 30 and 50^0C. But, according to Gotaas (1956), the optimum temperature range is 50-70^0C, around 60^0C usually being the most satisfactory for successful composting.

2.3.3.5 pH

The pH of compostable material influences the type of organisms involved in the composting process. Fungi tolerate a wider pH range than bacteria do. The optimum pH range for most bacteria is between 6.0 and 7.5; whereas for fungi it can be between 5.5 and 8.0. Most of the waste materials available for composting are within the above pH range and hence pose no problem of pH control.

All the factors mentioned above influence the activities of the bacteria, fungi, and actinomycetes responsible for decomposition and thus affect the speed and course of the composting process.

Generally, composting is considered complete when the product can be stored without causing nuisance such as odours, and when risk to public health through the impact of pathogenic organisms is acceptable. Bitton *et al.*, (1980) presented an overview of health risks through the application of sewage sludge on land. Most of these health risks are also applicable in the case of pig slurry. The final compost is primarily used as a soil conditioner. Due to significant reduction in nitrogen during the composting process of wastewater sludge only a reduced amount of nitrogen is available to soil and plants (Golueke, 1977).

It has been demonstrated that the application of compost to soil improves some important physical properties of soil and increases the percentage of organic matter and cation exchange capacity (CEC). Swift and Posner (1977) found that high CEC values were accompanied by a highly oxidised state of the humic acid fraction. Composting increases the CEC of organic matter. Oxygenation of the compost pile is conducive to a rapid increase of the CEC (Harada *et al.*, 1981). Organic matter improves the aggregate stability, soil structure and reduces wind erosion (Baver *et al.*, 1972; Tisdall and Oades, 1982). Organic matter increases soil porosity and, as a result, improves soil aeration and soil penetrability by plant roots. Occasionally, negative aspects can merge from compost incorporation into soil such as increase in organic pollutants and heavy metals (Gallardo-Lara and Nogales, 1987).

The composting process is carried out using different methods. A classification of these methods leads to the following description:

- Open system processes
  - Windrow (conventional and aerated)
  - Aerated static pile
- Enclosed reactor system processes

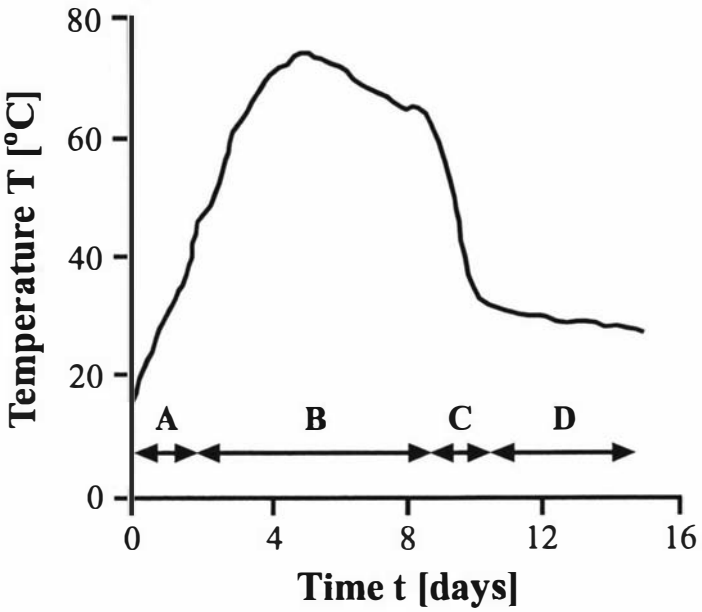
Section 2.5 provides a more detailed discussion of the different composting systems currently in use.

2.4 Composting process fundamentals

Organic materials contain varied and widespread microorganisms responsible for composting (Finstein *et al.*, 1986a). The addition of special inocula to the composting mass is not beneficial to the composting process (Golueke, 1977). Under aerated conditions, when the moisture content of composting mass is brought to a suitable level, the rate of microbial action increases and the material undergoes stabilisation. Apart from oxygen and moisture, the microorganisms also require a source of carbon for their growth. This source is provided by the organic fraction of the waste. Macro nutrients such as nitrogen, phosphorus and potassium and certain trace elements are also needed. During the decomposition process, the microorganisms utilise organic matter and reproduce themselves. During this the microorganisms liberate CO_2, H_2O and other organic products and energy, some of which is used in metabolism, the remainder given off as heat. The end product, compost, consists of stable organic residue, breakdown products, dead and some living microorganisms together with products from further chemical reactions occurring between these materials.

A heap, sufficiently large to store heat despite losses to the surrounding, is prepared from the raw material to be composted. Bulking agents for porosity and moisture control (e.g. wood chips or sawdust) are added to the separated solid waste to provide a porous, structurally stable mixture of about 40 to 70% solids. This enables the solid waste to self-sustain the aerobic respiration reactions.

The composting process passes through four characteristic stages distinguished by temperature as shown in Figure 2.2. These stages are:



1. mesophilic phase with temperatures up to 40^0C;
2. thermophilic phase, 45 to 65^0C;
3. cooling; and
4. maturing.

Figure 2.2 Temperature-time pattern indicating the phases of microbial activity. A- mesophilic; B- thermophilic; C- cooling; D- maturing (Gray *et al.*, 1971)

2.4.1 Biochemical aspects

Organic wastes from agricultural or industrial origin, e.g. food industry (Katsuyama, 1979), meat industry (Keeley and Skipper, 1988; van Oostrom *et al.*, 1991), or municipalities (Moreno *et al.*, 1998 and 1997; Fang *et al.*, 1999) are mixtures of sugars, proteins, fats,

hemicelluloses, celluloses, lignin, minerals and other compounds in a wide variety of concentrations. These may serve as starting material for composting (Genevini and Negri, 1986; Zucconi and De Bertoldi 1987). An estimate of the chemical composition is given in Table 2.5. The organic matter in sludge is ordinarily not susceptible to total oxidation. However, Higgins *et al.* (1982) in a comparative study of biological treatments have demonstrated that composting can achieve a significant reduction in volatile solids and other indicators of the effectiveness of biological treatment. The maturity of the final compost product is important for the assessment of its quality and possible use. Analytical methods and definitions of product quality and maturity have been reported by many workers (Morel *et al.*, 1985; Penninck and Verdonck, 1987; Witter and Lopez-Real, 1987b; Zucconi and De Bertoldi, 1987; Mooijman and Lustenhouwer, 1987).

Table 2.5 Composition of organic matter (Gray *et al.*, 1971)

Fraction	Percentage in dry matter	
	Plants	Manures
Hot/cold water solubles: sugar, starches, amino acids, aliphatic acids, urea and ammonium salts	5-30	2-20
Ether/alcohol solubles: fats, oils, waxes and rasins	5-15	1-3
Proteins	5-40	5-30
Hemicelluloses	10-30	15-25
Cellulose	15-60	15-30
Lignin	5-30	10-25
Minerals (ash)	1-13	5-20

Composting is both a catabolism (breaking down) process and an anabolism (building up) process. Water soluble, low molecular weight materials can pass though the cell wall easily and take part in cell metabolism, providing energy and being synthesised into larger

polymers. The higher molecular weight components of the organic wastes cannot pass through the microbial cell membrane and cannot be used without first being degraded. In these cases, the microorganisms secrete extracellular enzymes which hydrolyse the polymers into their respective short chain units. Cellulose and hemicelluloses are subject to these reactions, the former and lignin being most resistant to microbial attack (Golueke, 1977).

Compost is organic matter and, when added to soils, becomes part of the soil organic pool. However, since compost represents a more advanced stage of decomposition than much of the organic matter that is normally applied to soils (e.g. leaves, manures, crop residues), most of the sugars, proteins, simple sugars and amino acids have been metabolised as a source of C and N for the microorganisms. The remainder is humic substance (Epstein, 1997).

Knowledge of the composition of material to be composted is important in the design of composting systems. A combination of materials high in protein (nitrogen) with cellulolytic materials reduces the potential for odours because of more favourable C/N ratio to the microbial population. Materials high in cellulose and lignin take longer to decompose whereas materials high in sugars, other carbohydrates and lipids take less time to stabilise (Epstein, 1997). Food wastes, biosolids or grass have readily available carbohydrates and sugars and break down quickly. Combining these with high hemicellulose or cellulose containing materials reduces the composting time by raising the level of microbial activity. The relative rate of microbial decomposition for various organic matter constituents is shown in Table 2.6.

Table 2.6 The relative rate of microbial decomposition of organic materials (after Stentiford, 1993).

Readily biodegradable (Group 1)
Sugars
Starches, glycogen, pectin
Fatty acids, glycerol
Lipids, fats
Amino acids
Protein
Slower to biodegrade (Group 2)
Hemicellulose
Cellulose
Chitin
Low molecular weight
Resistant to biodegradation (Group 3)
Lignocelluloses

High water containing substrates such as piggery solid or sewage sludge pose special problems to alternative treatment methods. Thermal processes, for example, become less efficient for high moisture organic substrates and make composting more attractive as a method to biologically dry and convert wet materials to a more suitable form. Outside energy input for composting is often minimal compared with other treatment methods (Haug, 1993). Due to water content of 70 to 80% of separated piggery solids lack porosity and also tend to compact. High moisture content hinders the gas exchange and these solids require adequate handling for a successful composting process, e.g. bulking agent addition aeration, etcetera.

Most of the carbon in the bulking agent (e.g. woodchips) becomes available to bacteria at a very slow rate, since it forms part of the xylem. For the most part the xylem is lignaceous and therefore highly resistant to microbial attack. Woodchips and other bulking agents

should consequently be considered almost entirely as bulking and moisture absorption agents, and very little, if at all, as sources of carbon (Golueke and Diaz, 1987).

2.4.2 Microbiology

As a biological process composting involves a huge range of microorganisms. The main classes of organisms involved are bacteria, algae and fungi. Other microbes such as protozoa and viruses may also be present (Haug, 1993). These microorganisms work together to degrade the organic material. Nakasaki *et al.* (1985) presented the average number of these microorganisms in a decomposing waste material (Table 2.7).

Table 2.7 Number of microorganisms isolated in raw sludge

Microorganisms	Cells/g (dry wt.) of material (Raw sludge)
Mesophilic	
Bacteria	3.6×10^7
Actinomycetes	$<10^3$
Fungi	4.2×10^2
Thermophilic	
Bacteria	1.4×10^6
Actinomycetes	1.4×10^5
Fungi	<10

These microorganisms may not be all present at once or active at once. Golueke (1977) reported that the bacterial metabolism during the decomposition is limited by the genotype of the respective microorganisms, assuming that all environmental conditions and equipment design are optimal for the process. A wide variety of actinomycetes species in the composting mass can be detected olfactorily and visually a few days after the process starts (Golueke, 1977). These species decompose mainly cellulosic as well as some lignaceous components. However, many other organic substrates can also be metabolised

by these microorganisms.

Fungi occur in the mass at about the same time as actinomycetes. Fungi are also able to use many different substrates as carbon and energy sources. Due to the similarity of substrate utilisation, the existence of both fungi and actinomycetes are closely related. Large numbers of actinomycetes and most of the fungi are obligate aerobes, which emphasises the importance of adequate aeration.

According to Krueger *et al.* (1973) microorganisms can be classified according to the temperature they can tolerate and grow (Table 2.8).

Table 2.8 Temperature range for microorganisms

Microorganisms	Temperature Range
Cryophiles or psychrophiles	0 to 25^{0}C
mesophiles	25 to 47^{0}C
Thermophiles	>45^{0}C

Organisms associated with composting fall into the two classes: mesophiles and thermophiles. Composting process is usually concerned with organisms at mesophilic and thermophilic temperatures, however, many organisms survive and grow at lower or higher temperatures.

Many critical factors (Section 2.3.1) influence the microbial activity during the composting process. McKinley *et al.* (1985) concluded that temperature seems to be the dominant physical-chemical parameter which controls the microbial activity during the composting process and the decomposition ceases or extremely reduced at temperatures exceeding 60^{0}C. However, Tansey and Brock (1978) indicated that there can be potential benefit in favouring thermotolerant organisms in composting, e.g. temperatures of 70 to 80^{0}C are required for productive compost in mushroom compost.

2.4.3 Heat generation and temperature

The heat generated by the decomposition process raises the temperature of the heap by the insulating effect of the material. The gas exchange inside the material is sufficient to prevent gross oxygen starvation. The decomposition process starts spontaneously at ambient temperature by mesophilic microbes with an optimum temperature for activity of about 30^{0}C (Alexander, 1977). The temperature will rise from ambient to about 45^{0}C as a result of heat production by these organisms. This temperature level is lethal to mesophilic organisms but it is suitable for thermophilic microorganisms and they will speed up the decomposition process. The temperature in the thermophilic stage may increase up to 70 or 75^{0}C. This temperature range proves lethal to many microorganisms and the process slows down and the temperature stabilises at this level or little below. The thermophilic stage proceeds until all easily degradable organic matter is decomposed. Then, the process slows down further and the maturing stage begins at about 30^{0}C.

2.4.4 Heat - Temperature interaction

Higher temperatures at first biologically favour the rate of growth and heat generation (Finstein *et al.*, 1986a). This phenomenon establishes a positive interaction between heat generation and temperature (i.e. both increasing). At temperatures which lead to maximum growth rates of mesophiles (approximately 38^{0}C), the interaction becomes negative because higher temperatures are unfavourable to mesophiles. This slows the temperature increase and would, in the absence of subsequent events, soon terminate the compositing process. However, the thermophilic growth is initiated at approximately 45^{0}C resulting in temperature increase. This re-establishes a positive interaction between heat generation and temperature. Organic mass is most active at approximately 55 to 60^{0}C because of the self-heating property of the thermophilic community. The interaction again becomes negative when the temperature exceeds this range. The temperature increase slows down again with values typically peaking at approximately 80^{0}C. Heat generation rate is low at this temperature.

A basic problem during the composting is to prevent the inactivation of microbial activity which occurs under thermophilic conditions , usually brought about if no aeration control is employed (Finstein *et al.*, 1987 a-d). To avoid temperatures greater than 60^0C which weaken the microbial mass suppressing decomposition, heat output and moisture removal, an enhanced heat removal in a controlled fashion (e.g. feedback control) is necessary (MacGregor *et al.*, 1981). Various studies of spent pig manure (Tiquia *et al.*, 1996 and 1997) and sewage sludge composting have shown that temperatures between 40 to 60^0C favour microbial activity and decomposition (Hoitink et al., 1984; Kuter *et al.*, 1985; Sikora and Sowers, 1985; McKinley and Vestal, 1984; Pereira-Neto *et al.*, 1987a, Finstein *et al.*, 1986a and 1986b).

2.4.5 Aeration, heat, and moisture removal

Radiation, conduction, vaporisation of water and sensible heating contribute to heat removal in a composting operation. Temperatures of about 55^0C to support optimum composting rates can be obtained using ventilative heat removal (Finstein *et al.*, 1986a; Finstein and Miller, 1985). The optimum decomposition rate also facilitates the prevention of odour development in the composting mass, which from the public point of view, is the worst impact of a composting facility (Haug, 1993; Finstein and Miller, 1985). Ventilation also supplies oxygen for the microbial decomposition and removes metabolic CO_2.

Water is vaporised extensively at composting temperatures and water removal generally exceeds that produced metabolically. In composting facilities where screening is required, a 15 to 20% moisture removal is desirable (Haug, 1993).

2.4.6 Pathogenic Organisms

Almost all organic solids contain pathogenic organisms such as bacteria, viruses, fungi and parasites in varying extents (Pike and Carrington, 1986). Careless handling of these solid wastes can lead to great health risks for humans and animals, e.g. the use of untreated organic solid waste on land can intensify infection transmission cycles (Burge and Millner, 1980).

Stabilizing the organic matter, mineralizing all simple compounds assimilable by pathogens and humifying other compounds, contributes to a transformed waste such that pathogens cannot regrow. A low moisture content of the product supports the stabilising effect (De Bertoldi *et al.*, 1988).

The first objective of sanitation in a composting operation is the prevention of growth and spread of mainly fungal (mold) pathogens and thus the mass production of dangerous spores during composting Finstein *et al.* (1987b).

The second sanitation objective is concerned with the destruction of pathogens originally present in the organic waste. Microbial antagonism, production and release of disinfecting agents such as ammonia and effects of high temperature are the main causes of pathogen kill-off.

The third objective aims at a well stabilised residue which is resistant to recolonisation by pathogens due to lack of decomposable substrate and the existence of nonpathogenic organisms not easily displaced by pathogens.

A widely used minimum standard for sanitisation in municipal sludge is to maintain a temperature of 55^0C for at least 3 days (Pereira-Neto *et al.*,1987b). However, De Bertoldi *et al.* (1988) suggest a temperature of 65^0C for 3 consecutive days.

The following organisms, categorized into four groups, are important with respect to organic solid disinfection (Strauch,1987):

- **Indicators:** Total coliform, faecal coliform, and faecal streptococcus bacteria, Clostridium perfringens (welchii), bacteriophage;

- **Pathogenic bacteria:** salmonellae, shigellae, pseudomonds, Mycobacterium spp., Candida albicans, Aspergillus fumigatus;

- **Enteric viruses:** Enterovirus and its subgroups (polioviruses, echoviruses and

coxsackieviruses), reovirus and adenovirus;

- **Parasites:** Entamoeba histoytica, Ascaris lumbricoides, Taenia spp., Schistosoma spp., and others.

Conditions of mesophilic composting may inactivate common indicator and pathogenic bacteria and viruses, provided that specified temperatures are attained uniformly throughout the compost mass for over the specified time period. The pathogenic fungus Aspergillus fumigatus grows under conditions of mesophilic composting, however, and parasitic ova appear to survive this process Strauch (1987).

Faecal streptococci appeared to be the most conservative indicator of both the density levels of pathogenic bacteria and enterovirus during composting operation (Strauch, 1987). De Bertoldi *et al.* (1988) indicate that total coliform, faecal streptococci, enterobacteriaceae, certain viruses and parasitic ova can serve as satisfactorily reliable indicator organisms.

Strauch (1987) also quoted experimental studies with the relatively heat resistant bacterial virus f2 whose inactivation could be used as a standard to assure greater destruction of the enteritic pathogens during composting.

Apart from heat, microbial competition is an important factor affecting pathogen survival during composting. Indigenous or natural microorganisms of the compost system have a distinct competitive advantage over the pathogens, for which composting material is not the natural environment. This system tends to eliminate the pathogens as the least fittest organisms. De Bertoldi *et al.* (1988) have presented a detailed discussion concerning how the principal factors such as organic matter, moisture content, temperature, oxygen supply and microbial competition and antagonism influence the growth and survival of pathogens in composting. These authors conclude that windrow composting with turning the material as a means of aeration does not guarantee good sanitisation, unless very small windrows are used. They could however achieve low counts of indicator organism by using horizontal reactors and/or static pile systems.

2.5 Composting technologies

2.5.1 General aspects

High moisture content feed such as piggery solids demand one of the three possible procedures in order to be treated by composting:

1. Recycle the compost and blending with the dewatered solid before composting;
2. Addition of an organic amendment such as sawdust, straw, peat, refuse, etc. to reduce bulk weight and increase air voids for proper aeration and to increase the organic in the mixture; and
3. Addition of an inorganic or organic (usually sawdust or woodchips) bulking agent to provide structural support and porosity.

The mixing of solid waste and bulking agent should result in a uniform, homogeneous mix without the formation of lumps or balls. Figure 2.3 represents a generalised schematic of the composting process. The block "composting process" can stand for many different systems, showing that the fundamentals of this solid waste treatment remain the same for all systems used.

Composting systems can be classified according to the reactor type, solid's flow mechanisms, bed conditions in the reactor and the manner of air supply (Haug, 1993). A more basic distinction for the process is made in terms of reactor systems (closed systems or in-vessel systems) and non-reactor (open) systems (Robinson and Kuchenrither, 1985; Stentiford, 1987). Non-reactor systems can be further divided into conventional windrow process, aerated windrow process and aerated static pile process (Benedict *et al.*, 1986).

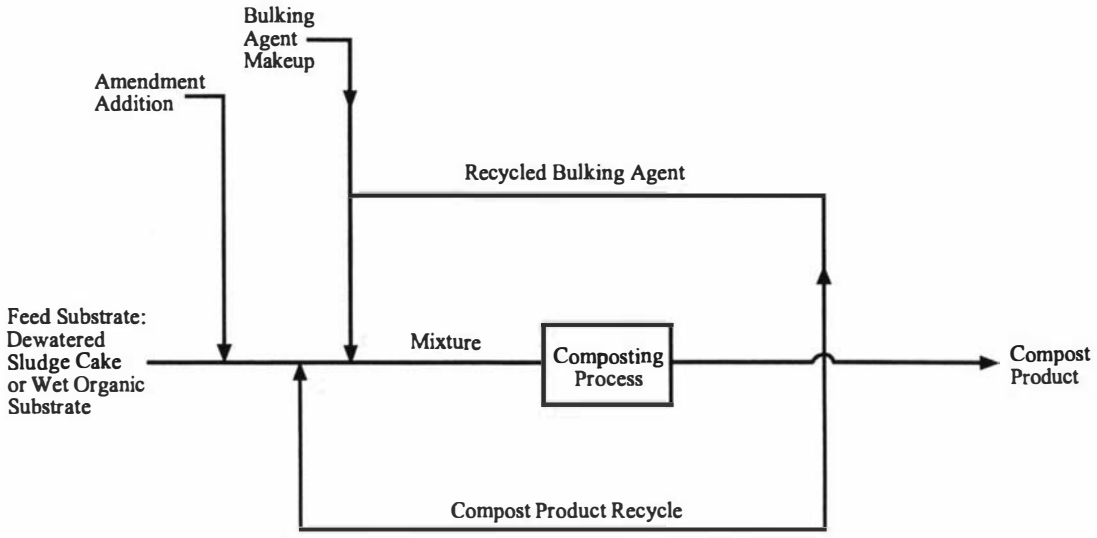


Figure 2.3 Generalised schematic for the composting process (Haug, 1993)

2.5.2 Conventional windrow process

The windrow system is the most popular example of a nonreactor, agitated solids bed system. Conventional windrow compositing involves mixing of dewatered solid (15 to 25% solids, w/w) with a sufficient quantity of previously composted material of about 60% solids (w/w). Alternatively, an external amendment or bulking agent can be added. Mixed feedstocks are placed in rows of variable length. The windrows are turned by mechanical equipment according to different criteria such as moisture content and temperature distribution in the heaps. The turning provides remixing and gas exchange. Natural ventilation occurring through upward movement of hot gases and water vapour also supplies oxygen. After the active windrow composting period, the composted material is usually subjected to curing. A portion of the finished compost is recycled, the rest stockpiled for distribution.

2.5.3 Aerated windrow process

In the forced aeration windrow system, oxygen transfer into the windrow is aided by forced or induced aeration from. In most composting literature the term forced aeration is used regardless of whether aeration is forced or induced. Strictly speaking, forced aeration applies to cases where ambient air is forced into the compost heap under positive pressure. Induced aeration applies to cases where gases are pulled from the material in heap under negative pressure. Periodic agitation by turning is used to restructure the window (Benedict *et al.*, 1986; Haug, 1993).

2.5.4 Aerated static pile system

The aerated static pile process is the premiere example of a nonreactor, static solids bed system. It involves mixing separated solids with a bulking agent (such as sawdust) at typical (v/v) ratios of 3.5 to 4.5 in order to achieve a minimal solids content of about 40% (w/w) in the solid-bulking agent mixture (Benedict *et al.*, 1986). Wood chips or other base materials are used to cover a perforated aeration piping layout to improve air distribution and to prevent blocking of the holes in the pipe. The mixture to be composted is placed on the base material. A source of air supply is connected by a manifold to the aeration piping.

The active composting period lasts at least 21 days, after which alternative pathways to produce finished compost may be used.

2.5.4.1 Process control

The course of composting process in the initial mix is influenced by C/N ratio, moisture content, and the porosity. These variables change, to a large extent free of direct control, although influenced by external control which can be accomplished in the form of mechanical agitation, forced aeration or material addition such as water in the case of closed systems (Stentiford, 1987).

To maintain the optimum temperature range of 55 to 65^{0}C, the accumulating heat must be removed. Studies have shown that a practical means of removing heat, maintaining the optimum temperature thus reaching high decomposition rates is the application of controlled ventilation (Donovan, 1985; Finstein *et al.*, 1987d). A temperature feed back control can be used to achieve controlled ventilation (Pareira-Neto *et al.*, 1987a). Aeration rates most commonly used range from 9 to 15 m^3 per hour per US dry ton of material, although different values can also be found in literature (Haug, 1993).

The temperature distribution through a compost pile or windrow varies depending upon many operational factors such as the height of the pile (Pareira-Neto *et al.*, 1987b; De Bertoldi *et al.*, 1985). Temperature variations occur through out the composting period. Heaps develop their coolest zones normally either at the outer surfaces or at the boundary with the base material on the ground. Due to these low temperature pockets in the compost heap, it is not possible to guarantee that the finished product presents no risk of pathogen survival or regrowth (Pareira-Neto *et al.*, 1987a).

2.5.5 Reactor (In-vessel) systems

Reactor systems are first classified according to the manner of solids flow as either vertical flow reactors or horizontal flow reactors (Haug, 1993). In horizontal flow systems, the reactor is inclined slightly from the horizontal to promote solids flow and include a number of reactor types.

2.5.5.1 Vertical flow reactor

Vertical flow reactors are further classified according to bed conditions and movement of the mixture in the reactor. Moving agitated bed reactors allow for agitation of solids during the passage down the reactor, which provides mixing. Forced aeration is applied. The mixture to be composted is usually fed on either a continuous or intermittent basis.

Moving packed bed reactors have their entire bed volume filled with solid and bulking agent mixture and are not agitated during the composting. This results in a plug flow

behaviour. Forced aeration is applied. This type of reactor can be fed on either continuous, intermittent, or batch basis. These beds often allow for periodic transfer of solids from the bottom to the top of the reactor via an external loop. The bed solids as a whole, however, remain unagitated during the batch cycle until their withdrawal from the bottom of the reactor at the end of the cycle.

2.5.5.2 Horizontal and inclined flow reactors

At least three different tumbling solids bed reactors can be distinguished, mainly based on the solids flow pattern within the reactor.

1. Dispersed flow pattern: Dispersion is provided by constant tumbling action. Material inlet and outlet are located on opposite ends of the drum. The flow pattern resembles plug flow except for the material dispersion.
2. Cells in series: Solids flow is provided by periodic emptying and transfer of material from one cell to another. Each cell is well mixed, which ensures that material does not short-circuit through the reactor. The product is discharged from the last cell and the feed is added intermittently to the first cell once it has been emptied.
3. Complete mix: Uniform feed and discharge along the length of the reactor are maintained along with a high level of mixing. In the case of continuous operation, further compost processing is required to ensure pathogen reduction due to the short detention time of a large proportion of material in the reactor. Intermittent feeding and withdrawal can avoid this problem.

In all three systems forced aeration is applied, the rotation speed of the reactor is kept constant and feeding occurs continuously or intermittently.

2.5.5.3 Agitated solid bed (or bin) reactors

A number of bin reactors of the horizontal flow, agitated solids bed type are in use. They use forced aeration and mechanical agitation of solids during composting. Reactors are usually uncovered at the top and are operated o a once-a-day feed cycle. Solid feed occurs

on a continuous, intermitted, or batch basis.

2.6 Losses of N from animal manures

Large amounts of N are lost from animal manures (Russell, 1961). According to one estimate, approximately 60-63% of manure N is lost under present management practices (Stewart, 1981). Physical, biological and chemical changes take place during storage, or composting, or after land application of manure, resulting in rapid loss of plant nutrients, especially N.

Loss of N from manures after land application has been extensively researched (Terman, 1979; Beauchamp, 1983). A limited number of studies have been carried out on the loses of N during storage or composting of manures. Some of the reported losses of N during the storage or composting are summarised in Table 2.7.

Table 2.9 N losses during the storage or composting of animal manure

Type of manure	Storage/composting	Total N loss (%)	References
Pig manure + straw	Composting	53.6	Martins and Dewes (1992)
Pig slurry	Composting	26	Loynachan *et al.* (1976)
Pig slurry + straw	Composting	27-40	Faassen and Dijk (1979)
Pig slurry + straw	Composting	15	Bernal and Lopez-Real (1993)
Cattle slurry	Storage	56.3	Dewes *et al.* (1990)
Cattle manure + straw	Composting	57.1	Martins and Dewes (1992)
Cattle slurry + straw	Composting	40-50	Jakobsen (1988)
Cattle manure (solid)	Stall barn storage	30-50	Muck and Richards (1983)
Dairy manure (solid)	Shallow pit storage	56	Moore and Beehler (1981)
Dairy manure (solid	Deep pit storage	23	Moore and Beehler (1981)
Sewage sludge + straw mixture	Composting	50	Witter and Lopez-Real (1988)
Sewage sludge + wood chips	Composting	10	Sikora *et al.* (1983)
Poultry manure	Storage	20-40	Kirchmann (1985a and b)
Poultry manure + straw	Composting	9-44	Kirchmann and Witter (1989)
Poultry manure + straw	Composting	77.4	Martins and Dewes (1992)
Poultry manure + sawdust + corncob	Composting	27-32	Hansen *et al.* (1989)

In these studies, approximately 9-77% of initial total N in manure was found to be lost, depending upon methods of storage or composting. It has often been suggested that the N in manure during storage or composting is lost mainly through NH_3 volatilisation and biological denitrification (Goulding and Webster, 1989; Kirchmann and Witter, 1989). Substantial amounts of N from manure can also be lost through leaching after land application (Pandey *et al.*, 1992; Adams, 1981).

The principles and factors affecting the N losses from manure during storage or composting are more or less similar to those of N loss from the manure applied to soil; therefore the loss of N from manure either during storage/composting, or after land application is discussed together.

2.6.1 N mineralisation and immobilisation

During the decomposition of plant and animal residues organic forms of nitrogen are converted to inorganic forms (e.g. NH_4^+) by the process of mineralisation. Microbial activity is the primary facilitator of this although some non-biological processes do occur.

Some of the N present in the residue during this breakdown is converted into inorganic forms and is either assimilated into microbial tissues or microbially complexed into soil humus, resistant to further microbial attack. This process is known as immobilisation.

These two processes occur simultaneously in the soil systems, the net effect being determined by the C:N ratio of residues being decomposed. If the C:N ratio is high (>25:1) net immobilisation usually occurs (Allison, 1973), and with a low C:N ratio e.g. (10:1) net mineralisation occurs (Bartholomew, 1965).

2.6.2 Nitrification

The nitrification of NH_4^+ is an important part of the mineralisation process whereby NH_4^+ is converted to NO_2^- and NO_3^- following the ammonification of organic N. The process of nitrification can be summarised as follows:

$$NH_4 \xrightarrow{Fast} NO_2 \xrightarrow{Veryfast} NO_3 \qquad (2.2)$$

The biological oxidation process, mediated by two groups of microbes, is responsible for the conversion of NH_4^+ to NO_3^-. Nitrosomonas is typical of six or so genera which oxidise NH_4^+ to NO_2^-; Nitrobacter represents the rather fewer genera which oxidise nitrite to nitrate. Nitrifying bacteria perform a valuable function in that NO_3^--N is more available for plant uptake and thus more effective as a plant nutrient than NH_4^+-N. However NH_4^+-N is retained well in soils compared to NO_3^--N which is readily leached. Nitrification therefore may result in loss of inorganic N from the rootzone (Postgate, 1978).

Rates of nitrification vary according to the factors affecting the biological environment, namely pH, mineral nutrient status, aeration, temperature and moisture. Well aerated, warm, moist soils close to neutral pH favour rapid rates of biological oxidation of NH_4^+. Nitrification rates decrease with depth and in soils below 15% soil moisture.

2.6.3 Denitrification, nitrification and cheomodenitrification losses

The processes of bacterial denitrification, nitrification and reactions of NO_2^- with the soil components represent possible pathways of loss of gaseous N from the ecosystem. Bacterial denitrification is a biochemical reduction process mediated principally by anaerobic bacteria such as Pseudomonas and a few other genera. The process can be summarised as follows:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO\uparrow \rightarrow N_2O\uparrow \rightarrow N_2\uparrow \qquad (2.3)$$

Early evidence for denitrification loss of N was given by Waksman (1952) who indicated that the greatest loss of N from stable manure could br due to biological denitrification. He observed a loss of 20 to 24% of N in manure inoculated with nitrifying bacteria as against only about 3% (largely as NH_3) in manure without nitrifying bacteria. He attributed this

difference in losses to denitrification.

Though the literature on direct measurement of denitrification loss from manure or compost is scarce, many researchers have recognised that biological denitrification together with NH_3 volatilisation could be a significant pathway of N loss from manure (Giddens and Rao, 1975; Hadas *et al.,* 1983; Gale and Gilmour, 1986; Bitzer and Sims 1988; Goulding and Webster, 1989).

Under anaerobic conditions certain microorganisms use O_2 from NO_3- ion as hydrogen acceptor and reduce NO_3- to N_2 or N_2O in manures. Several microorganisms are capable of reducing NO_3-, NO_2-, or N_2O, as terminal electron acceptors. Since most denitrifying bacteria are chemoheterotrophs, they use chemical energy sources, and use organic C compounds as electron donors (reductants) and as sources of cellular C (Firestone, 1982). Almost all denitrifiers are aerobic organism capable of anaerobic growth only in the presence of N oxides. Under conditions of limited O_2 availability, aerobic respiration can apparently provide the energy needed for syntheses of new enzymes required for NO_3- reduction.

In agricultural terms, denitrification is considered very important because it causes loss of valuable N. Many researchers have recognised that the denitrification loss of N fertilisers, animal manures, and biological wastes may contribute significant amounts of N_2O to the atmosphere , and thus cause the depletion of stratospheric ozone and add to the greenhouse effect (Knowles, 1982; Breitenbeck and Bremner, 1986). On the other hand, denitrification can remove excess NO_3- and minimise the nitrate contamination of ground water.

Non-denitrifying fermentative bacteria and fungi, and autotrophic nitrifying bacteria (e.g. Nitrosomonas) may also produce gaseous N products. Denitrifying bacteria are thought to be most important organisms contributing to the losses of nitrogenous gases from soils under anaerobic conditions.

The effect of gaseous N loss via bacterial denitrification and nitrification may vary considerably. Rolston and Broadbent (1977) calculated a loss of 13 kgN/ha (9% of applied

fertiliser) from cropped plots over an entire growing season. Rolston *et al.* (1976) measured gaseous N losses under different moisture, temperature and cover conditions following the application of manure. Up to 75% of N, applied as manure, was lost under wet treatments. In grass plots receiving either 250 or 500 kgN/ha/yr in the form of fertiliser, losses have been estimated at 11 and 29 kg N/ha/yr respectively (Ryden, 1981).

Although only small and variable amounts of data are available, Colbourn and Dowdell (1984) generalised that direct and indirect estimates of N_2 plus N_2O from soils range from 0-20% of fertiliser N applied to arable soils and 0-7% on grassland soils.

Chemodenitrification occurs when NO_2^- reacts with soil components resulting in a chemical reduction process unassociated with microbial activity forming gases such as N_2, N_2O and NO. Accumulation of NO_2^-, allowing significant rates of chemodenitrification, mainly occurs when nitrogenous fertilisers that form alkaline solutions upon hydrolysis are land applied. Build up of NO_2^- during denitrification of NO_3^--N applied as fertiliser also occurs.

The significance and magnitude of chemodenitrification under field conditions has yet to be established but gaseous losses via this process are not regarded to be large (Haynes, 1986).

2.6.4 Ammonia volatilisation

A significant loss of N in the form of NH_3 gas can result from application of ammonium containing fertilisers, urea, or urine-N, which hydrolyse to ammonia. The rate of hydrolysis, and therefore volatilisation, is affected by soil temperature, moisture levels and pH.

A large proportion of many organic manures is in the form of uric acid ($C_5H_4N_4O_3$) which is rapidly hydrolysed to urea ($CO(NH_2)_2$) by the enzyme uricase of several aerobic bacteria (Eq 2.4).

$$C_5H_4N_4O_3 + 2H_2O + 1.5O_2 \rightarrow 2CO(NH_2)_2 + 3CO_2 \qquad (2.4)$$

Through a chain of oxidative-hydrolysis reactions involving the enzyme urease, $(NH_4)_2CO_3$ and NH_4HCO_3 are formed from $CO(NH_2)_2$ (Schefferle, 1965) (Eq 2.5). These two chemical compounds are unstable and therefore readily dissociate into gaseous NH_3 and CO_2 (Schefferle, 1965). Species of *Bacillus, Micrococcus, Sarcina, Pseudomonas, Achromobacter, Corynebacterium, Clostridium,* and a diverse collection of filamentous fungi and actinomycetes are known to synthesize urease (Alexander, 1977).

$$CO(NH_2)_2 + 2H_2O \rightarrow (NH_4)_2CO_3 \rightarrow 2NH_3 + CO_2 + H_2O \quad (2.5)$$

Ammonia reacts with protons, metals and acidic compounds and dissolves in the manure solution to form a stable ionic form of ammonium (NH_4^+) (Eq 2.6). The ammonium thus formed exits in a chemical equilibrium with gaseous NH_3.

$$NH_3 + H_2O \Leftrightarrow NH_4 + O\overline{H} \quad (2.6)$$

The increase in the concentration of ammonium and CO_3/HCO_3 in the manure solution increase pH and result in the volatilisation of NH_3 from manure. According to Witter and Lopez-Real (1987a), the combination of high ammonium concentrations, high temperature and pH levels may lead to high NH_3 losses during composting.

Environmental quality degradation and fertiliser value loss due to NH_3 volatilisation are well documented. Ammonium forming fertilisers and animal manures applied to soil can lose as high as 50 to 80% of applied N (Terman, 1979). Direct measurement of surface applied NH_3 volatilisation has shown that 24 to 99% of the ammonium in manure can be lost within the first week (Lockyer *et al.*, 1989; Thompson *et al.*, 1987; Stevens and Logan, 1987; Beauchamp *et al.*, 1978; Lauer *et al.*, 1976).

Vanderholm (1975) estimated that 30 to 65% of N in manure is lost during storage. Total N losses between 30 and 50% were reported in free-stall barn by Muck and Richards

(1983). A loss of about 56% of total N within 12 weeks storage of cattle manure was reported by Moore and Beehler (1981). Several factors including meteorological variations, nature of manure or slurry and methods of measurements may have contributed to the large variation encountered in N loss from manure.

Environmental and health problems are posed by the NH_3 volatilisation. In Europe animal manures and slurries are reported to be contributing about 81% of total NH_3 emission, which results in an increase in atmospheric NH_3 (Buijsman *et al.*, 1987).

Release of NH_3 into the atmosphere also enhances the wet deposition of sulphate and increases the N load of surrounding ecosystem (Schuurkes, 1986; Breeman *et al.*, 1982). Many authors have reported the acidification of the soil due to increased deposition and nitrification of ammonium sulphate (Van der Molen *et al.*, 1989; Witter and Lopez-Real, 1988; Ryden *et al.*, 1987).

As a comparison, Haynes and Sherlock (1986) concluded that amounts of NH_3 volatilised from fertilisers are variable but loss of fertiliser N applied to the surface of grassland or bare soil could be in the range of 0-25%. Volatilisation from urine patches can be high. Ball and Keeney (1981) measured losses of up to 66% of applied urine-N during warm dry weather with a 28% average calculated over a range of seasonal conditions. Sherwood (1981) concluded that 40-80% of ammonium nitrogen was lost through ammonia volatilisation of NH_3 within approximately seven days of pig slurry application on grassland.

2.7 Design approach for composting systems

The rate of biochemical reaction determines the speed at which composting proceeds. Similar degree of degradation can be achieved by a fast reaction rate operating over a short time, or a slower reaction rate operating over a longer time (Haug, 1993). Kinetics deals with rates of reaction and makes the concept of time very important to the design and operation of composting system.

For liquid phase systems, two detention times can be defined, one based on liquid retention time and the other based on solids residence time. Detention time based on liquid retention time is usually termed "hydraulic retention time (HRT)". Detention time based on the average residence time of solids in the system is usually termed "solids residence time (SRT)". For a composting system where recycling of solids (or bulking material) is not used, both residence times are equivalent. SRT is the most important factor in determining the stability of the compost product. SRT is function of, among many other factors, (1) the type of substrate and amendments and their corresponding reaction rate constants; (2) the extent to which kinetic rate limitations are avoided; and (3) the end use of the product. Haug (1983), on the basis of the review of the data from a number of composting systems suggest that a minimum system SRT of about 60 to 180 days is required to produce compost with sufficient stability and maturity to avoid reheat and phytotoxic effects.

SRT for a composting system can be defined as the Mean Residence Time (MRT) of the feed solids excluding recycles. The recommended design approach for a composting operation would be to establish the minimum system SRT necessary to produce a given product quality. In order to establish the minimum SRT, it is important to establish the reaction rates (or rate of decomposition) of substrates. The mass of biodegradable organic times its heat content determines the quantity of energy available to drive the process. The subject of process kinetics is also of vital importance to determine detention time required in the design of an organic stabilisation process.

Rates of decomposition vary widely depending on the organic substrate. In a study of anaerobic fermentation of various substrates, Chandler *et al.*, (1980) found significant differences in the rate of fermentation between substrates. In their study the decomposition rate for chicken manure was over four times as fast as that for wheat straw. Other factors remaining the same, in a composting precess designed to achieve a certain level of decomposition, the residence time for wheat straw will be four times more than that for chicken manure (Haug, 1993).

2.7.1 Rate of biodegradation

The subject of oxygen consumption during composting has been investigated by numerous researchers using a variety of experimental procedures and feed materials (Haug, 1993). Schulze (1960 and1962) carried out detailed studies of oxygen uptake rate by using continuous composters to achieve steady state conditions. Schulze (1962) examined a number of feed mixtures and rates of oxygen consumption were determined through the run which used a mixture of garbage , sludge cake and vermiculite. Oxygen consumption, a function of temperature, followed the following relationship:

$$w_{o_2} = 0.1\,1(1.066)^T \tag{2.7}$$

where,

w_{o2} = rate of oxygen consumption, mg O_2/g VS-h

T = temperature, ^{0}C

Jeris and Regan (1973) and Wiley (1957) have also studied the oxygen uptake rates and presented relationships similar to Schulze (1962).

2.7.2 First order reaction rates

The shape of the oxygen consumption curves in numerous studies strongly suggest a first order rate equation of the form:

$$\frac{d(BVS)}{dt} = -k_d(BVS) \tag{2.8}$$

where,

BVS = the quantity of biodegradable volatile solids, kg

t = time, days

k_d = rate constant, day $^{-1}$

According to Equation 2.8, the rate of BVS degradation is a function of the quantity of remaining BVS. The negative sign indicated that the quantity of BVS decreases with time.

The assumption of first order kinetics has worked well in describing various processes involving biological oxidation (Haug, 1993). In a study cited by Haug (1993), the decomposition of papermill sludges and other substrates incubated with soil was studied. This study used a first order rate equation to model the data and divided the substrate volatile solid content into "fast" and "slow" fractions each with their own first order rate constant. It was found that in some cases this gave a better fit to the experimental data. Some complex substrates are made up of mixture of organics, some of which are likely to degrade faster than others, hence dividing the substrate into faster and slower fractions (Haug, 1993). Table 2.8 presents first order rate constants from this study.

Table 2.10 First order rate constants at 25^{0}C for various substrates incubated with soil (adapted from Haug, 1993)

Substrate	k_d (day $^{-1}$)		Percent	
	Fast	Slow	Fast	Slow
Digested sludge	0.0282	0.0037	34	66
Limed raw sludge	0.0293	0.0045	32	68
Primary papermill sludge		0.0033	0	100
Kraft papermill sludge		0.0015	0	100
Sawdust	0.01	0.0016	20	80
Crude oil	0.017	0.011	35	65
Wheat straw		0.0029	0	100
Wood bark		0.0004	0	100
Bermuda grass	0.0383	0.0132	40	60
Rye grass	0.0699	0.0172	28	72

Haug (1993) concluded that the first order kinetic models appear to accurately describe the decomposition of many composting substrates, even in some studies spanning over 800

days duration. He also observed that the accuracy of fit can sometimes be improved by dividing the substrate into fractions with different rate constants.

2.8 Conclusions from literature review

It is common in New Zealand to discharge waste materials, either raw or treated, into coastal and inland waters. This is putting stress on these aquatic habitats and is also offending the cultural and spiritual values of New Zealanders. With the steady growth of the New Zealand pig industry in recent years, piggeries have been identified as the most significant point source contributors to surface and groundwater pollution among the agriculture and livestock industry.

Solid-liquid separation followed by treatment appears to be a popular option for farmers in view of the high concentrations of suspended solids, biochemical oxygen demand (BOD), and nutrients in piggery wastes. The separated piggery solids are fibrous in nature, and form an ideal substrate for composting.

The rate of biochemical reaction determines the speed at which composting can proceed. Similar degree of degradation can be achieved by a fast reaction rate operating over a short time, or a slower reaction rate operating over a longer time.

SRT is the most important factor in determining the stability of the compost product. SRT is function of, among many other factors, the type of substrate and amendments and their corresponding reaction rate constants.

In order to establish the minimum SRT, it is important to establish the reaction rate (or rate of decomposition) of substrates. Rates of decomposition vary widely depending on the organic substrate. Although numerous guidelines are available for the design of effective composting plants (Finstein and Morris, 1975; Epstein *et al.*, 1976; Haug, 1993; Kuter *et al.*, 1985; Finstein *et al.*, 1986a; Nakasaki *et al.*, 1987), most of these guidelines or studies deal with sewage sludge or municipal solid waste. There is a complete lack of data on

composting process design or reaction rates for piggery solids. Also, there is lack of information to suggest that the design data available for sewage sludge composting can be readily used for piggery solids.

To address these specific issues raised by the literature review, the main objectives of this thesis are to (a) examine the composting process in relation to bulking material and operating conditions; (b) analyse the disappearance of Total Organic Carbon with temperature development in order to determine first order reaction rates; and (c) to analyse the inactivation or decay of indicator pathogens in piggery solids and sawdust composting trials.

CHAPTER 3

MATERIAL AND METHODS

3.1 Equipment and materials

3.1.1 Piggery solid: Source and characteristics

The solids used in the pilot scale composting trials were collected from the overflow of a rotary screen which separated the solids from piggery effluent generated at Oxnam piggery, Foxton, New Zealand. The pigs are meal fed. The moisture content in the piggery solid was in the range of 75 to 85%.

The fresh solid was transported to the pilot scale trial site in a utility truck. The compost piles were constructed on the same day in order to prevent degradation before the trials.

The solids used in the controlled laboratory scale composting experiments were collected from the overflow of a rotary screen which separated the solids from the piggery effluent generated at Janis Webby's piggery near Thames, New Zealand. Here, the pigs are also meal fed and the piggery solids from both sources have similar characteristics. The moisture content in the piggery solids for laboratory experiments was approximately 82%. The composting experiments were started on the same day of fresh piggery solids collection to prevent degradation before the experiments.

3.1.2 Bulking agent

In all composting experiments, sawdust was used as the bulking agent in order to facilitate the following actions:

I. reduction of bulk weight;

II. increase of air voids for proper aeration

III. increase the carbon content; and

IV. conserve nitrogen through adsorption.

The reason behind the selection of sawdust was its easy availability and compatibility with the piggery solids to give a homogeneous mix. The sawdust for pilot scale trials was obtained from Tiritea sawmill in Palmerston North and was produced from untreated logs. The sawdust from untreated logs for controlled laboratory scale experiments was obtained from the Carter Holt Harvey sawmill in Putaruru. In both cases, the sawdust was exposed to all weather conditions due to their storage in an open area outside the sawmill. In some of the trials the moisture content of the sawdust was adjusted by adding water to achieve the required final moisture content of the substrate-bulking agent mixture.

3.1.3 Experimental site conditions

The atmospheric conditions in the room used for composting pilot scale trials were not temperature and humidity controlled and were subjected to normal fluctuations. The composting trials were conducted indoors at Massey University, Palmerston North to minimise these fluctuations.

The laboratory scale controlled temperature experiments were conducted in the workshop at Landcare Research, Hamilton.

3.1.4 Aeration equipment

3.1.4.1 Piping materials for pilot trials

A piping manifold made up of PVC header and lateral pipes was used in all the pilot scale trials. It consisted of the following parts with their indicated sizes (the letters in bracket below refer to Figure 3.1):

Low pressure PVC pipe, 20 mm internal diameter (i.d.), (P.a)
T-pieces, PVC, 50 x 20 mm i.d., (T)

T -pieces, PVC, 50 x 50 mm i.d., (T)

Low pressure PVC pipe, 50 mm i.d., (P.b)

50 mm PVC end caps, (C)

20 mm PVC ball valve, (V)

PVC reducing sleeves

PVC 90 degree elbows

3.1.4.2 Material for laboratory experiments

Clear rubber tubing of approximately 5 mm diameter was used for aeration in the laboratory experiments.

3.1.4.3 Air supply

A centrifugal air blower (LLC/5, 190 watt, Woods air movement, GEC (New Zealand Ltd., Woods/Satchwell Division) was installed for pilot trials. Figure 3.2 shows the 'on-off' timer configuration for aeration and temperature measurement.

A Sharp 1300 Watts vacuum cleaner with blower port at the back was used to supply air for the laboratory experiments. It was connected to a timer switch for power supply at designated times.

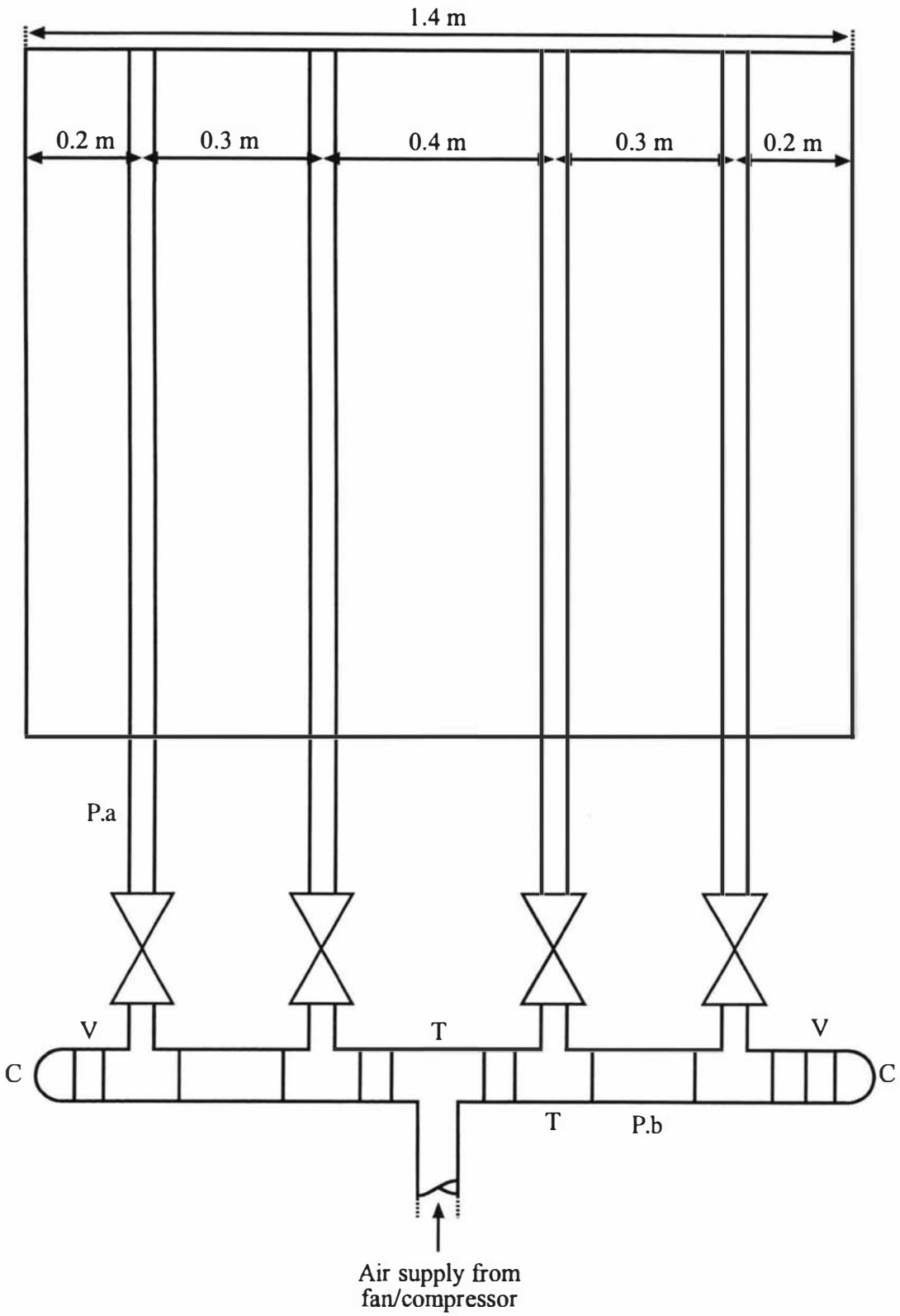


Figure 3.1 **Schematic representation of the aeration piping layout used in the composting trials (not to scale). For details refer to Section 3.1.4.1.**

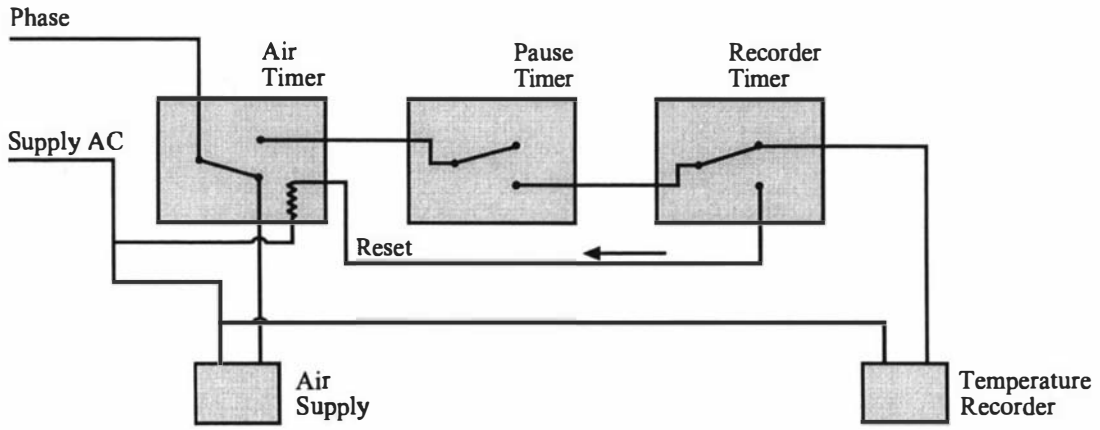


Figure 3.2 Timer configuration for the 'on-off' regime of the aeration and the temperature measurement

3.1.5 Temperature recorder

The ambient temperature and progression of temperature build up in pilot trials was recorded using a Honeywell Versaprint multipoint continuous recorder. Type K thermocouples were used to measure the temperature.

In controlled laboratory experiments, a mercury thermometer was used to check the temperature at regular intervals.

3.1.6 Sampling

A remote handling concentric pipe sampling device was used to collect grab samples from within the compost heap during the composting process in pilot trials. The device had a hollow cylindrical shaped capsule of about 20 cm length at one end, inside which a pointed piston could be moved in backward or forward direction with the help of a long handle at the other end. The handle could be locked when the piston was at the top end of the cylinder. The device was inserted vertically in the composting heap, with piston locked in

the cylinder at the top end. Once the device reached the desirable depth inside the compost heap by moving backward and forward, the piston was unlocked and pulled back leaving the empty capsule exactly at the point of sample collection. The capsule was filled with compost sample by subsequent pushing of the device in the heap. Finally, the device was pulled out from the compost heap. A sampling mass of about 100 to 150 grams was taken from the mass by this procedure.

Common kitchen tongs (long) were used to grab samples from the laboratory experiments.

3.2 Experimental procedure

Five composting pilot scale trials with natural temperature development using different substrate to bulking agent ratios and aeration frequencies were performed. Two controlled laboratory experiments at 70 ^{0}C and 60 ^{0}C, respectively, using similar substrate to bulking agent ratio and aeration frequency to trial 4were also performed. These are summarised in Table 3.1.

Table 3.1 Aeration and sawdust-waste ratios for various trials/experiments

Trial number	Aeration	Sawdust-Waste ratio (%, v/v)
1	48 hrs continuous followed by 10 min/hr	50:50
2	24 hrs continuous followed by 10 min/hr	50:50
3	10 min/hr	50:50
4	10 min/hr	25:75
5	10 min/hr	75:25
6	30 minutes every 3 hrs	25:75
7	30 minutes every 3 hrs	25:75

3.2.1 Mixing of solid and bulking agent

In all the pilot scale trials, the separated solids were mixed with bulking agent (sawdust) with the help of a front-end loader. The components were thoroughly mixed by alternately driving the loader back and forth over the mixture and turning the mixture with the loader bucket.

In the laboratory experiments the separated solids were mixed with sawdust by hand.

3.2.2 Aeration distribution

To get uniform distribution along the length of the pipe (laterals), Perry and Chilton (1973) have presented a rule of thumb: "the ratio of kinetic energy in the inlet stream to pressure drop across the outlet hole and of friction loss in the pipe to pressure drop across the outlet hole should be equal to or less than one-tenth". When this rule is satisfied, the expected mal-distribution in the flow is less than 5% (Kneabel, 1981) and these constraints can be stated as:

$$\alpha \frac{\rho \overline{V}_p^2 / 2}{\Delta P_o} \leq 0.1 \qquad (3.1)$$

and,

$$\frac{\Delta P_p}{\Delta P_o} \leq 0.1 \qquad (3.2)$$

Where,

α = Correction factor (1.05 for turbulent flow)

ρ = Fluid density

V_p= Inlet velocity of fluid entering pipe

ΔP_o = Pressure drop across each orifice

To convert Equation 3.1 to a useful form, ΔP_o should be first calculated using a relationship for turbulent flow through a sharp-edged orifice with an A_o/A_p ratio between 0.05 and 0.70 (Denn, 1980).

$$\Delta P_o \approx 2.6\rho \frac{\overline{V}_o^2}{2}\left[1-\left(\frac{A_0}{A_p}\right)^2\right] \tag{3.3}$$

where,

V_o = Velocity of fluid leaving orifice

A_o = Area of one orifice

A_p = Cross-sectional area of pipe

By continuity, we know that:

$$A_o \overline{V}_o N = A_p \overline{V}_p \tag{3.4}$$

Where,

N = Number of orifices

Using this relationship and Equation 3.3, we can convert Equation 3.1 to an expression for orifice diameter:

$$D_o \leq D_p / (1+4.04N^2)^{1/4} \tag{3.5}$$

Where,

D_o = Diameter of each orifice

D_p = Diameter of pipe

Since N is generally large, this reduces further to a simple constraint (Kneabel, 1981):

$$D_o \leq 0.7 D_p / \sqrt{N} \tag{3.6}$$

To convert Equation 3.2, we can estimate the friction loss in the pipe as approximately one velocity head per 150 pipe diameters (Perry and Chilton, 1973):

$$\Delta P_p \approx \frac{L}{150 D_p} \rho \frac{\overline{V}_p^2}{2} \tag{3.7}$$

Where,

ΔP_p = Pressure drop in pipe caused by friction

L = Length of pipe

Combining Equation 3.7 with Equations 3.2 and 3.3, we can get the other constraint:

$$D_o \leq D_p / \left(1 + \frac{LN^2}{39 D_p}\right)^{1/4} \tag{3.8}$$

When the L/D_p ratio is less than 150, Equation 3.6 is the only constraint that need to be considered.

For a lateral pipe of 2200 mm length and 20 mm diameter, the L/D_p ratio is less than 150, therefore Equation 3.6 can be used to determine the diameter of each orifice. For a total of

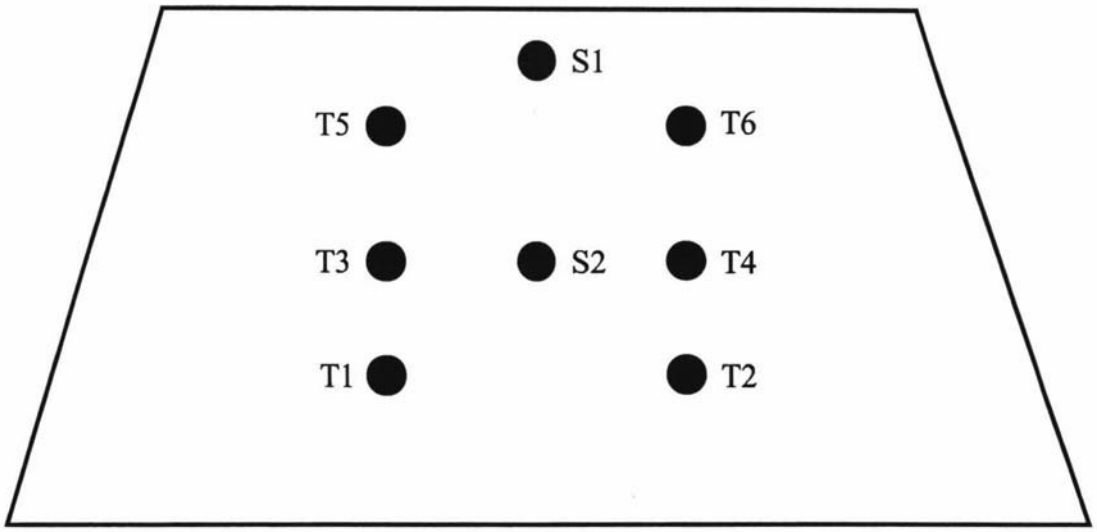
20 orifices along two sides of the lateral length, Equation 3.6 gave an orifice diameter of approximately 3 mm.

3.2.3 Construction of static piles

Different ratios of piggery waste and sawdust, as required for individual trials (Table 3.1) were placed in two heaps and mixed together according to the procedure described previously in section 3.2.1. The aeration piping layout as shown in Figure 3.1, was placed over an appropriate sloping concrete floor for drainage. The aeration piping was covered with a plastic mesh and a layer of wood chips of about 10 cm uniform thickness was placed to facilitate even distribution of air through the pipe. This layer also prevented the holes (orifices) in the lateral pipes from being blocked by the solids.

The mixture was then placed over the piping layout in the form of a pile. The effective length of the pile was 2.2 m with a width and height of 1.4m and 1.5m , respectively.

In order to record the temperature throughout the composting mass, a total of 6 thermocouples were placed at different positions within the pile and connected to a temperature recorder. The location of thermocouples in the pile is shown in Figure 3.3. The coverage of the compost pile, usually applied in static pile systems (Pareira-Neto *et al.*, 1987; Donovan, 1985; Stentiford, 1987), was not employed in these trials.



LONGITUDINAL SECTION
(T=thermocouple, S=sampling point)

Figure 3.3 Position of thermocouples and sampling points

3.2.4 Laboratory experimental setup

10 litre flasks were modified to act as vessels for laboratory experiments. Three additional ports were created by the glass blower next to the neck of the flask to accommodate aeration tubings and mercury thermometer. The long neck of the flask was cut short and acted as a sampling port where the long kitchen tongs were used to grab the sample from the vessel. Aeration by means of a vacuum cleaner, operating as a blower, was provided at the same rate and frequency from the beginning of each laboratory experiment alternating an 'on' and 'off' regime by a timer switch. A Coke bottle was glued to one end of the vacuum cleaner hose, while other end of the hose was inserted in the blower port situated at the back of the vacuum cleaner. Four holes were made on the wall of the Coke bottle to accommodate the clear rubber tubing which was inserted inside the bottle through these holes. The other end of the aeration tube was connected to an air diffuser. Two tubing and the air diffuser assemblies were lowered in composting vessel for each experiment which rested at the bottom of the vessel. The composting mixture was placed inside these vessels over the aeration system. The vessels were placed in water baths at pre-determined temperatures. Polystyrene pieces were used to keep vessels in place in side the water bath and also to prevent evaporation of water from the water bath. The schematic of the

laboratory set up is shown in Figure 3.4.

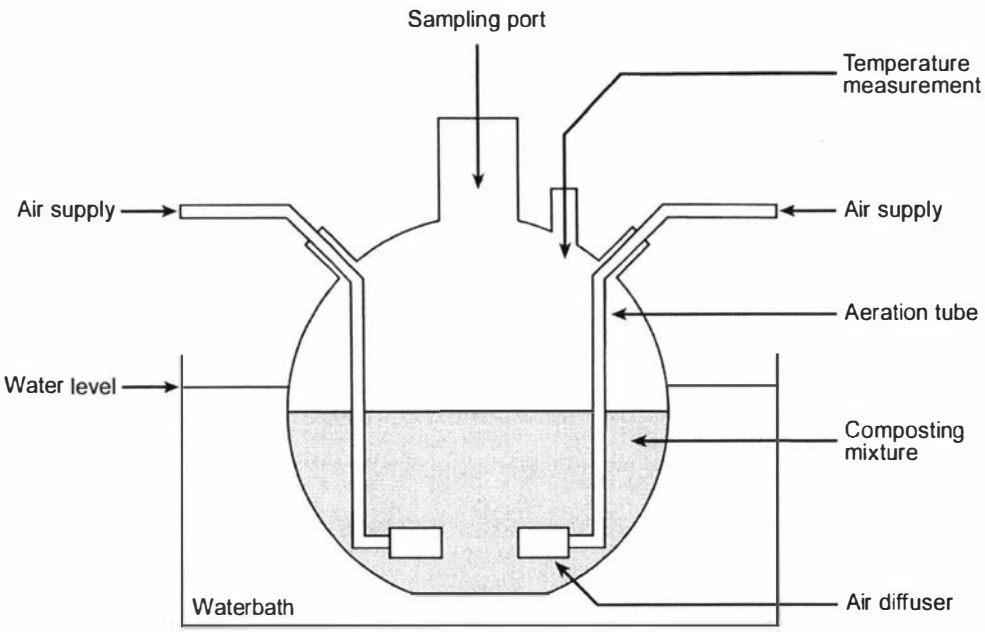


Figure 3.4 Schematic of the setup used for laboratory experiments

3.2.5 Aeration pattern

Aeration by means of a blower (Section 3.1.4.2) was provided at the same rate but different frequencies from the beginning of each pilot composting trial alternating an 'on' and 'off' regime. Table 3.1 shows different aeration rates for various trials.

Aeration by means of a vacuum cleaner, operating as a blower, was provided at the same rate and frequency from the beginning of each laboratory experiment alternating an 'on' and 'off' regime by a timer switch. The timer switch operated the vacuum cleaner every 3 hours for 30 minutes.

3.2.6 Sampling procedure

Samples from the compost heap in pilot trials were withdrawn and analysed from top and middle layers according to the procedures and methods described in Sections 3.1.6 and 3.3, respectively. The sampling ports were located at 15 cm and 75 cm from the top. The position of the ports in the compost heap is shown in Figure 3.3.

In addition to temperature, pH, Total Nitrogen , Total Phosphorus, Total Organic Carbon, Total Solids, Volatile Solids and the Microbial counts of Streptococci and *Escherichia coli (E.coli)* (MPN) were monitored initially every day up to 10 days and every 5 days thereafter until the completion of the trial, that is up to 23 days.

Samples from the laboratory experiment vessels were withdrawn with the help of a long kitchen tongs. They were analysed according to the procedures and methods described in Section 3.3.

In addition to temperature, Total Nitrogen , Total Phosphorus, Total Organic Carbon, Total Solids, and the Microbial counts of total coliforms, faecal coliform, *E.coli* and enterococci were monitored initially every day up to 7 days and then on days 9, 11, and 14, thereafter.

3.3 Analytical methods

Analytical methods used were same for both pilot trials and laboratory experiments, unless otherwise stated in the following sections.

3.3.1 Chemical analysis

3.3.1.1 pH measurement

10 g of compost mixture without screening was placed in a 250 mL screw capped Duran glass bottle (Schott, West Germany) containing 50 mL of distilled water. After shaking the

bottle for 5 minutes, the pH of the sample was determined using a pH metre (Orion Research model, 701 A/digital Ionalyzer).

3.3.1.2 Total and volatile solids

Compost

Compost samples weighing 50 g were screened manually using a pair of tweezers to remove stones or foreign particles. After screening, the compost samples were subjected to analysis for the determination of total and volatile solids, according to the procedures set out in Standard Methods (APHA, 1985). Fresh piggery solids were also subjected to these analysis from the samples taken before the composting began.

Sawdust

Samples of sawdust (weighed to a precision of ± 0.01g), were randomly taken from the sawdust storage bin, placed in crucible dishes and dried at 105^0C for 25 to 30hrs. After cooling in a desiccator, the samples were weighed and the total solids content calculated according to the procedure described in Standard Methods (APHA, 1985). The dried and weighed samples were then heated carefully over a Bunsen burner flame in order to avoid losses of material due to explosive burning of larger sawdust particles. Volatile solid content was then determined using the procedure of Standard Methods (APHA, 1985).

3.3.1.3 Total Nitrogen and Phosphorus

Sample preparation

Approximately 10 g of compost sample was dried in an oven at 65^0C for at least 48 hours in order to minimise volatilisation of nitrogen occurring.

Digestion mixture

2.5g selenium powder (Ajax Chemicals, Australia) and 250 g K_2SO_4 (BDH Chemicals Ltd., Poole, England) were added to 2.5 L concentrated H_2SO_4 (BDH Chemicals Ltd., Poole, England) in a 5L Pyrex beaker. The mixture was then heated to 300^0C for about 3 hrs until it became clear.

Digestion

The total nitrogen and phosphorus were determined by digesting the samples according to McKenzie and Wallace (1954). Samples of dried and ground compost weighed on a rice paper to a precision of ± 0.0001 g) were placed in a Pyrex tube (100mL), which was previously calibrated to 50 mL. Digestion mixture (4mL) was added to the sample and heated in an aluminium digestion bloc (350^0C for 4 hrs). After cooling, the samples were diluted deionised water to 50 mL, thoroughly mixed on a vortex mixer and finally transferred into screw capped glass containers previously cleaned with chromic acid. The bottles were kept undisturbed in storage so sedimentation of undissolved particles could occur. The supernatant was used to measure total nitrogen (Total Kjeldahl Nitrogen concentration, excluding nitrate) by a colorimetric method, using a Technicon autoanalyser. Total phosphorus (total elemental phosphorus concentration, inorganic and organic) content was determined using same supernatant by vanadomolybdate method (AOAC, 1975).

A blank sample using the rice paper alone as well as a herbage standard sample of known nitrogen and phosphorus content was also run with each set of samples.

3.3.1.4 Total Carbon

The total carbon content of the compost was determined by the dry combustion method using the Leco furnace (Bremner and Tabatabai, 1971).

3.3.2 Microbial Analysis

3.3.2.1 Media

BEA (Bile Esculin Azide) Agar and peptone water were obtained from Gibco Laboratories, Madison, Wisconsin, USA.

MacConkey Broth (purple) was obtained from Oxoid Ltd., Basingstoke, England.

Lauryl tryptose, EC + mug, Azide dextrose broth, EIA agar, mE agar were all obtained from Becton Dickinson and Company, Sparks, MD, USA.

3.3.2.2 Media preparation

Commercial media as well as peptone water and phosphate buffer for serial dilution were prepared prior to autoclaving according to the instructions from the manufacturers.

3.3.2.3 Sterilisation of media, glassware and equipment

All media, glass bottles for serial dilution and sample collection containing dilution solutions were sterilised in the autoclave at 121^0C for 15 minutes.

Glass pipettes were sterilised in the hot air oven at 160^0C for 2 hrs.

Plastic pipette tips were sterilised in the autoclave at 121^0C for 15 minutes.

3.3.2.4 Sample preparation

The method and recommendations of Donnison (1992) were used to prepare the samples from the laboratory experiments.

The method of Dudley *et al.*, (1980) was modified to prepare the samples for microbiological analysis for pilot trails.

10 g of compost mixture from the heap was placed in a sterile screw capped 250 mL Duran glass bottle (Schott, West Germany), containing 90 mL of peptone water and approximately 20-25 pieces of 3 mm glass beads. The bottle was vortexed for two minutes to disperse the compost mixture and immediately prepared for microbial counts, or stored at 4^0C for a period not exceeding three hours.

3.3.2.5 Analysis for indicator microorganisms

For the analysis of indicator microorganisms, serial dilutions were prepared in sterile screw capped glass bottles containing peptone water.

Where the agar medium had to be melted, it was heated at 110^0C for 10 minutes in the autoclave. Before pouring the agar in plates, agar was cooled and held until needed in a waterbath at 45^0C.

Group D-streptococci (faecal streptococci) were enumerated using BEA Agar. The pour plate method and serially diluted samples according to Standard methods (APHA, 1985) were used to determine the counts. Plates were incubated at 37^0C for 36 to 48 hours. Enterococci were enumerated using mE media according to Donnison (1992).

Bacteria of the coliform group in pilot trials were determined using the Most Probable Number (MPN) test according to Standard Methods (APHA, 1985). Five MacConkey broths of each of five successive 10-fold sample dilutions were incubated at 37^0C for a period of 36 to 48 hours. Total coliforms, faecal coliform and *Escherichia coli (E.coli)* in the laboratory experiments were analysed according to Donnison (1992). The estimation of microbial number by the multiple tube technique was performed using the tables of Harrigan and McCance (1976).

CHAPTER 4

EXPERIMENTAL RESULTS

The main purpose of these composting studies was to investigate the composting process of screened piggery solids in relation to bulking material and operating conditions. The changes in temperature, Total Solids, Volatile Solids, Total Nitrogen, Total Phosphorus during composting, as well as reduction in the counts of indicator microorganisms were the major factors investigated in these experimental studies.

Aerated static pile system was employed in pilot scale studies. Aerated static pile systems are more suitable for composting piggery solids mixed with a bulking agent. Piggery solids usually have a high moisture content. Solid-liquid separation of piggery solids using commonly used technology, such as rotary or stationary screen does not remove a lot of moisture from the solids. The process is generally successful with these substrates because the use of bulking agents enhances the porosity. High aeration rates can be maintained because of the porous structure of the mixture. Although conventional windrow process is also very popular, it is used in a variety of relatively dry substrates. Windrows are turned by mechanical means for aeration and quite often produce offensive odour if lack of oxygen through the windrows has turned a portion anaerobic. Highly odorous piggery solids require more aeration which the aerated static piles can provide.

It was hypothesised that by changing the operating conditions in pilot trials, such as moisture content, solids to sawdust ratio, aeration, etcetera, in different trials a "best-mix" rate constant would be achieved. The best reaction rate constant would not only indicate the fastest degradation of volatile substrate but indicate the best possible operating conditions within the limits of the experimental set up. First three trials had same sawdust to solids ratio (50:50) but had different frequency of air supply during the initial phase. Due to the fibrous and friable nature of piggery solids, the initial moisture contents were also kept higher than literature to test whether or not composting can take place successfully under these circumstances. This is to promote rapid development of microbial activity. The

third trial had the aeration frequency reduced because the first two trials showed initial cooling due to continuous aeration in the initial phase. It was evident from the temperature profiles for the first two trials that as soon as the continuous aeration stopped the temperature started to rise, especially in the lower zone of the compost heap. The fourth trial had 25:75 ration of sawdust and solids and had same aeration rate as trial 3 to see if extra amount of substrate (solids) would provide better decomposition rates. The initial moisture levels in trials 3 and 4 were kept at approximately same level. Trial 5 had the smallest amount of solids but moisture was at about the same level as in trial 1.

Laboratory experiments were carried out under controlled temperature and aeration conditions. These experiments were carried out to independently verify rate constants developed from pilot trials 1 to 5. It was also hoped that these experiments would confirm the "best-mix" from within the pilot trials.

Results of these studies are presented here. In results from pilot trials, day 1 of composting time represents time 0, i.e. the day when composting started under aerated pile conditions. In laboratory experiments, day 0 represents time 0, or the day when aerated laboratory experiments started. The rate constants are derived in Chapter 5 and explanation of these results and relationships are presented in Chapter 6.

Due to the homogeneous nature of the composting mixture treated in these studies, it was not necessary or possible to screen out the bulking agent from composting samples. Justification for the selection of sawdust as bulking agent is presented in Section 3.1.2.

The experimental procedure employed for these trials is described earlier under Section 3.2.

In the pilot scale trials, the course of decomposition at two sampling points (Figure 3.3) was followed. It was based on the assumption that a position effect existed in addition to the usual changes occurring during the composting time. The two way analysis of variance statistical analysis was carried out to test for any time effect at two positions as well as for any position effect over the experimental period. The results of the statistical analysis are presented in section 4.2.

In the laboratory experiments 6 and 7, the course of decomposition was followed at only one sampling point in the vessel due to the small amount of composting mixture in it.

4.1 Analysis of variables

4.1.1 Temperature development

A total of six thermocouples were inserted into the pile in trials 1 to 5, as shown earlier in Figure 3.3. Daily temperature was monitored during the compost cycle at all six thermocouple positions. Thermocouple position six (T6) represents temperature development at sampling position 1 (S1), where as T4 represents temperature development at sampling position 2 (S2). The temperature was kept constant in laboratory experiments by keeping the vessel in temperature controlled water baths. The temperature was monitored at various depths within the vessel several times during the day.

In the first trial, screened piggery solids were mixed with untreated sawdust in a ratio of 50:50 (volume basis). The resulting initial moisture content of the mixture was approximately 67%. The mass was aerated for 48 hours continuously, followed by 10 minutes of aeration every hour once the continuous aeration was stopped.

The temperature development in the first trial is shown in Appendix 1.

Maximum temperatures in the range of 62 to 72^{0}C were reached at most of the thermocouple positions within five days of operation, but then declined to a range of 35 to 50 ^{0}C at the end of the composting trial. The decline at the bottom of the heap (T1and T2) was more rapid where ambient temperatures were reached within two weeks of the composting cycle.

In the second trial, screened piggery solids was mixed with untreated sawdust in a ration of 50:50 (volume basis). The resulting initial moisture content of the mixture was approximately 71%. The mass was aerated for 24 hours continuously, followed by 10

minutes of aeration every hour once the continuous aeration was stopped.

Maximum temperatures in the range of approximately 70 to 73^{0}C were reached at most of the thermocouple positions within five days of operation, but then declined very slowly in a range of 56 to 61^{0}C at the end of the composting trial. The decline at the bottom of the heap (T1and T2) was more rapid where close to ambient temperatures were reached by day 18.

The temperature development in the second trial is shown in Appendix 1.

In the third trial, freshly screened piggery solids were mixed with untreated sawdust in a ration of 50:50 (volume basis). The resulting initial moisture content of the mixture was approximately 72%. The mass was aerated for 10 minutes every hour till the end of the composting trial.

The temperature development in the third trial is shown in Appendix 1.

Maximum temperatures in the range of approximately 68 to 75^{0}C were reached at most of the thermocouple positions within five days of operation. The temperature in the top of the pile remained above 60^{0}C for most of the composting trial. There was a decline in temperature to about 40^{0}C at other thermocouple positions by day 18, except one thermocouple at the bottom of the heap that reached near ambient temperature by this time.

In the fourth trial, screened piggery solids were mixed with untreated sawdust in a ration of 75:25 (volume basis). The initial moisture content of the mixture was approximately 73%. The mass was aerated for 10 minutes every hour till the end of the composting trial.

The temperature development in the fourth trial, as a typical example, is shown in Figure 4.1.

Maximum temperatures in the range of approximately 64 to 75^{0}C were reached at most of the thermocouple positions within five days of operation. The temperature in most of the

heap remained above 60^{0}C till the end of the composting trial. There was a decline in temperature to about 40^{0}C at one (T3) thermocouple position and another (T1) thermocouple at the bottom of the heap that reached ambient temperature by day 16.

In the fifth trial, screened piggery solids were mixed with untreated sawdust in a ration of 25:75 (volume basis). The initial moisture content of the mixture was approximately 67%. The mass was aerated for 10 minutes every hour till the end of the composting trial.

The temperature development in the fifth trial is shown in Appendix 1.

Top of the composting pile (thermocouples T5 and T6) reached maximum temperature between 55 and 65^{0}C within 4 days of operation. The temperature declined very rapidly and reached below 20^{0}C within 10 days. Temperatures in the middle (T3 and T4) reached a maximum between 40 and 50^{0}C and followed the same pattern as in the top layer, reaching below 30^{0}C within 8 days. Temperature at T1 in the bottom of the heap never rose above ambient whereas T2 rose up to 35^{0}C on day 3 and rapidly declined below 30^{0}C after 5 days.

In temperature controlled experiments (6 and7), partially enclosed vessels were placed in water baths and the temperature through out the mass reached to designated levels of 70 ^{0}C and 60 ^{0}C within few hours of starting the experiment. The temperature in the 70 ^{0}C vessel never exceeded the designated 70 ^{0}C where as in the 60 ^{0}C vessel it exceeded 60 ^{0}C within few hours. The heat generated by the piggery solid/sawdust mass decomposition would have contributed to this increase. The water bath temperature had to be kept lower than 60 ^{0}C to accommodate the heat generated in the mass. However, this phenomenon stopped after 2 days. As compared to other trials (for example trials 1 to 4) the self generated heat did not last several days because the small amount of substrate in a large vessel volume could not have sustained prolonged heat generation.

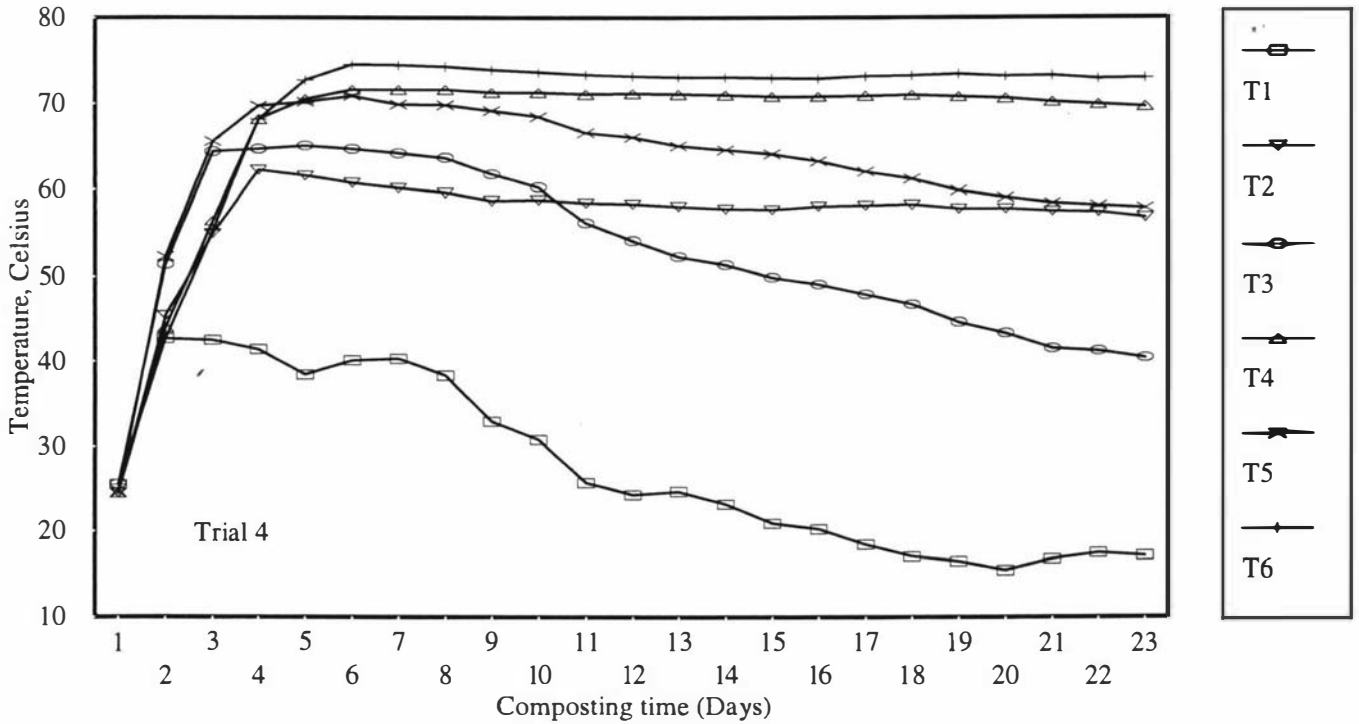


Figure 4.1 Temperature profile during composting in fourth trial at thermocouple positions T1 to T6

4.1.2 Total Solids and Volatile Solids

In the first trial, initially the composting mixture consisted of approximately 33.5% TS, decreasing to 31.6% at S1 and increasing up to 53.2% at S2 after 21 days of composting. The composting mixture consisted of 85% volatile solids initially. At the end of 21 days, this trial saw an increase of VS to 89.8% at S1 and 90.6% at S2.

The total solids and volatile solids contents versus time during the operation of first trial are shown in Appendix 2.

In the second trial, initially, the composting mixture consisted of approximately 29% TS, decreasing to 24.8% at S1 and increasing up to 41% at S2 after 21 days of composting. The composting mixture consisted 87.8% volatile solids initially. At the end of 21 days, the volatile solids dropped to 77.6% at S1 and 81.9% at S2, respectively.

The Total Solids and Volatile Solids contents versus time during the operation of the second trial are shown in Appendix 2.

In the third trial, initially, the composting mixture consisted of approximately 28.6% TS, decreasing to 24.3% at S1 and increasing up to 41.7% at S2 after 21 days of composting. The composting mixture consisted 86.2% volatile solids initially. At the end of 21 days, the volatile solids dropped to 79.8% at S1 and 82.83% at S2, respectively.

Appendix 2 shows the Total Solids and Volatile Solids content versus time during the operation of third trial.

During the fourth trial, initially, the composting mixture consisted of approximately 27.6% TS, decreasing to 24.5% at S1 and increasing up to 35.7% at S2 after 21 days of composting. The composting mixture consisted 82.9% volatile solids initially. At the end of 21 days, the volatile solids dropped to 70.67% at S1 and 79.14% at S2, respectively.

Figure 4.2 shows the Total Solids content versus time during the operation of fourth trial.

Figure 4.3 shows the Volatile Solids content versus time during the operation of fourth trial.

In the fifth trial, initially, the composting mixture consisted of approximately 33.63% TS, decreasing to 27.49% at S1 and increasing up to 42.45% at S2 after 21 days of composting. The composting mixture consisted approximately 82% volatile solids initially. At the end of 21 days, the volatile solids dropped to 77.11% at S1 and 77.25% at S2, respectively.

Appendix 2 shows the Total Solids and Volatile Solids content versus time during the operation of fifth trial.

In laboratory experiments 6 and 7, screened piggery solids were mixed with untreated sawdust in a ration of 75:25 (volume basis). The initial moisture contents of the mixture were approximately 61.3% and 60.8%, respectively. The mass was aerated for 30 minutes every three hours till the end of the composting experiment.

During the laboratory experiment 6, initially, the composting mixture consisted of approximately 38.6% TS, increasing to 46.34% after 15 days of composting.

Figure 4.4 shows the Total Solids content versus time during the operation of laboratory experiment 6.

In the laboratory experiment 7, initially, the composting mixture consisted of approximately 39.21% TS, increasing to 45.99% after 15 days of composting.

Figure 4.5 shows the Total Solids content versus time during the operation of laboratory experiment 7.

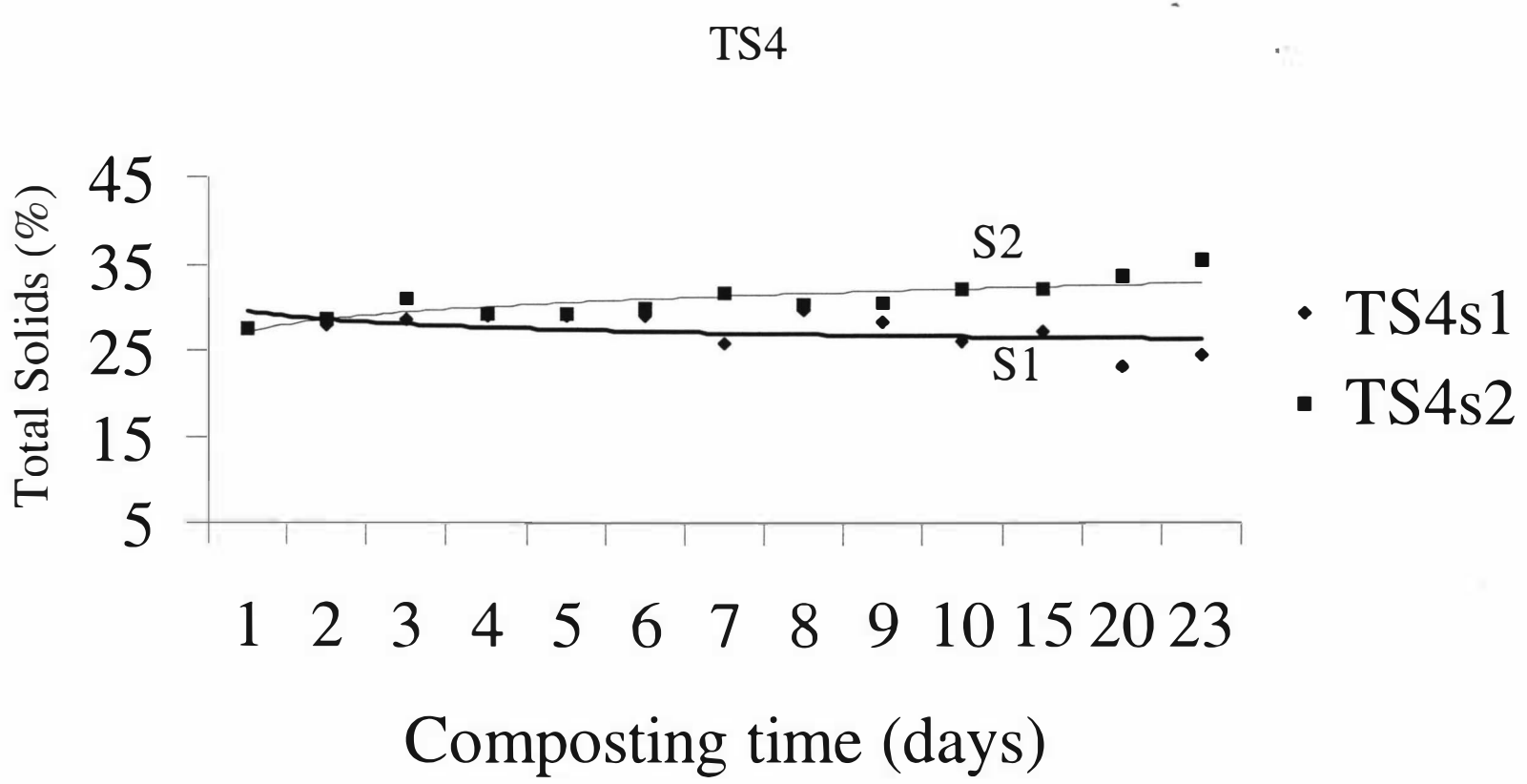


Figure 4.2 **Changes in Total solids content during composting in fourth trial at positions S1 and S2**

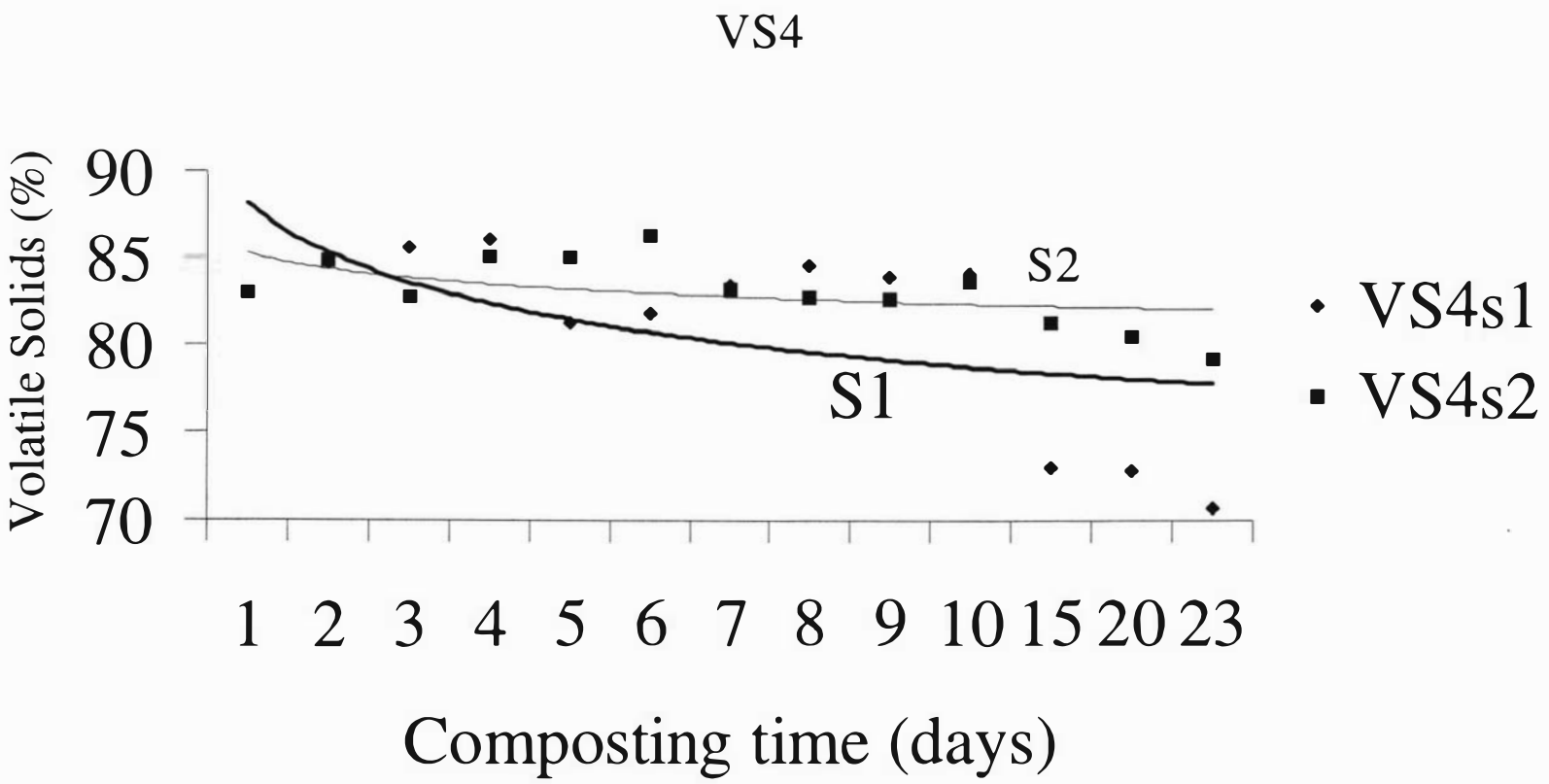


Figure 4.3 **Changes in Volatile solids content during composting in fourth trial at positions S1 and S2**

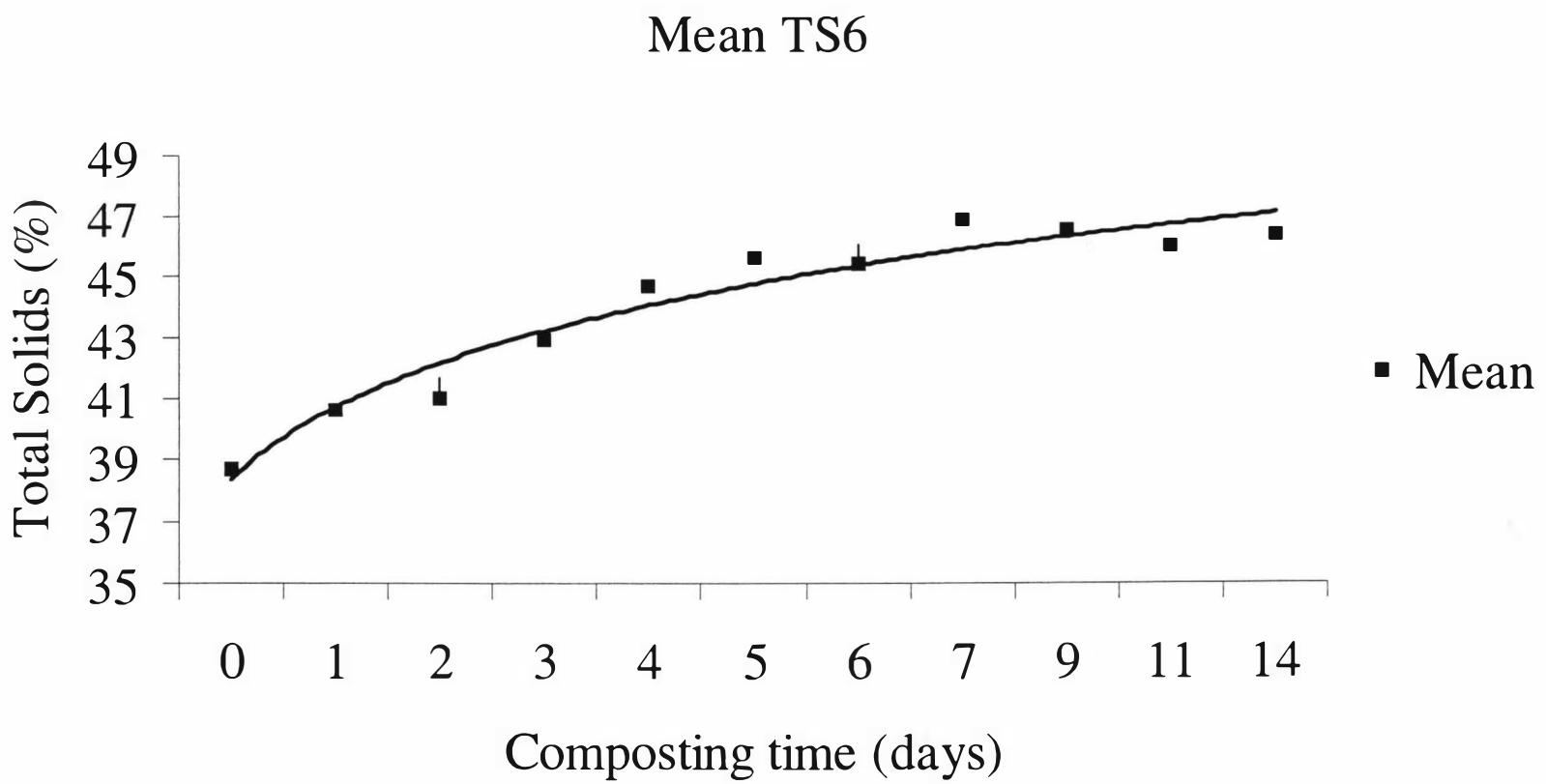


Figure 4.4 Changes in Total solids content during composting in experiment 6

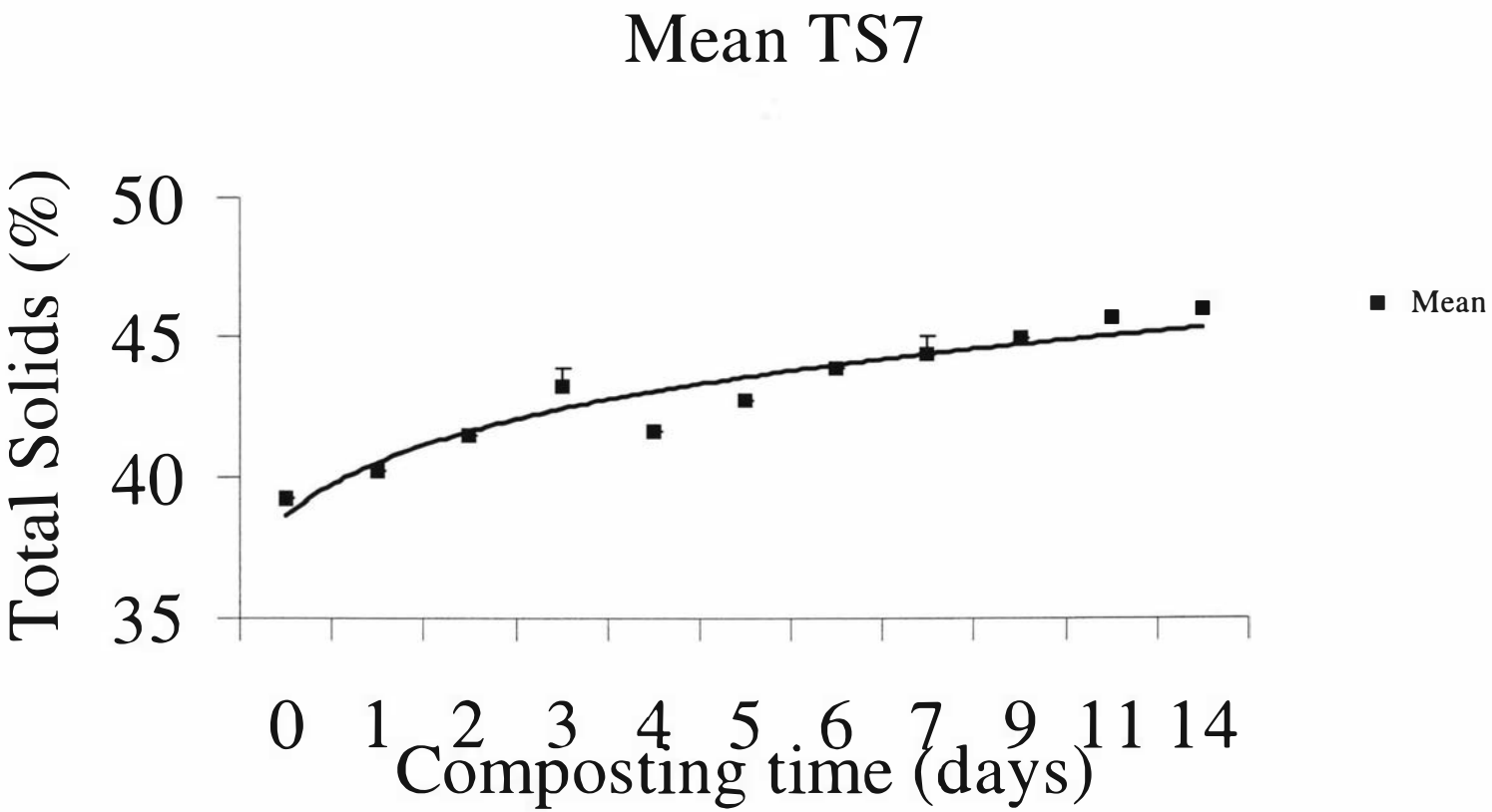


Figure 4.5 **Changes in Total solids content during composting in experiment 7**

4.1.3 Total Nitrogen

In trial1, the freshly screened solid consisted of about 15.8 mg/g total nitrogen. Using the bulk densities of piggery solid and sawdust, and the ratio of piggery solid and sawdust, the calculated value of total nitrogen in the composting mixture (ratio 50:50; solids:sawdust; v/v) on day 1 was 12.54 mg/g. The composting mixture total nitrogen changed to about 4.95mg/g and 6.68mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the calculated nitrogen content of 12.54 mg/g in freshly prepared mixture of piggery solids and sawdust, this amounted to approximately 39% and 53% conservation of nitrogen at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Nitrogen over time during first trial are shown in Appendix 3.

In trial 2, the freshly screened solid consisted of about 18.54 mg/g total nitrogen. Using the bulk densities of piggery solid and sawdust, and the ratio of piggery solid and sawdust, the calculated value of total nitrogen in the composting mixture (ratio 50:50; solids:sawdust; v/v) on day 1 was 14.71 mg/g. The composting mixture total nitrogen changed to about 11.28 mg/g and 9.28 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial nitrogen content of 14.71 mg/g in freshly prepared mixture of piggery solids and sawdust, this amounted to approximately 77% and 63% conservation of nitrogen at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Nitrogen over time during second trial are shown in Appendix 3.

In trial 3, the freshly screened solid consisted of about 16.52 mg/g total nitrogen. Using the bulk densities of piggery solid and sawdust, and the ratio of piggery solid and sawdust, the calculated value of total nitrogen in the composting mixture (ratio 50:50; solids:sawdust; v/v) on day 1 was 13.11 mg/g. The composting mixture total nitrogen changed to about 6.53 mg/g and 6.57 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial nitrogen content of 13.11 mg/g in freshly prepared mixture of piggery solids and sawdust, this amounted to approximately 50% conservation of nitrogen at the end of 21 days at both positions S1 and S2.

Changes in Total Nitrogen over time during third trial are shown in Appendix 3.

Freshly screened piggery solids consisted of approximately 17.5% total nitrogen before the fourth trial began. Using the bulk densities of piggery solid and sawdust, and the ratio of piggery solid and sawdust, the calculated value of total nitrogen in the composting mixture (ratio 75:25; solids:sawdust; v/v) on day 1 was 16.07 mg/g. The composting mixture total nitrogen changed to about 9.75 mg/g and 9.90 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial nitrogen content of 16.07 mg/g in freshly prepared mixture of piggery solids and sawdust, this amounted to approximately 61% and 62% conservation of nitrogen at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Nitrogen over time during the fourth trial are shown in Figure 4.6.

In trial 5, the freshly screened solid consisted of about 19.5 mg/g total nitrogen. Using the bulk densities of piggery solid and sawdust, and the ratio of piggery solid and sawdust, the calculated value of total nitrogen in the composting mixture (ratio 25:75; solids:sawdust; v/v) on day 1 was 10.97 mg/g. The composting mixture total nitrogen changed to about 5.88 mg/g and 5.26 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial nitrogen content of 10.97 mg/g in freshly prepared mixture of piggery solids and sawdust, this amounted to approximately 53% and 48% conservation of nitrogen at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Nitrogen over time during the fifth trial are shown in Appendix 3.

In laboratory study 6, the freshly screened solid consisted of about 15.7 mg/g total nitrogen. Using the bulk densities of piggery solid and sawdust, and the ratio of piggery solid and sawdust, the calculated value of total nitrogen in the composting mixture on day 0 was 14.45 mg/g. The composting mixture consisted about 7.97 mg/g total nitrogen at the end

of the composting experiment period. This amounted to approximately 44.84% change in total nitrogen content, or a total nitrogen conservation of about 55.16%.

Changes in Total Nitrogen over time during experiment 6 are shown in Figure 4.7.

In laboratory study 7, the freshly screened solid consisted of about 18.8 mg/g total nitrogen. Using the bulk densities of piggery solid and sawdust, and the ratio of piggery solid and sawdust, the calculated value of total nitrogen in the composting mixture on day 0 was 17.3 mg/g. The composting mixture consisted about 9.22 mg/g total nitrogen at the end of the composting experiment period. This amounted to approximately 46.70% change in total nitrogen content, or a total nitrogen conservation of about 53.30%.

Changes in Total Nitrogen over time during experiment 7 are shown in Figure 4.8.

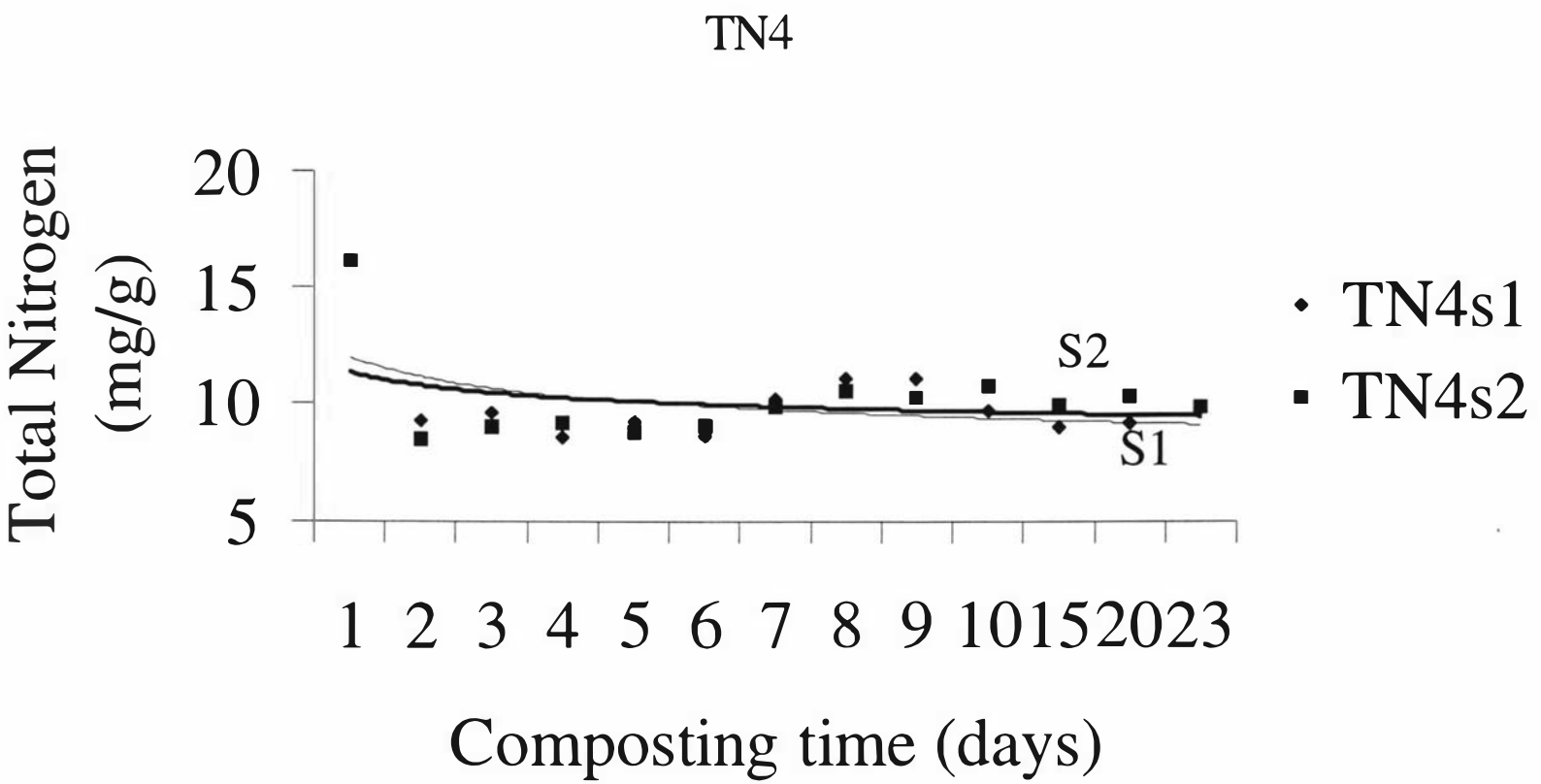


Figure 4.6 **Changes in Total Nitrogen contents during composting in fourth trial at positions S1 and S2**

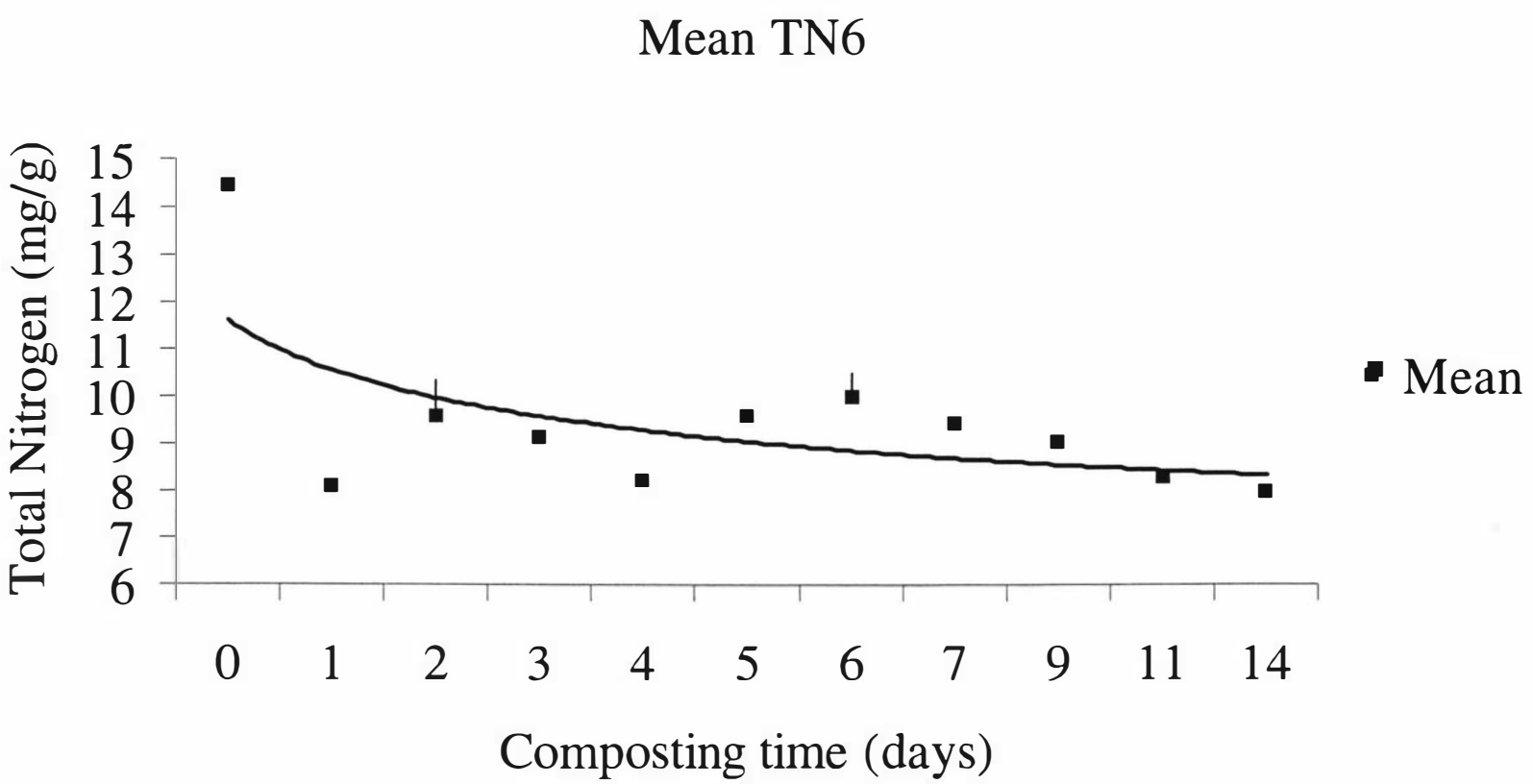


Figure 4.7 Changes in Total nitrogen content during composting in experiment 6

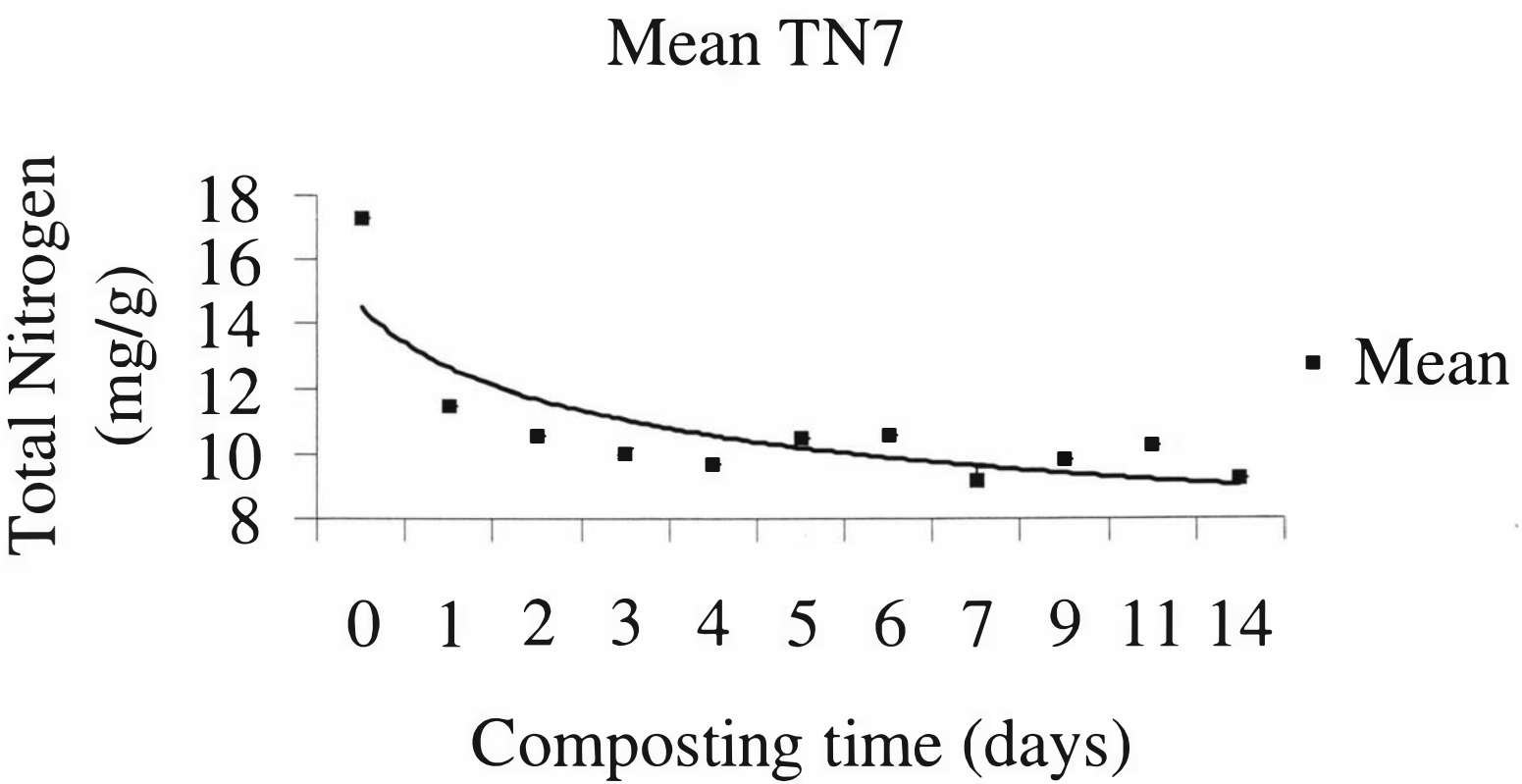


Figure 4.8 **Changes in Total nitrogen content during composting in experiment 7**

4.1.4 Total Phosphorus

Freshly prepared composting mixture consisted of 2.26 mg/g total phosphorus before the first trial began. The mixture total phosphorus changing to about 5 mg/g and 3.71 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial phosphorus content of 2.26 mg/g in freshly prepared mixture of piggery solid and sawdust, this amounted to approximately 116% and 61.3%increase and of phosphorus at the end of 21 days at positions S1 and S2, respectively.

Appendix 4 presents the changes in total phosphorus content over time in the first trial.

Before the second trial began, freshly prepared composting mixture consisted of approximately 3.69 mg/g total phosphorus . The mixture total phosphorus changing to about 5.89 mg/g and 4.96 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial phosphorus content of 3.69 mg/g in freshly prepared mixture of piggery solid and sawdust, this amounted to approximately 59 % and 34.42 %increase and of phosphorus at the end of 21 days at positions S1 and S2, respectively.

Appendix 4 presents the changes in Total Phosphorus content over time in the second trial.

Freshly prepared composting mixture consisted of approximately 3.93 mg/g total phosphorus before the third trial began. The mixture total phosphorus changing to about 3.96 mg/g and 3.86 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial phosphorus content of 3.93 mg/g in freshly prepared mixture of piggery solid and sawdust, this amounted to approximately 0.80 % increase and 3.30% decrease of phosphorus at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Phosphorus content over time in trial three are presented in Appendix 4.

Before the fourth trial began, freshly prepared composting mixture consisted of approximately 4.65 mg/g total phosphorus . The mixture total phosphorus changing to about 5.16 mg/g and 5.19 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial phosphorus content of 4.65 mg/g in freshly prepared mixture of piggery solid and sawdust, this amounted to approximately 10.97% and 11.61 %increase and of phosphorus at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Phosphorus content over time in fourth trial are presented in Figure 4.9.

In the fifth trial, freshly prepared composting mixture consisted of approximately 2.24 mg/g total phosphorus . The mixture total phosphorus changing to about 2.29 mg/g and 3.14 mg/g at S1 and S2, respectively at the end of active composting of 21 days. Based on the initial phosphorus content of 2.24 mg/g in freshly prepared mixture of piggery solid and sawdust, this amounted to approximately 2.23% and 40 %increase and of phosphorus at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Phosphorus content over time in the fifth trial are presented in Appendix 4.

In the laboratory experiment 6, freshly prepared composting mixture consisted of approximately 4.26 mg/g total phosphorus . The mixture total phosphorus changing to about 5.32 mg/g at the end of composting period. Based on the initial phosphorus content of 4.26 mg/g in freshly prepared mixture of piggery solid and sawdust, this amounted to approximately 24.88% increase of phosphorus at the end of composting operation. The freshly screened piggery solids had

Changes in Total Phosphorus content over time in experiment 6 are presented in Figure 4.10.

In the laboratory experiment 7, freshly prepared composting mixture consisted of approximately 4.51 mg/g total phosphorus . The mixture total phosphorus changing to about 5.74 mg/g at the end of composting period. Based on the initial phosphorus content

of 4.51 mg/g in freshly prepared mixture of piggery solid and sawdust, this amounted to approximately 27.27% increase of phosphorus at the end of composting operation.

Changes in Total Phosphorus content over time in experiment 7 are presented in Figure 4.11.

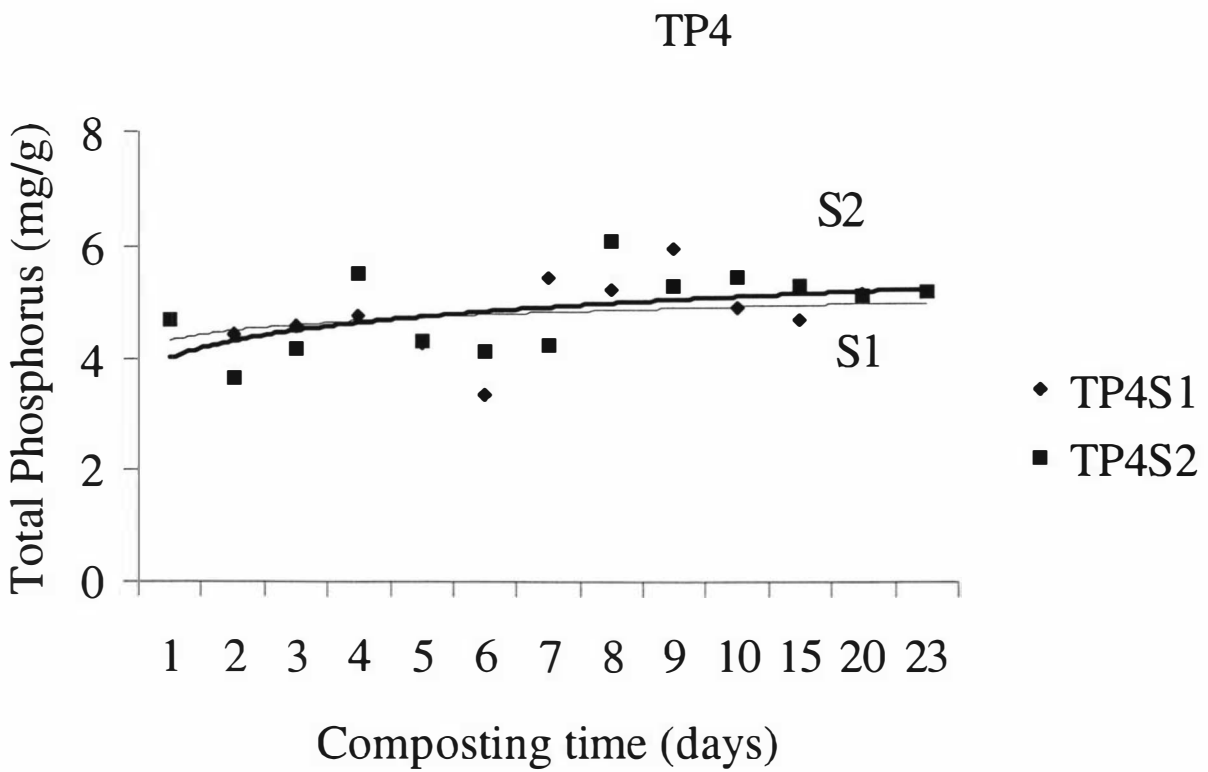


Figure 4.9 **Changes in Total Phosphorus contents during composting in fourth trial at positions S1 and S2**

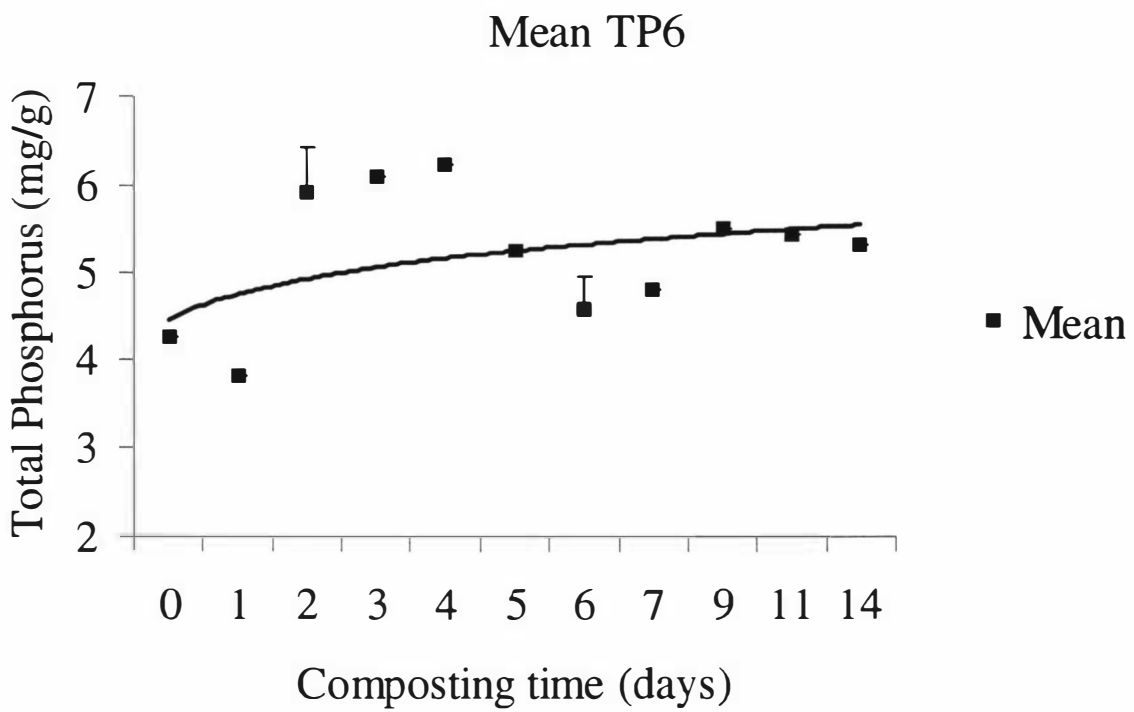


Figure 4.10 Changes in Total phosphorus content during composting in experiment 6

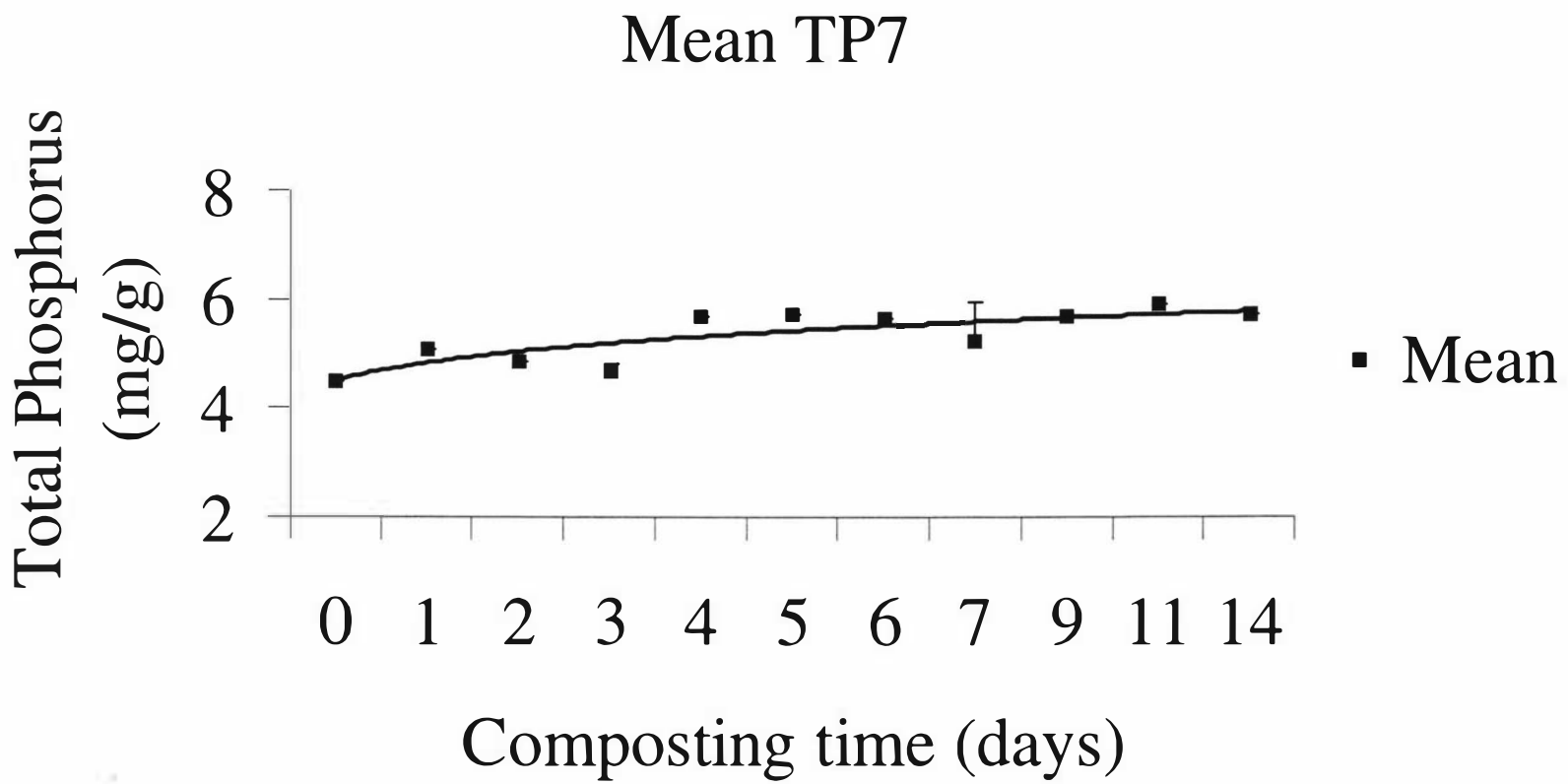


Figure 4.11 Changes in Total phosphorus content during composting in experiment 7

4.1.5 Total Organic Carbon

In the first trial, the composting mixture consisted of about 55.73% TOC initially, changing to about 53.80% and 56.31% at the end of active composting of 21 days at S1and S2, respectively. This amounted to approximately 4% loss and 1% gain of TOC at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Organic Carbon over time during the first trial are shown in Appendix 5.

The composting mixture in the second trial consisted of about 55.76% TOC initially, changing to about 51.6% and 49.14% at the end of active composting of 21 days at S1and S2, respectively. This amounted to approximately 7.5% and 12% loss of TOC at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Organic Carbon over time during the second trial are shown in Appendix 5.

In the third trial, the composting mixture consisted of about 51.91% TOC initially, changing to about 50.2% and 51% at the end of active composting of 21 days at S1and S2, respectively. This amounted to approximately 3.4% and 1.7% loss of TOC at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Organic Carbon over time during this trial are shown in Appendix 5.

The composting mixture in the fourth trial consisted of about 52.58% TOC initially. This changed to about 41.13% and 43.24% at the end of active composting of 21 days at S1and S2, respectively. This amounted to approximately 21% and 17% loss of TOC at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Organic Carbon over time during the fourth trial, as a typical example, are shown in Figure 4.12.

In the fifth trial, the composting mixture consisted of about 50.73% TOC initially, changing to about 49.53% and 50.58% at the end of active composting of 21 days at S1and S2, respectively. This amounted to approximately 2.4% and 0.3% loss of TOC at the end of 21 days at positions S1 and S2, respectively.

Changes in Total Organic Carbon over time during the fifth trial are shown in Appendix 5.

In the laboratory experiment 6, freshly prepared composting mixture consisted of approximately 54.36% total organic carbon . The mixture total organic carbon changing to about 46.97% at the end of composting period. This amounted to approximately 14.60% loss of TOC at the end of composting operation.

Changes in total organic carbon content over time in experiment 6 are presented in Figure 4.13.

In the laboratory experiment 7, freshly prepared composting mixture consisted of approximately 57.06% total organic carbon . The mixture total organic carbon changing to about 44.29% at the end of composting period. This amounted to approximately 22.38% loss of TOC at the end of composting operation.

Changes in total organic carbon content over time in experiment 7 are presented in Figure 4.14.

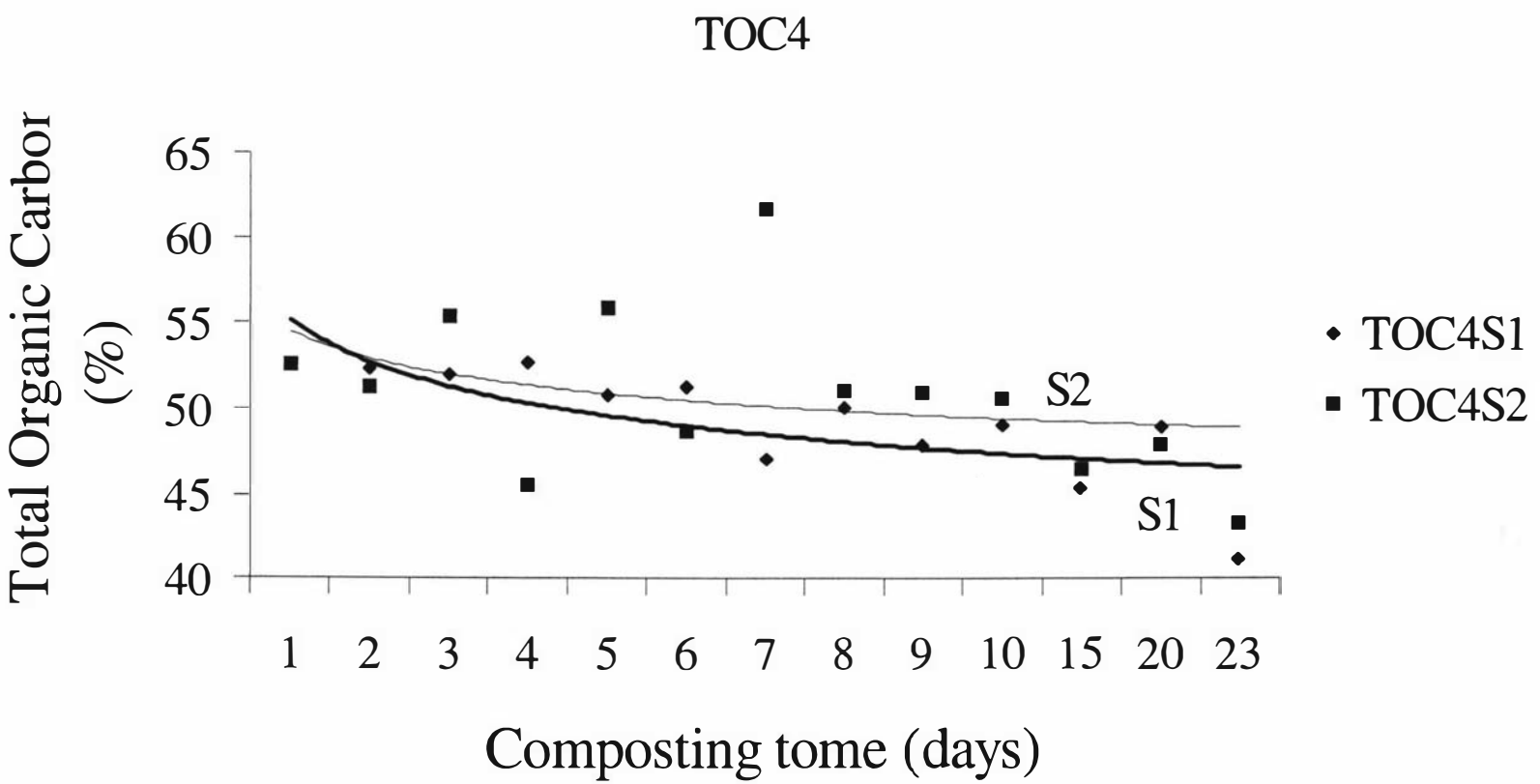


Figure 4.12 Changes in Total Organic Carbon content during composting in fourth trial at positions S1 and S2

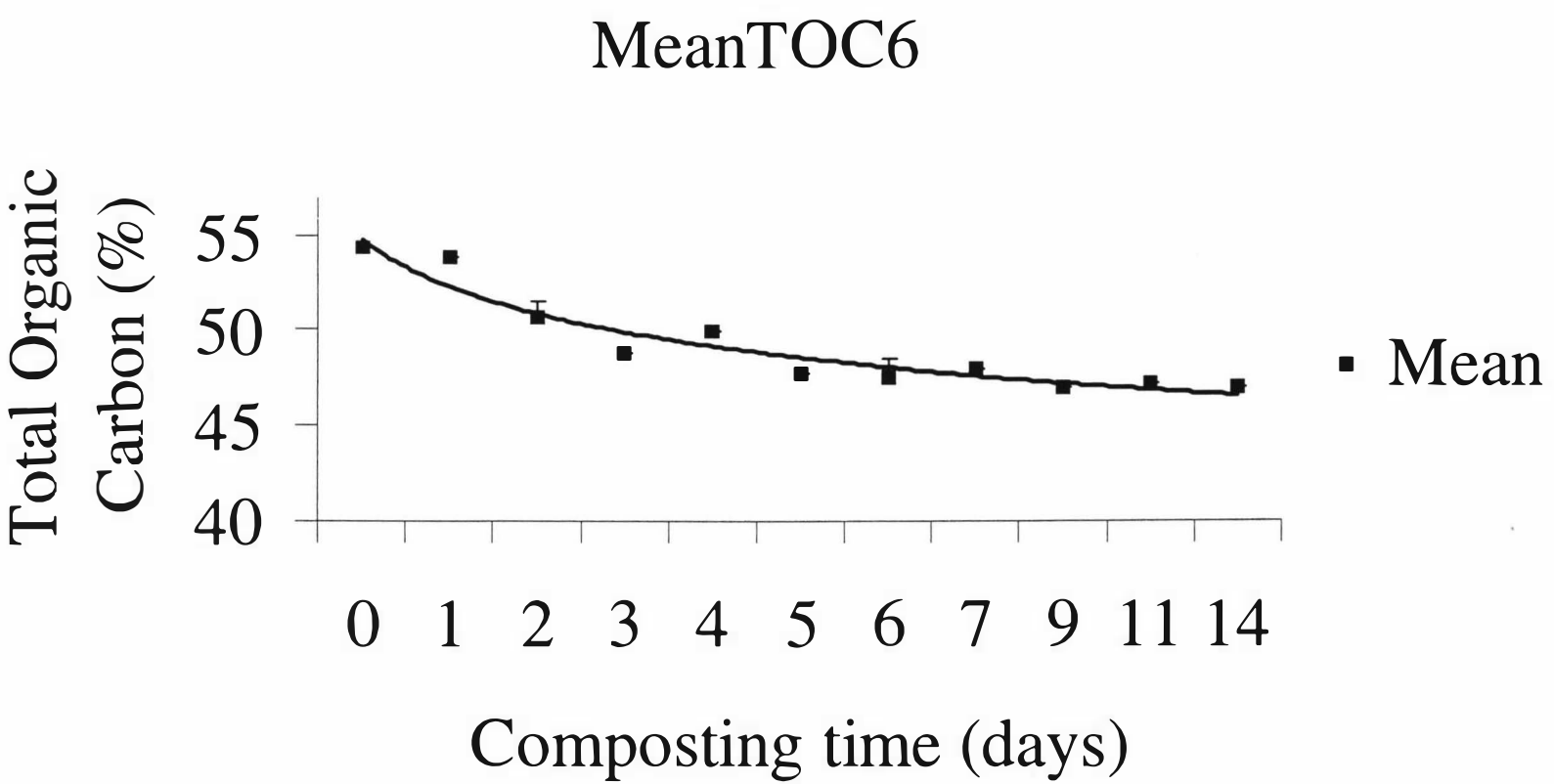


Figure 4.13 Changes in Total Organic Carbon content during composting in experiment 6

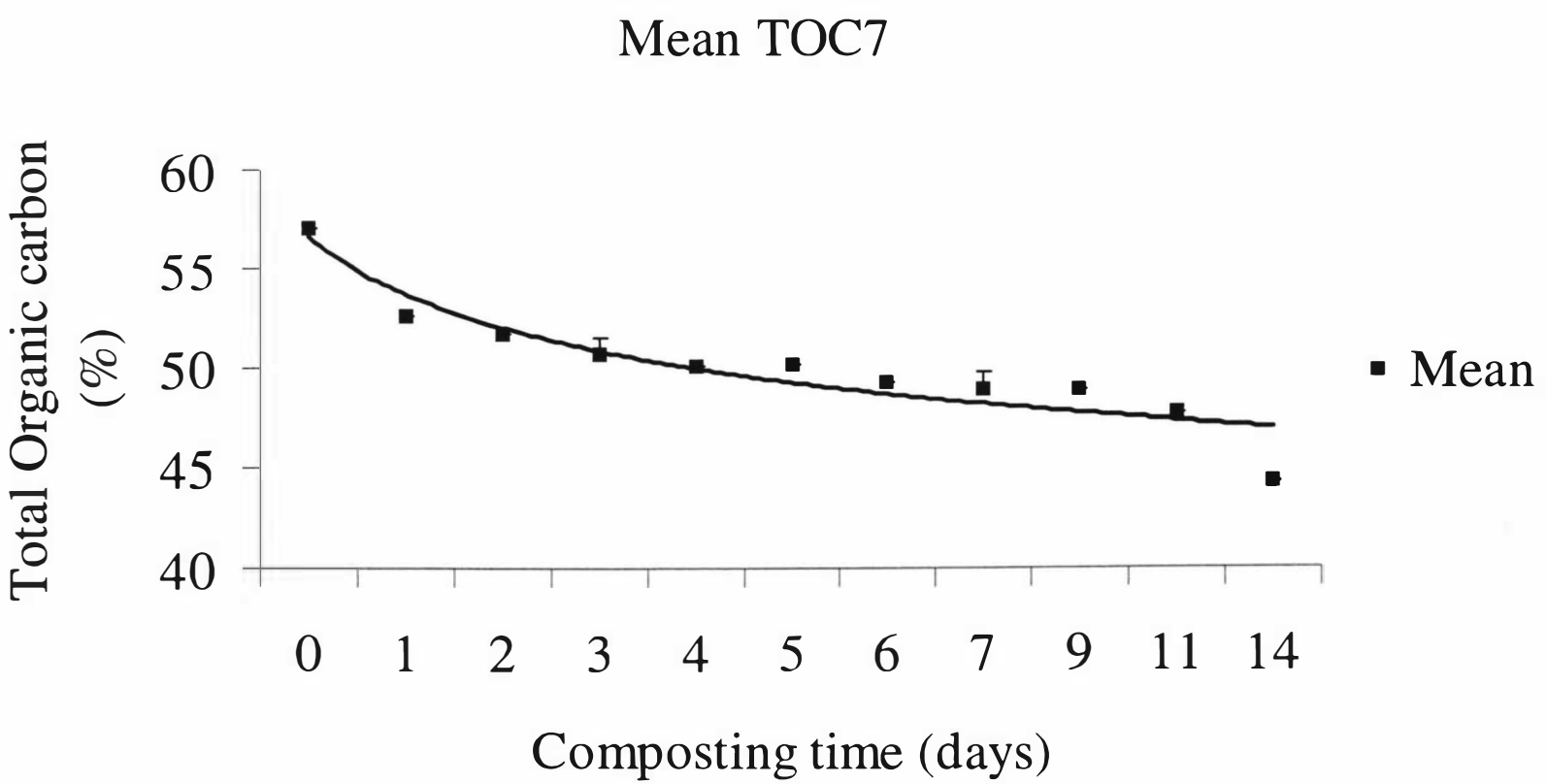


Figure 4.14 Changes in Total Organic Carbon content during composting in experiment 7

4.1.6 pH

Appendix 6 presents the changes in pH values over time in the first trial. The composting mixture had a pH value of 7.74 initially, changing to about 6.68 and 6.58 at the end of active composting of 21 days at S1and S2, respectively.

In the second trial, the composting mixture had a pH value of 6.93 initially, changing to about 7.15 and 6.91 at the end of active composting of 21 days at S1and S2, respectively. In other words, pH remained unchanged in most of the heap during the trial.

Appendix 6 presents the changes in pH values over time in the second trial.

The composting mixture in the third trial had a pH value of 7.00 initially, changing to about 6.20 and 7.00 at the end of active composting of 21 days at S1and S2, respectively.

The changes in pH values over time in the third trial are presented in Appendix 6.

In the fourth trial, the composting mixture had a pH value of 7.40 initially, changing to about 7.10 and 7.20 at the end of active composting of 21 days at S1and S2, respectively.

Changes in pH values over time in the fourth trial are shown in Figure 4.15.

In the fifth trial, the composting mixture had a pH value of 6.70 initially, changing to about 5.80 and 5.70 at the end of active composting of 21 days at S1and S2, respectively.

The changes in pH values over time in trial five are presented in Appendix 6.

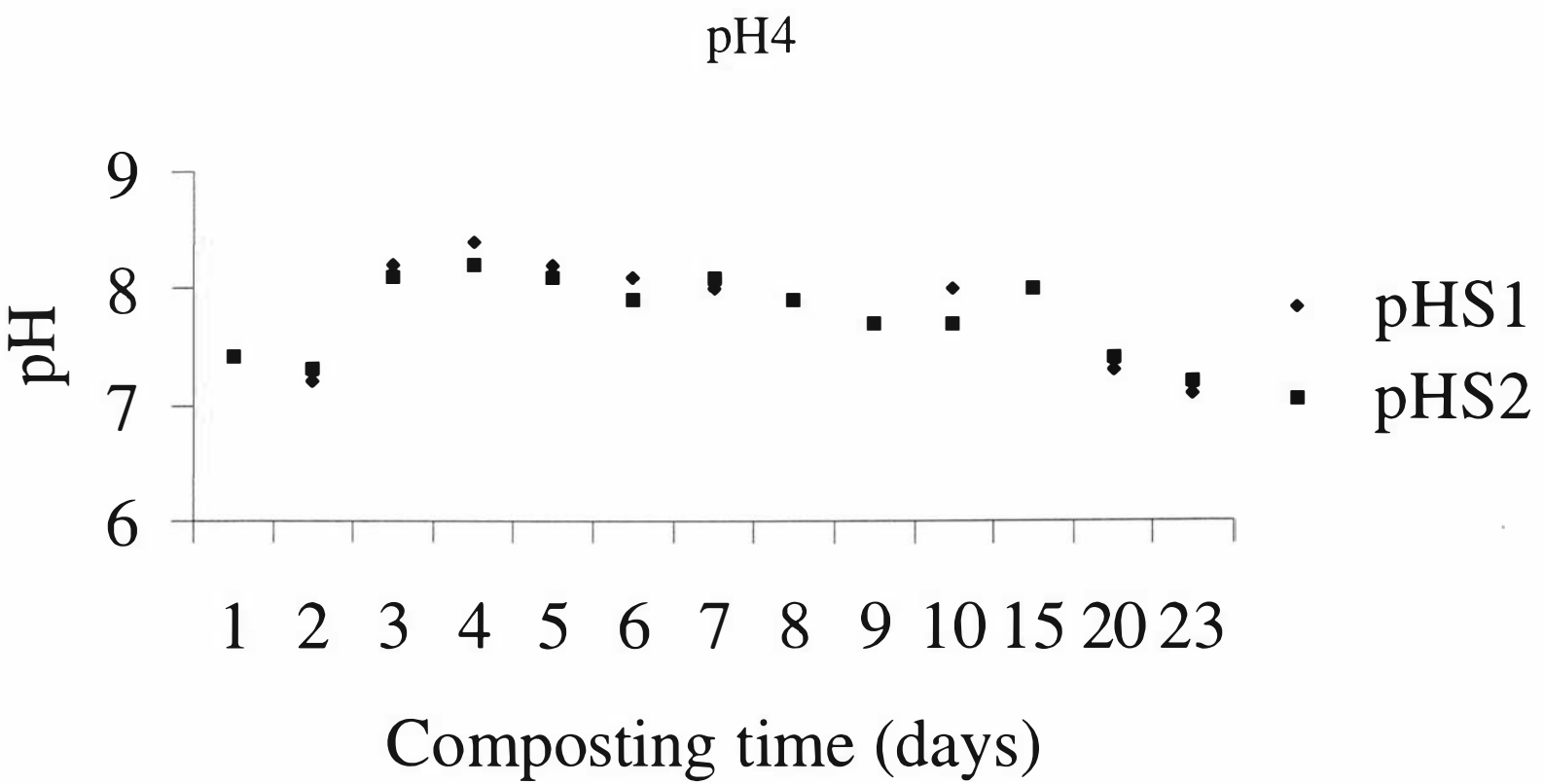


Figure 4.15 Changes in pH values during composting in fourth trial at positions S1 and S2

4.1.7 Microbiological counts

The composting mixture in the first trial consisted of about 7E+06 microbes of coliform group and 4.8E+5 streptococci initially, changing to about 1.3E+4 and 400,respectively at the end of active composting of 21 days at S1. This represents approximately 2 orders of magnitude loss in coliform and streptococci counts.

Changes in the coliform group of bacteria expressed as Most probable Number over time, and the counts of enteric streptococci (Group D) over time at position S1 in trial one are presented in Appendix 7.

The composting mixture consisted of about 7E+06 microbes of coliform group and 4.8E+5 streptococci initially, changing to about 9.2E+5 and 4.2E+4, respectively at the end of active composting of 21 days at S2. This represents approximately 1 order of magnitude decrease in coliform and streptococci numbers.

Changes in the coliform group of bacteria expressed as Most Probable Number over time; and the counts of enteric streptococci (Group D) over time at position S2 in trial 1 are presented in Appendix 8.

In the second trial, the composting mixture consisted of about 1.7E+7 microbes of coliform group and 3.0E+6 streptococci initially, changing to about 3.5E+4 and 3.1E+4, respectively at the end of active composting of 21 days at S1. This represents approximately 3 orders of magnitude loss in coliform and 2 orders of magnitude loss in streptococci counts, respectively.

Changes in the coliform group of bacteria expressed as Most Probable Number over time; and the counts of enteric streptococci (Group D) over time at position S1 in trial 2 are presented in Appendix 7.

The composting mixture consisted of about 1.7E+07 microbes of coliform group and

3.0E+6 streptococci initially, changing to about 5.4E+4 and 2.0E+3, respectively at the end of active composting of 21 days at S2. This represents approximately 3 orders of magnitude loss in coliform and streptococci numbers at S2.

Appendix 8 presents changes in the coliform group of bacteria expressed as Most Probable Number over time; and the counts of enteric streptococci (Group D) over time at position S2 in trial 2.

In the third trial, the composting mixture consisted of about 1.7E+7 microbes of coliform group and 6.5E+5 streptococci initially, changing to about 1.6E+4 and 90, respectively at the end of active composting of 21 days at S1. This represents approximately 3 orders of magnitude loss in coliform and 4 orders of magnitude loss in streptococci counts, respectively.

These Changes in the coliform group of bacteria expressed as Most Probable Number over time; and the counts of enteric streptococci (Group D) over time at position S1 in trial 3 are presented in Appendix 7.

In the third trial, the composting mixture consisted of about 1.7E+07 microbes of coliform group and 3.0E+6 streptococci initially, changing to about 3.3E+4 and 1.0E+4, respectively at the end of active composting of 21 days at S2. This represents approximately 2 orders of magnitude loss in coliform and streptococci numbers, respectively.

The changes in the coliform group of bacteria expressed as Most Probable Number over time; and the counts of enteric streptococci (Group D) over time at position S2 in trial 3 are presented in Appendix 8.

For the fourth trial, the composting mixture consisted of about 4.9E+6 microbes of coliform group and 8.5E+5 streptococci initially, changing to about 2.0E+1 and 1.1E+1, respectively at the end of active composting of 21 days at S1. This represents approximately 5 orders of magnitude loss in coliform and 4 orders of magnitude loss in streptococci counts, respectively.

Changes in the coliform group of bacteria expressed as Most Probable Number over time; and the counts of enteric streptococci (Group D) over time at position S1 in trial four are presented in Figure 4.16.

At sampling point S2 in this trial, the composting mixture consisted of about 4.9E+06 microbes of coliform group and 8.5E+5 streptococci initially, changing to about 2.3E+3 and 4.0E+3, respectively at the end of active composting of 21 days. This represents approximately 3 orders of magnitude loss in coliform and 2 orders of magnitude loss in streptococci numbers, respectively.

Changes in the coliform group of bacteria expressed as Most Probable Number over time and the counts of enteric streptococci (Group D) over time at position S2 in trial four are presented in Figure 4.17.

In the fifth trial, the composting mixture consisted of about 7.9E+6 microbes of coliform group and 8.5E+5 streptococci initially, changing to about 1.3E+5 and 3.2E+3, respectively at the end of active composting of 21 days at S1. This represents approximately 1 orders of magnitude loss in coliform and 2 orders of magnitude loss in streptococci counts, respectively. Significantly though, large number of coliform and streptococci survived.

Changes in the coliform group of bacteria expressed as Most Probable Number over time and the counts of enteric streptococci (Group D) over time at position S1 in the fifth trial are presented in Appendix 7.

At S2, the composting mixture consisted of about 7.9E+06 microbes of coliform group and 8.5E+5 streptococci initially, changing to about 1.7E+6 and 2.6E+3, respectively at the end of active composting of 21 days. Similar to S1, this represents approximately 2 orders of magnitude loss in streptococci numbers but no order of magnitude reduction in coliform, resulting in the survival of large number of coliform and streptococci.

Appendix 8 presents changes in the coliform group of bacteria expressed as Most Probable Number over time; and the counts of enteric streptococci (Group D) over time at position

S2 in trial five.

In laboratory experiment 6, the composting mixture consisted of about 1.3E+9 total coliforms, changing to about 0.2 at the end of composting operation. This represents approximately 10 orders of magnitude change in total coliform counts. The faecal coliforms changed from 7.90E+08 to about 0.1 at the end of the composting operation representing a approximately 9 orders of magnitude change. The *E.coli* counts changed from 2.70E+08 to about 0.1, again representing approximately 9 orders of magnitude change. The number of enterococci changed from 1.30E+6 to about0.2 at the end of the composting operation, representing approximately 7 orders of magnitude change.

Changes in the total coliform group of bacteria expressed as Most Probable Number over time; in experiment 6 are presented in Figure 4.18.

Changes in faecal coliform expressed as Most Probable Number over time; in experiment 6 are presented in Figure 4.19.

Changes in the E. coli expressed as Most Probable Number over time; in experiment 6 are presented in Figure 4.20.

Changes in enterococci numbers expressed over time in experiment 6 are presented in Figure 4.21.

In laboratory experiment 7, the change in total coliforms, faecal coliforms, and *E.coli* followed the same trend as in laboratory experiment 6, representing a change of 10, 9, and 9 orders of magnitude, respectively. The number of enterococci changed from 2.70E+05 to about 0.2 at the end of the composting operation, representing approximately 6 orders of magnitude change.

Changes in the total coliform group of bacteria expressed as Most Probable Number over time; in experiment 7 are presented in Figure 4.22.

Changes in faecal coliform expressed as Most Probable Number over time; in experiment 7 are presented in Figure 4.23.

Changes in the E. coli expressed as Most Probable Number over time; in experiment 7 are presented in Figure 4.24.

Changes in enterococci numbers expressed over time in experiment 6 are presented in Figure 4.25.

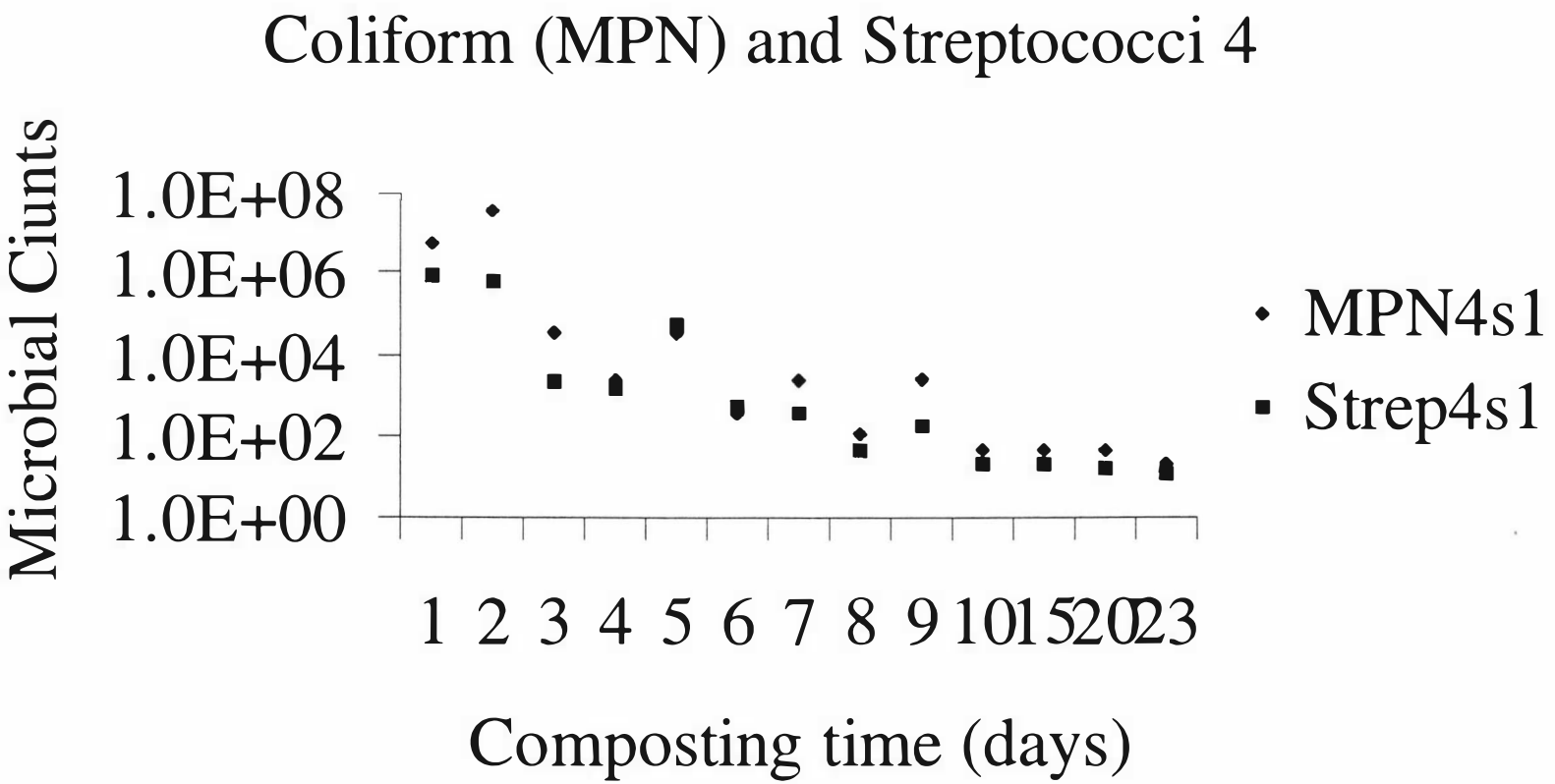


Figure 4.16 Changes in coliform (MPN) and streptococci counts during composting in fourth trial at positions S1

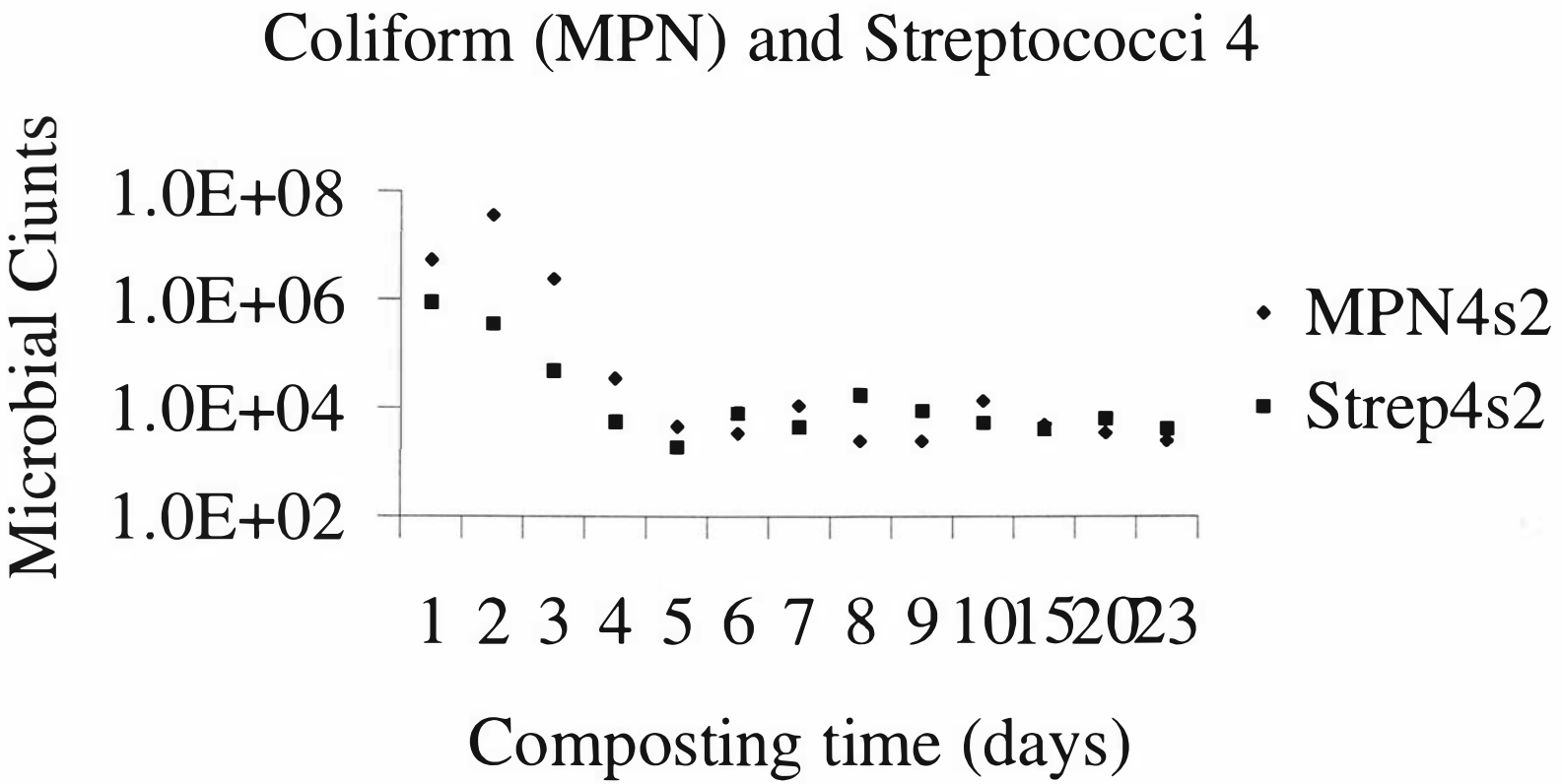


Figure 4.17 Changes in coliform (MPN) and streptococci counts during composting in fourth trial at positions S2

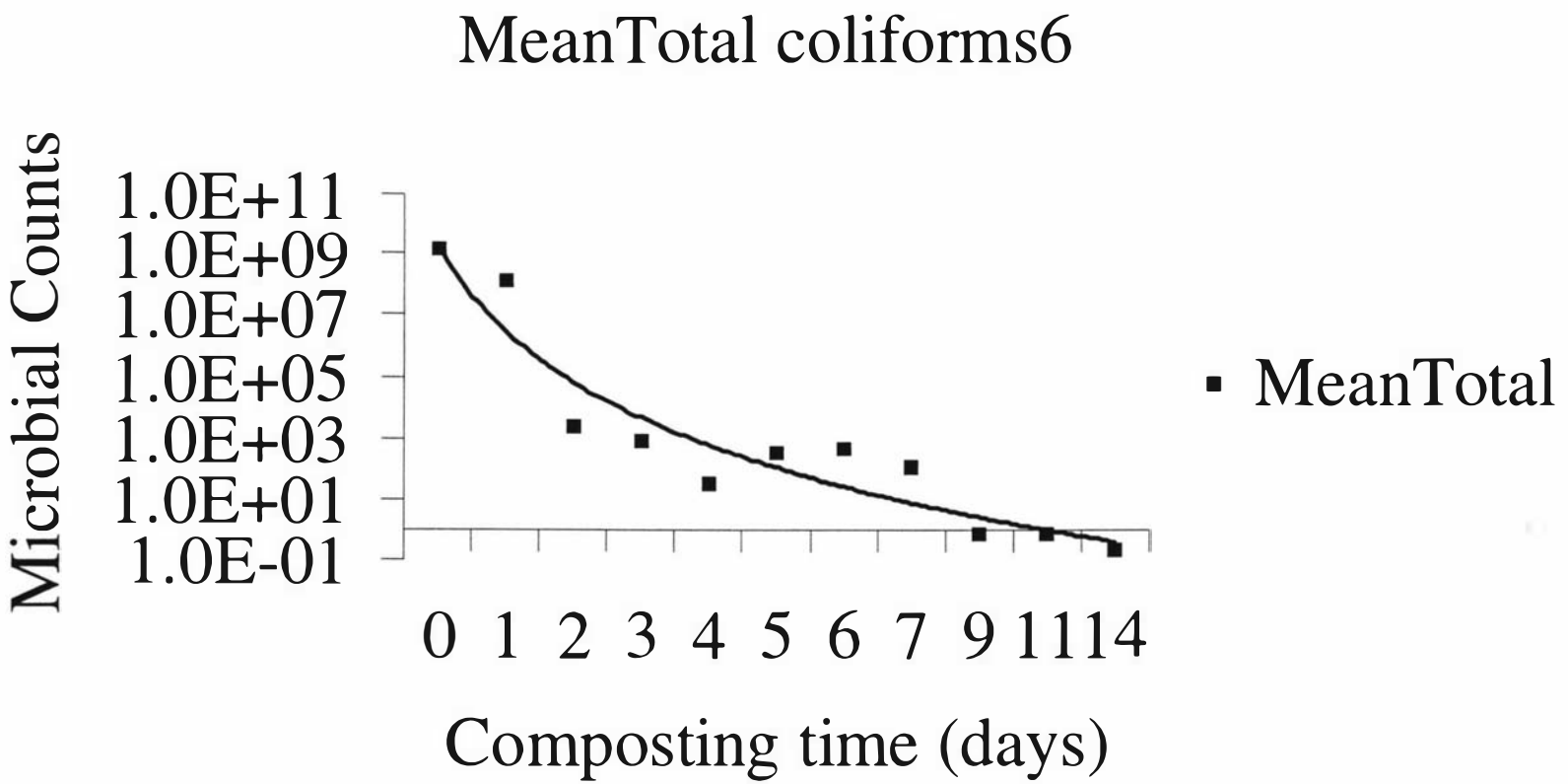


Figure 4.18 Changes in total coliform (MPN) during composting in experiment 6

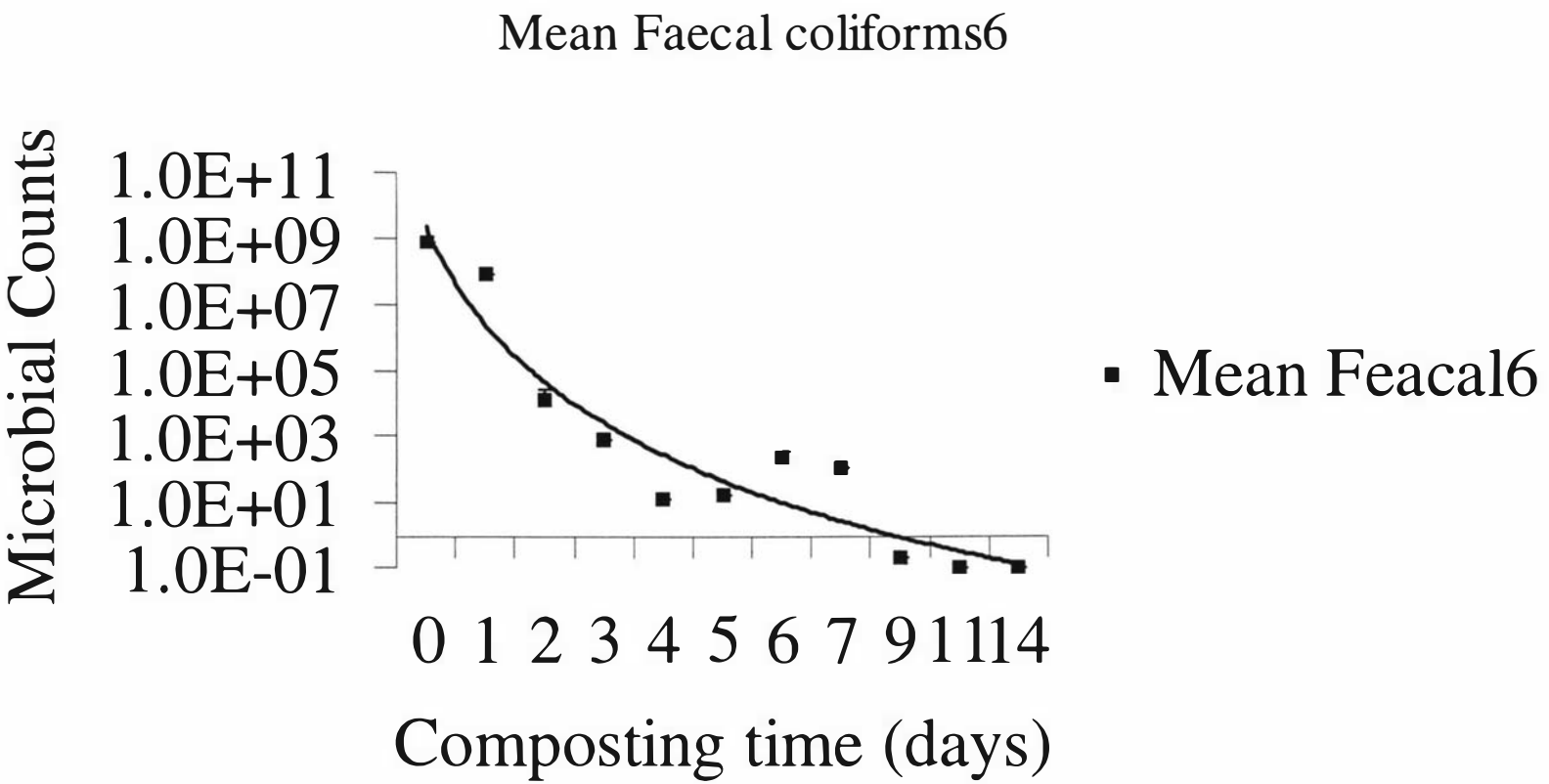


Figure 4.19 Changes in faecal coliform (MPN) during composting in experiment 6

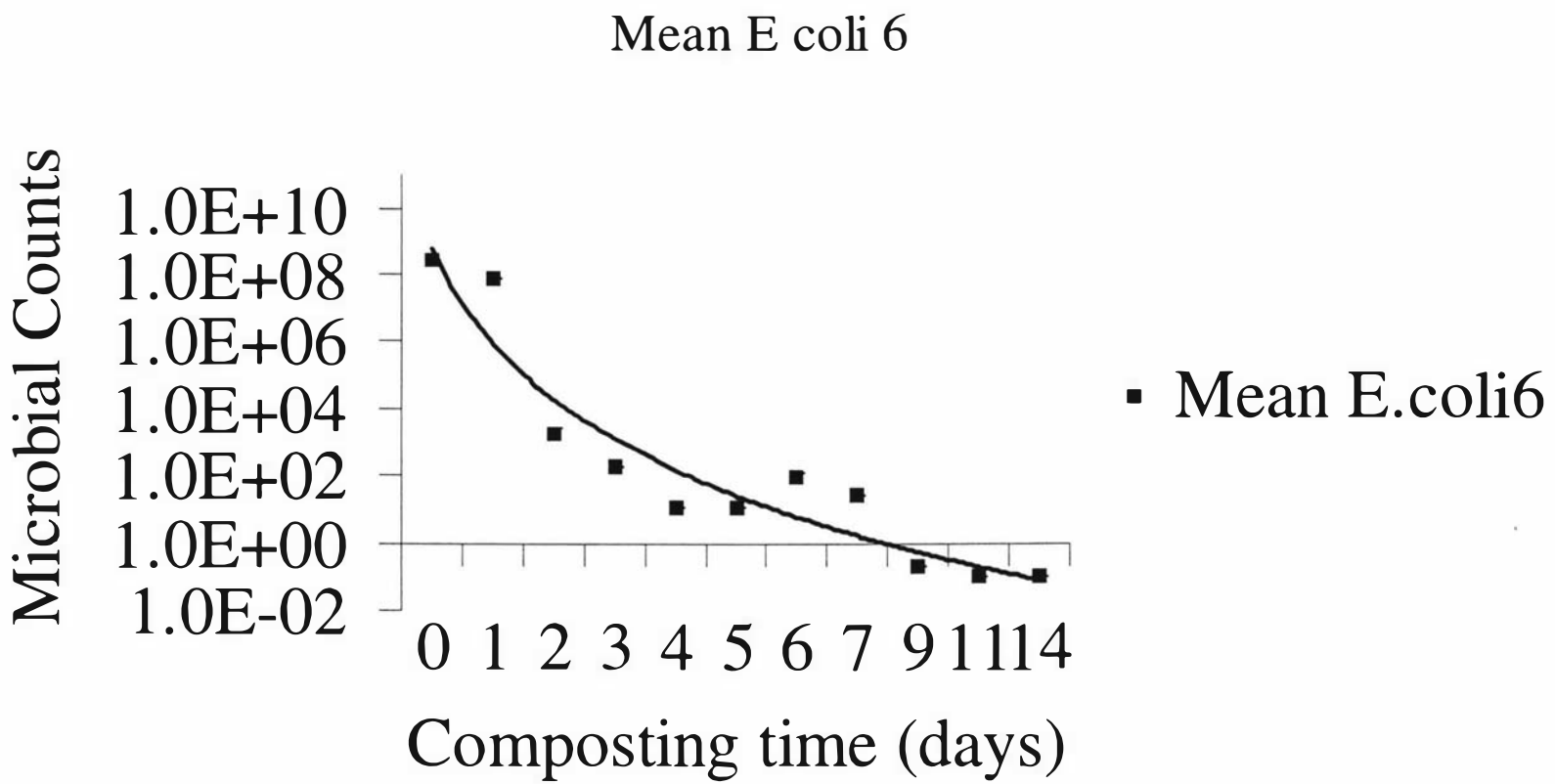


Figure 4.20 Changes in *E.coli* (MPN) during composting in experiment 6

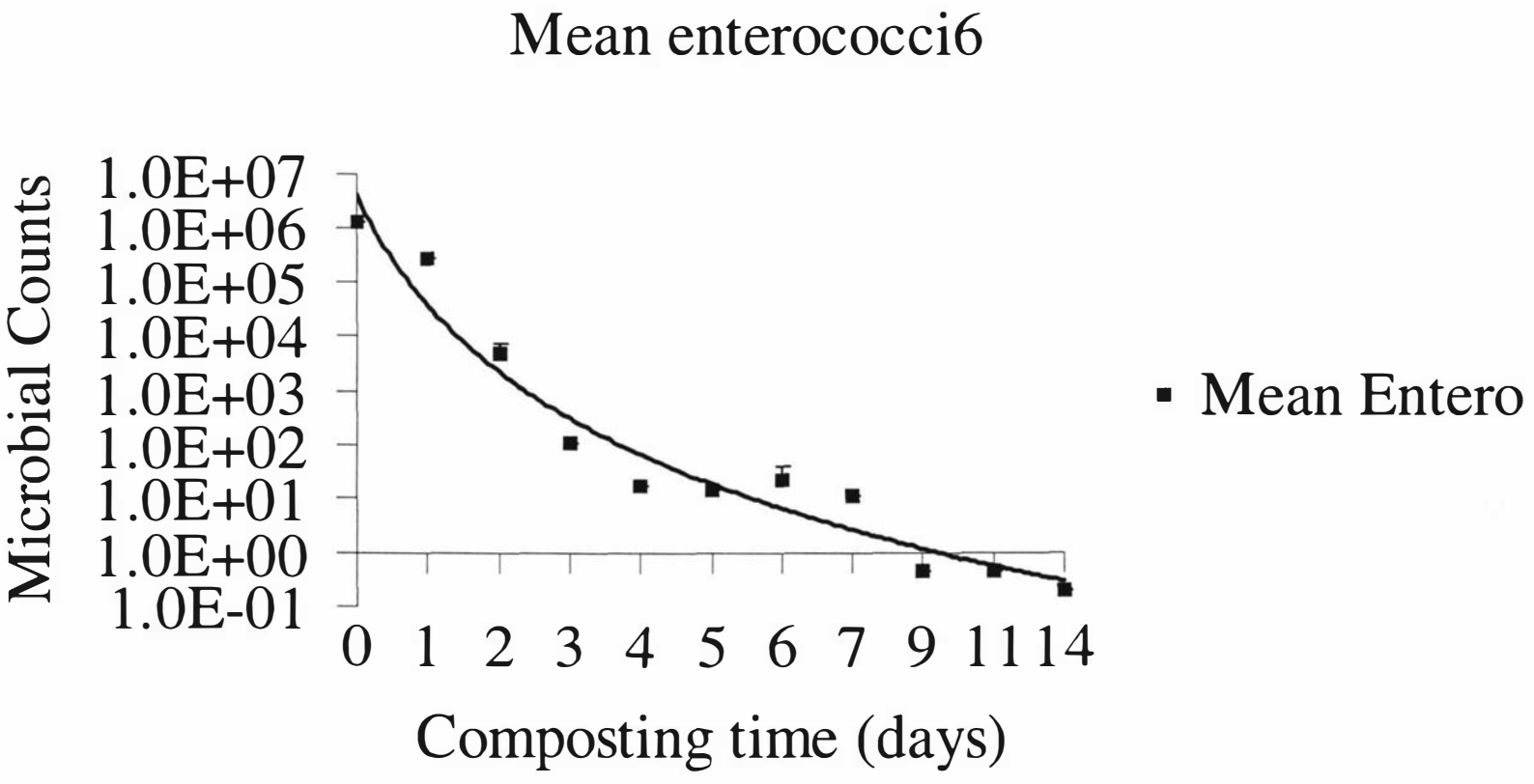


Figure 4.21 Changes in enterococci numbers during composting in experiment 6

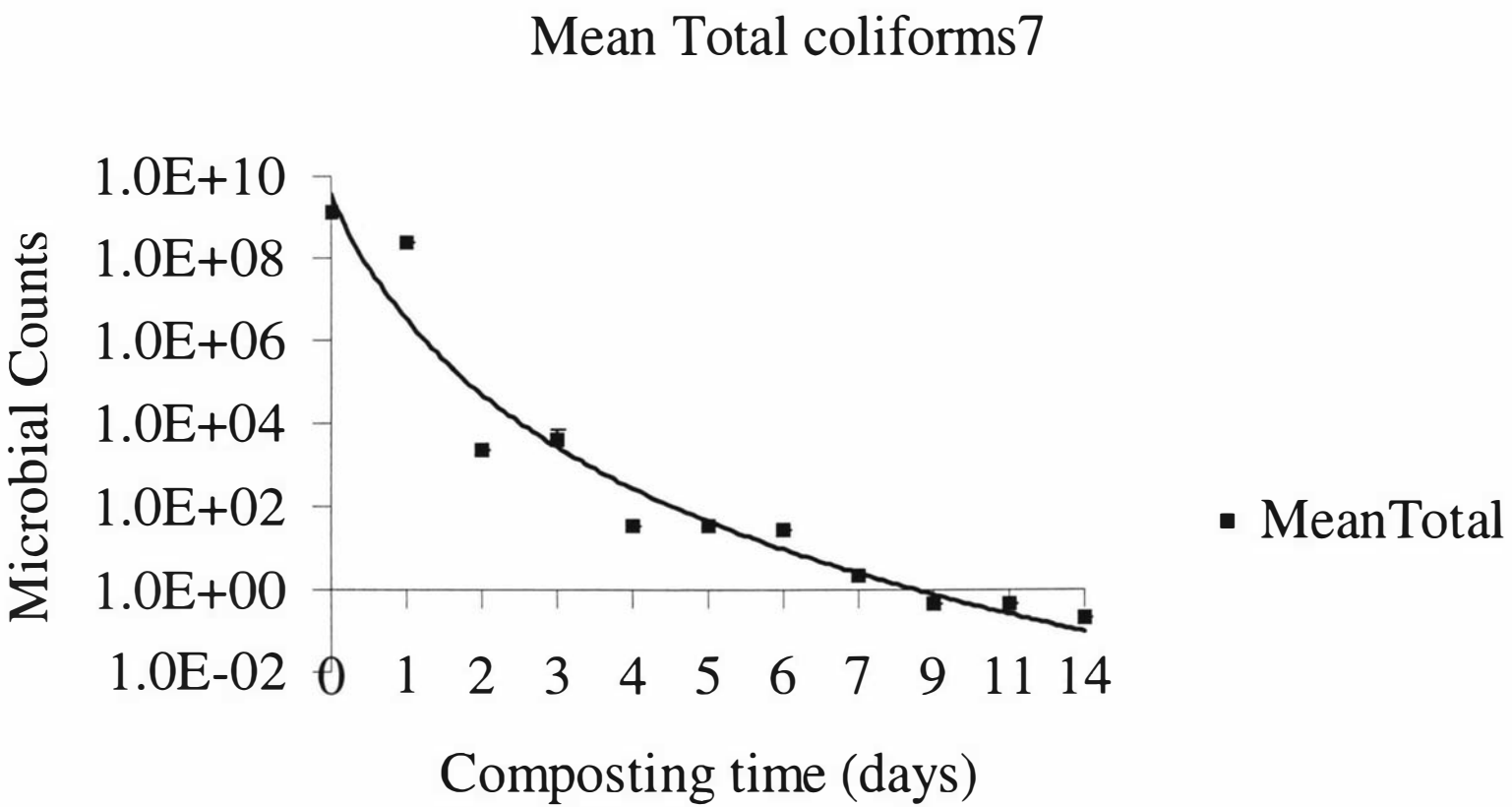


Figure 4.22 Changes in total coliforms (MPN) during composting in experiment 7

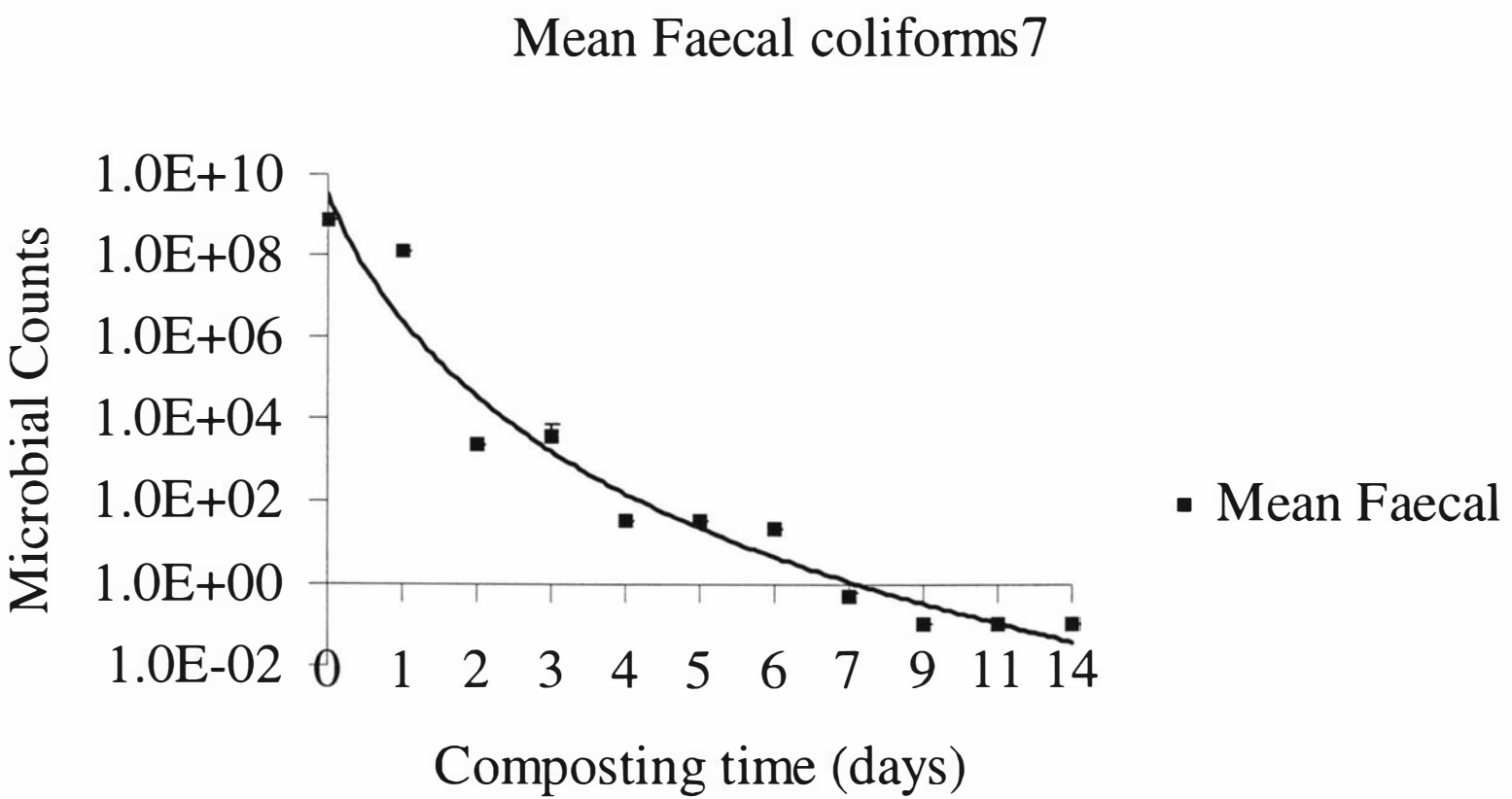


Figure 4.23 Changes in faecal coliforms (MPN) during composting in experiment 7

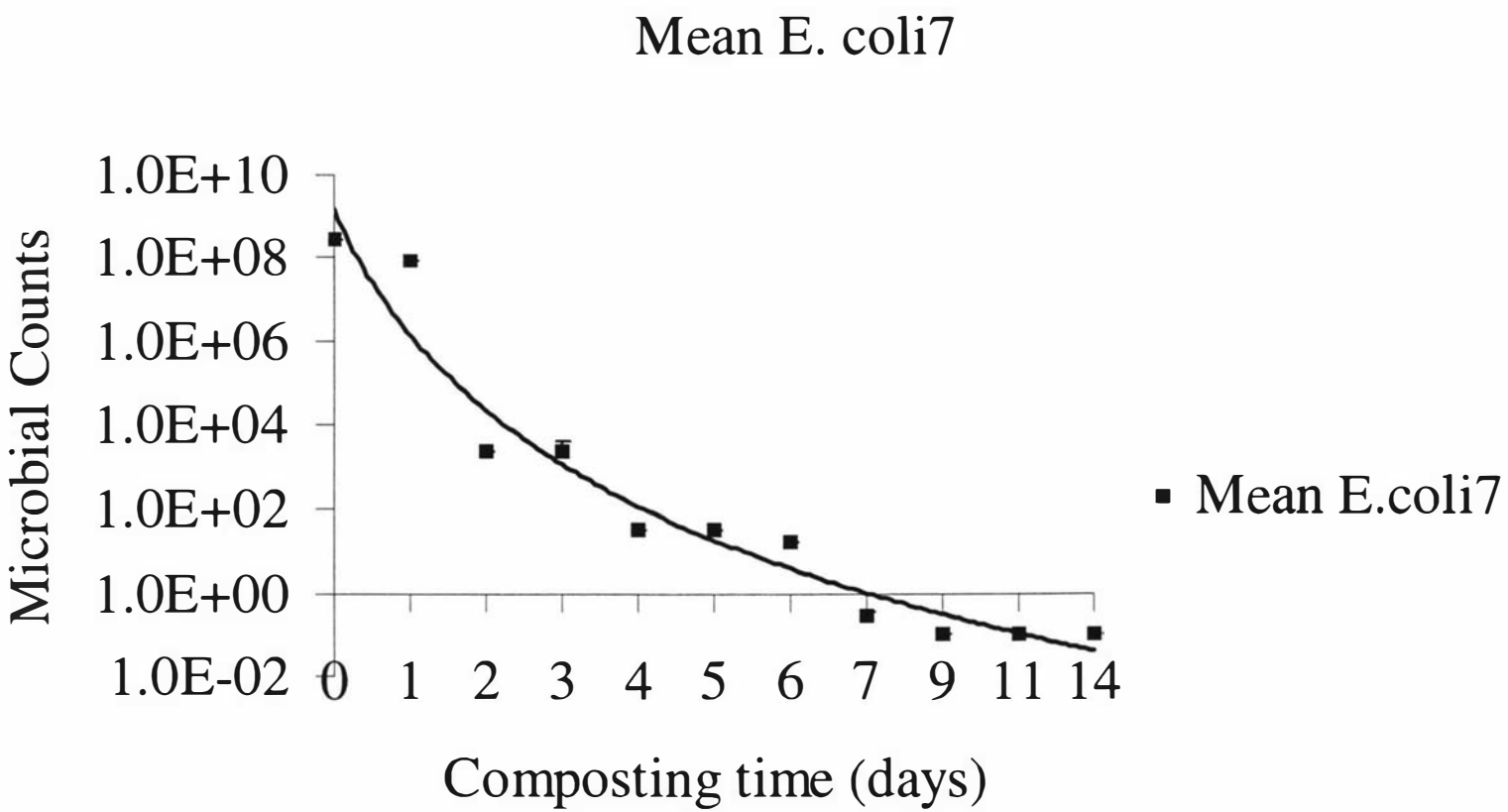


Figure 4.24 Changes in E. coli (MPN) during composting in experiment 7

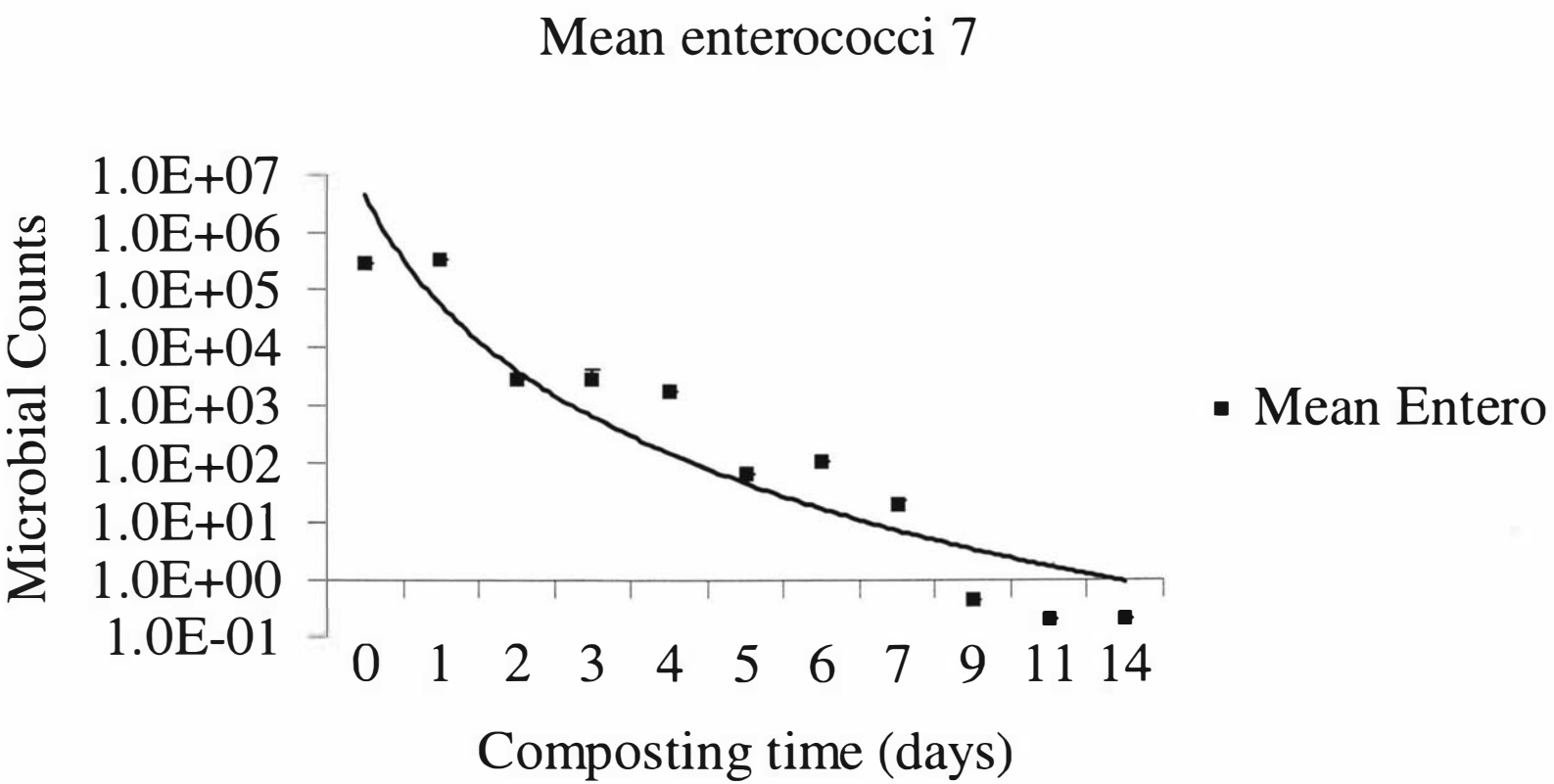


Figure 4.25 Changes in enterococci numbers during composting in experiment 7

4.2 Statistical analysis

The results obtained in each trial were subjected to a statistical analysis. The two way analysis of variance technique was used for this purpose and the calculated F values were compared with the tabulated F values at 95 and 99% levels of significance. The effects were considered to be significantly different if the calculated F values were equal or greater than the tabulated values.

In carrying out the statistical analysis it was assumed that the response at different positions as well as different time periods were independent of each other. Significance of the interaction term was also worked out wherever possible.

The statistical analysis was carried out using the SAS 6.11.

4.2.1 Data transformation

The data for the variables Coliform (MPN) and Streptococci were ln transformed, and hence the mean values in the text hereafter are transformed values of MPN and Streptococci.

Trial 1

Table 4. 1 presents the calculated F values and probability levels for various variables for trial 1. The Table reveals that the effects of positions (pooled over time periods) and time (pooled over positions) were found to be significantly different for the variable TS. However for VS, MPN, TN, TOC, and TP, all the effects were non-significantly different. Position and time effects for the variable Streptococci were also significantly different at 1% level of significance. The effect of time period on the pH levels was also highly significant.

Trial 2

Table 4.2 presents the calculated F values and probability levels for various variables for trial 2. The Table reveals that the effects of positions (over times) and time (over positions) were found to be highly significant for the variables TS, VS, and pH. TP showed significant variation at different positions and time periods. MPN and TOC were almost unchanged over different positions and time periods. In case of Streptococci the only variation was found over different time periods.

Trial 3

Table 4.3 presents the calculated F values and probability levels for various variables for trial 3. The Table shows that the effects of positions (over times) and time (over positions) were highly significant for the variables TS and VS. Streptococci and TP were found to be varying significantly (at 5%) at different time periods. Similarly pH and Streptococci were significantly different at different positions. MPN levels showed large variations at different times. Rest of the effects were not significant.

Trial 4

Table 4.4 presents the calculated F values and probability levels for various variables for trial 4. The Table shows that the effects of positions (over times) and time (over positions) were highly significant for the variables TS, VS and MPN. The effect of varying times was significant at 5% level of significance for Streptococci, TN, and TP, whereas TOC remained in-significantly different. The effect of position was highly significant on Streptococci. However, pH, TN, TOC, and TP showed significant difference with respect to positions.

Trial 5

Table 4.5 presents the calculated F values and probability levels for various variables for trial 5. The Table reveals that the effect of positions (over time) and time periods (over

positions) were not significant for the variables VS, N, and TP, whereas TS was found to be varying considerably at different levels of these factors. The effect of time periods was highly significant for variables Streptococci and pH but MPN did not change significantly. Streptococci and pH varied significantly from one position to another but TOC did not show any significant variation.

Table 4.1 Calculated F values and probability levels for Trial 1

Variables	Effects	
	Position (over time)	**Time (over position)**
TS	F(1,26) = 442.31 p > F = 0.0001	F(12,26) = 20.09 p > F = 0.0001
VS	F(1,26) = 0.02 p > F = 0.9004	F(12,26) = 1.93 p > F = 0.0785
MPN	F(1,12) = 0.27 p > F = 0.61	F(12,12) = 1.35 p > F = 0.3064
Streptococci	F(1,12) = 20.73 p > F = 0.0007	F(12,12) = 4.66 p > F = 0.0062
pH	F(1,12) = 0.00 p > F = 0.9863	F(12,12) = 8.24 p > F = 0.0005
TN	F(1,12) = 0.94 p > F = 0..3513	F(12,12) = 0.73 p > F = 0.7051
TOC	F(1,12) = 1.70 p > F = 0.2173	F(12,12) = 1.00 p > F = 0.5002
TP	F(1,12) = 2.28 p > F = 0.1572	F(12,12) = 1.38 p > F = 0.2941

Table 4.2 Calculated F values and probability levels for Trial 2

Variables	Effects	
	Position (over time)	**Time (over position)**
TS	F(1,24) = 227.42 p > F = 0.0001	F(11,24) = 6.50 p > F = 0.0001
VS	F(1,24) = 28.73 p > F = 0.0001	F(11,24) = 10.18 p > F = 0.0001
MPN	F(1,11) = 0.33 p > F = 0.5776	F(11,11) = 2.73 p > F = 0.0549
Streptococci	F(1,11) = 1.90 p > F = 0.1953	F(11,11) = 11.06 p > F = 0.0002
pH	F(1,12) = 21.40 p > F = 0.0006	F(12,12) = 23.44 p > F = 0.0001
TN	F(1,10) = 70.47 p > F = 0.0001	F(11,10) = 7.97 p > F = 0.0014
TOC	F(1,10) = 1.34 p > F = 0.2736	F(11,10) = 0.78 p > F = 0.6580
TP	F(1,10) = 8.55 p > F = 0.0152	F(11,10) = 3.16 p > F = 0.0403

Table 4.3 Calculated F values and probability levels for Trial 3

Variables	Effects	
	Position (over time)	**Time (over position)**
TS	F(1,26) = 275.51 p > F = 0.0001	F(12,26) = 3.58 p > F = 0.0031
VS	F(1,26) = 11.11 p > F = 0.0001	F(12,26) = 6.91 p > F = 0.0001
MPN	F(1,12) = 0.02 p > F = 0.8911	F(12,12) = 16.08 p > F = 0.0001
Streptococci	F(1,12) = 9.30 p > F = 0.0101	F(12,12) = 3.68 p > F = 0.0162
pH	F(1,12) = 6.66 p > F = 0.0240	F(12,12) = 4.34 p > F = 0.0084
TN	F(1,12) = 0.04 p > F = 0.8362	F(12,12) = 9.99 p > F = 0.5081
TOC	F(1,12) = 0.63 p > F = 0.4441	F(12,12) = 0.54 p > F = 0.8491
TP	F(1,12) = 0.87 p > F = 0.3699	F(12,12) = 2.79 p > F = 0.0348

Table 4.4 Calculated F values and probability levels for trial 4

Variables	Effects	
	Position (over time)	Time (over position)
TS	F(1,26) = 407.04 p > F = 0.0001	F(12,26) = 5.20 p > F = 0.0002
VS	F(1,26) = 46.55 p > F = 0.0001	F(12,26) = 45.64 p > F = 0.0001
MPN	F(1,12) = 13.89 p > F = 0.0029	F(12,12) = 10.62 p > F = 0.0001
Streptococci	F(1,12) = 13.13 p > F = 0.0035	F(12,12) = 3.34 p > F = 0.0232
pH	F(1,12) = 1.09 p > F = 0.3160	F(12,12) = 33.13 p > F = 0.0001
TN	F(1,12) = 0.11 p > F = 0.7407	F(12,12) = 3.81 p > F = 0.0141
TOC	F(1,12) = 1.23 p > F = 0.2893	F(12,12) = 1.82 p > F = 0.1568
TP	F(1,12) = 0.10 p > F = 0.7541	F(12,12) = 3.08 p > F = 0.0312

Table 4.5 Calculated F values and probability levels for Trial 5

Variables	Effects	
	Position (over time)	**Time (over position)**
TS	F(1,24) = 1544.58 p > F = 0.0001	F(11,24) = 17.89 p > F = 0.0002
VS	F(1,24) = 2.77 p > F = 0.1090	F(11,24) = 2.16 p > F = 0.0561
MPN	F(1,11) = 18.18 p > F = 0.0013	F(11,11) = 1.98 p > F = 0.1358
Streptococci	F(1,11) = 7.24 p > F = 0.0210	F(11,11) = 5.94 p > F = 0.0032
pH	F(1,11) = 4.46 p > F = 0.0584	F(11,11) = 22.88 p > F = 0.0001
TN	F(1,11) = 0.95 p > F = 0.3508	F(11,11) = 0.47 p > F = 0.8885
TOC	F(1,11) = 2.01 p > F = 0.1841	F(11,11) = 3.76 p > F = 0.0188
TP	F(1,11) = 0.07 p > F = 0.7900	F(11,11) = 1.39 p > F = 0.2974

CHAPTER 5

COMPOSTING PROCESS RATES

5.1 Introduction

This chapter analyses the disappearance of Total Organic Carbon over a period of up to 23 days in sawdust and piggery solids pilot composting trials and laboratory experiments. Two models with first order reaction rates, with and without temperature effects have been tested.

Fundamental equations based on biological and physical parameters that are necessary for a successful composting operation design are also presented.

5.2 System parameters

Many researchers have identified various controllable factors to facilitate a proper composting operation design. The analysis of the composting process, with the goal of proper system design, requires consideration of the following parameters (Keener *et al.*, 1993).

- Material properties
- Environmental conditions
- Biological constraints
- Physical constraints, and
- Economic constraints.

From a research viewpoint Hansen *et al.* (1989) identified 20 controllable factors for the composting process. These are presented in table 5.1.

Table 5.1 Controllable factors for composting

Organic amendment	Moisture control
Carbon/Nitrogen ratio	Aeration
Particle size	Ambient temperature
Percent recycled compost	Retention time
Mixing equipment	Depth
Reactor vessel size	Percent recycled air
Stirring frequency	Type of process
Chemical pH modelling agent	Curing time
Initial moisture content	Inoculation
temperature	Bulking agent

Some of these factors are discussed in Section 2.3.1. For a scientific analysis of composting, these factors can be rewritten as parameters of the process. A partial list of the significant parameters of the process is presented in Table 5.2.

Optimization of a design based on any one or many parameters from Table 5.2 can be done through field experimentation and mathematical models (Keener *et al.*, 1993). Field experimentation implies collection of basic information of pilot or full scale systems and evaluation of the results. Process modelling can be done by analytical or numerical models developed on the basis of heat and mass transfer principles and the reaction kinetics of biological systems. These models are used interactively with cost models that describe the system. Haug (1993), Finstein *et al.*, (1986a), Anderson (1990), Golob and Selby (1991), and Curtis *et al.* (1992) have presented the analysis of numerous composting systems

Table 5.2 Major compost system parameters required for optimization analysis of the system (Keener *et al.*, 1993)

Material properties	**Physical constraints**
k: rate of composting	m_o: initial mass of material to be composted
a, n: pressure drop parameters	A: bed area
h_c: heat of biocombustion	d: depth
ρ_c: density of compost	
ρ_{cb}: density of compostibles	
m_e: equilibrium mass of material after composting	
Environmental	**Economic constraints**
HAI: enthalpy of incoming air	C_f: fixed cost
ρ_a: density of air	C_v: variable cost
Biological constraints	
T_c: compost temperature	
W_c: moisture level of compost	
C/N: carbon nitrogen level	
mR*: desired final mass ratio (maturity rating)	

5.3 The rate of disappearance of carbon

During the initial stages of composting the active microbial population grows exponentially until the available substrate or other factors limit growth (Marugg *et al.*, 1993). Only a small portion of the substrate is used up in this initial stage, and therefore, does not contribute substantially to the stabilization process. Process control during this initial phase

is not generally maintained in most composting systems. The second active stage of composting which follows the initial stage provides readily available substrate for microbial breakdown. This stage can last for a longer period of time.

The rate of disappearance of compostibles during this period has been characterized by many researchers as a first order reaction (Haug, 1993). Haug (1993) has presented a detailed kinetics of the composting system.

In this work, the rate of disappearance of total organic carbon in sawdust and piggery solid during composting trials is described by a first order reaction term:

$$\frac{dC}{dt} = -kC \tag{5.1}$$

with the initial condition given by

$$C(0) = C_0 \tag{5.2}$$

Equation 5.1 has the exact solution given by:

$$C = C_0 e^{(-kt)} \tag{5.3}$$

where k = reaction rate coefficient (per day), which can be affected by substrate compounds, microbial populations, temperature, moisture content, surface exposed and interstitial atmosphere

C = mass of carbon in compost heap (dry basis) at time t

t = time (days)

5.3.1 The reaction rate constant

Evaluation of k can be derived from the decomposition curve of total organic carbon values. Various factors affect the reaction rate constant, k. Bach *et al.*, (1987) have shown that the effect of moisture content on the rate of composting was less significant than that of temperature. The effect of the composition of the surrounding atmosphere on k is not taken into account.

5.3.2 Effect of temperature

The effect of temperature on reaction rate in this study (trials 1 to 5) can not be neglected, because the temperature variations amongst trials were too varied. The effect of temperature on reaction rate has been considered by several authors (Schulze, 1962; Marugg *et al.*,1993).

$$\frac{dC}{dt} = -kF(T)C, \tag{5.4}$$

with initial conditions $C(0) = C_0$, where k incorporates parameter 'a' in Equation 5.6.

where F(T) = rate modifying factor to account for effect of temperature
T = temperature (^{0}K)

This has the exact solution given by:

$$C = C_0 e^{-k\int_0^t e^{-b/T(t')}dt'} \tag{5.5}$$

In literature (Campbell *et al.*, 1981; Addiscott, 1983), F(T) is often given by an Arrhenius type equation:

$$F(T) = ae^{-b/T} \tag{5.6}$$

where

a = constant

b = constant (K)

Equation 5.5 can be written as:

$$C = C_0 e^{-k\int_0^t F(T)dt'} \tag{5.7}$$

In this work, we look for F(T) which will fit the criteria of having an analytical solution and fitting through temperature profile of each trial.

The arbitrary selection of an empirical equation for T(t) will be a much more simpler exercise. The empirical relationship in Eq. 5.5 can then be used and k and C_0 may be estimated.

$$T(t) = \frac{t}{(p + qt + rt^2)} \tag{5.8}$$

Many researchers have provided optimum temperature guidelines for activity of the composting microbiological population (Finstein and Morris, 1975; Bach *et al.*, 1984; McKinley and Vestal, 1984; Kuter *et al.*, 1985). These studies have shown that the maximum temperature for optimum microbial decomposition during composting is at or below 60^0C.

Marugg *et al.*, 1993 have introduced a correction factor based on data from Schulze (1962) in reaction rate calculations. In the work carried out by Schulze (1962), oxygen consumption during composting of garbage and digested dewatered sludge cake was represented by the following relationship:

$$\text{Oxygen consumption} \cong 1.066^{T} \tag{5.9}$$

where T = temperature (^{0}C)

The temperature at which maximum breakdown of substrate is achieved during the active stage is most important in designing a composting operation. Therefore, the reaction rate constant is given at this temperature (Marugg *et al.*, 1993). The correction factor for the influence of temperature on reaction rate is therefore set to be 1 at 60°C in the study carried out by Marugg *et al.*, 1993. As substrate is used up by microbial activity and process reaches the final stage, the temperature dependence on rate constant becomes smaller.

The temperature correction for the reaction rate constant can therefore be written as follows (Marugg *et al.*, 1993):

$$F(T) = \frac{1.066^{T(t)}}{46.28} \tag{5.10}$$

This correlation was employed in this analysis.

where F(T) = Temperature correction, and

$$T(t) = \frac{t}{(p + qt + rt^2)} \tag{5.11}$$

Equation 5.7 can be used to estimate the reaction rate constant with Equations 5.10 and 5.11 accounting for temperature correction.

5.4 Results of carbon degradation

5.4.1 The rate of disappearance of carbon mass

As discussed in Chapter 4, losses of carbon in different trials varied. Except in trial 5 where significant difference was found over time, there was no significant effect on total carbon loss of positions or time. There was no significant difference in total carbon loss amongst the rest of trials. Only trial 4 had no significant difference at both positions S1 and S2 in comparison with laboratory experiments 6 and 7.

5.4.2 Reaction rate constant

Reaction rate constants for disappearance of carbon mass in all composting trials were calculated by a regression analysis using Equation 5.3. The results of this analysis are presented in Table 5.3.

These results are derived from Total Organic Carbon decomposition curves for trials 1 to 5 that had no temperature correction factors associated with calculations. Experiments 6 and 7 were laboratory scale investigations under controlled conditions and had constant temperature throughout the composting period.

Table 5.3 Reaction rate constants of carbon loss without temperature correction

Trial	Sampling point	C_0	k
1	S1	57.84	0.00355
	S2	53.80	-
2	S1	49.55	-
	S2	54.95	0.00589
3	S1	53.11	0.00066
	S2	51.84	0.00021
4	S1	53.08	0.00864
	S2	54.31	0.00773
5	S1	50.55	0.00053
	S2	49.65	-
6		52.194	0.00995
7		54.051	0.01338

To test whether or not, Eq. 5.3 is appropriate in these situations, a two compartment kinetic model is also considered:

$$\frac{dc_1}{dt} = -k_1 c_1,\ c_1(0) = A_0 \tag{5.12}$$

$$\frac{dc_2}{dt} = -k_2 c_1,\ c_2(0) = B_0 \tag{5.13}$$

So that

$$C = c_1 + c_2$$

has an exact solution given by:

$$C = A_0 e^{(-k_1 t)} + B_0 e^{(-k_2 t)} \qquad (5.14)$$

A two compartment system assumes that there are different reaction rate constants in a composting process. The first one explains the rapid microbiological activity in the first stage where as the second rate constant represents the somewhat slower activity in later stages. In most of the cases in our study there was no difference in reaction rate constants using the first order two compartment kinetic model represented by Equation 5.14. The difference found in some constants was so small that it was decided to collapse the two compartment model into a single compartment.

5.4.3 Effect of temperature

A non-linear regression analysis was used to calculate rate constant over time from the temperature development curves. The empirical relationship given by Equation 5.8 was used to perform this analysis. Table 5.4 presents the results from this analysis for temperature profile in all pilot scale trials from two thermocouples (T6 and T4) representing temperature regime at sampling point S1 and S2, respectively. Figures 5.1 and 5.2 present best fit curves to calculate constant values for Eq. 5.8 at two sampling points (T6 and T4)for trial 1, respectively. For trials 2 to 5, these curves are presented in Appendix 9.

A medium-order, Newton-Raphson algorithm, which solved non-stiff differential equation was used to solve Equations 5.7 numerically with MATLAB 5.1. The parameters k and C_0 were estimated from data and the numerical solution using a nonlinear least squares algorithm. The results of this analysis are presented in Table 5.5.

Table 5.4 Temperature coefficients over time

Trial	Sampling point	p	q	r
1	S1	0.02252	0.00589	0.00075
	S2	0.04063	0.00344	0.00093
2	S1	0.01527	0.00867	0.00042
	S2	0.01897	0.00776	0.00041
3	S1	0.02887	0.00696	0.00035
	S2	0.02498	0.00707	0.00038
4	S1	0.02512	0.00880	0.00019
	S2	0.02417	0.00925	0.00020
5	S1	0.05729	0.01308	0.00357
	S2	0.05568	0.00854	0.00376

Table 5.5 Reaction rate constants over time with temperature corrections

Trial	Sampling point	C_0	k (day^{-1})
1	S1	57.84575	0.00347
	S2	53.8006	-
2	S1	49.54778	-
	S2	54.9190	0.00534
3	S1	53.10148	5.9628E-4
	S2	51.8426	1.9079E-4
4	S1	53.01489	0.00782
	S2	54.2635	0.00703
5	S1	50.554	5.171E-4
	S2	49.6549	-

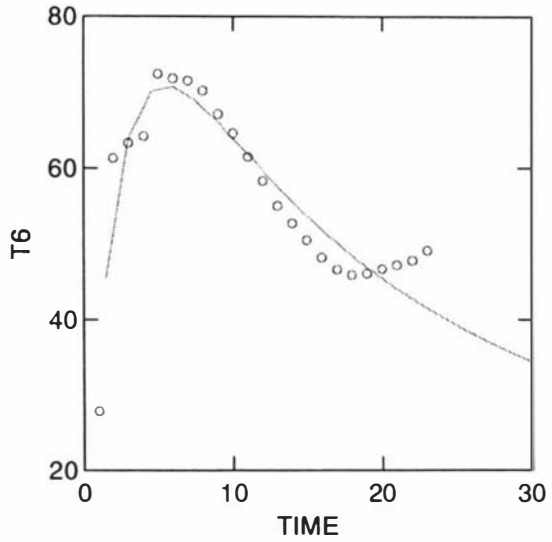


Figure 5.1 Best fit curve to calculate parameter values for Eq. 5.8 at S1 in Trial 1

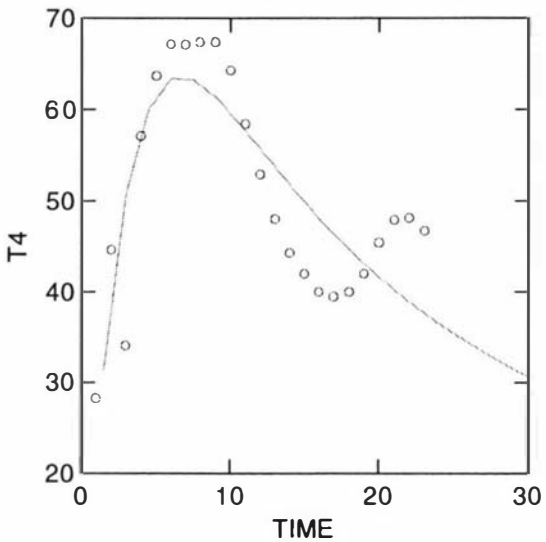


Figure 5.2 Best fit curve to calculate parameter values for Eq. 5.8 at S2 in Trial 1

5.5 Discussion on carbon degradation

Purpose designed composting facilities are usually constructed to treat specific types of wastes such as piggery solids. Depending upon the material to be composted and seasonal variability, the composting process or methodology is changed and operators need to evaluate the effects of various fractions on the process.

Temperature plays a major role in composting process. At the same time it is also a function of the process. As discussed earlier, probably the most important aspect of temperature is its impact on the microbiological community, resulting in changes in other important reactions. The composting process is often depicted in terms of time-temperature relationship. In many well managed systems temperature is regulated or manipulated to achieve the objectives desired. Where complete destruction of pathogens is required (e.g. sewage sludge) certain temperature levels must be reached for disinfection. Other wastes (e.g. animal wastes) may require temperature control for plant pathogen destruction or weed seed destruction.

Comparison of the model given by Equation 5.3 with model given by Equation 5.7 using the residual sum of squares gave the following results (Table 5.6). Sampling points S2 in Trial 1, S1 in trial 2 and S2in Trial 5, respectively gave a negative value of the rate constant. These negative values are unrealistic and may have resulted due to significant variations in sampling and analyses.

Table 5.6 Residual Sum of Squares for two models used to compare reaction rate constants over time

Trial	Sampling point	$\sum$ (Residual)^2	
		$C = C_0 e^{(-kt)}$	$C = C_0 e^{-k\int_0^t F(T)dt}$
1	S1	60.7850	60.9408
	S2	91.7598	91.7258
2	S1	413.7792	413.75
	S2	79.2076	79.2501
3	S1	142.2149	142.225
	S2	70.8034	70.8047
4	S1	38.0489	38.1138
	S2	200.6291	200.38
5	S1	22.7650	22.7524
	S2	18.5487	18.564

As can be seen from Table 5.6, there is virtually no difference between the residual sum of squares for two models used in this study. In Equation 5.3, k is independent of temperature but takes into account the average temperature of the heap. Equations 5.7, 5.10 and 5.11 have a temperature correction component associated with them but the changes in temperature, deviation from mean temperature, does not significantly improve the fit. This means that a simple first order kinetic model, as given by Equation 5.3 can be used for rate constant determination without a need to use a more complicated equation such as 5.7.

5.5.1 Mean residence time

The mean residence time (MRT) is a time constant from statistical moment theory which is useful in estimating the average life of a molecule of a substance within a system (Saggar

et al.,1996). For a single compartment model such as given by Equation 5.3, it equals to the turnover time. The MRT may be related to average temperature in order to derive temperature rate modifying factors.

The MRT in composting system is the residence time of solids in the composting system. It is the most important factor in determining the stability of the compost product. It is a function of the type of substrate and bulking agent and their corresponding reaction rate constants, and provides very useful information for designing a composting system. In this study, the MRT of solids has been based on degradation of carbon reaction rate constant).

The MRT which is given by 1/k for different trials and experiments of composting of piggery solid and sawdust is presented in Table 5.7.

Table 5.7 Mean Residence Time of carbon

Trial	Sampling point	k	MRT (1/k)
1	S1	0.00355	281.69
	S2	-0.00190	-
2	S1	-0.00141	-
	S2	0.00589	169.78
3	S1	0.00066	1515.15
	S2	0.00021	4761.9
4	S1	0.00864	115.74
	S2	0.00773	129.37
5	S1	0.00053	1886.8
	S2	-0.00049	-
6		0.00995	100.50
7		0.01338	74.73

The values of Mean Residence Time (MRT) differed widely in trials. Trial 4 using natural temperature increase in the heap due to biodegradation process had the lowest MRT of approximately 115 and 129 days at position S1 and S2, respectively. From these values it can be concluded that the maximum decomposition of total organic carbon took place in trial 4 and at conditions that prevailed in trial 4, the average residence time of solids in the heap is of the order of approximately 100 days. In laboratory experiments 6 and 7, the average residence time of solids in the system was not very different from this value. Haug (1983), on the basis of the review of the data from a number of composting systems, also suggests that a minimum system MRT of about 60 to 180 days is required to produce compost with sufficient stability and maturity to avoid reheat and phytotoxic effects. According to Rodrigo *et al.* (1997) the effect of temperature on decomposition may be compared with other substrates by normalising the decomposition rate equation.

Other trials had MRT ranging between 170 and 4760 days at least at one sampling point in the heap. The higher value of MRT could be due to the bulking agent used in our studies which is very high in carbon content. For example, trial 5 had a 75% sawdust by volume. Naturally, any rate related to this trial will have to accommodate the slow degradation of carbon particles in composting mixture.

5.5.2 Carbon/Nitrogen ratio

It was not the aim to study how long the carbon will last in the system. A complete stabilisation of compost (or complete disappearance of carbon) is not desirable because the value of compost as a soil conditioner depends in part on its organic content (Haug, 1993). The ultimate goal in composting is to achieve a stable and mature humus-like product that can be used for soil improvement and plant growth. By stabilisation it means the state in which the composted material can be stored without giving rise to odour problems or can be applied to the soil without causing health problems (Gloueke, 1977). When the readily degradable constituents have been oxidised to relatively stable intermediates then a stabilised state is obtained.

Many methods have been suggested in the literature to assess the state of decomposition and suitability of the compost as a plant growth medium. Carbon and nitrogen are the building blocks of plant and animal cells and, therefore, are impacted by microbial activity. Hence they are the most studied parameters during the decomposition process. Epstein (1993) has provided comprehensive list of the methods used to assess compost stability and maturity.

The time-temperature relationship affects the rate of decomposition of the organic matter and therefore is important for the production of a stable and mature product for consumer use. The rate at which organic matter decomposes is principally dependent upon the C/N ratio of the materials to be composted. Part of carbon is utilised for cellular growth while part of it is lost as CO_2. The important parameter is the carbon available to microorganisms, not the total carbon in the material.

The C/N ratio has often been used to indicate the stability of compost. Living organisms require available carbon as a source of energy and need nitrogen to synthesise protoplasm. Inasmuch as the efficiency of the living organisms necessarily is less than 100%, more carbon than nitrogen is needed. However, if the excess of carbon over nitrogen is too big, biological activity diminishes. The lowering of the C/N ratio is brought about by the fact that two-thirds of the carbon consumed is given off as CO_2,while the other third is combined with nitrogen in the living cell. A large amount of nitrogen can be lost due to ammonia volatilisation. Upon death of the microbes, the fixed carbon and nitrogen again become available, but their utilisation once more requires the burning of a fraction of the carbon to CO_2. Thus the amount of carbon is reduced by way of partial conversion to CO_2, while nitrogen continues to be recycled. Although after the high initial loss of nitrogen due to volatilisation some more nitrogen may be lost during the composting operation, the amount does not match that of the carbon loss, therefore the ratio of carbon to nitrogen declines (Golueke, 1977).

The bulking agent used in all out trials (sawdust) has a very high carbon and low nitrogen content (and hence high C/N ratio) and at the same time breaks down very slowly. The piggery solids lost a big portion of total nitrogen at the start of the composting process

during mixing and then by aeration. The C/N ratios varied according to the piggery solids to sawdust ratio in these trials. Table 5.8 presents the initial and final C/N ratios in composting trials. Trial 4 had the largest rate of decomposition of organic carbon under normal composting conditions. As can be seen from Table 5.8, only trial 4 came close to obtaining a C/N ratio of the order of the suitability values provided in the literature. Remembering that this trial had 75% piggery solid by volume, we can conclude that in our trials this was the best mix. Laboratory experiments 6 and 7 also gave similar results. As can be seen from Table 5.8, the composting process started at a lower C/N ratio due to the high initial total nitrogen content. Once the aeration started there was a rapid loss of nitrogen due to volatilisation of ammonia. After this stage, the nitrogen loss stabilised and due to slow reduction of carbon in the mixture during the composting, the final C/N ratio remained higher than the initial C/N ration.

Table 5.8 Initial and final Carbon/Nitrogen ratios

Trial	Sampling point	C/N ratio (Initial)	C/N ratio (Final)
1	S1	44.44	109.82
	S2	44.44	82.80
2	S1	37.91	45.66
	S2	37.91	52.84
3	S1	40.40	77.2
	S2	40.40	77.29
4	S1	32.72	44.71
	S2	32.72	41.98
5	S1	46.25	83.94
	S2	46.25	95.43
6		37.61	58.0
7		32.98	47.0

5.5.3 Time required to obtain required decomposition

As discussed earlier, although some more nitrogen may be lost during the composting operation after the initial rapid drop, the amount does not match that of the carbon loss, therefore the ratio of carbon to nitrogen declines (Golueke, 1977). It might be true in some other wastes, but in case of piggery solids, where there was a rapid initial nitrogen loss, and the carbon breakdown was slow, if it was to be assumed that the total nitrogen levels in the composting heap will not drop any further after active composting process, it is possible to calculate the time required to achieve a certain drop in the C/N ratio from the first order decomposition relationship (Equation 5.3).

The rate of disappearance as a first order reaction term is:

$$C = C_0 e^{(-kt)} \tag{5.16}$$

and at $C = \hat{C}$

$$t = -\frac{1}{k} \ln\left(\frac{\hat{C}}{C_0}\right) \tag{5.16a}$$

where,

t = time required to achieve a certain drop in the C/N ratio

k =rate constant

$\hat{C}$ = C/N ratio desirable

C_0 = initial condition

Based on Equation 5.16a, Table 5.9 presents the time (days) required to achieve a C/N ratio of 20 $(\hat{C} = 20)$ in composting trials at different positions.

Table 5.9 Time (days) required to achieve a C/N ratio of 20 in various trials

Trial	Sampling point	C_0	k	Time required (C/N = 20)
1	S1	57.84	0.00355	299.14
	S2	53.80	-0.00190	-
2	S1	49.55	-0.00141	-
	S2	54.95	0.00589	171.60
3	S1	53.11	0.00066	1491.11
	S2	51.84	0.00021	4535.38
4	S1	53.08	0.00864	112.97
	S2	54.31	0.00773	129.24
5	S1	50.55	0.00053	1749.5
	S2	49.65	-0.00049	-
6		52.194	0.00995	87.23
7		54.051	0.01338	71.01

It is evident from the table that approximately 120 days will be required to achieve the selected C/N ratio of 20 in trial 4 under normal composting conditions. Laboratory experiments 6 and 7 had constant temperature, hence provided more opportunities for the stabilisation of C/N ratio and would require approximately 80 days to achieve the selected C/N ratio of 20.

5.6 Conclusions on carbon degradation

Evaluation of k can be derived from the decomposition curve of Total Organic Carbon values. A comparison of two models with first order reaction rates with and without temperature effects shows that a simple first order reaction model can be used for the

piggery solid composting process. Within the limits reported in this chapter, data presented can be used for designing piggery solid composting process. Factors influencing the composting process such as moisture content, C/N ratio, result in variations of the reaction rate constants. Values of reaction rate constant varied under different operating conditions of compost piles. In trial four, rate constant values were of the order of .008 d^{-1} and .007 $^{-1}$ at S1 and S2, respectively.

Laboratory experiments 6 and 7 gave similar reaction rate constants to trial 4. This is beside the fact that a constant temperature profile was maintained throughout the composting period in these two experiments.

The values of Mean Residence Time (MRT) differed widely in trials. Trial 4 using natural temperature increase in the heap due to biodegradation process had the lowest MRT of approximately 115 and 129 days at position S1 and S2, respectively. From these values in can be concluded that the maximum decomposition of total organic carbon took place in trial 4 and at conditions that prevailed in trial 4, an average residence time of solids in the heap is of the order of approximately 100 days. In laboratory experiments 6 and 7, the average residence time of solids was not very different from this value.

A complete stabilisation of compost (or complete disappearance of carbon) is not desirable because the value of compost as a soil conditioner depends in part on its organic content. Based on reaction rate constant values, the time required to achieve a required C/N ratio was calculated at different positions in the compost pile. Again, from trial four it was demonstrated that approximately 120 days, and approximately 80 days in trials 6 and 7, will be required to achieve a selected C/N ratio of 20.

5.7 Rate of thermal inactivation

From various trials and studies of composting process, it appears that it is desirable to maintain a composting mass below a maximum temperature of 55^{0}C, thereby retaining the population of thermophilic fungi. However this desirable top temperature appears to conflict with the recommended temperature to ensure destruction of pathogens. This destruction is very important in case of animal wastes or raw sewage sludge. Gotaas (1956) stated that pathogens would be rapidly destroyed when all parts of a compost pile were subjected to a temperature regime of 60^{0}C. A minimum operating conditions at 55^{0}C for 3 days in static pile composting has been suggested by Appleton et al. (1986 a and b).

Thermal inactivation of enzymes in a cell body is caused by heat. Enzymes that may be reversibly inactivated by mild heat are irreversibly inactivated by higher temperatures (Haug, 1993). If an enzyme is inactivated reversibly with temperature, at equilibrium a fraction of enzyme will be in the active form while the remainder stays in inactivated status. The fraction in the active form decreases significantly over a narrow temperature range (Bailey and Ollis, 1986).

The following sections analyse the inactivation or decay of indicator pathogens for period of up to 23 days in piggery solids and sawdust composting pilot trials. Two first order reaction rate equations, with and without temperature normalisation have been tested. For laboratory experiments 6 and 7, first order reaction rate equation without the temperature normalisation has been tested.

5.7.1 Kinetics of heat inactivation

Assuming that there is exponential decay, the rate of thermal inactivation can be of the form:

$$\frac{dn}{dt} = -k_d n \tag{5.17}$$

with the initial condition given by;

$n(0) = n_0$

where n = viable cell population at time t

k_d = average overall thermal inactivation coefficient

n_0 = initial cell population

t = time (days)

Equation 5.17 has the exact solution given by:

$$n = n_0 e^{(-k_d t)} \tag{5.18}$$

Taking the log of both sides and rearranging:

$$t = \frac{1}{k_d} \ln\left(\frac{n_0}{n}\right) \tag{5.19}$$

Converting to 10 logs and considering a one log reduction in cell concentration (or a reduction of 90%),

$$t_{90} = D_r = \frac{2.303}{k_d} \tag{5.20}$$

The term D_r is the decimal reduction factor and is the time required to achieve a tenfold reduction in cell population.

The value of k_d is a function of temperature, the effect of which is often modelled by an Arrhenius type of equation (Haug, 1993):

$$k_d = Ce^{(-E_a/RT_k)} \tag{5.21}$$

where

T_k = Temperature, K.

R = Universal gas constant, 1.99 cal/deg-mole

The range of inactivation energies E_a for many spores and vegetative cells is between 50 and 100 kcal/mole (Bailey and Ollis, 1986). This implies that heat inactivation of microbes is much more sensitive to temperature than most chemical reactions.

Log transformation of Equation 5.21 gives:

$$\ln k_d = \ln C - \frac{E_a}{R}\left(\frac{1}{T_k}\right) \tag{5.22}$$

A plot of log of k_d versus $1/T_k$ allows a preliminary determination of the constant C and the interactive energy E_a, which can be improved by non-linear regression.

5.7.2 Thermal inactivation coefficient

Evaluation of k_d can be derived from the decay curve of MPN and Streptococci in our trials. The value of k_d is a function of temperature. However, study by Wiley (1962) suggest that temperature and time regime are not the only reasons for pathogen destruction. Formation of antibiotic substances in the composting mass is also responsible for pathogen destruction. In this thesis, the discussion centers on kinetics of heat inactivation in a composting system.

5.7.3 Effect of temperature

As mentioned earlier, value of k_d is a function of temperature. Equation 5.18 takes into account an overall average temperature in the compost heap. Most functions describing the effect of temperature on microbial process are based on the Arrhenius or Van't Hoff laws. The Arrhenius function gives the relationship between the natural logarithm of the pathogen inactivation rate k_d and the reciprocal of the absolute temperature ,T.

$$\ln k_d = \ln a - \frac{b}{T} \tag{5.23}$$

where a is a constant and $b=E_a/R$ is the ration between the inactivation energy and the ideal gas constant. The ratio between the inactivation rates (k_{d1} and k_{d2}) at two temperatures (T_1 and T_2) can be expressed as:

$$\frac{k_{d2}}{k_{d1}} = \exp\left(\frac{b(T_2 - T_1)}{T_1 T_2}\right) \tag{5.24}$$

The Arrhenius function has a thermodynamic basis, but this may not be useful in a complex system such as compost heap, where each group of microorganisms is likely to have its own temperature response. The Van't Hoff function describes the exponential change in the inactivation rate with temperature:

$$\frac{k_{d2}}{k_{d1}} = \exp\left(k\left(T_2 - T_1\right)\right) = Q_{10}^{(T_2 - T_1)/10} \tag{5.25}$$

where Q_{10} is a constant representing the change in the inactivation rate for a temperature increase of 10^0C. Comparison of Equation 5.24 and Equation 5.25 shows that the Q_{10} coefficient of the Van't Hoff law is related to the Arrhenius "b" coefficient:

$$Q_{10} = e^{(10b/T_1T_2)} \tag{5.26}$$

Therefore the Q_{10} coefficient varies with the temperature in the Arrhenius equation. The Arrhenius function can only explain part of this variation in Q_{10} with temperature in the range normally encountered in compost heaps. There was no heat loss control provided in this research, therefore a temperature effect on the inactivation coefficient has also been modelled. This effect can be incorporated in the Arrhenius Equation by introducing a 'reference temperature'.

The Arrhenius equation is given as:

$$F(T) = ae^{-b/T} \tag{5.27}$$

where F(T) = temperature rate modifying factor

T = temperature (^{0}K)

a = constant

b = constant (K)

Here,

$$\frac{dn}{dt} = -k_d F(T) n \tag{5.28}$$

with initial condition $n(0) = n_0$

where k_d incorporates the parameter "a"

To account for reference temperature, Equation 5.28 can be written as:

$$\frac{dn}{dt} = -k_d e^{-b\left(\frac{1}{T_t} - \frac{1}{T_{ref}}\right)} n \tag{5.29}$$

so that F(T) = 1 at $T = T_{ref}$

where T_t = overall average temperature by equation 5.8

T_{ref} = reference temperature, 70°C

k_d'= thermal inactivation coefficient incorporating reference temperature

If the reference temperature is optimum then,

$$e^{-b\left(\frac{1}{T_t}-\frac{1}{T_{ref}}\right)} \qquad (5.30)$$

is a rate reduction factor.

5.8 Results and Discussion on thermal inactivation

5.8.1 Rate of disappearance of pathogens

As shown in Chapter 4, inactivation of pathogens in various pilot trials varied. Only trial 4 had significant drop at 5% level in MPN numbers and streptococci. All streptococci numbers dropped significantly (except between positions in trial 2). There was significant difference among trials for both MPN and streptococci numbers. However, in laboratory experiments a complete destruction of pathogens was achieved within the composting period.

5.8.2 Inactivation rate coefficient

Overall average thermal inactivation coefficients for all the trials were calculated by a regression analysis using equation 5.18. SYSTAT 7.0 for Windows was used for this exercise. The results of this exercise are presented in table 5.10 and 5.11 for Coliforms (MPN) and streptococci, respectively. Table 5.10 also includes results from controlled laboratory experiments 6 and 7. The streptococci inactivation was not followed in experiments 6 and 7. There was no significant difference (Anova, P=0.05) in overall average thermal inactivation coefficient for MPN in various trials. However, there was significant difference (Anova, P=0.01) in overall average thermal inactivation coefficient for streptococci in various trials.

These results are derived from Coliform (MPN) and streptococci inactivation curves and have had no temperature correction factors associated with calculations.

Table 5.10 Overall thermal inactivation coefficient for Total coliforms (MPN) using equation $MPN = MPN_0 e^{(-k_d t)}$

Trial Number	MPN S1		MPN S2	
	MPN_0	k_d	MPN_0	k_d
1	3.8E+7	1.702	2.06E+7	0.408
2	4.61E+8	3.30	1.31E+10	6.648
3	3.92E+7	0.769	3.99E+7	0.787
4	2.31E+7	0.394	2.33E+7	0.380
5	2.37E+7	0.440	1.83E+7	0.237
6	1.3E+9	61.97		
7	1.3E+9	47.339		

Table 5.11 Overall thermal inactivation coefficient for Streptococci using equation $Strep = Strep_0 e^{(-k_d t)}$

Trial Number	Strep S1		Strep S2	
	$Strep_0$	k_d	$Strep_0$	k_d
1	8.17E+6	2.833	7.46E+5	0.347
2	4.36E+8	4.979	1.83E+9	6.413
3	1.44E+6	0.627	6.10E+6	2.240
4	2.02E+6	0.394	2.47E+6	1.054
5	1.89E+6	0.705	1.68E+6	0.594

5.8.3 Effect of temperature

The principal mode of disinfection of wastes through composting is based on temperature-time relationship (Epstein, 1997). The temperature-time requirements for the destruction of pathogens in sewage sludge have been presented by Epstein (1997). Data on heat inactivation of total coliforms, faecal coliforms, faecal streptococcus, and *Salmonella enteritidis* showed great reduction of organisms when the temperature exceeded 55 to 65^{0}C (Ward and Brandon, 1977). Knoll (1961) described several experiments where different Salmonella strains were subjected to composting temperatures. After 14 days of composting time with temperature of 55 to 60^{0}C, the product did not contain pathogens.

Study of composting by aerated static pile by Burge et al., 1978 and Epstein et al., 1976 showed that salmonellae increased in growth initially but were destroyed within 10 days of composting. In another study Pereira-Neto et al. (1986) concluded that salmonellae were destroyed in 7 to 15 days; *Escherichia coli* decreased from 10^7 to $< 10^2$ in 15 days; and faecal streptococci from 10^7 to 10^2 in 30 days.

These studies clearly indicate that composting can be effective in the inactivation of pathogens or disinfection of compost. It is also evident that on occasions or through poor management practice the survival of pathogens in compost is possible.

In pilot scale trials, data were collected to examine the decay or inactivation of indicator pathogen Total coliforms and Group D-streptococci. Non-linear least squares with Simplex Method algorithm within SYSTAT 7.0 was used to calculate regression parameters over time from the temperature-time relationship in various trials (Equation 5.8). Table 5.4 presents the results from this analysis for temperature profile in all trials from two thermocouples (T6 and T4) representing temperature regime at sampling point S1 and S2, respectively.

A medium-order, Newton-Raphson algorithm, which solved non-stiff differential equation was used to solve Equation 5.29 numerically with MATLAB 5.1. The parameters k_d and b were estimated from data and the numerical solution using a nonlinear least squares

algorithm. The results of this analysis are presented in Table 5.12 and 5.13 for Coliforms (MPN) and Streptococci, respectively. There was no significant difference (Anova, P=0.05) in thermal inactivation coefficient for MPN in various trials. However, there was significant difference (Anova, P=0.05) in thermal inactivation coefficient for streptococci in various trials.

Table 5.12 Thermal inactivation coefficient for Total coliforms (MPN) using equation $\frac{dn}{dt} = -k_{d'} e^{-b\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)} n$

Trial Number	MPN S1			MPN S2		
	n_0	k_d'	b	n_0	k_d'	b
1	3.84E+7	1.7913	96.1047	2.06E+7	0.4493	271.527
2	4.61E+8	3.3982	64.0019	1.31E+10	6.8340	55.6064
3	3.92E+7	0.8080	107.02	3.99E+7	0.8241	106.3129
4	2.31E+7	0.4325	328.0931	2.33E+7	0.4150	318.87
5	2.37E+7	0.4632	243.4	1.83E+7	0.2512	154.67

Table 5.13 Thermal inactivation coefficient for Streptococci using equation

$$\frac{dn}{dt} = -k_{d'} e^{-b\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)} n$$

Trial Number	Strep S1			Strep S2		
	n_0	k_d'	b	n_0	k_d'	b
1	8.17E+6	2.8827	31.3416	7.19E+5	0.4523	921.8025
2	4.36E+8	5.0049	10.6554	1.83E+9	6.5106	29.9070
3	1.41E+6	0.9628	1173.2	6.1E+6	2.2501	47.2886
4	2.01E+6	1.068333	635.9947	2.7E+6	1.1072	100.002
5	1.87E+6	0.9869	749.097	1.66E+6	0.7924	24.5

Comparison of models given by Equation 5.18 and Equation 5.29 using the Residual Sum of Squares gave no significant difference either for MPN (Table 5.14) or streptococci (Table 5.15). However, there is significant difference between overall thermal inactivation coefficient and thermal inactivation coefficient for Equation 5.18 and Equation 5.29, respectively for MPN at position S1. There is no significant difference in coefficients at position S2.

Similarly, there is significant difference between overall average thermal inactivation coefficient and thermal inactivation coefficient for Equation 5.18 and Equation 5.29, respectively for streptococci at position S2. There is no significant difference in coefficients at position S1. In Equation 5.18, K_d takes into account the overall average temperature of the heap. Equation 5.29 accounts for the reference temperature incorporated in Arrhenius equation. As discussed in section 5.8.3, the incorporation of reference temperature in Arrhenius equation provided a better estimate of thermal inactivation coefficient. This means that a simple first-order kinetic model, as given by Equation 5.18 can be used for the determination of inactivation coefficient, but using Arrhenius equation incorporating the reference temperature would provide a better thermal inactivation coefficient estimates.

It is of interest to know whether inactivation is more sensitive to temperature because this influences the use of compost as a finished product. The Arrhenius "a" coefficient is not easy to interpret and it is the "b" coefficient, which measures the temperature sensitivity, that is more important (Addiscott, 1983).

Table 5.14 Residual Sum of Squares (RSS) for two models used to compare thermal inactivation coefficient for total Coliform over time

Trial	Sampling point	RSS	
		$MPN = MPN_0 e^{(-k_d t)}$	$\frac{dn}{dt} = -k_d \cdot e^{-b(\frac{1}{T} - \frac{1}{T_{ref}})} n$, where n is MPN
1	S1	6.62E+11	6.62E+11
	S2	3.02E+14	2.98E+14
2	S1	2.91E+13	2.91E+13
	S2	9.75E+9	9.75E+9
3	S1	3.67E+13	3.67E+13
	S2	4.07E+13	4.01E+13
4	S1	7.98E+14	7.98E+14
	S2	7.77E+14	7.70E+14
5	S1	4.47E+14	4.47E+14
	S2	1.85E+14	1.84E+14

Table 5.15 Residual Sum of Squares for two models used to compare thermal inactivation coefficient for Streptococci over time

Trial	Sampling point	RSS	
		$Strep = Strep_0 e^{(-k_d t)}$	$\frac{dn}{dt} = -k_d \cdot e^{-b(\frac{1}{T} - \frac{1}{T_{ref}})} n$, where n is Strep
1	S1	7.57E+8	7.57E+8
	S2	9.20E+10	8.79E+10
2	S1	4.02E+9	4.02E+9
	S2	1.46E+9	1.46E+9
3	S1	2.31E+11	2.19E+11
	S2	1.10E+9	1.10E+9
4	S1	8.00E+10	7.78E+10
	S2	7.12E+9	7.0E+9
5	S1	1.39E+11	1.30E+11
	S2	9.19E+10	8.74E+10

5.8.4 Decimal Reduction Factor

The decimal reduction factor (D_r) is the time required to achieve a ten fold reduction in microbial population. The D_r which is given by Equation 5.20 is presented in Tables 5.16 to 5.19 for different trials.

Table 5.16 Decimal reduction factor for Total coliforms (MPN) using equation

$$MPN = MPN_0 e^{(-k_d t)}$$

Trial Number	MPN S1		MPN S2	
	k_d	D_r	k_d	D_r
1	1.702	1.353	0.408	5.645
2	3.30	0.698	6.648	0.346
3	0.769	2.995	0.787	2.926
4	0.394	5.845	0.380	6.061
5	0.440	5.234	0.237	9.717
6	61.917	0.04	-	-
7	47.339	0.05	-	-

Table 5.17 Decimal reduction factor for Total coliforms (MPN) using equation

$$\frac{dn}{dt} = -k_d e^{-b(\frac{1}{T} - \frac{1}{T_{ref}})} n$$

Trial Number	MPN S1		MPN S2	
	k_d	D_r	k_d	D_r
1	1.7913	1.286	0.4493	5.126
2	3.3982	0.678	6.8340	0.337
3	0.8080	2.850	0.8241	2.795
4	0.4325	5.325	0.4150	5.549
5	0.4632	4.972	0.2512	9.168

Table 5.18 Decimal reduction factor for Streptococci using equation

$$Strep = Strep_0 e^{(-k_d t)}$$

Trial Number	Strep S1		Strep S2	
	k_d	D_r	k_d	D_r
1	2.833	0.813	0.347	6.637
2	4.979	0.463	6.413	0.359
3	0.627	3.673	2.240	1.028
4	0.394	5.845	1.054	2.185
5	0.705	3.267	0.594	3.877

Table 5.19 Decimal reduction factor for Streptococci using equation

$$\frac{dn}{dt} = -k_d \cdot e^{-b(\frac{1}{T} - \frac{1}{T_{ref}})} n$$

Trial Number	Strep S1		Strep S2	
	k_d	D_r	k_d	D_r
1	2.8827	0.799	0.4523	5.092
2	5.0049	0.460	6.5106	0.354
3	0.9628	2.392	2.2501	1.024
4	1.0683	2.156	1.1072	2.080
5	0.9869	2.334	0.7924	2.906

The values of D_r differed widely in trials. There was significant difference (Anova, P= 0.05) in the value of D_r in composting trials in MPN at both positions S1 and S2 when Equation 5.18 and Equation 5.29 were used. There was also significant difference in the value of D_r among composting trials in Streptococci at positions S2 when Equation5.18 and Equation

5.29 were used. However, there was no significant difference in the value of D_r in Streptococci at positions S1 when Equation5.18 and Equation 5.29 were used.

Rapid decay may be responsible for varied decimal reduction factors in different trials. It influenced the estimation for inactivation rates considerably. Trial 2 had the most rapid decay in the number of MPN within 2 days of starting of composting operation at both positions S1 and S2, and hence had the lowest D_r value among all the trials. Similar patterns were observed in streptococci decay in trial 2 at both positions S1 and S2. Laboratory experiments 6 and 7 also had rapid decay within 2 days of starting of composting activity and show similar patterns to trial 2. However, a constant temperature throughout the experiment reduced the decimal reduction factor even further.

5.8.5 Limitations on pathogenic inactivation

It is generally assumed that all organisms experience the time-temperature profile to an equal extent. Large particles or lumps may form in the compost and may not receive adequate oxygen. This would prevent the temperature buildup from within the particle itself. Pathogen inactivation in this situation can only occur if sufficient heat from surrounding compost is transported (Haug, 1993).

An experiment was conducted to study the survival of indicator pathogen, total coliform under controlled temperature regime. Approximately 250 g of compost mixture obtained on Day 0 from trial 3 was placed in a 500 mL screw capped Duran glass bottle (Schott West Germany). Three water baths were filled with water and their temperature maintained at 75^0C, 60^0C, and 47^0C, respectively. A thermometer was placed in each Duran glass bottle through a hole in the cap. These bottles were then placed in temperature controlled water baths. When the temperature of the water in the bath and inside Duran bottles reached an equilibrium, samples were analysed for bacteria of total coliform group using the most probable number test. The procedure for sample preparation and analysis for indicator microorganism has been described in Section 3.3.2.

Figure 5.3 presents the results from this experiment and shows the survival of Total coliform at different controlled temperatures. It is evident that the coliforms showed a first order decay and declined to very low numbers in the compost within 2 days at temperatures 75°C and 60°C. There was an exponential drop in coliform numbers in compost at 47°C until about 7 days when the value reached 20 coliforms per g of compost. This number remained same for the rest of the study period.

Survival of indicator microorganisms in the compost heap during various trials at some positions may be an indication that there are certain spore formers which survive the composting process. Formation of lumps might also have created an anaerobic zone and lack of heat within lumps to destroy the indicator microorganisms.

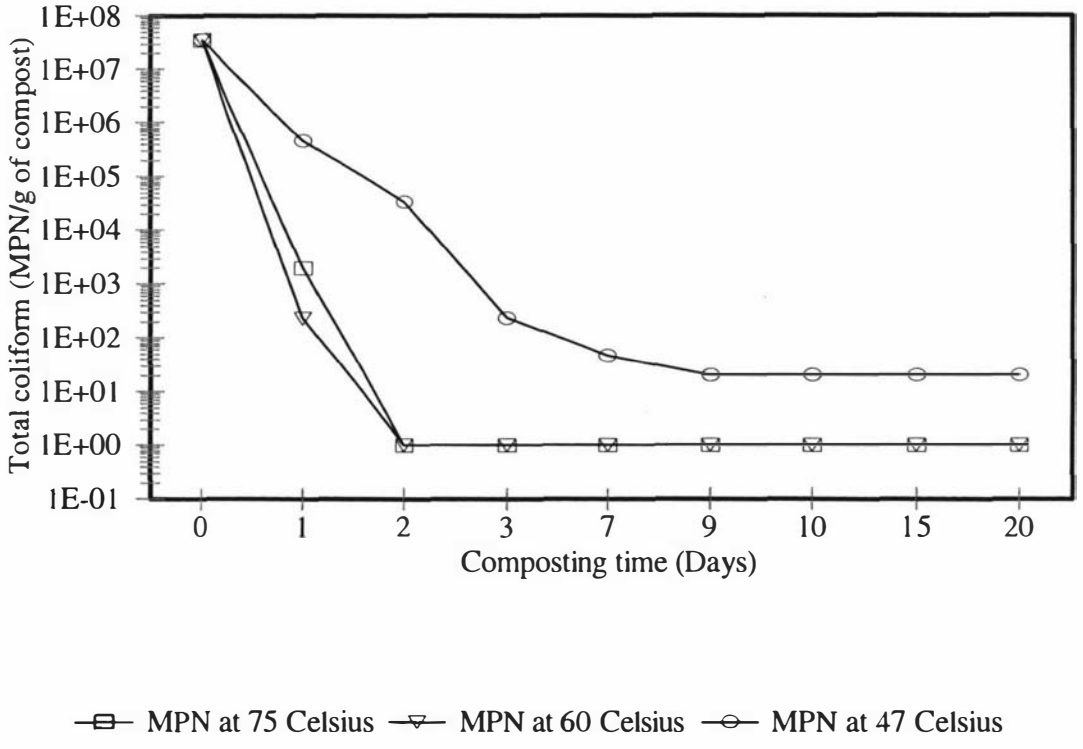


Figure 5.3 Survival of Total coliform at different controlled temperatures

5.9 Conclusions on thermal inactivation

Data were collected to examine the decay or inactivation of indicator pathogen total coliforms and Group D-streptococci. Non-linear least squares with Simplex Method algorithm within SYSTAT 7.0 was used to calculate regression parameters over time from the temperature-time relationship in various trials (Equation 5.29).

A medium-order, Newton-Raphson algorithm, which solved non-stiff differential equation was used to solve Equation 5.29 numerically with MATLAB 5.1.

Comparison of models given by Equation 5.18 and Equation 5.29 using the residual sum of squares gave no significant difference either for MPN or streptococci. However, there was significant difference between overall average thermal inactivation coefficient and thermal inactivation coefficient for Equation 5.18 and Equation 5.29, respectively for MPN at position S1. There was no significant difference in coefficients at position S2.

Similarly, there was significant difference between overall average thermal inactivation coefficient and thermal inactivation coefficient for Equation 5.18 and Equation 5.29, respectively for streptococci at position S2. There was no significant difference in coefficients at position S1. The incorporation of reference temperature in Arrhenius equation provided a better estimate of thermal inactivation coefficient. This means that a simple first-order kinetic model, as given by Equation 5.18 can be used for the determination of inactivation coefficient, but using Arrhenius equation incorporating the reference temperature would provide a better thermal inactivation coefficient estimates.

Inactivation of pathogens in various pilot trials varied. Only trial 4 had significant drop at 5% level in MPN numbers and streptococci. All streptococci numbers dropped significantly (except between positions in trial 2). There was significant difference among trials for both MPN and streptococci numbers.

Analyses of the two composting experiments carried out under controlled temperature and airflow conditions provided independent verification of inactivation rate coefficient. In trial

4, inactivation rate coefficient values were of the order of 0.394 and 0.380 day^{-1} at S1 and S2, respectively. Only one sampling position used in laboratory experiments provided inactivation rate coefficient values of the order of 61.97 and 47.34 day^{-1} in experiment 6 and 7, respectively. Decimal Reduction Factors (D_r) were also markedly different between trial 4 and experiments 6 and 7. These values were expected under controlled temperature and air flow conditions where a complete destruction of pathogens was achieved.

CHAPTER 6

PROCESS PERFORMANCE

6.1 General observation

Separated piggery solids are fibrous in nature and retain very high moisture levels of over 75%. The change in the physical appearance of the compost pile in pilot study was quite distinct during the trials. The surface of the pile quickly became dry, while the material just below it was relatively wet. Haug (1993) has discussed the use of an insulating cover in static pile composting to avoid these problems. However, such a cover could trap moisture thus preventing drying process completely.

Water vapor could be seen leaving the pile within two days of composting time, indicating an on-going heat generation. The appearance of water vapor indicates the high temperature development in the pile in situations where no temperature feedback control is applied (Finstein *et al.*, 1986a and 1986b; Haug, 1993). However, within two days the offensive smell of the mass had largely disappeared.

Similar conditions were also observed in controlled temperature experiments. The water vapor could be seen leaving the aerated composting vessel within few hours of starting the experiment.

Results from pilot trials 1 to 5 and laboratory experiments 6 and 7 are discussed in this chapter. The discussion takes into account the process taken place in individual pilot trials or laboratory experiments, as well among all the trials and experiments.

6.2 Performance comparison between pilot scale and laboratory scale conditions

Analyses of the two composting experiments carried out under controlled temperature and airflow conditions provided independent verification of process rates developed by pilot trials. In some cases, the evidence suggested that the relationships for different sets of data are not identical. In these cases it was investigated whether the trends (or slopes) of various relationships might be the same but the relationships are not identical. Similar mathematical analysis was also carried out to investigate the possibility whether or not trends or slopes of various relationships among other trials are the same or identical with respect to experiments 6 and 7. The procedure to carry out this mathematical analysis is described below.

6.2.1 Method of parallelism for mathematical analysis

If the evidence suggests that the relationships for different sets of data are not identical then we want to investigate the possibility that trends (or slopes) of various relationships might be the same but the relationships are not identical. Similar mathematical analysis could also be carried out to investigate the possibility whether or not trends or slopes of various relationships among other trials are the same or identical with respect to experiments 6 and 7.

Parallel model analysis has been described in many texts (Mead and Curnow, 1983) and used by many researchers (Ross *et al.*, 1984) to obtain estimates of the parameters of a pair of fitted parallel lines and the use of mathematical results based on least squares.

To obtain estimates of the parameters of a pair of fitted lines mathematical results based on the principle of least squares is used. The estimate of the common slope is a weighted average of the individual slopes.

$$b_c = \frac{(S_{xy})_1 + (S_{xy})_2}{(S_{xx})_1 + (S_{xx})_2} \tag{6.1}$$

This slope is the regression slope of y on x. S_{xy} and S_{xx} are referred to as the corrected sum of products of x and y. The estimate of the intercepts are

$$a_1 = \frac{\Sigma(y_1) - b\Sigma(x_1)}{n_1} \tag{6.2}$$

$$a_2 = \frac{\Sigma(y_2) - b\Sigma(x_2)}{n_2} \tag{6.3}$$

where n_1 and n_2 are the number of observations of y_1 and y_2.

The Residual Sum of Squares is given by:

$$RSS_c = (S_{yy})_1 + (S_{yy})_2 - \frac{\left[(S_{xy})_1 + (S_{xy})_2\right]^2}{(S_{xx})_1 + (S_{xx})_2} \tag{6.4}$$

The RSSc has $(n_1 + n_2 - 3)$ degrees of freedom (d.f.). This can be justified in two ways. First the RSS is the difference between the sum of the two corrected sums of squares of y (based on $(n_1 - 1)$ and $(n_2 - 1)$ degrees of freedom) and the sum of squares for fitting the common regression coefficient (1d.f.). Alternatively, it can be argued that from $(n_1 + n_2)$ observations, three parameters a_1, a_2, and b, have been estimated leaving $(n_1 + n_2 - 3)$ degrees of freedom for the residual variation.

We can then test whether the slopes of the two relationships (either between experiments 6 and 7, experiment 6 and trial 4, or experiment 7 and trial 4) are the same by examining

whether the Residual Sum of Squares (RSSc) is substantially greater than sum of individual residuals (RSS_1 and RSS_2). If the difference is small compared with s^2 (average squared deviation or variance) then we can accept that the slopes or trends are the same (see Figure 6.1 for an example). If the difference is significant compared with s^2 then we can accept that the slopes or trends are the same but the lines are not certainly identical. We can set the analysis of variance and test the hypothesis that the slopes or trends are equal by comparing

$$F = \frac{difference\ m.s.}{s^2} = \frac{RSS_c - (RSS_1 + RSS_2)}{s^2} \qquad (6.5)$$

with the F-distribution on 1 and $(n_1 + n_2 - 4)$ degrees of freedom.

The comparative results presented here have been calculated on the basis of 11 observations (up to day 15) in pilot study trials, as well as laboratory experiments. Although comparison of slopes resulting from different numbers of observation did not change the level of significance, it was decided to use similar number of observations for this analysis.

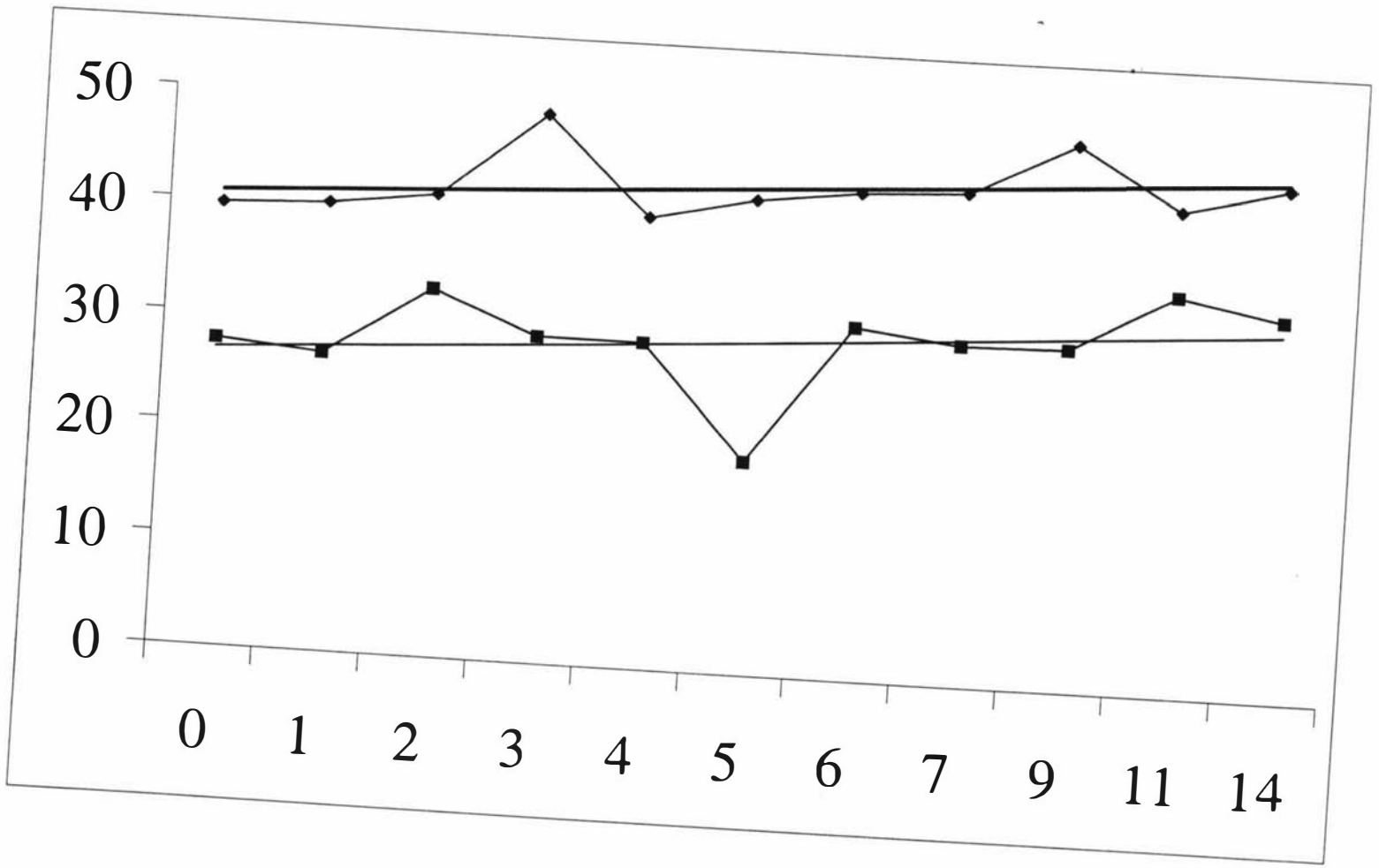


Figure 6.1 **Two parallel lines fitted to x and y_1 & y_2 values**

6.3 Decomposition activity

6.3.1 Temperature development

The development of temperature profiles in three layers of the pile in pilot trials 1 to 5 was similar. In the first trial, the upper region (T5 and T6) reached the highest temperatures after five days of operation (72^{0}C). This could be due to the natural convective movement of heat in the pile. However, the development of such high temperatures may not be desirable because it inhibits the microorganisms responsible for the decomposition in their metabolism which consequently slows down the decomposition activity in the composting material (Golueke, 1977; Haug, 1993). Similarly, a sharp decline in temperature could be an indicator of the termination of the microbial activity in the pile. Many researchers have demonstrated that optimum composting temperatures lie in the range of 55^{0}C and 60^{0}C (Golueke, 1977; Haug, 1993; Biddlestone and Gray, 1985; Nakasaki *et al.*, 1985; Sikora and Sowers, 1985; Pereira-Neto *et al.*, 1987a). Without controlled aeration these values can not be reached and maintained for the period recommended to achieve partial destruction of pathogens as well as to obtain a sufficiently stabilized end product (Finstein *et al.*, 1987 a-d).

The upper and middle regions in the first trial (T5, T6 and T3, T4) reached the highest temperatures after 7 days of operation (approximately 67^{0}C). The temperature in the lower region (T1 and T2) of this trial initially dropped for 48 hours and then reached a maximum between 31^{0}C and 51^{0}C after seven days of operation (Appendix 1). The initial drop in the temperature in lower zone can be explained by the continuous aeration for 48 hours that could have produced excessive cooling. Excessive cooling would slow the temperature rise to the optimal thermophilic range. Apart from the initial drop of temperature in the lower zone, the temperature pattern observed in this trial is quite typical of composting systems where aeration is not feedback controlled (MacGregor *et al.*, 1981; Finstein *et al.*, 1986 a and 1986b).

In the second trial (Appendix 1), the upper and middle regions (T5, T6 and T3, T4) reached the highest temperatures after about six days of operation (approximately 72^{0}C). Again, an explanation of that could be the natural convective movement of heat in the pile. The lower region (T1 and T2) showed the similar pattern as in trial 1, i.e., the initial drop in temperature due to continuous aeration for 24 hours. The remarkable difference between trial 1 and 2 was in the middle region. Trial 1 had a distinct top and middle region temperature profiles, where as in trial 2 both top and middle regions showed same pattern of temperature rise. This difference could have been due to the reason that continuous aeration was stopped after 24 hours, allowing the temperature in the middle region to rise. This also indicates that continuous aeration for 24 hours, followed by 10 minutes every hour results in lower temperatures in the bottom region.

Trials 3 (Appendix 1) and 4 (Figure 4.1) showed similar patterns of temperature rise. Top and middle regions reached the highest temperature between 67^{0}C and 75^{0}C after 5 days of operation, respectively. There was no initial drop in the temperature in lower zone. This justifies the argument that trials 1 and 2 saw the initial temperature drop in this region because of continuous aeration.

Trial 5 gave a very distinct temperature profile for all three regions, all reaching maximum within 4 days of operation (appendix 1). A rather fast decrease in temperature could indicate the termination of the microbial activity in this pile, although maximum temperature never exceeded 65^{0}C. One reason for temperature drop in the bottom region (S3) was that there was a net gain of moisture. This coupled with aeration and lower ambient temperature in the month of June when the trial was conducted kept the temperature low. Only the top region remained between temperatures of 55^{0}C and 65^{0}C for 3 days. This trial also had the lowest amount of piggery solids. Several countries have independently established standards for sanitization of sewage sludge ranging from 55^{0}C to 65^{0}C covering a time span ranging from 24 hours to three days (De Bertoldi *et al.*, 1988). Pereira-Neto *et al.* (1987a) stated that a widely used minimum standard for sanitization is to maintain a temperature of 55^{0}C for at least three days.

In temperature controlled experiments (6 and 7), partially enclosed vessels were placed in water baths and the temperature through out the composting mass in the vessel reached to designated levels of 70 ^{0}C and 60 ^{0}C within few hours of starting the experiment. The temperature in the 70 ^{0}C vessel never exceeded the designated 70 ^{0}C where as in the 60 ^{0}C vessel it exceeded 60 ^{0}C within few hours. The heat generated by the piggery solid/sawdust mass decomposition would have contributed to this increase. The water bath temperature had to be kept lower than 60 ^{0}C to accommodate the heat generated in the mass. However, this phenomenon stopped after 2 days. As compared to other trials (for example trials 1 to 4) the self generated heat did not last several days because the small amount of substrate in a large vessel volume could not have sustained prolonged heat generation.

6.3.2 Moisture

The change in moisture levels at two sampling points within the compost heap in trials 1 to 5 were similar. Moisture was removal from heaps at S2, where as the moisture content increased at S1 in all trials. These results are presented in Table 6.1.

Table 6.1 Change in moisture content

Trial	Initial Moisture (%)	Final moisture (%)			Change in moisture (%)		
		Position S1	Position S2	Position S3	Position S1	Position S2	Position S3
1	66.54	68.44	46.77	-	2.86	-29.71	-
2	70.96	75.24	58.94	-	6.03	-16.94	-
3	71.43	75.70	58.33	62.93	5.98	-18.34	-11.9
4	72.38	75.55	64.34	67.42	4.38	-11.11	-6.85
5	66.37	72.51	57.55	69.97	9.25	-13.29	5.42
6	61.34	53.65			-12.54		
7	60.79	54.01			-11.15		

To explain the moisture reduction at S2 and moisture increase at S1, we might consider the middle region of compost heaps to be similar to those in temperature controlled systems. These systems maintain the temperature of the composting heap in the range of 55^0C and 65^0C. Many studies have shown that maximum heat production takes place at temperatures near 55^0C (Suler and Finstein, 1977; MacGregor *et al.*, 1981). Many studies have demonstrated that nearly twice the amount of moisture was removed in the temperature controlled systems. Evaporative cooling is the dominant heat removal mechanism in composting, removing nearly nine times more heat than by convection (MacGregor *et al.*, 1981). The evaporation can be accelerated by increasing aeration rate in aerated piles. The mechanism involved to remove moisture in the middle region of the compost heap in all the trials was similar to those in temperature controlled aeration systems. The rate of aeration was sufficient to maintain near ideal conditions in the middle of the heap and to facilitate the moisture removal by evaporation.

To prove that evaporative cooling was the main mechanism involved in removing greater amounts of moisture from the middle of the heap, duplicate samples of compost mixture were collected at S3 (bottom layer) in trials 3, 4 and 5. Determination of moisture content on these samples showed that there was net moisture loss from the bottom layer in trials 3 and 4 (Table 6.1). This could have been due to the fact that temperature rise in the bottom layer in these trials followed the same pattern as in the middle layer and evaporative cooling did take place. Moisture content increased at the bottom of the pile (S3) in trial 5. Since most of the water vaporization is driven by microbiologically generated heat, the small amount of heat occurring in the composting material at the bottom of the pile was not sufficient for a distinct water loss through evaporation. Simple drainage of free moisture from the bottom layer would also have contributed to net moisture loss.

This shows that moisture removal from the compost heap depends upon not only a suitable temperature range, but also on the mode of heat movement.

In laboratory trials 6 and 7, only one sampling point was used in the vessel due to the small amount of composting mixture in it. The temperature development at various depths indicated that there was a uniform profile through out the vessel. This , along with the

aeration, would have ensured that moisture removal from the entire depth of substrate in the vessel was also uniform. In laboratory experiment 6, four replicates analysed for moisture content on two separate samples gave a standard error of 0.67% (s.d. 1.33). If it is assumed that the similar degree of standard errors would have occurred in trials 1 to 5, it could be explained why a usual downward moisture removal trend was not obvious in some pilot trial cases. The size of the compost heap in trials 1 to 5, difference in temperature profiles, and possible incomplete mixing could also have contributed to variability of moisture removal data. The standard error in trial 7 was 0.68% (s.d. 1.35), further emphasising that correct protocols were observed for the determination of moisture content on all samples.

Now we can set the calculations for Residual Sum of Squares in the structure of an analysis of variance to compare change in moisture content in experiments 6 and 7, and trial 4.

It is clear from Table 6.2 that experiments 6 and 7 provided no evidence of any significant difference in moisture removal trend. It is also evident that there is no significant difference in moisture removal slopes between experiment 6 and sampling point S2 in trial 4. In pilot trials 1 to 5, there was a consistent moisture loss from position S2. Trial 4 had the highest initial moisture content as compared to experiment 6. A non-significant difference in slopes between experiment 6, and position S2 in trial 4 concludes that piggery solids could be composted at higher initial moisture contents than the literature suggests. The values for optimum initial moisture content provided in the literature are generally for sewage sludge composting. Piggery solids are more fibrous and friable in nature and can facilitate more air flow through them, even at higher moisture contents.

Table 6.2 Residual Sum of Squares for moisture contents

MC6 Vs MC 7	s.s.	d.f.	m.s.	F	Significance
RSS_c	0.01	19			
$RSS_1 + RSS_2$	0.0094	18	0.0005		
$RSS_c - (RSS_1+RSS_2)$	0	1	0.0001	0.1936	NS
MC6 Vs MC4S1					
RSS_c	0.021	19			
$RSS_1 + RSS_2$	0.0102	18	0		
$RSS_c - (RSS_1+RSS_2)$	0.0108	1	0.011	18.933	S
MC6 Vs MC4S2					
RSS_c	0.0114	19			
$RSS_1 + RSS_2$	0.0092	18	0.0005		
$RSS_c - (RSS_1+RSS_2)$	0.0023	1	0.0023	4.4528	NS
MC7 Vs MC4S1					
RSS_c	0.0132	19			
$RSS_1 + RSS_2$	0.0044	18	0.0002		
$RSS_c - (RSS_1+RSS_2)$	0.0088	1	0.01	36.013	S
MC7 Vs MC4S2					
RSS_c	0.005	19			
$RSS_1 + RSS_2$	0.003	18	0		
$RSS_c - (RSS_1+RSS_2)$	0.0018	1	0.0018	9.8616	S

There is a significant difference between slopes of experiment 7 moisture removal and position S2 in trial 4. If the standard errors, as discussed before, in these experiments are taken into consideration, this situation may change.

The differences in slopes of moisture removal for experiments 6 and 7, and position S1 in trial 4 were consistently significant. This can be attributed to moisture gain at position S1 in trial 4.

6.3.3 Total Solids and Volatile Solids

Composting, as a process, is primarily used for the stabilization of organic materials that are relatively high in volatile solids. Screened piggery solids contain volatile solids in excess of 80%. The degradation of the volatile solids results in the production of heat and a subsequent temperature increase characteristic of the composting system. The increase in temperature causes a reduction in moisture content and increase in total solids (Haug, 1993). Miller and Finstein (1985) also stated that increase in total solids is an indication of decomposition because drying is caused by vaporization which in turn, is driven mainly by heat generated at the expense of organic matter.

As discussed in Section 6.3.2, maximum heat generation and decomposition of organic material occurs at temperatures near 55^0C. The explanation for greater decomposition in this range is that a larger, more diverse microbial population is present at 55^0C as opposed to higher temperatures (Finstein and Morris, 1975). At higher temperatures, fungi are completely inhibited and bacteria and actinomycete populations are reduced to thermotolerant species. The greater the decomposition, the more stabilised the organic material becomes.

In Trial 1 there was net increase in the total solid content (Table 6.3). The increase in total volatile solids (Table 6.4) is not in agreement with trends observed in other trials. The increase in total solids and decrease in the fraction of volatile solids during the composting period in trials 2, 3, 4, and 5 are in agreement with trends described by many authors (Haug, 1993; Golueke, 1977; Finstein *et al.*, 1986b, Witter and Lopez-Real, 1987b). There was significant difference at 5% level from the start to finishing of each composting trial in total solids contents at position 2. There was also significant difference at 5% level between position S1 and S2 in total solids content in all trials 1 to5. The difference in the amount of total solids change between positions S1 and S2 is related to moisture removal and has

been discussed in the previous section.

Table 6.3 present a summary of changes in total solids in trials 1 to 5 and experiments 6 and 7.

Table 6.3 Change in total solids

Trial	Initial TS (%)	Final TS (%)		Change in TS (%)		Significance (P=0.05)
		Position S1	Position S2	Position S1	Position S2	
1	33.46	31.56	53.23	-5.68	59.09	S
2	29.04	24.76	41.06	-14.74	41.39	S
3	28.57	24.30	41.67	-14.95	45.85	S
4	27.62	24.45	35.66	-11.48	29.11	S
5	33.63	27.49	42.45	-18.26	26.23	S
6	38.66	46.34		19.86		S
7	39.21	45.99		17.29		S

Now we can set the calculations for Residual Sum of Squares in the structure of an analysis of variance to compare change in total solids in experiments 6 and 7, and trial 4.

It is clear from Table 6.4 that experiments 6 and 7 provided no evidence of any significant difference in the trend (slope) for total solids change. It is also evident that there is no significant difference in total solids slopes between experiment 6 and sampling point S2 in trial 4. In pilot trials 1 to 5, there was a consistent total solids gain from position S2. Trial 4 had the lowest initial total solids content as compared to experiment 6. A non-significant difference in slopes between experiment 6 and position S2 in trial 4 concludes that piggery solids could be composted at lower initial total solids contents than the literature suggests.

Also, there is no significant difference between slopes of experiment 7 total solids content and position S2 in trial 4. It justifies the assumption in the previous section that inclusion of standard errors, and subsequent analysis of the difference in slopes in these experiments may change the significant difference of Residual Sum of Squares between experiment 6 and position S2 in trial 4 moisture removal.

Table 6.4 Residual Sum of Squares for total solids

TS6 Vs TS7	s.s.	d.f.	m.s.	F	Significance
RSS_c	0.0178	19			
$RSS_1 + RSS_2$	0.0176	18	0.0010		
$RSS_c - (RSS_1+RSS_2)$	0.0001	1	0	0.1486	NS
TS6 Vs TS4S1					
RSS_c	0.0550	19			
$RSS_1 + RSS_2$	0.0317	18	0.0018		
$RSS_c - (RSS_1+RSS_2)$	0.0233	1	0.0233	13.267	S
TS6 Vs TS4S2					
RSS_c	0.0229	19			
$RSS_1 + RSS_2$	0.0220	18	0.0012		
$RSS_c - (RSS_1+RSS_2)$	0.0009	1	0.0009	0.7023	NS
TS7 Vs TS4S1					
RSS_c	0.0398	19			
$RSS_1 + RSS_2$	0.0209	18	0.0012		
$RSS_c - (RSS_1+RSS_2)$	0.0189	1	0.0189	16.269	S
TS7 Vs TS4S2					
RSS_c	0.0114	19			
$RSS_1 + RSS_2$	0.0112	18	0.0006		
$RSS_c - (RSS_1+RSS_2)$	0.0002	1	0.0002	0.3105	NS

The differences in slopes of total solids contents for experiments 6 and 7, and position S1 in trial 4were consistently significant. This can again be attributed to moisture gain at position S1 in trial 4.

There was significant difference (Anova, P=0.05) in volatile solids reduction among trials (Table 6.17).

Table 6.5 presents a summary of changes in volatile solids in five trials. The progress in volatile solids destruction clearly indicates the progress of decomposition process. Many workers have proposed the use of volatile solids destruction as a means of following the decomposition process, since aerobic biological activity decreases the volatile solids content by converting organic carbon to CO_2. Finstein *et al.* (1986b) have recommended the use of volatile solids as a measure of organic matter content, whereas its measurement over time during the process might serve as a rate parameter. Witter and Lopez-Real (1987b) state that a reduction in volatile solids appears to be an accurate measure of dry solids losses during the composting process. However, sensitivity of volatile solids test is a problem which can affect the use of volatile solids as a measure of degradation (Finstein *et al.*, 1986b).

Table 6.5 Change in volatile solids

Trial	Initial VS (%)	Final VS (%)		Change in VS (%)		Significance (P=0.05)
		Position S1	Position S2	Position S1	Position S2	
1	84.99	89.80	90.46	5.66	6.44	NS
2	87.82	77.63	81.94	-11.6	-6.7	S
3	86.21	79.80	82.83	-7.46	-3.92	S
4	82.98	70.67	79.14	-14.83	-4.63	S
5	81.57	77.11	77.25	-5.47	-5.3	NS

The increase in total solids contents or decrease in moisture content measured in all composting trials can also be used as an indicator for the course of decomposition. This is supported by Miller and Finstein (1985) who stated that this is because the drying is caused by vaporisation, which in turn is driven mainly by heat generation at the expense of organic matter.

A complete reduction of volatile solids is not desirable because the value of compost as a soil amendment depends in part on its organic content (Haug, 1993). From the stabilisation point of view (excluding the degree of disinfection) the piggery compost in this study exhibiting volatile solids reduction presented in Table 6.5 can be used as a soil conditioner. There is a lot of controversy in literature concerning the assessment of maturity or degree of stabilisation of compost (Penninck and Verdonck, 1987; Witter and Lopez-Real, 1987b; Zucconi and De Bertoldi, 1987). Carbon and nitrogen are the building blocks of plant and animal cells and, therefore, are impacted by microbial activity. Hence they are the most studied parameters during the decomposition process. Epstein (1997) has provided comprehensive list of the methods used to assess compost stability and maturity.

Piggery solid wastes are nutrient rich fibrous material readily amenable to aerobic composting (Bhamidimarri and Pandey, 1996). The bulking agent used in all out trials (sawdust) has a very high carbon and low nitrogen content. Due to these properties, and the sensitivity with the use of volatile solids reduction as a means of decomposition indicator, total organic carbon decomposition was selected for the determination of reaction rate constant in this research.

6.3.4 Nutrients

In composting, the nitrogenous content generally decreases during the course of the process, mainly because of nitrogen volatilisation (Golueke, 1977; Haug, 1993). However, the reactions of nitrogen loss as well as the reactions of partial recovery by fixation are very complex (Pereira-Neto *et al.*, 1987b). De Bertoldi *et al.* (1982) stated that an optimum functioning of these complex reactions, which relate very closely to the temperature development in the heap, could be best achieved by using combined temperature-feedback

control and forced aeration. It was not intended in this work to optimise these factors. Instead, a decrease in total nitrogen concentration was used as an indication of an ongoing composting activity in the heap.

Total nitrogen trends from trials 1 to 5 shown in Figure 4.6 and Appendix 3 generally exhibit such a downward trend. The standard error calculations were not carried out for total nitrogen change over time in these trials. However, laboratory experiments 6 and 7 under controlled conditions provided an indication of standard error of total nitrogen contents for 4 replicates. The standard error analysed in trial 6 on day 2 of the operation was of the order of 0.75 (s.d. 1.49), whereas it was of the order of 0.50 (s.d.0.98) on day 6.

In laboratory experiment 7, the standard deviation (n=4) was of the order of 0.43 and 1.07 and standard error of 0.22 and 0.54 on days 3 and 7, respectively.

The total nitrogen content of fresh piggery solids was measured prior to mixing it with sawdust. Mixing of solids and sawdust, and subsequent construction of piles took a long time. A lot of nitrogen would have lost through ammonia volatilization during this period. In view of this, it was decided to derive the initial total nitrogen in the composting mixture on day 1 from the values of bulk densities and volume ratios of piggery solids and sawdust, and total nitrogen present in the freshly screened piggery solids, the measured value of which is very similar to that reported in the literature (Vanderholm, 1984; Bolan, 1989). This value is then used to calculate whether there is a nitrogen loss or conservation in the system.

Changes in total nitrogen (loss or conservation) observed in trials 1 to 5 (Table 6.6) based on the above assumption were typical with regard to piggery solids composting. Trials had up to about 75% of total nitrogen conserved (up to 25% loss) during the composting process.

In laboratory study 6, the freshly screened solid consisted of about 15.7 mg/g total nitrogen. Using the bulk densities of piggery solid and sawdust, the ratio of piggery solid and sawdust, and total nitrogen in freshly screened solids, the calculated value of total nitrogen

in the composting mixture on day 0 was 14.45 mg/g. The composting mixture consisted about 7.97 mg/g total nitrogen at the end of the composting experiment period. This amounted to approximately 44.84% change in total nitrogen content, or a total nitrogen conservation of about 55.16%.

In laboratory study 7, the freshly screened solid consisted of about 18.8 mg/g total nitrogen. Using the bulk densities of piggery solid and sawdust, and the ratio of piggery solid and sawdust, the calculated value of total nitrogen in the composting mixture on day 0 was 17.3 mg/g. The composting mixture consisted about 9.22 mg/g total nitrogen at the end of the composting experiment period. This amounted to approximately 46.70% change in total nitrogen content, or a total nitrogen conservation of about 53.30%.

Table 6.6 Change in total nitrogen

Trial	Initial TN (%)	Final TN (%)		TN Change (%)		TN Conservation (%)	
		Position S1	Position S2	Position S1	Position S2	Position S1	Position S2
1	12.54	4.95	6.68	-60.53	-47.73	39.47	53.27
2	14.71	11.28	9.28	-23.32	-36.91	76.68	63.09
3	13.11	6.53	6.57	-50.2	-49.89	49.8	50.11
4	16.07	9.75	9.9	-39.33	-38.39	60.67	61.61
5	10.97	5.88	5.26	-46.4	-52.05	53.6	47.95
6	14.45	7.97		-44.84		55.16	
7	17.3	9.22		-46.71		53.29	

Although ammonia volatilisation was not measured , the rapid loss of N on initial day in these trials could have resulted in the form of NH_3 gas from ammonium containing piggery solids, which hydrolyse to ammonia. The rate of hydrolysis, and therefore volatilisation, is affected by system temperature, moisture levels and pH. Ammonia would have reacted with

protons, metals and acidic compounds and dissolves in the composting solution to form a stable ionic form of ammonium (NH_4^+). The ammonium thus formed exits in a chemical equilibrium with gaseous NH_3. The increase in the concentration of ammonium in compost solution would have increased pH and result in the volatilisation of NH_3 from the composting heap. An increase in pH after the initial drop for a certain period during composting process was recorded in trials 1 to 5. Witter and Lopez-Real (1987a) have also supported this finding that the combination of high ammonium concentrations, high temperature and pH levels may lead to high NH_3 losses during composting.

Vanderholm (1975) estimated that 30 to 65% of N in manure is lost during storage. Total N losses between 30 and 50% were reported in free-stall barn by Muck and Richards (1983). A loss of about 56% of total N within 12 weeks storage of cattle manure was reported by Mooreand Beehler (1981). Several factors including meteorological variations, nature of manure or slurry and methods of measurements may have contributed to the large variation encountered in N loss from manure.

In the case of sewage sludge composting, most of the nitrogen was reported to be lost as ammonia (Stentiford, 1987). Up to half of nitrogen loss was reported by Bogoni (1988) during the composting of sewage sludge mixed with woodchips. Martins and Dewes (1992) reported the greatest amount of nitrogen loss as ammonia emission (46.8-77.4% of total nitrogen in composting of animal waste). Some of the other reported losses of nitrogen during the storage or composting are summarised in Table 2.9.

Now we can set the calculations for Residual Sum of Squares in the structure of an analysis of variance to compare change in total nitrogen in experiments 6 and 7, and trial 4.

Table 6.7 Residual Sum of Squares for total nitrogen

TN6 Vs TN7	s.s.	d.f.	m.s.	F	Significance
RSS_c	0.4066	19			
$RSS_1 + RSS_2$	0.4041	18	0.0225		
$RSS_c - (RSS_1+RSS_2)$	0.0025	1	0.0025	0.1125	NS
TN6 Vs TN4S1					
RSS_c	0.5076	19			
$RSS_1 + RSS_2$	0.5009	18	0.028		
$RSS_c - (RSS_1+RSS_2)$	0.0067	1	0.0067	0.2405	NS
TN6 Vs TN4S2					
RSS_c	0.532	19			
$RSS_1 + RSS_2$	0.5072	18	0.0282		
$RSS_c - (RSS_1+RSS_2)$	0.0248	1	0.0248	0.8794	NS
TN7 Vs TN4S1					
RSS_c	0.5151	19			
$RSS_1 + RSS_2$	0.4977	18	0.0277		
$RSS_c - (RSS_1+RSS_2)$	0.0174	1	0.0174	0.6308	NS
TN7 Vs TN4S2					
RSS_c	0.5471	19			
$RSS_1 + RSS_2$	0.5040	18	0.0280		
$RSS_c - (RSS_1+RSS_2)$	0.0431	1	0.0431	1.5403	NS

It is clear from the above Table 6.7 that experiments 6 and 7 provided no evidence of any significant difference in the trend (slope) for total nitrogen change. It is also evident that there is no significant difference in total nitrogen change slopes between experiment 6 &7 and sampling point S1 and S2 in trial 4.

Changes in total phosphorus observed in all trials, except in trial 1, (Table 6.8) were typical with regard to piggery solids composting. The analytical data indicate the value of the

compost in agricultural application. The changes that occurred in phosphorus concentration were probably due to losses of dry solids by volatilisation (volatile solids). This leads to a slight relative increase in phosphorus, since its determination occurred on a dry solids basis. The drop in volatile solids content and other decomposition activities in trials support this change. It may not be difficult to explain why in trial 1 there was high increase in phosphorus concentration, and if we take into consideration the average standard error for 4 replicates on two different samples in experiments 6 and 7 this situation might change.

Table 6.8 Change in total phosphorus

Trial	Initial TP (%)	Final TP (%)		Change in P (%)	
		Position S1	Position S2	Position S1	Position S2
1	2.26	4.99	3.71	116	61.3
2	3.69	5.89	4.96	59	34.42
3	3.93	3.96	3.86	0.8	-3.3
4	4.65	5.16	5.19	10.97	11.61
5	2.24	2.29	3.14	2.23	40
6	4.26	5.32		24.88	
7	4.51	5.74		27.27	

The laboratory experiments 6 and 7 under controlled conditions provided an indication of standard error of total phosphorus contents for 4 replicates. The standard error analysed in trial 6 on day 2 of the operation was of the order of 0.51 (s.d. 1.02), whereas it was of the order of 0.36 (s.d.0.74) on day 6.

In laboratory experiment 7, the standard deviation (n=4) was of the order of 0.29 and 1.36 and standard error of 0.15 and 0.68 on days 3 and 7, respectively.

Now we can set the calculations for Residual Sum of Squares in the structure of an analysis

of variance to compare change in total phosphorus in experiments 6 and 7, and trial 4.

Table 6.9 Residual Sum of Squares for total phosphorus

TP6 Vs TP7	s.s.	d.f.	m.s.	F	Significance
RSS_c	0.2667	19			
$RSS_1 + RSS_2$	0.2628	18	0.0146		
$RSS_c - (RSS_1+RSS_2)$	0.0039	1	0	0.2667	NS
TP6 Vs TP4S1					
RSS_c	0.4225	19			
$RSS_1 + RSS_2$	0.4225	18	0.024		
$RSS_c - (RSS_1+RSS_2)$	0.0000	1	0	0	NS
TP6 Vs TP4S2					
RSS_c	0.4072	19			
$RSS_1 + RSS_2$	0.3948	18	0.0219		
$RSS_c - (RSS_1+RSS_2)$	0.0124	1	0.0124	0.5643	NS
TP7 Vs TP4S1					
RSS_c	0.2402	19			
$RSS_1 + RSS_2$	0.2368	18	0.0132		
$RSS_c - (RSS_1+RSS_2)$	0.0034	1	0.0034	0.2604	NS
TP7 Vs TP4S2					
RSS_c	0.2115	19			
$RSS_1 + RSS_2$	0.2091	18	0.0116		
$RSS_c - (RSS_1+RSS_2)$	0.0024	1	0.0024	0.2055	NS

It is clear from Table 6.9 that experiments 6 and 7 provided no evidence of any significant difference in the trend (slope) for total phosphorus change. It is also evident that there is no significant difference in total phosphorus change slopes between experiment 6 &7 and sampling point S1 and S2 in trial 4. These non-significant differences in the Residual Sums

of Square values further reiterate that pilot trial 4 and controlled experiments 6 and 7 gave same, and in some cases identical trends of decomposition.

The decrease in total organic carbon concentration paralleled changes in the volatile solids content. This trend was also observed by Pereira-Neto *et al.* (1987b). These losses in this study were less than expected. This was primarily because the bulking agent has a very high organic carbon content and therefore, the decrease in the organic carbon of the mixture is small. Table 6.10 presents a summary of changes in total organic carbon in five pilot trials and two laboratory experiments.

Table 6.10 Change in total organic carbon

Trial	Initial TOC (%)	Final TOC (%)		Change in TOC (%)	
		Position S1	Position S2	Position S1	Position S2
1	55.73	53.80	56.31	-3.46	1.04
2	55.76	51.60	49.14	-7.46	-11.87
3	51.91	50.18	51.02	-3.33	-1.71
4	52.58	41.13	43.24	-21.88	-17.76
5	50.73	49.53	50.58	-2.37	-0.3
6	54.36	46.97		-14.6	
7	57.06	44.29		-22.38	

The laboratory experiments 6 and 7 under controlled conditions provided an indication of standard error of total organic carbon contents for 4 replicates. The standard error analysed in trial 6 on day 2 of the operation was of the order of 0.89 (s.d. 1.79), whereas it was of the order of 0.98 (s.d.1.97) on day 6.

In laboratory experiment 7, the standard deviation (n=4) was of the order of 1.59 and 1.66 and standard error of 0.80 and 0.83 on days 3 and 7, respectively.

Now we can set the calculations for Residual Sum of Squares in the structure of an analysis of variance to compare change in total organic carbon in experiments 6 and 7, and trial 4.

Table 6.11 Residual Sum of Squares for total organic carbon

TOC6 Vs TOC7	s.s.	d.f.	m.s.	F	Significance
RSS_c	0.0162	19			
$RSS_1 + RSS_2$	0.0151	18	0		
$RSS_c - (RSS_1+RSS_2)$	0.001	1	0	1.3244	NS
TOC6 Vs TOC 4s1					
RSS_c	0.025	19			
$RSS_1 + RSS_2$	0.0232	18	0		
$RSS_c - (RSS_1+RSS_2)$	0.002	1	0	1.4085	NS
TOC6 Vs TOC 4s2					
RSS_c	0.0886	19			
$RSS_1 + RSS_2$	0.0885	18	0		
$RSS_c - (RSS_1+RSS_2)$	0	1	0	0.024	NS
TOC7 Vs TOC 4s1					
RSS_c	0.0198	19			
$RSS_1 + RSS_2$	0.0197	18	0		
$RSS_c - (RSS_1+RSS_2)$	0	1	0	0.079	NS
TOC7 Vs TOC 4s2					
RSS_c	0.0869	19			
$RSS_1 + RSS_2$	0.085	18	0		
$RSS_c - (RSS_1+RSS_2)$	0.002	1	0	0.4114	NS

It is clear from Table 6.11 that experiments 6 and 7 provided no evidence of any significant difference in the trend (slope) for total organic carbon change. It is also evident that there is no significant difference in total organic carbon change slopes between experiment 6 &7 and sampling point S1 and S2 in trial 4. These non-significant differences in the Residual Sums of Square values among experiment 6 & 7 and trial 4 are useful indicator of similar decomposition taking place in a pilot scale study and a controlled laboratory study.

The Residual Sum of Squares comparison of C/N ratios from start to end of trial 4 and experiments 6 & 7 also gave very useful results. Table 6.12 shows clearly that experiments 6 and 7 provided no evidence of any significant difference in the trend (slope) for C/N ratio change. It is also evident that there is no significant difference in C/N ratio change slopes between experiment 6 &7 and sampling point S1 and S2 in trial 4.

Laboratory experiments 6 and 7 started with comparatively higher and similar initial C/N ratios to trial 4, respectively. A non-significant difference in slopes between experiments 6 & 7, and positions S1 and S2 in trial 4 suggests that piggery solids could be composted at higher initial C/N ratio than the literature suggests. The values for optimum initial C/N ratio provided in the literature are generally for sewage sludge or solid municipal waste composting. The fibrous nature of piggery solids supports more decomposition in the composting process.

Table 6.12 Residual Sum of Squares for C/N ratios

C/N6 Vs C/N 7	s.s.	d.f.	m.s.	F	Significance
RSS_c	0.3702	19			
$RSS_1 + RSS_2$	0.3676	18	0.0204		
$RSS_c - (RSS_1+RSS_2)$	0.0027	1	0.0027	0.1301	NS
C/N6 Vs C/N 4S1					
RSS_c	0.5761	19			
$RSS_1 + RSS_2$	0.5744	18	0.0319		
$RSS_c - (RSS_1+RSS_2)$	0.0017	1	0.002	0.052	NS
C/N6 Vs C/N 4S2					
RSS_c	0.4395	19			
$RSS_1 + RSS_2$	0.4131	18	0.0229		
$RSS_c - (RSS_1+RSS_2)$	0.0264	1	0.0264	1.1491	NS
C/N7 Vs C/N 4S1					
RSS_c	0.4505	19			
$RSS_1 + RSS_2$	0.4417	18	0.0245		
$RSS_c - (RSS_1+RSS_2)$	0.0089	1	0.0089	0.3619	NS
C/N7 Vs C/N 4S2					
RSS_c	0.4279	19			
$RSS_1 + RSS_2$	0.4252	18	0.0236		
$RSS_c - (RSS_1+RSS_2)$	0.0027	1	0.0027	0.1148	NS

6.3.5 pH

Measured pH values of compost samples were consistent throughout the study and in agreement with values in literature. A decrease in pH was registered at the initial stage of the composting process in all trials, except in trial 2. Initial decrease in pH has been reported by Pereira-Neto *et al.* (1987b). Acid formation is the consequence of microbial

degradation of complex carbonaceous materials to organic acids and other end products. These substances cause the pH to drop. With good aeration the products so formed are metabolised readily to CO_2 and H_2O. The increase in pH values after initial stage might indicate a poor aeration which supports the protein degradation reactions which release basic compounds such as ammonia and amines thereby increasing the pH. The increase in pH during this stage might also indicate a slow microbial degradation in trials due to higher temperature regimes. Overall, there was pH drop in all trials between the starting and finishing of active composting process. Table 6.13 summarises the change in pH levels during the composting trials.

Table 6.13 Change in pH

Trial	Initial pH	Final pH	
		Position S1	Position S2
1	7.74	6.68	6.58
2	6.93	7.15	6.91
3	7.00	6.20	7.00
4	7.40	7.10	7.20
5	6.70	5.80	5.70

6.3.6 Microbiology

The changes in microbial counts of MPN and Streptococci are presented in Tables 6.14 and 6.15, respectively. There was varying order of magnitude reduction in Streptococci numbers in different pilot trials. In trials where almost all Streptococci were inactivated, the thermophilic temperatures prevailed sufficiently long enough. For example, in trial 1 there was 3 orders of magnitude reduction in streptococci number at S1 because of longer period of thermophilic temperature. On the other hand there was only one order of magnitude

reduction in streptococci at position S2 because the temperature regime was not maintained long enough in thermophilic stage. As stated earlier, such results emphasise the importance of adequate time-temperature processing conditions which are also necessary in composting to achieve successful sanitation of the final product (De Bertoldi *et al.*, 1988; Strauch, 1987). In trials 3 and 4 where thermophilic condition prevailed for long time at both positions S1 and S2, the difference in Streptococci number reduction at these positions may only be explained by non-homogeneous mixing of piggery solid and sawdust.

Similar trends were observed for MPN reduction. The high temperatures of the pile for prolonged periods are expected to decrease the bacterial counts to levels lower than those observed. The high values of MPN indicate that there are certain spore formers which survive the composting process.

Table 6.14 Change in MPN

Trial	Initial MPN	Final MPN		Change in MPN (%)	
		Position S1	Position S2	Position S1	Position S2
1	7000000	13000	920000	99.81	86.86
2	17000000	35000	54000	99.79	99.68
3	17000000	16000	33000	99.91	99.81
4	4900000	20	2300	100.00	99.95
5	7900000	130000	1700000	98.35	78.48
6	1.30e+09	0.2		100	
7	1.30e+09	0.2		100	

Table 6.15 Change in Streptococci counts

Trial	Initial Strep	Final Strep		Change in Strep (%)	
		Position S1	Position S2	Position S1	Position S2
1	480000	400	42000	99.92	91.25
2	3000000	31000	2000	98.97	99.93
3	650000	90	10000	99.99	98.46
4	850000	11	4000	100.00	99.53
5	850000	3200	2600	99.62	99.69

Laboratory experiments 6 and 7 provided controlled environment, both in terms of the temperature control as well as homogeneous mixing of piggery solids and sawdust. Not only the total coliforms were monitored over the composting period, but faecal coliform and *E.coli* were also monitored to see if any particular bacteria can survive. All these were completely destroyed by the end of the composting process. Monitoring of enterococci also presented similar results and a near complete die-off was achieved by the end of the composting process.

It is clear from Table 6.16 that experiments 6 and 7 provided no evidence of any significant difference in the trend (slope) for total coliform, faecal coliform, *E.coli*, or enterococci changes. It is also evident that there is no significant difference in total coliform change slopes between experiment 6 &7 and sampling point S1 in trial 4. There was significant difference in total coliform change slopes between experiment 6 &7 and sampling point S2 in trial 4. In trials 4 where thermophilic condition prevailed for long time at both positions S1 and S2, the significant difference in total coliform reduction slopes compared with laboratory experiments 6 and 7, further emphasises that homogeneity is critical in any composting process. It also emphasises the need for a temperature feedback aeration

system. Any anaerobic pockets that might be present in pilot or large scale composting may render the whole composted mass unsuitable for use, especially when public health is at risk. However, the laboratory experiments 6 and 7 under controlled conditions provided an indication of standard error of total coliform counts for 4 replicates. The standard error analysed in trial 6 on day 2 of the operation was of the order of 75 (s.d. 150), whereas it was of the order of 1095 (s.d.2188) on day 6. In laboratory experiment 7, the standard deviation (n=4) was of the order of 6085 and standard error of 3042 on days 3. If it is assumed that the similar degree of standard errors would have occurred in trial 4 at S2, the difference in comparative total coliform reduction slopes may change.

Table 6.16 Residual Sum of Squares for microbial indicators

Totalcoli6 Vs Totalcoli7	s.s.	d.f.	m.s.	F	Significance
RSS_c	347.7820	19			
$RSS_1 + RSS_2$	346.4218	18	19.2457		
$RSS_c - (RSS_1+RSS_2)$	1.3602	1	1.3602	0.0707	NS
Totalcoli6 Vs Totalcoli4S1					
RSS_c	262.2062	19			
$RSS_1 + RSS_2$	234.3184	18	13.0177		
$RSS_c - (RSS_1+RSS_2)$	27.8878	1	27.8878	2.1423	NS
Totalcoli6 Vs Totalcoli4S2					
RSS_c	292.6606	19			
$RSS_1 + RSS_2$	228.0562	18	12.6698		
$RSS_c - (RSS_1+RSS_2)$	64.6044	1	64.6044	5.0991	S
Totalcoli7 Vs Totalcoli4S1					
RSS_c	288.2528	19			
$RSS_1 + RSS_2$	246.5469	18	13.6971		
$RSS_c - (RSS_1+RSS_2)$	41.7058	1	41.7058	3.0449	NS

Totalcoli7 Vs Totalcoli4S2					
RSS_c	325.1973	19			
$RSS_1 + RSS_2$	240.2847	18	13.3492		
$RSS_c - (RSS_1+RSS_2)$	84.9126	1	84.9126	6.3609	S
Ecoli6 Vs Ecoli7					
RSS_c	348.7381	19			
$RSS_1 + RSS_2$	348.1264	18	19.3404		
$RSS_c - (RSS_1+RSS_2)$	0.6116	1	0.6116	0.0316	NS
Faecal6 Vs Faecal7					
RSS_c	369.525	19			
$RSS_1 + RSS_2$	368.7235	18	20.4846		
$RSS_c - (RSS_1+RSS_2)$	0.8013	1	0.8013	0.0391	NS
Entero6 Vs Entero7					
RSS_c	83.7873	19			
$RSS_1 + RSS_2$	83.5497	18	4.6417		
$RSS_c - (RSS_1+RSS_2)$	0.2376	1	0.2376	0.051	NS

6.3.7 Reaction Rate constants

The reaction rate (k) is a function of several factors. Biological degradation of a substrate during composting involves simultaneous evaporation of moisture and generation of heat. The process is governed by mass, momentum, and energy balances. These basic equations require heat generation and loss of dry matter terms when applied to composting.

Reaction rate constants, based on the degradation of total organic carbon, were calculated to have a "measure" of the process in composting heap in trials 1 to 5. It was hypothesised that by changing the operating conditions, such as moisture content; solids to sawdust ratio, etcetera, in different trials a "best-mix" rate constant would be achieved. Further more, the best reaction rate would not only indicate the fastest degradation of total organic carbon but indicate the best possible operating conditions within the limits of the experimental set up.

The observed optimum reaction rates based on pilot trials were independently verified under controlled laboratory conditions.

The reaction rate constants of trials 1 to 5, as expected, are different from each other due to varying operating conditions. Further more they are different at positions S1 and S2 with in the same trial, except in trial 4. The mean residence time and the time required to achieve a certain C/N ratio is also markedly different as they depend on the reaction rate. Various operating conditions would have contributed to these vastly different values of reaction rate. It must be noted again that the trials 1 to 5 had different ratio of sawdust and piggery solid mixture or different aeration regime.

Analyses of the two composting experiments carried out under controlled temperature and airflow conditions provided independent verification of process rates. As discussed in previous sections, mathematical analysis to find difference in slopes for two different data sets proved that there was no significant difference among various parameters in trial 4 and laboratory experiments 6 & 7. Wherever there was significant difference, it was not too far out from the non-significant F-distribution values and if the standard errors were to be taken into consideration, those situations would have changed. In trial 4, rate constant values were of the order of 0.008 and 0.007 day^{-1} at S1 and S2 , respectively. Only one sampling position used in laboratory experiments provided rate constant values of the order of 0.0095 and 0.0134 day^{-1} in experiment 6 and 7, respectively. Obviously, no difference among these values supports the finding that operating conditions prevailing in trial 4 provided the best results for piggery solids composting. Further more, it suggests that piggery solids may be composted at higher moisture rates, or C/N ratios than suggested in the literature.

6.3.8 Inactivation rate coefficient

Inactivation of pathogens in various pilot trials varied. Only trial 4 had significant drop at 5% level in MPN numbers and streptococci. All streptococci numbers dropped significantly (except between positions in trial 2). There was significant difference among trials for both

MPN and streptococci numbers. However, in laboratory experiments a complete destruction of pathogens was achieved within the composting period.

Analyses of the two composting experiments carried out under controlled temperature and airflow conditions provided independent verification of inactivation rate coefficient. As discussed in previous sections, mathematical analysis to find difference in slopes for two different data sets proved that there was no significant difference among various parameters in trial 4 at S1 and laboratory experiments 6 & 7. At position S2 there was significant difference, but not too far out from the non-significant F-distribution values and if the standard errors were to be taken into consideration, this situations might change. In trial 4, inactivation rate coefficient values were of the order of 0.394 and 0.380 day^{-1} at S1 and S2, respectively. Only one sampling position used in laboratory experiments provided inactivation rate coefficient values of the order of 61.97 and 47.339 day^{-1} in experiment 6 and 7, respectively. These values were expected under controlled temperature and air flow conditions where a complete destruction of pathogens was achieved. Rapid decay may be responsible for higher values of inactivation rate constants in laboratory experiments. Trial 2 also had the most rapid decay in the number of MPN within 2 days of starting of composting operation at both positions S1 and S2, and hence had the highest inactivation rate constant value among all the pilot trials.

Table 6.17 Calculated F values and probability levels (5%) for different variables

Variable	Effect	
	Treatment	Position
TS	F(4,4) =2.349 p > F =0.2142	F(1,4) =92.139 p > F =0.0006
VS	F(4,4) =10.485 p > F =0.021	F(1,4) =4.929 p > F =0.091
MPN	F(4,4) =282.89 p > F =3.7E-05	F(1,4) =2.50 p > F =0.189
STREP	F(4,4) =6704.52 p > F =6.7E-08	F(1,4) =0.210 p > F =0.670
pH	F(4,4) =5.864 p > F =0.057	F(1,4) =0.247 p > F =0.645
TN	F(4,4) =7.54 p > F =0.0379	F(1,4) =0.054 p > F =0.828
TOC	F(4,4) =18.74 p > F =0.0075	F(1,4) =0.856 p > F =0.407
TP	F(4,4) =0.9431 p > F =0.522	F(1,4) =0.579 p > F =0.489

6.4 Conclusions

The development of temperature profiles in the pilot trial pile at different thermocouple positions were similar in all the trials and in agreement with trials conducted by various authors. The change in moisture levels at two sampling points within the compost heap for each trial were similar. The increase in Total Solids and decrease in the fraction of Volatile Solids during the composting period in many trials were in agreement with trends described by many authors and demonstrated the decomposition process.

The temperature development in the vessel used for laboratory experiments was uniform

throughout the depth of the substrate due to controlled condition. The moisture removal in these experiments was similar to that in trial 4 at position S2,which exhibited similar response to laboratory experiments. The increase in Total Solids and decrease in the fraction of Volatile Solids during the composting period in laboratory experiments were also similar to that of trial 4. Laboratory experiments provided no evidence of any significant difference in moisture removal trend. They also showed that there was no significant difference in moisture removal slopes between experiment 6 and sampling point S2 in trial 4.This trial had the highest initial moisture content as compared to experiment 6. A non-significant difference in slopes between experiment 6, and position S2 in trial 4 concluded that piggery solids could be composted at higher initial moisture contents than the literature suggests. The values for optimum initial moisture content provided in the literature are generally for sewage sludge composting. Piggery solids are more fibrous and friable in nature and can facilitate more air flow through them, even at higher moisture contents.

Changes in Total Nitrogen observed in all pilot trials and laboratory experiments were typical with regard to piggery solid composting, and up to 60% of Total Nitrogen was conserved during the composting process in trial 4. Laboratory experiments recorded similar conservation. The change in the phosphorus concentration in trials and experiments during the composting operation was attributed to reduction in volatile solids and decomposition of composting mixture. The decrease in Total Organic Carbon concentration paralleled changes in the Volatile Solids content. Measured pH values of compost samples were consistent throughout the study and in agreement with values in literature. In pilot trials where almost all Streptococci were inactivated, the thermophilic temperatures prevailed sufficiently long enough, however, the high values of MPN indicate that there are certain spore formers which survive the composting process. Controlled laboratory experiments achieved a complete pathogen destruction.

Laboratory experiments provided no evidence of any significant difference in the trend (slope) for C/N ratio change. It is also evident that there is no significant difference in C/N ratio change slopes between experiment 6 &7 and sampling point S1 and S2 in trial 4.

Laboratory experiments 6 and 7 started with comparatively higher and similar initial C/N ratios to trial 4, respectively. A non-significant difference in slopes between experiments 6 & 7, and positions S1 and S2 in trial 4 suggests that piggery solids could be composted at higher initial C/N ratio than the literature suggests. The values for optimum initial C/N ratio provided in the literature are generally for sewage sludge or solid municipal waste composting. The fibrous nature of piggery solids supports more decomposition in the composting process.

Values of reaction rate constant varied under different operating conditions of compost piles. In trial four, rate constant values were of the order of .008 and .007 day^{-1} at S1 and S2, respectively. Laboratory experiments gave similar reaction rate constants to trial 4. This is beside the fact that a constant temperature profile was maintained throughout the composting period in these two experiments.

Inactivation rate coefficient values were of the order of 0.394 and 0.380 day^{-1} at two sampling positions, respectively in trial 4.. The laboratory experiments provided inactivation rate coefficient values of the order of 61.97 and 47.339 day^{-1}, respectively. The significant difference in total coliform change slopes between controlled experiments and trial 4 further emphasises that homogeneity is critical in any composting process. It also emphasises the need for a temperature feedback aeration system.

CHAPTER 7

CONCLUSIONS AND APPLICATION

The following conclusions can be drawn from the work presented in this thesis :

7.1 Review of literature

Commercial piggery operations produce substantial quantities of solid waste requiring further treatment and disposal. Screened piggery solids contain recyclable nutrients and pathogenic organisms. Processes used for biological degradation and pathogen control in organic solid wastes include aerobic and anaerobic digestion, heat drying, heat pasteurization and chemical treatment, usually with lime.

Composting is the biological decomposition of organic wastes under controlled conditions to a state where storage, handling and land application can be achieved without adversely affecting the environment.

Point source contribution from piggeries to surface and ground water pollution can be minimised by the application of composting process and technology. Composting can serve as the treatment component of an overall waste management plan of a commercial piggery to biologically convert the putrescible to a stabilised form free of pathogenic organisms.

The rate of biochemical reaction determines the speed at which composting can proceed. Solids Retention Time (SRT) is the most important factor in determining the stability of the compost product. SRT is function of, among many other factors, the type of substrate and amendments and their corresponding reaction rate constants.

In order to establish the minimum SRT, it is important to establish the reaction rate of

substrates. Reaction rates vary widely depending on the organic substrate. Although numerous guidelines are available for the design of effective composting plant, most of these guidelines or studies deal with sewage sludge or municipal solid waste. There is a complete lack of data on composting process design or reaction rates for piggery solids. Also, there is lack of information to suggest that the design data available for sewage sludge composting can be readily used for piggery solids. Due to these specific issues raised by the literature review, the main objectives of this thesis were to examine the composting process in relation to bulking material and operating conditions; analyse the disappearance of Total Organic Carbon with temperature development in order to determine first order reaction rates; and to analyse the inactivation or decay of indicator pathogens in piggery solids and sawdust composting trials and experiments.

7.2 Composting operation

Five composting trials, using different substrate to bulking agent ratios and aeration frequencies were performed. The composting mixtures were placed over an aerated base in the form of a pile. In addition to temperature, pH, Total Nitrogen, Total Phosphorus, Total Organic Carbon, Total Solids, Volatile Solids and the microbial counts of Streptococci and *E.coli* (MPN) were monitored initially every day up to 10 days and every 5 days thereafter until the completion of the trial, that is up to 23 days. Due to the fibrous and friable nature of piggery solids, the initial moisture contents were kept higher than literature to test whether or not composting can take place successfully under high moisture content, or other different conditions. This was to promote rapid development of microbial activity.

Two controlled laboratory experiments at 70 ^{0}C and 60 ^{0}C, respectively, using similar substrate to bulking agent ratio and aeration frequency to the fourth pilot trial were also performed because trial four presented the best result in comparison to other trials. Temperature, Total Nitrogen, Total Phosphorus, Total Organic Carbon, Total Solids, and the Microbial counts of Streptococci, *E.coli*, faecal coliform, and total coliforms were monitored initially every day up to 7 days and then on days 9, 11, and14 thereafter in the

laboratory experiments. These experiments had initial moisture content similar to those provided in the literature, and were carried out to independently verify rate constants developed from pilot trials 1 to 5.

7.3 Composting process performance

The development of temperature profiles in the pilot trial pile at different thermocouple positions were similar in all the trials and in agreement with trials conducted by various authors. The change in moisture levels at two sampling points within the compost heap for each trial were similar. The moisture removal results demonstrated that its removal from the compost pile depends upon not only a suitable temperature range, but also on the mode of heat movement. The increase in Total Solids and decrease in the fraction of Volatile Solids during the composting period in many trials were in agreement with trends described by many authors and demonstrated the decomposition process.

The temperature development in the vessel used for laboratory experiments was uniform throughout the depth of the substrate due to controlled condition. The moisture removal in these experiments was similar to that in trial 4 at position S2,which exhibited similar response to experiments 6 and 7. The increase in Total Solids and decrease in the fraction of Volatile Solids during the composting period in laboratory experiments were also similar to that of trial 4. A mathematical analysis was carried out to test whether the slopes of relationship of two parameters with respect to time were same, or different.

Experiments 6 and 7 provided no evidence of any significant difference in moisture removal trend. They also showed that there was no significant difference in moisture removal slopes between experiment 6 and sampling point S2 in trial 4.This trial had the highest initial moisture content as compared to experiment 6. A non-significant difference in slopes between experiment 6, and position S2 in trial 4 concluded that piggery solids could be composted at higher initial moisture contents than the literature suggests. The values for optimum initial moisture content provided in the literature are generally for sewage sludge composting. Piggery solids are more fibrous and friable in nature and can

facilitate more air flow through them, even at higher moisture contents.

Changes in Total Nitrogen observed in all pilot trials and laboratory experiments were typical with regard to piggery solid composting, and up to 60% of Total Nitrogen was conserved during the composting process in trial 4. Laboratory experiments recorded similar conservation. The change in the phosphorus concentration in trials and experiments during the composting operation was attributed to reduction in volatile solids and decomposition of composting mixture. The decrease in Total Organic Carbon concentration paralleled changes in the Volatile Solids content. Measured pH values of compost samples were consistent throughout the study and in agreement with values in literature. In pilot trials where almost all Streptococci were inactivated, the thermophilic temperatures prevailed sufficiently long enough, however, the high values of MPN indicate that there are certain spore formers which survive the composting process. Controlled laboratory experiments achieved a complete pathogen destruction.

7.4 Reaction rate constant (k)

Evaluation of k can be derived from the decomposition curve of Total Organic Carbon values. A non-linear regression analysis was used to calculate rate constant over time from the temperature development curves. A medium-order, Newton-Raphson algorithm, which solved non-stiff differential equation was used to solve the reaction rate equation numerically. Two models were compared for the determination of reaction rate constant. In the first model, k is independent of temperature but takes into account the average temperature of the heap. Second model had a temperature correction component associated with it but the changes in temperature, deviation from mean temperature, did not significantly improve the fit. This means that a simple first order kinetic model can be used for rate constant determination without a need to use a more complicated equation. Values of reaction rate constant varied under different operating conditions of compost piles. In trial four, rate constant values were of the order of .008 and .007 day^{-1} at S1 and S2, respectively.

Laboratory experiments 6 and 7 gave similar reaction rate constants to trial 4. This is beside the fact that a constant temperature profile was maintained throughout the composting period in these two experiments.

7.5 Mean residence time

The MRT in composting system is the residence time of solids in the composting system. It is the most important factor in determining the stability of the compost product. It is a function of the type of substrate and bulking agent and their corresponding reaction rate constants, and provides very useful information for designing a composting system.

The values of MRT differed widely in trials. Trial 4 had the lowest MRT of approximately 115 and 129 days at position S1 and S2, respectively. From these values in can be confirmed that under natural temperature increase conditions the maximum decomposition of total organic carbon took place in pilot trial 4. In laboratory experiments 6 and 7, the average residence time of solids was not very different from these values.

7.6 C/N ratio

A complete stabilisation of compost (or complete disappearance of carbon) is not desirable because the value of compost as a soil conditioner depends in part on its organic content. Based on reaction rate constant values, the time required to achieve a required C/N ratio was calculated at different positions in the compost pile. Again, from trial four it was demonstrated that approximately 120 days will be required to achieve a selected C/N ratio of 20 in this case.

7.7 Rate of thermal inactivation

The principal mode of disinfection of wastes through composting is based on temperature-time relationship that destroy pathogens. In this study, data were collected to examine the decay or inactivation of indicator pathogen total coliform and Group D-streptococci. Non-

linear least squares with Simplex Method algorithm within SYSTAT 7.0 was used to calculate regression parameters over time from the temperature-time relationship in various trials. A medium-order, Newton-Raphson algorithm, which solved non-stiff differential equation was used to solve overall thermal inactivation coefficient equation. The comparison of two models showed that a simple first-order kinetic model can be used for the determination of inactivation coefficient, but using Arrhenius equation incorporating the reference temperature would provide a better thermal inactivation coefficient estimates.

In trial 4, inactivation rate coefficient values were of the order of 0.394 and 0.380 day^{-1} at two sampling positions, respectively. The laboratory experiments 6 and 7 provided inactivation rate coefficient values of the order of 61.97 and 47.339 day^{-1}, respectively. The significant difference in total coliform change slopes between experiment 6 &7 and sampling point S2 in trial 4 where thermophilic condition prevailed for long time at both positions S1 and S2, further emphasises that homogeneity is critical in any composting process. It also emphasises the need for a temperature feedback aeration system.

7.8 Application of research

The New Zealand Pork Industry Board (NZ PIB) wanted to explore composting of piggery solid wastes as a viable management option at a commercial piggery. Subsequently, the NZ PIB identified a suitable site where the pilot compost facilities were to be established. The designated site is a piggery owned and operated by Mr Denis Lepper and family at Lepperton, near Inglewood. Initial investigations were carried out at the piggery and volume and characteristics of the screened piggery solids were established.

The solid-liquid separation at Lepperton piggery is achieved by using a rotating drum contra shear screen mounted on rails and is deposited in 3 separate bins. A concrete pad was constructed in front of these bins and used to mix the separated solids with the bulking agent (sawdust) by a front-end loader. The mixture is then constructed into a heap (approximately 9m x 7m x 2m) by front-end loader over the roofed aerated composting facility situated adjacent to the mixing pad (Plate 7.1). The drainage from this area is

collected and delivered to a storage tank, from where it is pumped to an oxidation pond. The finished compost (after 21 days) is then transferred to a curing area where it is allowed to mature for about 30 days (Plate 7.2).

Bases on the findings of this research, the design of the composting facility (including size of heap, aeration requirements and technique, pipe material and size, blower size, piggery solid - sawdust ratio, etc.) was carried out to suit the specific site. The final product of the Lepperton composting facility is a stabilised soil conditioner or plant growth media. The product is marketed by Mr Lepper under the brand name "Grunt". The final product contains 0.8 % Nitrogen, 0.4% Phosphorus and 0.04% K. Pathogen counts are reduced significantly following a maturation period of at about one month.

7.9 Suggestions for future research

Within the limits reported in this thesis, data presented can be used for designing piggery solid composting process. Factors influencing the composting process such as solids to bulking agent ratio and heat generation result in variations of the reaction rate constants. Other factors such as oxygen status and particle size influencing the composting process can be examined in a similar manner or by large scale studies.

The high temperatures of the pile for prolonged periods were expected to decrease the bacterial counts to levels lower than those observed. The high values of MPN indicate that there are certain spore formers which survive the composting process. Further work on the nature of these organisms is required to determine the need and method for their inactivation. There is also a need to examine the temperature-feedback control to ensure substantial reduction of indicator microorganisms.

Composting processes in this study were examined at small scale piles (approximately 5 m^3) in a closed environment. Laboratory studies were conducted to verify the process derived rates. Further research is needed to examine the process performance under large scale open systems to fine-tune the reaction rate constants and rate of thermal inactivation.

Untreated sawdust was used as the bulking material in this study. The easy availability of large amounts of untreated sawdust may not be possible in many areas of New Zealand for large composting operations. The use of other bulking agents, such as straw needs to be investigated.

Figure 7.1 Roofed aerated composting facility at Lepperton Piggery

Figure 7.2 Piggery compost at curing stage

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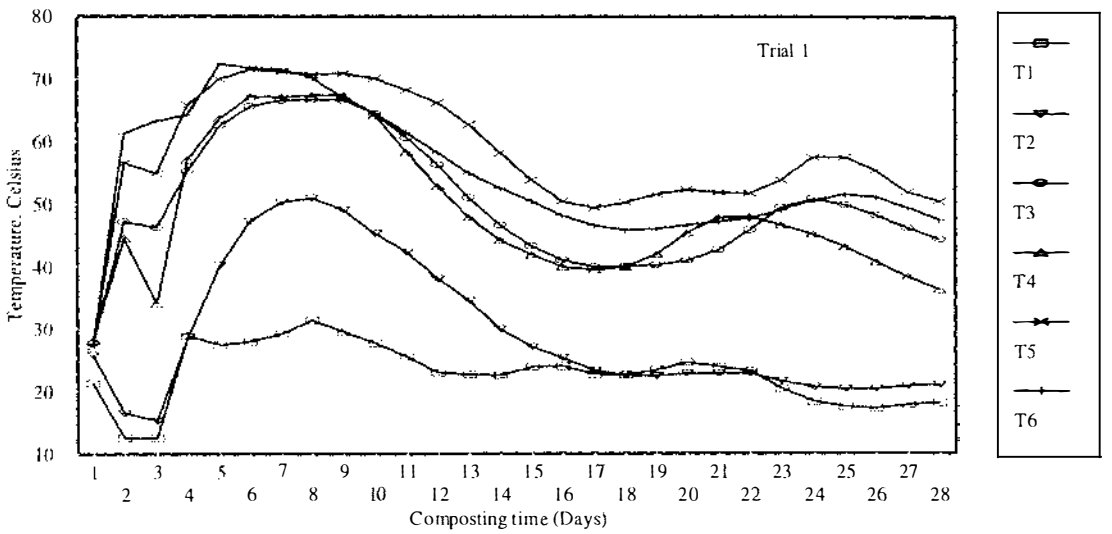
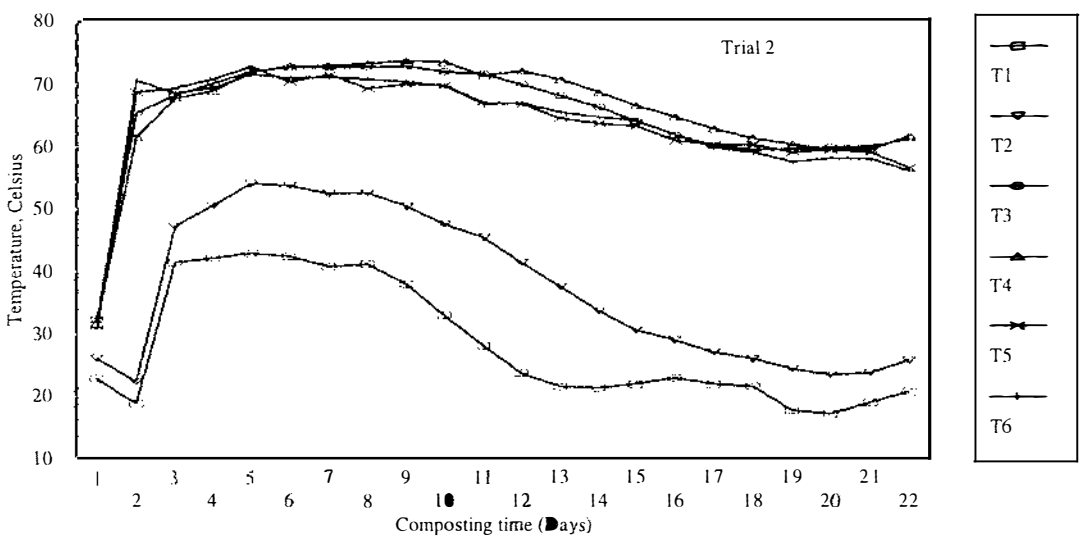
APPENDIX 1

Temperature profile during composting at thermocouple positions T1 to T6



Temperature profile during composting in first trial at thermocouple positions T1 to T6



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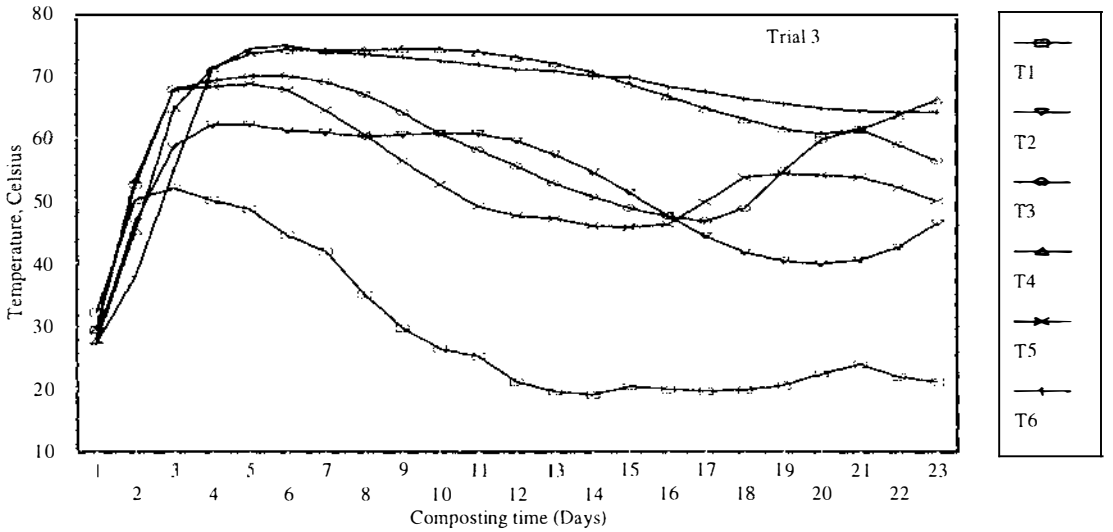
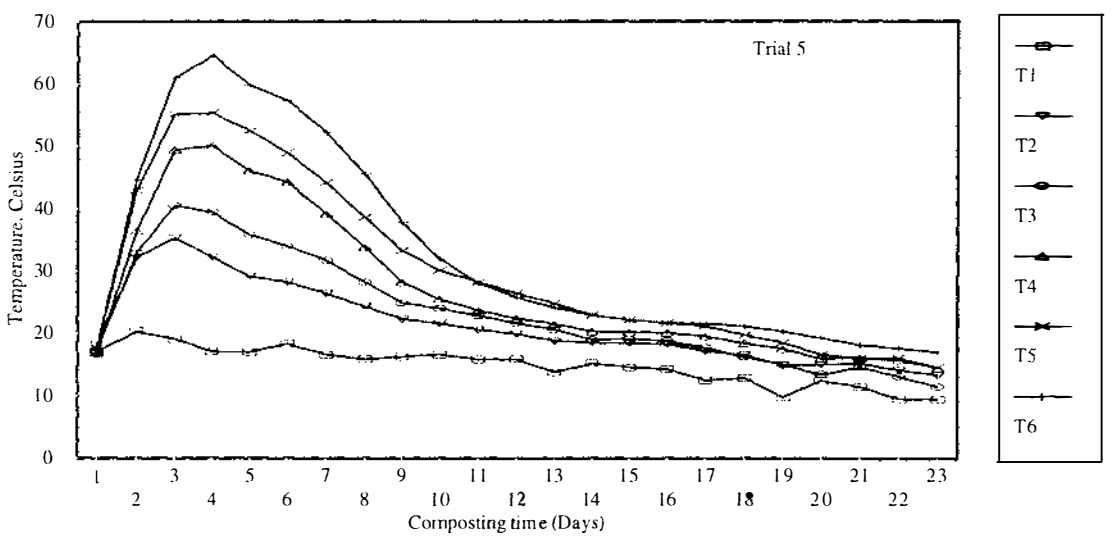


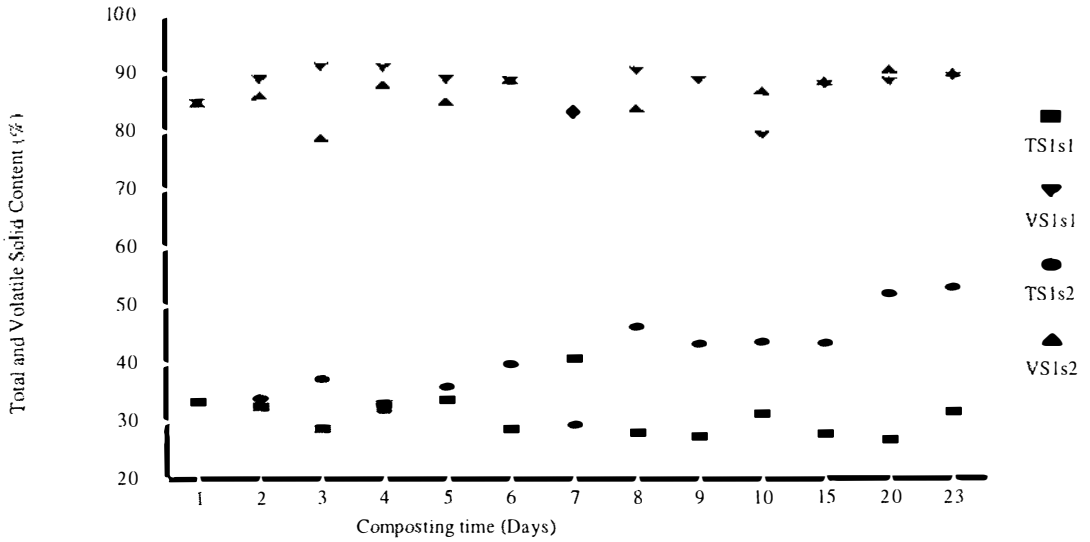
Temperature profile during the composting in third trial at thermocouple positions T1 to T6



Temperature profile during the composting in fifth trial at thermocouple positions T1 to T6

APPENDIX 2

Changes in Total Solids and Volatile Solids content at positions S1 and S2



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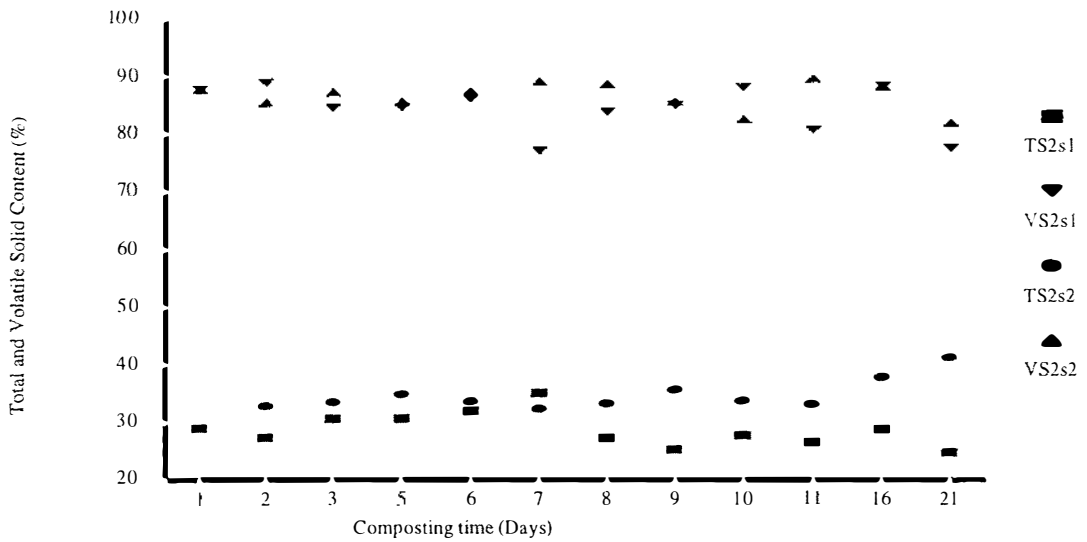

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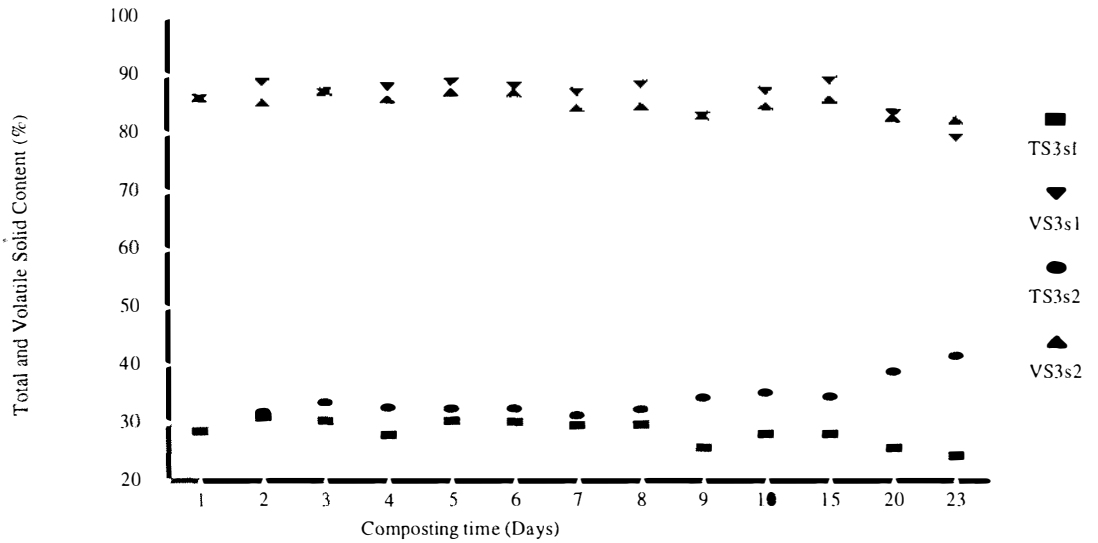

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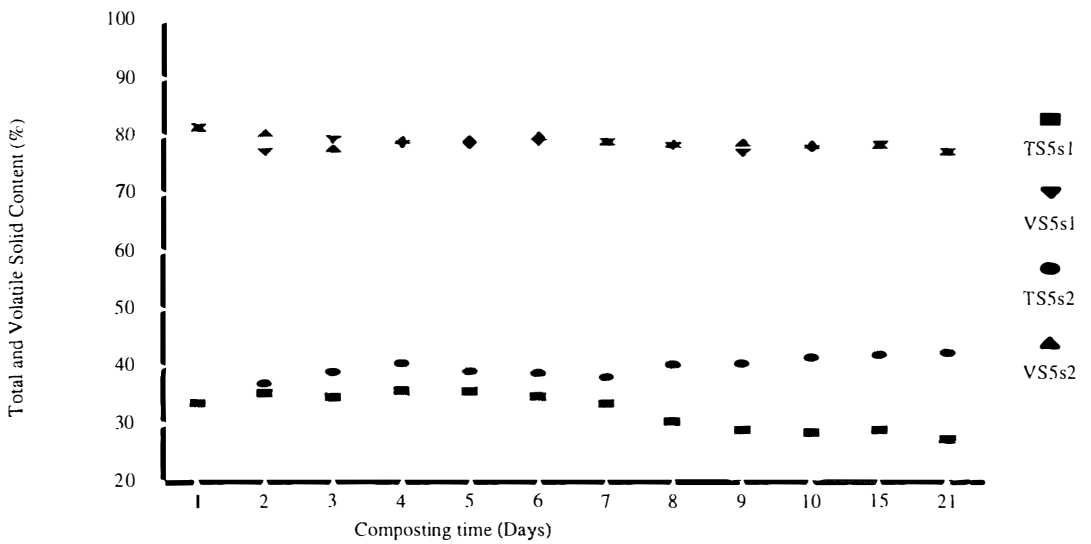
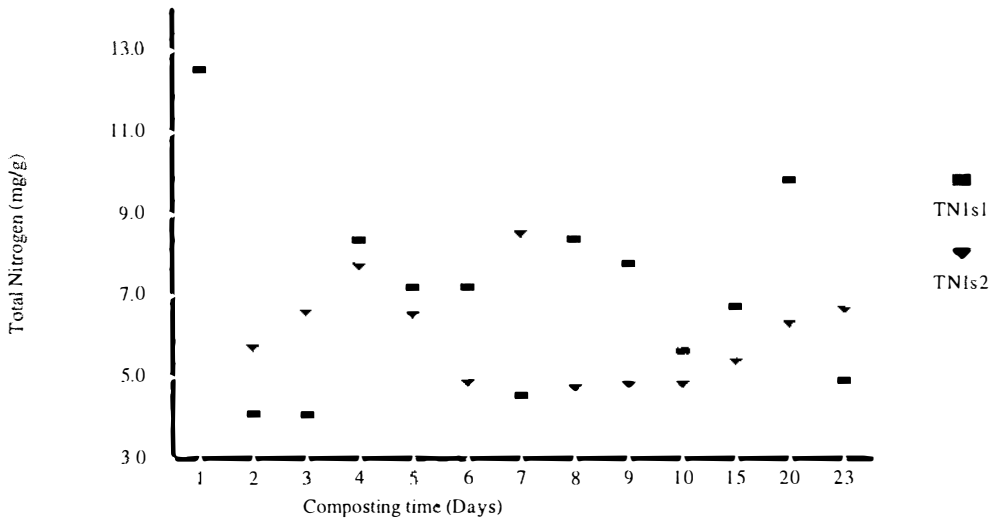


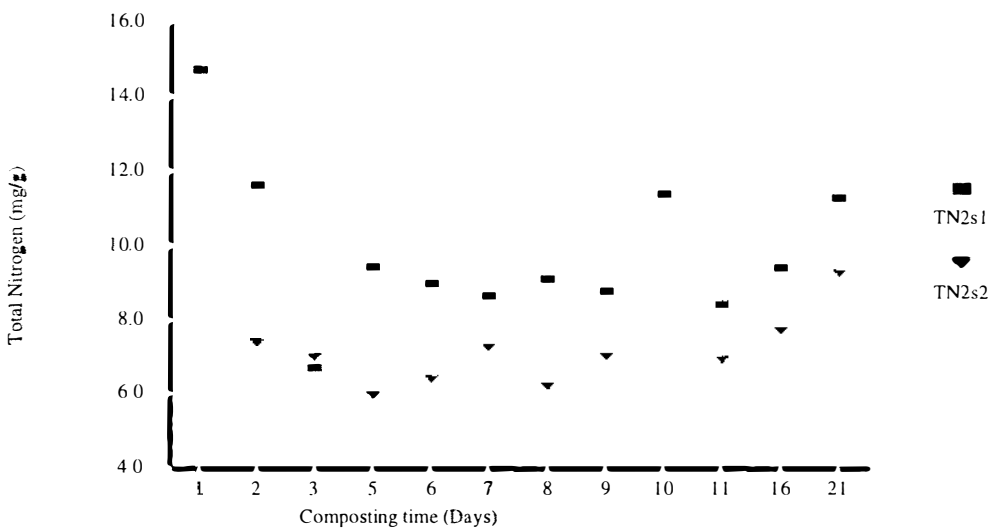
Changes in Total Solids and Volatile Solids content during composting in fifth trial at positions S1 and S2

APPENDIX 3

Changes in Total Nitrogen content at positions S1 and S2



Changes in Total Nitrogen contents during composting in first trial at positions S1 and S2



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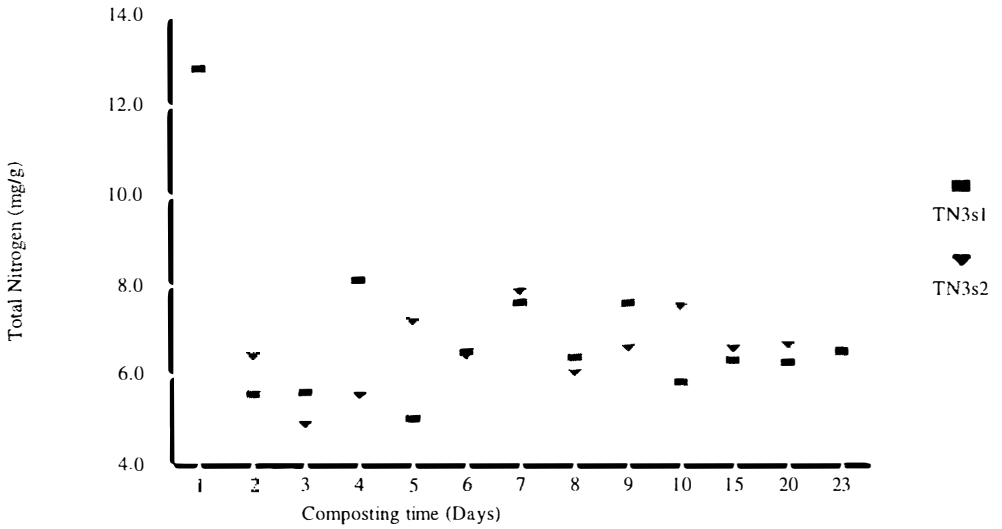
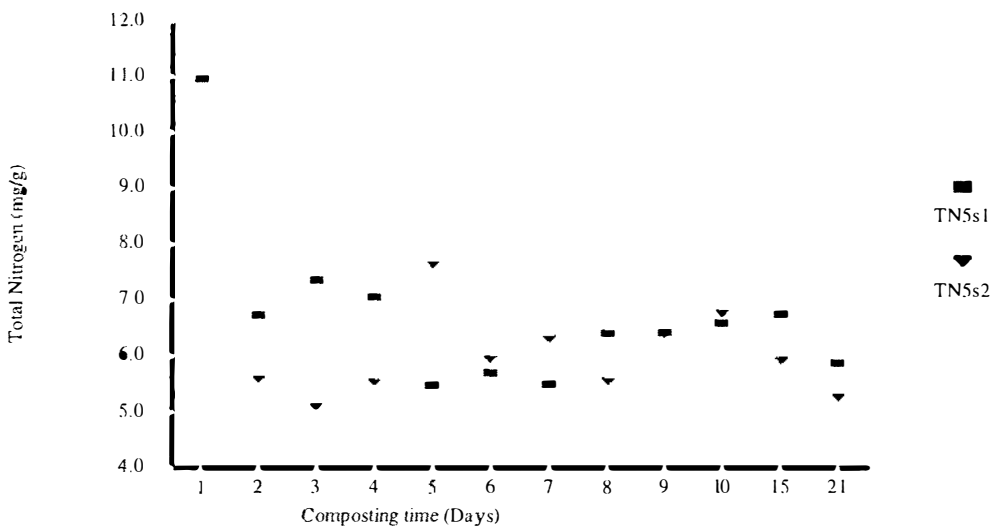


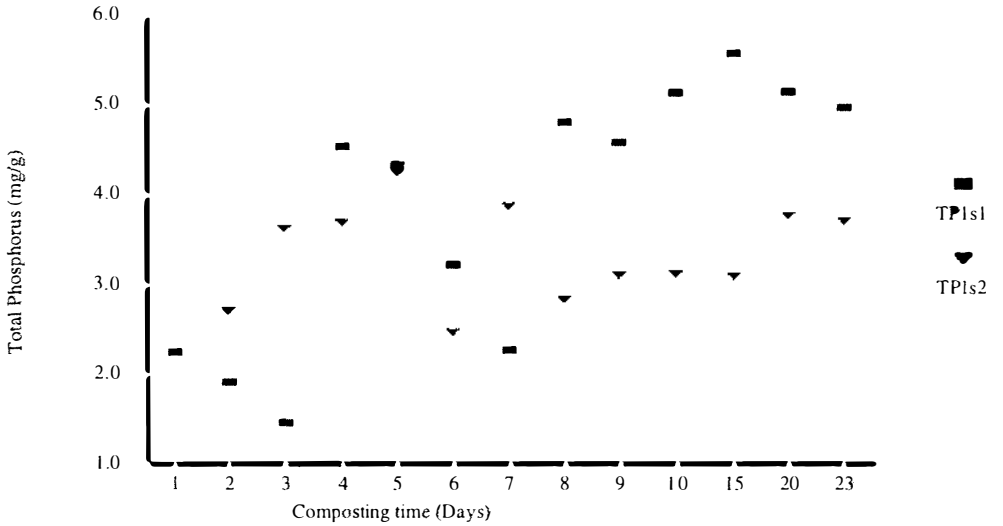
Changes in Total Nitrogen content during composting in third trial at positions S1 and S2



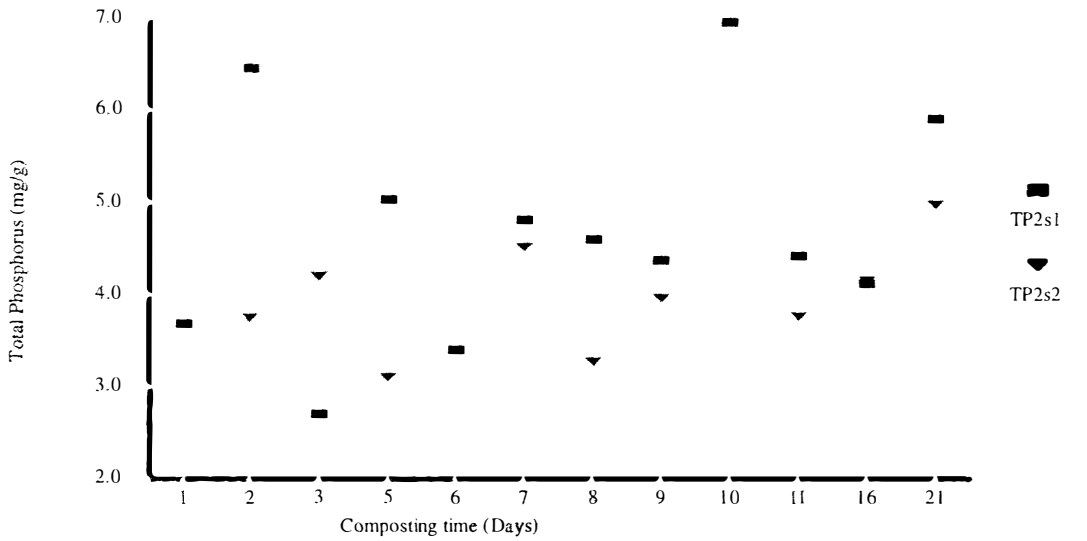
Changes in Total Nitrogen content during composting in fifth trial at positions S1 and S2

APPENDIX 4

Changes in Total Phosphorus content at positions S1 and S2



Changes in Total Phosphorus contents during composting in first trial at positions S1 and S2



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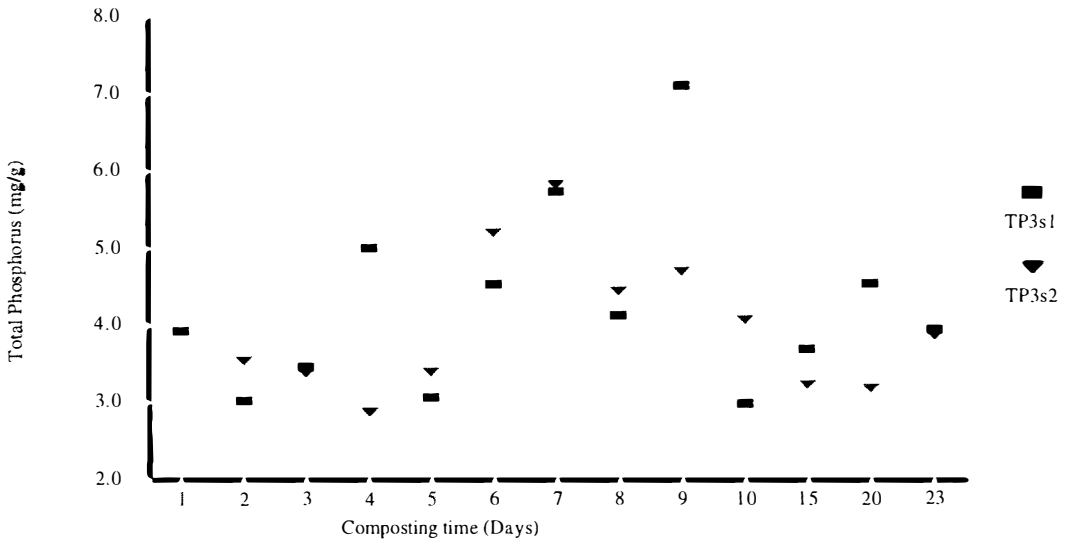
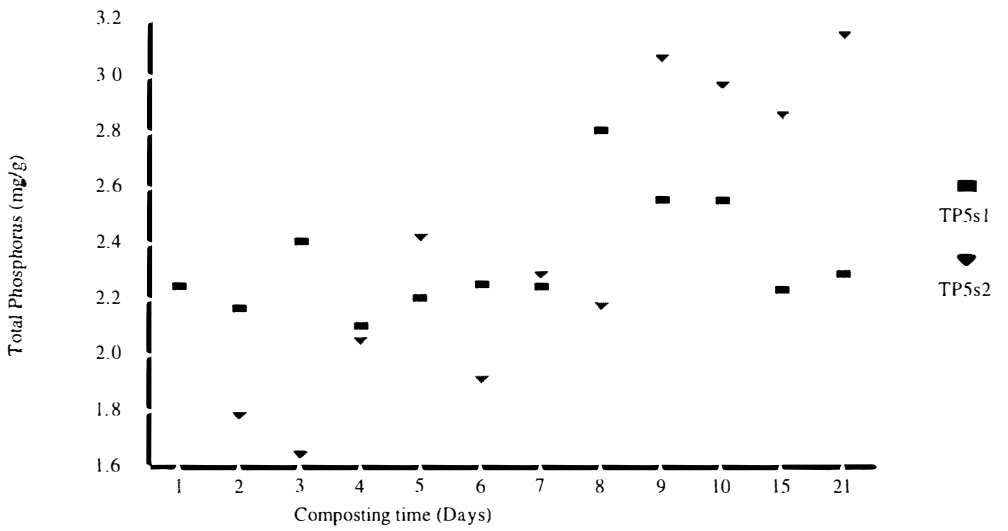


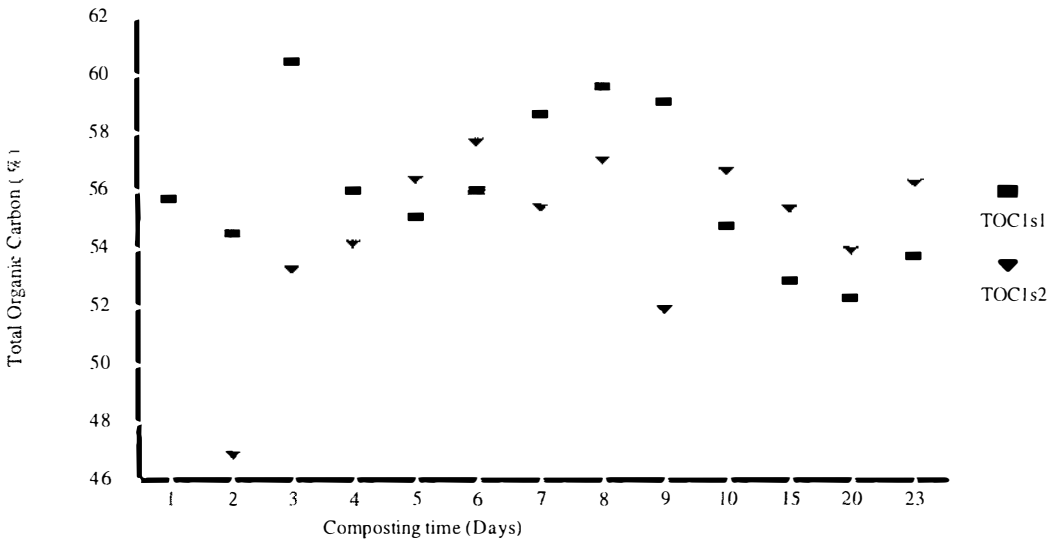
Changes in Total Phosphorus content during composting in third trial at positions S1 and S2



Changes in Total Phosphorus content during composting in fifth trial at positions S1 and S2

APPENDIX 5

Changes in Total Organic Carbon content at positions S1 and S2



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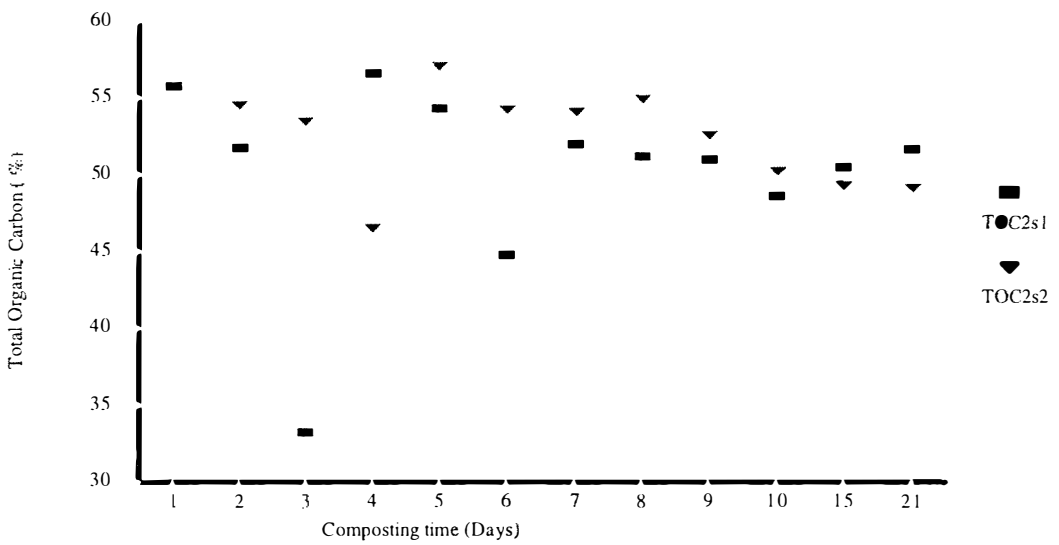

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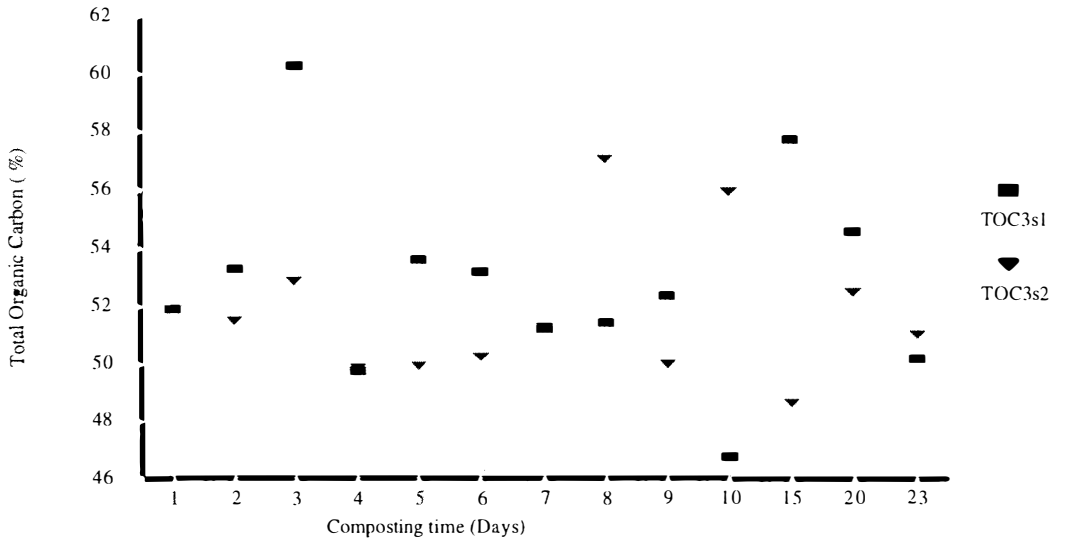
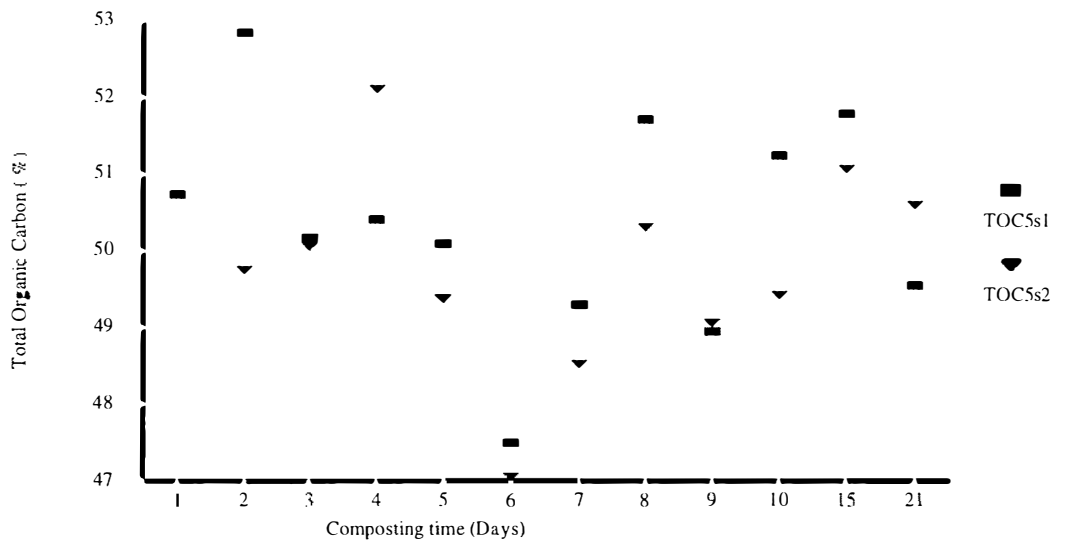


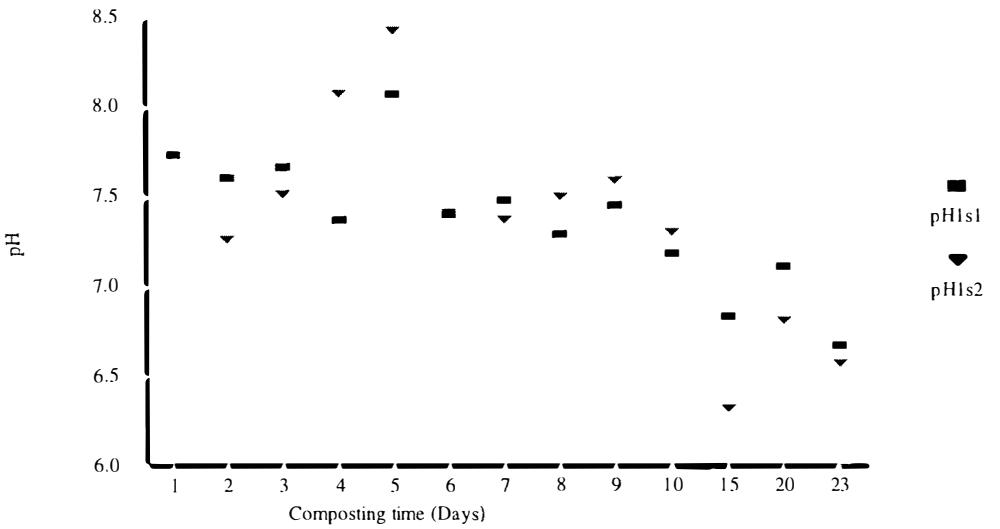
Changes in Total Organic Carbon content during composting in third trial at positions S1 and S2



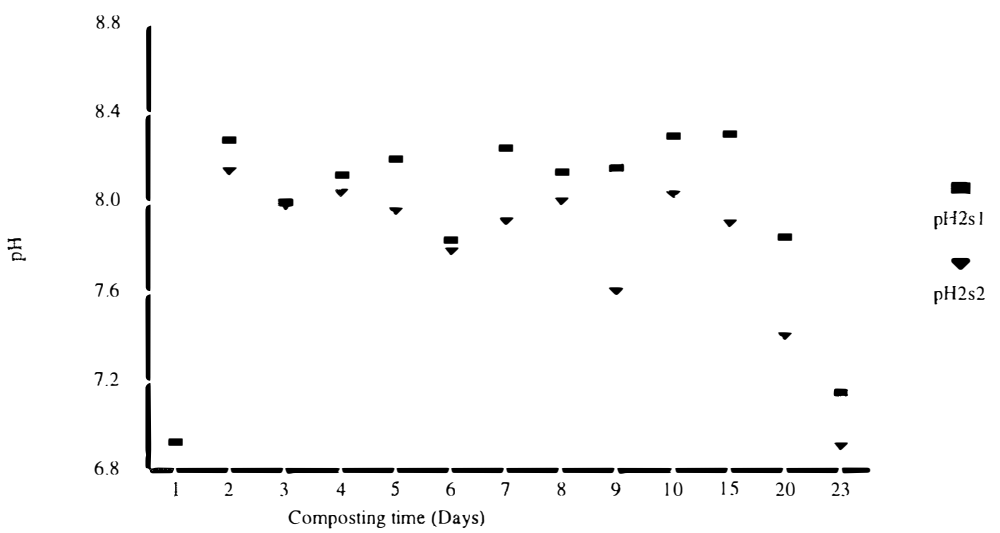
Changes in Total Organic Carbon content during composting in fifth trial at positions S1 and S2

APPENDIX 6

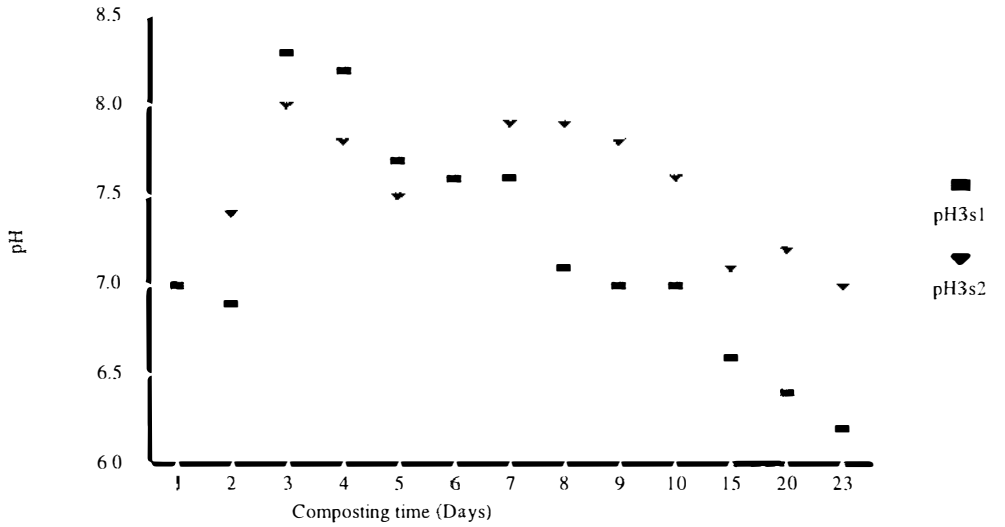
Changes in pH values at positions S1 and S2



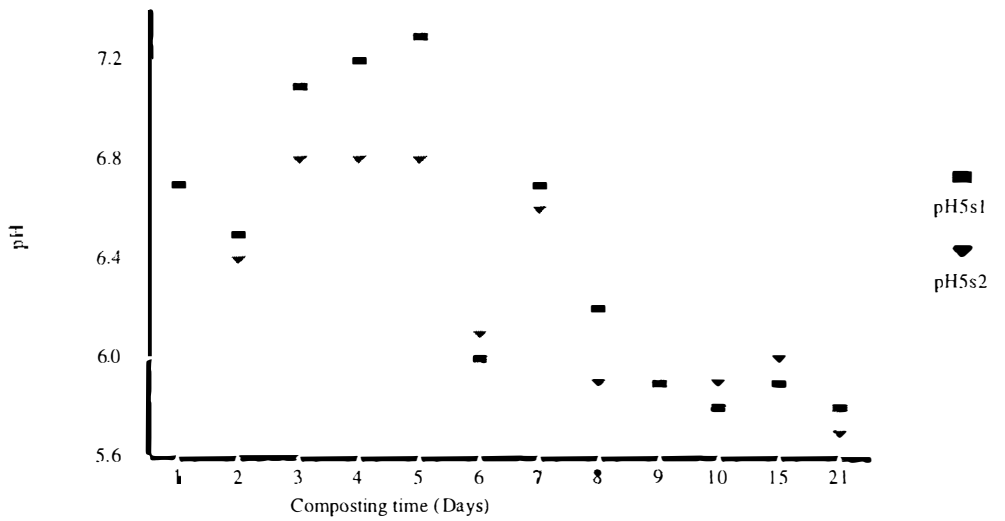
Changes in pH values during composting in first trial at positions S1 and S2



Changes in pH values during composting in second trial at positions S1 and S2



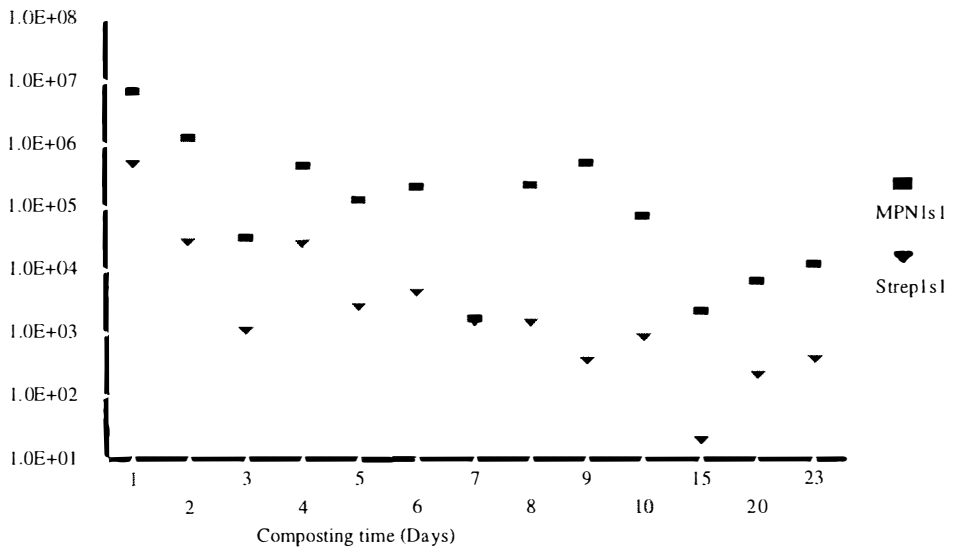
Changes in pH values during composting in third trial at positions S1 and S2



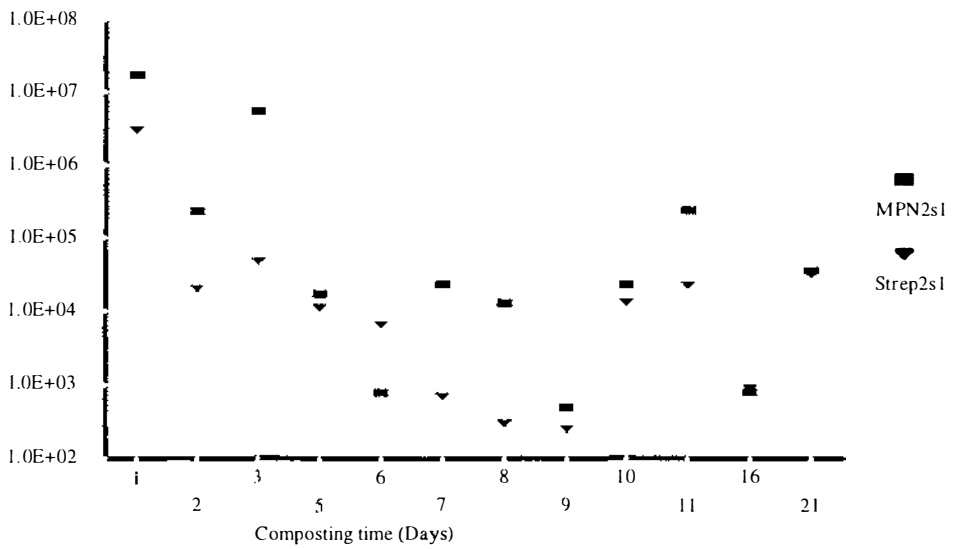
Changes in pH values during composting in fifth trial at positions S1 and S2

APPENDIX 7

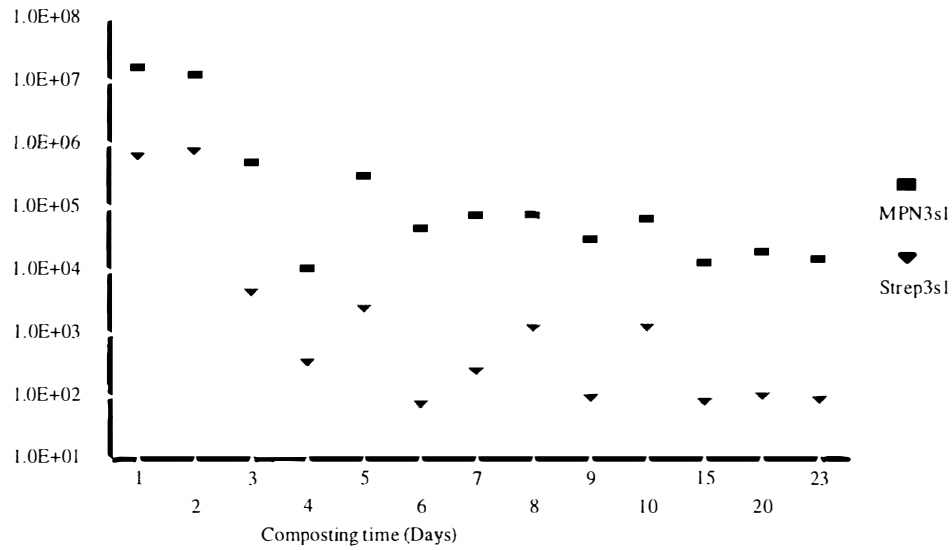
Changes in coliform (MPN) and streptococci counts during composting at positions S1



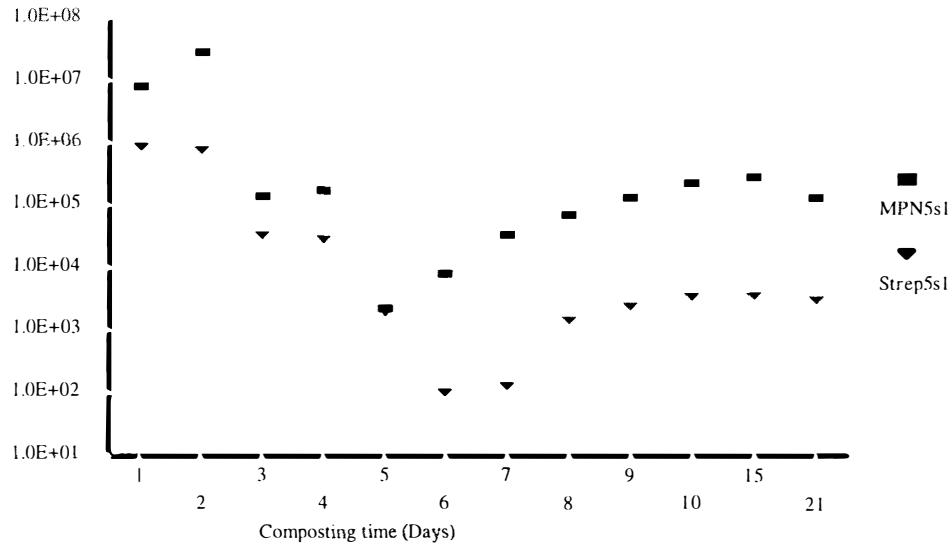
Changes in coliform (MPN) and streptococci counts during composting in first trial at positions S1



Changes in coliform (MPN) and streptococci counts during composting in second trial at positions S1



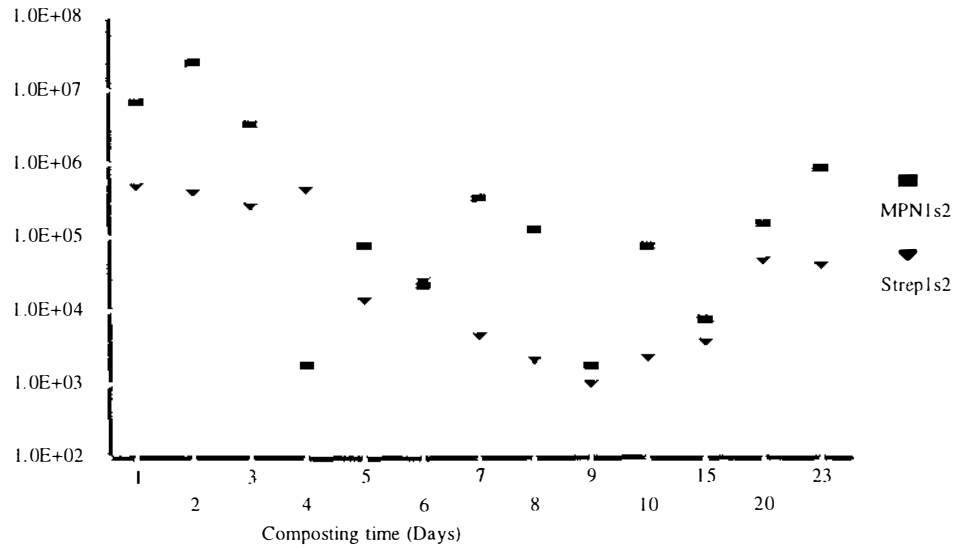
Changes in coliform (MPN) and streptococci counts during composting in third trial at positions S1



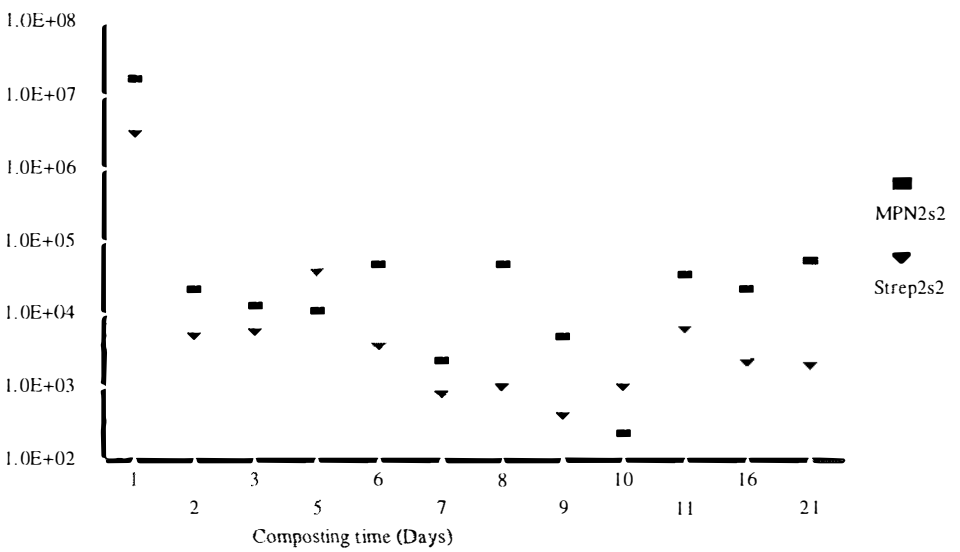
Changes in coliform (MPN) and streptococci counts during composting in fifth trial at positions S1

APPENDIX 8

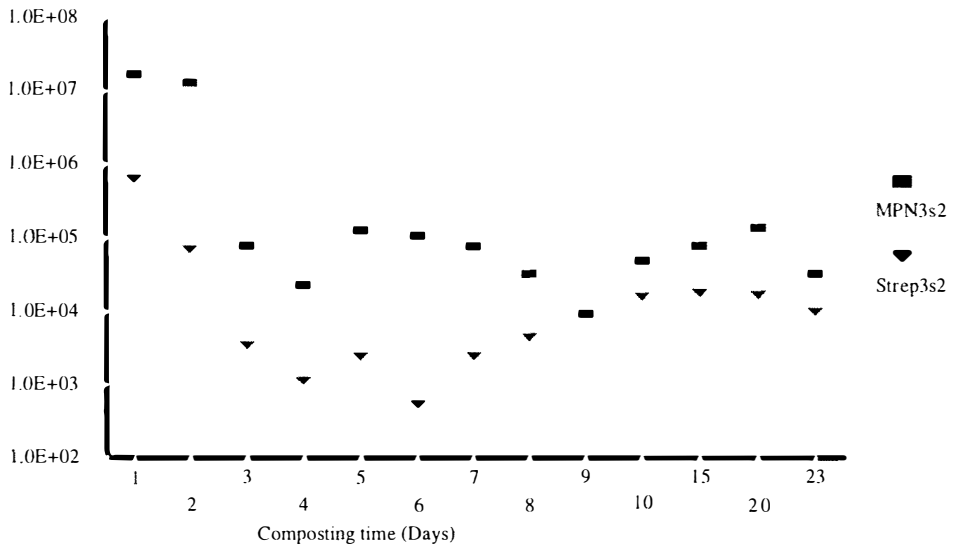
Changes in coliform (MPN) and streptococci counts during composting at positions S2



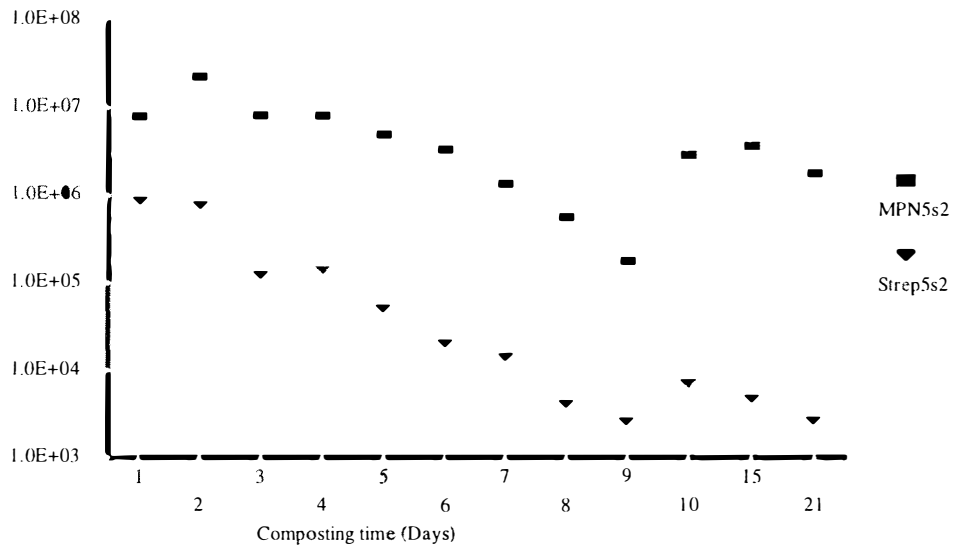
Changes in coliform (MPN) and streptococci counts during composting in first trial at positions S2



Changes in coliform (MPN) and streptococci counts during composting in second trial at positions S2



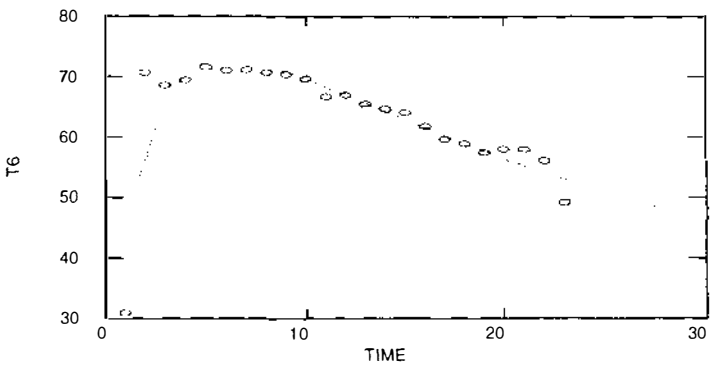
Changes in coliform (MPN) and streptococci counts during composting in third trial at positions S2



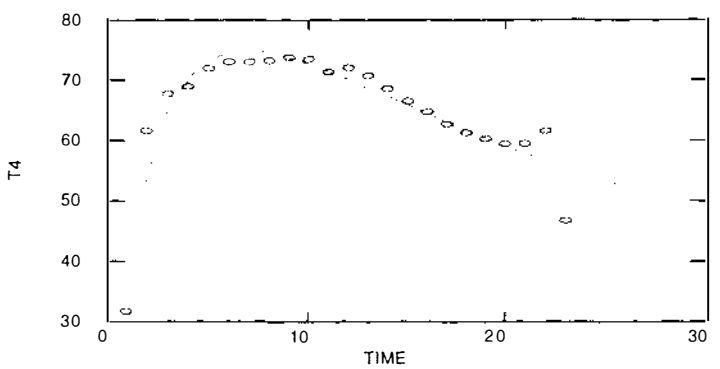
Changes in coliform (MPN) and streptococci counts during composting in fifth trial at positions S2

APPENDIX 9

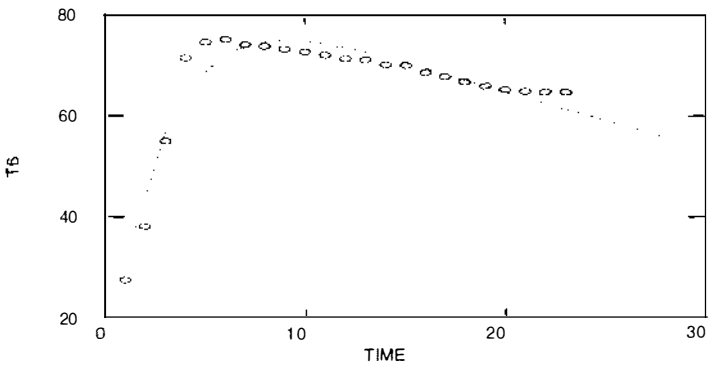
Best fit curves to calculate parameter values for Eq. 5.8 at S1 and S2



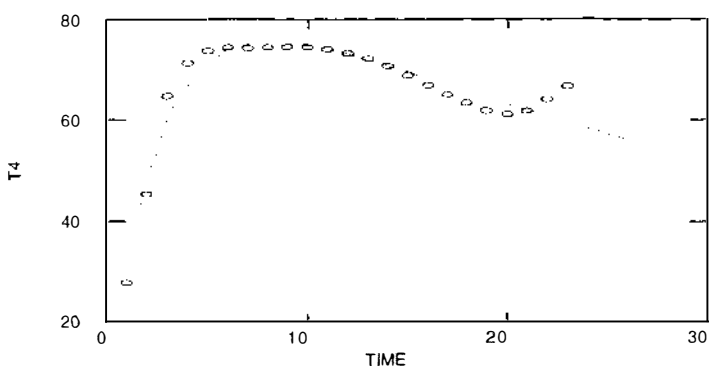
Best fit curve to calculate parameter values for Eq. 5.8 at S1 in Trial 2



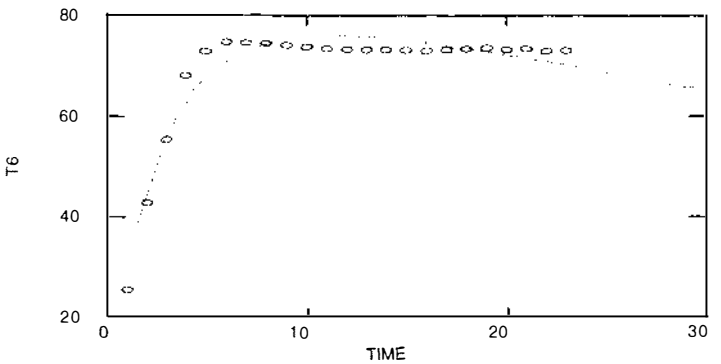
Best fit curve to calculate parameter values for Eq. 5.8 at S2 in Trial 2



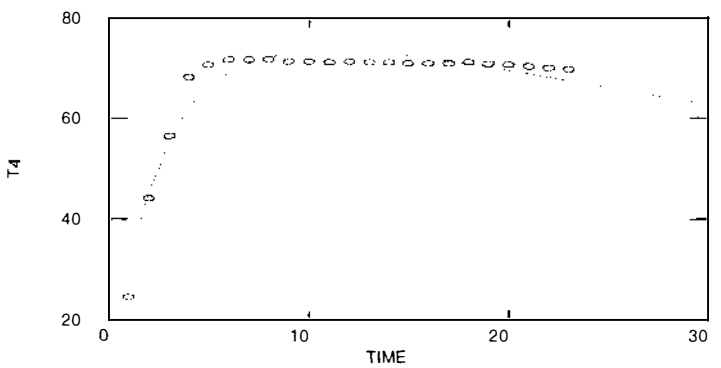
Best fit curve to calculate parameter values for Eq. 5.8 at S1 in Trial 3



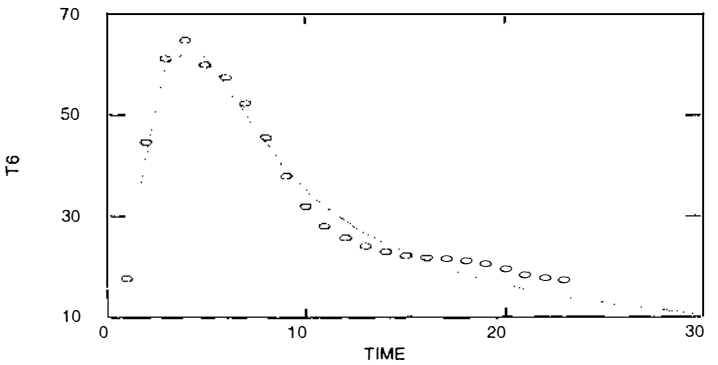
Best fit curve to calculate parameter values for Eq. 5.8 at S2 in Trial 3



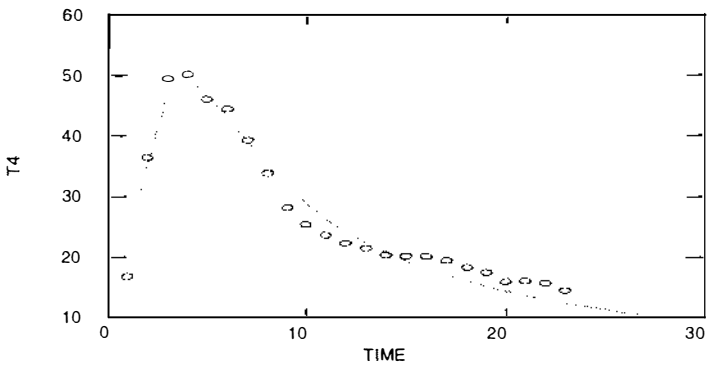
Best fit curve to calculate parameter values for Eq. 5.8 at S1 in Trial 4



Best fit curve to calculate parameter values for Eq. 5.8 at S2 in Trial 4



Best fit curve to calculate parameter values for Eq. 5.8 at S1 in Trial 5



Best fit curve to calculate parameter values for Eq. 5.8 at S2 in Trial 5