Comparative Study of Methods of Aeration for Composting Manure Slurries

by

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To my wife, Firouzeh

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Abstract

Composting is a simple and economically attractive method to treat and stabilize animal wastes slurries. However, a comparison of different methods of aeration for composting under high moisture content (MC) and the influence zones of the aeration pipes have not been reported in the literature. Therefore, a large scale study was conducted to investigate and compare the performance of three modes of aeration, namely natural, passive and forced aeration. A total of 9 piles, 3 replicates for each treatment, were built in trapezoidal shape with a volume of 5.03 m^3 each and monitored for a period of 90 days. Peat was used as the bulking agent. Initial MC of raw compost was 76%. A total of 233 thermocouples were built and installed in the compost piles to monitor the temperature profiles and distribution.

Since the temperatures inside the piles reached the thermophilic range within 4 to 5 days it showed that the initial conditions including carbon to nitrogen ratio (C/N), MC and pH were appropriate for the process to start. Statistical analysis showed that the passive aeration (PA) pipes influenced the interior part of the bottom half of the PA pile. In the case of forced aeration (FA) pile, the interior part of the pile was affected by FA pipe. In both PA and FA, air diffusion was predominant aeration mechanism at locations near the pile surface and they had the same performance as the natural aeration pile. These results were verified by applying Cluster analysis.

Temperature distribution inside the piles revealed that 1) the distance of a given point to the surface of the pile was an important factor affecting oxygen availability and microbial activity and hence the rate of temperature rise, 2) temperatures inside the FA pile cooled down at a faster rate than natural aeration (NA) and PA, 3) temperatures in area around the FA pipe did not go above 55°C, 4) a more uniform temperature distribution was observed in PA pile, 5) the use of PA pipes increased air availability at the locations around the PA pipe and 6) temperatures at locations near the pile surface and corners did not go above 35°C.

Three treatments were compared in terms of peak temperature, time to reach peak, increasing and decreasing temperature rates, duration above 55°C and time to drop to 15°C. Passive aeration was the best method under the initial conditions of this study *i.e.* initial MC of 76%, size and shape of the pile and the use of peat as the bulking agent. It allowed the temperature to increase above 55°C for sufficiently long time (more than three days) and it was much quicker than no aeration (natural aeration). The process was completed in less than 10 weeks.

FA and PA provided more oxygen than natural aeration. FA was more effective in CO_2 removal. Changes in carbon to nitrogen ratio, volatile solids and ash content were not significant. Natural aeration was more effective in conservation of ammonia.
The final product was rich in nitrogen and phosphorous and had a dark brown colour and an earthy smell.

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Glossary

AAD	average of absolue differences
BF	biodegradable fraction
C/N	carbon to nitrogen ratio
DM	dry matter
FA	forced aeration
LC	lignin content
MC	moisture content
MSW	municipal solid waste
NA	natural aeration
PA	passive aeration
TN	total nitrogen
TP	total phosphorous
VS	volatile solids
σ^2	variance
Y	mean value
Y_{GA}	grand average

Chapter 1

INTRODUCTION

In poultry production the major trend during the past two decades has been towards confined systems with large number of animals. This results in the generation of large amounts of wastes, either solid or liquid manure form, which need to be treated and/or disposed of. Since treatment of these wastes involves time and money, direct land application is used most often. Stewart (1980) estimated that 73% of manures from confined production were directly applied to the land.

However, the amount of manure applied to the land is much higher than the natural systems' capacity to absorb it. As a result, environmental pollution occurs. Presence of pathogens, eutrophication, nutrient imbalance, ground water pollution, fish kill, acidic depositions, and high ammonia and nitrate concentrations in the soil are some of the adverse effects of direct land application of animal wastes (Edwards and Daniel, 1992; Mathur, et al., 1990; Loehr, 1984; Weil et al., 1979; and Witter and Lopez-Real, 1988).

1.1 Composting

Awareness of the adverse impacts of the land application of the wastes and rising concerns about recycling of resources, have promoted a wave of interest in developing technologies to abate pollution and conserve resources. Among them, composting has received greater attention. Congressman Hochbrueckner calls composting " the sleeping giant of waste management" (Sheehan, 1992).

In essence composting is a biological process, during which microorganisms convert organic matter into a stable form with accompanying release of heat. Composting technologies are classified as natural, passive, turned windrows, forced aeration and in-vessel systems. The end product of composting is beneficial to crop yield and is used as a soil conditioner. Leger et al. (1991) stated that there is a high degree of interest in the farming communities in composting of manures. The most important parameters affecting composting are moisture content, aeration, pH, physical state of the material, temperature, and carbon to nitrogen ratio.

Manure slurry is high in moisture content, about 90%, and low in carbon to nitrogen ratio, about 10%. For successful composting, a suitable bulking agent should be used to adjust these properties. Peat is reported to have all characteristics of a good bulking agent (Mathur et al., 1990). The use of bulking agent material results in higher operating costs. Therefore, its use should be minimized, *i.e.*, composting should be conducted with raw waste containing relatively high moisture content.

Composting of manure slurry with minimum use of bulking agent material is an attractive method for animal waste treatment. Mathur (1991) reported on effective peat-based passive composting of manure with 70-90% moisture content. Zhan (1993) successfully used the same method to treat manure under high moisture conditions up to 80%. However, there is a lack of knowledge on the effectiveness of perforated pipes or the influence zone of the pipes used in the passive aeration composting systems. Information on the zone of influence of the aeration pipes can help to optimize the passive composting process.

Comparison of natural, passive, and forced aeration composting of manure has not been documented. Some researchers believe that the physical state of raw material plays a very important role in providing the air. Emerton et al. (1988) stated that if air permeability of material is great enough, natural aeration system can supply enough air for good composting. If a comparative study reveals that natural or passive peat-based composting performance is as good as forced aeration composting, then the use of natural or passive systems would be favoured because they are much simpler and lower in cost than forced aeration composting, and more suitable for application on small to medium farms.

1.2 Study Objectives

Accordingly, a large scale study on peat-based composting of poultry manure slurries using natural, passive and forced aeration systems was initiated and carried out at Greenbelt Farm, Agriculture Canada, Nepean. The objectives of this study were:

1) to find the influence zone of passive and forced aeration pipes;
2) to compare natural, passive, and forced aeration peat-based composting of poultry manure under high initial moisture content;
3) to assess the temperature distributions in compost piles using these three modes of aeration;
4) to investigate the effect of modes of aeration on concentrations of oxygen, CO_2, CH_4, and H_2S within the gas phase inside the compost piles; and
5) to evaluate the stability and reproducibility of the process.

Chapter 2

LITERATURE REVIEW

2.1 Historical Background

Recent rising concerns about environmental pollution, global warming, depletion of ozone layer, landfilling, health, nonrenewable resources and recycling of resources have all inspired a strong wave of interest in strategies for conserving resources and reducing pollution. As a result, many stringent environmental legislations have been passed. Hierarchies were set by the waste management decision-makers such as the '4Rs' strategy: Reduce, Re-use, Recover, and Recycle wastes to abate pollution, conserve resources and natural ecosystems.

Natural ecosystems are essentially maintained by the cycling of elements and nutrients, such as carbon and nitrogen, so that the loss of these materials from the system are balanced with their gain.

From time immemorial, humans have used the earth's resources to support life and to dispose of wastes. In early times, the loss of nutrients through cultivation and waste disposal due to human actions were not serious problems. Agriculture was confined to river valleys and deltas which recouped the nutrient losses through alluvial deposits from flood waters. Population was small and the amount of land available for assimilating wastes was large.

Problems with waste disposal and the loss of earth's nutrients originated from the time when humans began to congregate in communities. Intensive use of land and accumulation of wastes became consequences of life, which resulted in overloading the natural systems' capacity to cycle the elements and nutrients.

Composting is one way of recycling waste. It is not a new technology. Written references to composting can be found in the Bible (Rynk, 1992). According to Mathur (1991), the development of the scientific principles of composting originated in India, where Indore and Banglore methods were introduced in the beginning of 20th century. Layers of different types of wastes were placed in trenches up to 0.9 m deep, turned manually, and operated with a detention time of 4 to 6 months. Application of scientific principles to composting enhanced the rate of process with selected materials, mechanical devices and specific methods for constructing composting piles. However, by that time advances in composting coincided with advances in farming techniques. With the advent of cheap chemical fertilizers and mechanization, recycling of waste through composting was perceived to be unnecessary and composting largely disappeared.

In the latter part of this century, interest in composting shifted to urban municipalities where it offered a way to treat solid wastes and sewage sludge. Goldestein (1987) reported that by the end of 1987, 200 composting facilities for municipal sewage sludge were either in operation or scheduled for construction, compared with 61 plants in operation in 1983. Now, with shrinking landfill space and increasing concerns about the environment, composting is becoming very popular. Beck *et al.* (1989) stated that more than two thirds of the U.S. landfills had closed since the 1970s and that about one third of the remaining ones would reach their maximum capacity in the next five years. Furthermore, getting permission to open new landfills is becoming more restricted and costly.

Throughout the rest of this chapter, composting principles, studies on different composting aspects, and relevant achievements in the past years are reviewed with special emphasis on composting of manure and the use of peat as the bulking agent.

2.2 Animal Waste Management

There has been a major change in livestock production during the past 20 years. Growing consumer demand and market competition have put pressures on farmers for more cost effective production. Industrialization has resulted in the improvement of animal husbandry systems. The major trend is towards confined livestock and poultry production, with increasing animal numbers (Overcash *et al.*, 1983). Fogg (1980) reported that 99% of broiler production in the U.S. were confined. There were 998,000 sheep, 7,374,000 swine, and 97,401,000 poultry in Canada in 1971 (McLean and Hore, 1979). Miner and Smith (1975) estimated that 13.4 kg (dry basis) per day of manure was produced for each 1000 kg live-weight.

Intensive confined production results in large amounts of waste which need to be treated and/or disposed of. Refeeding for animals, anaerobic digestion with biogas production, composting, and direct land application are the main measures undertaken for waste management. Among these methods, direct land application is used most often.

Land application of animal waste is beneficial to crop yield if applied at adequate rates. However, when the primary objective of land application is waste disposal, animal wastes are applied at much greater rates which results in adverse environmental impacts. Edwards and Daniel (1992) stated that decreased yields associated with high rate poultry manure application might be attributed to toxic concentrations of ammonia (NH_3), nitrite

(NO_2), and nitrate (NO_3), and soluble salts. Pratt (1979) identified NO_3 leaching and accumulations in the soil as the negative impact of poultry manure application. Wengel and Kolega (1972) reported NO_3^- concentrations greater than 1000 mg/kg of soil as a result of poultry manure application. Weil *et al.* (1979) measured NH_3 and nitrite concentrations in soil as high as 800 mg/kg and 60 mg/kg, respectively. Mathur *et al.* (1990) stated that NH_3 losses tended to promote eutrophication of water bodies and acidification of soils. Witter and Lopez-Real (1988) also reported that the NH_3 emission into the atmosphere enhanced wet depositions. In Europe, 81% of 6.4 x 10^6 t/yr emissions of NH_3 are believed to be a result of animal husbandry (Martins and Dewes, 1992). Nutrients imbalance is another consequence of direct land application reported by Edwards and Daniel (1992). Loehr (1984) mentioned that eutrophication, fish kill, high chlorine concentrations, and pathogen presence may result from land application of poultry wastes.

2.3 Principles of Composting

2.3.1 Definition, objectives and benefits of composting

Composting is the biological conversion of organic materials, under controlled conditions, into a stable, soil-like (humus rich) end product, which is environmentally safe for land application and conditions the soil. The key terms in the above definition which distinguishes composting from other processes are: a) biological conversion; b) controlled conditions; and c) stable, soil-like end product which conditions the soil. For example, radiation process sanitizes the wastes but it is not a biological process and does not produce a soil-like end product. Inclusion of the term controlled conditions distinguishes simple biodegradation of organic materials that takes place in nature from engineered composting. Moreover, an end product with the above mentioned characteristics is not achieved by direct application of wastes to the soil.

The primary objectives of composting include: 1) resources recycling through creation of a valuable commodity, compost; and 2) waste stabilization with an accompanying reduction in volume.

In essence, during the process of composting, microorganisms consume oxygen, nutrients and organic matter to produce new cells, stable organic residues, energy in the form of heat, large quantities of carbon dioxide, water, ammonia and some minor end products according to the following reaction:

$$\textbf{Org. matter+ microorganisms+ } O_2 \Longrightarrow \textbf{Compost (stable org. matter and dead cells)+ } CO_2\textbf{+ } H_2O\textbf{+ } NH_3\textbf{+ New cells+ Heat} \qquad \textbf{(2.1)}$$

Composting begins as soon as organic materials are mixed together and suitable conditions such as moisture, pH and nutrients exist. Initial mixing provides enough oxygen to start the process and almost immediately, microbial activity begins. Aeration is continuously required to replace consumed oxygen. Temperature in the compost pile rises to the mesophyllic range (25 to 50°C) and then to the thermophilic range (45 to 75°C). Temperature remains in the thermophilic range until readily biodegradable material is depleted. After this time, active composting starts to slow down, and the temperature gradually drops to ambient level. Due to high temperatures achieved during the active period almost all pathogens die and significant quantities of water escape through evaporation. The variation of temperature during the composting process is shown in Fig. 2.1-a. A curing period follows the active composting, during which the materials continue to decompose but at a much slower rate. The volume of the compost pile reduces by 25 to 50% as a consequence of water evaporation and organic material decomposition. Changes in pile dimensions of a refuse/sludge compost pile as the composting progresses are shown in Fig. 2.1-b.

Composting has many advantages. Compost from a well operated process is an excellent soil conditioner. Application of compost to the soil improves its structure, reduces soil erosion, adds organic materials and valuable nutrients, reduces fertilizer requirements, and increases the water holding capacity (WHC) of soil. The addition of organic materials by applying compost to soil provides protection against soil-borne diseases through the oxygen-ethylene cycle (Cook, 1976). Also reduction of fertilizer requirements has a direct effect on lowering nitrous oxide concentrations in the atmosphere, which is one of the main gases responsible for global warming. Nitrous oxide is also responsible for acidic depositions and depletion of the ozone layer. Results from a 6-year study showed that the use of compost, even after several years, improves

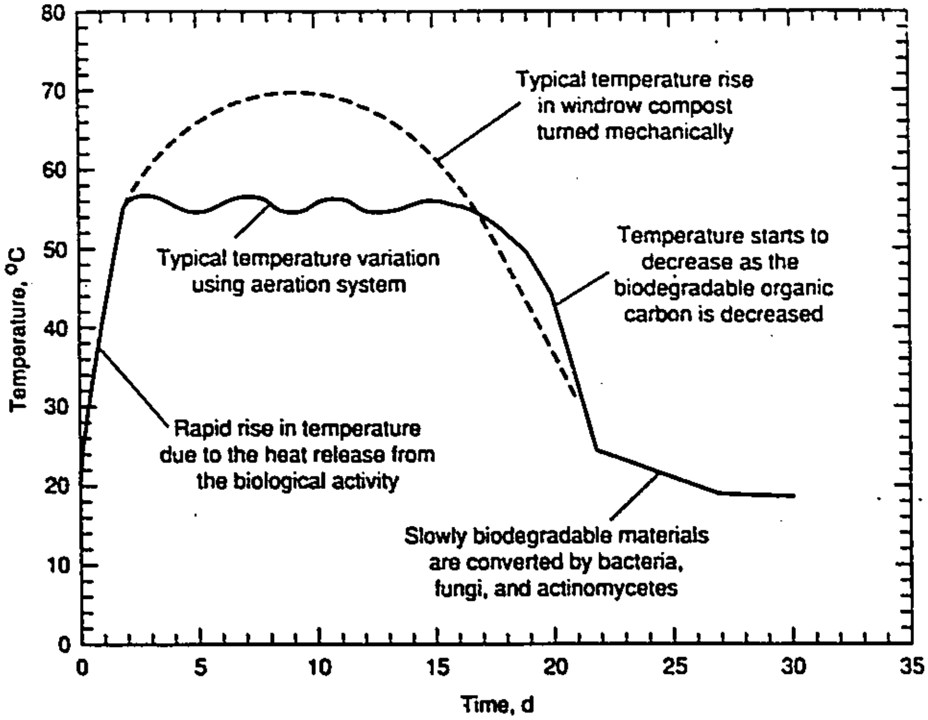


Figure 2.1-a: Temperature profile in composting (Tchobanoglous *et al.*,1993)

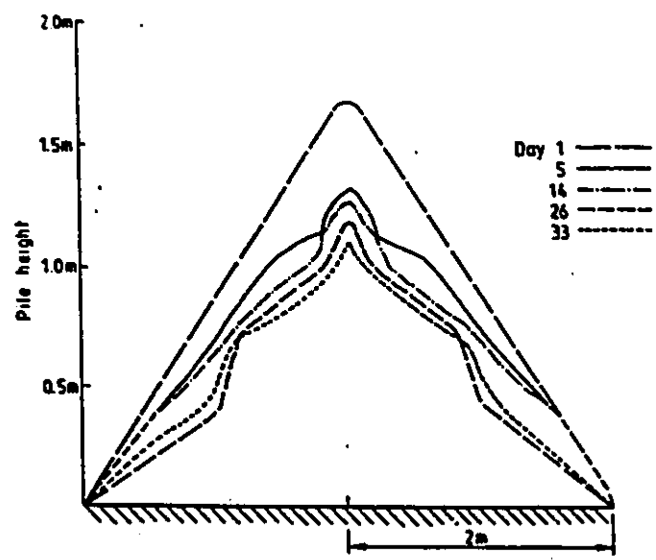


Figure 2.1-b: Volume reduction in composting (Stentiford *et al.*, 1985)

soil fertility, crop yield and product quality (Allievi et al., 1993). McConnell et al. (1993) proved that the application of 10 to 30 tons of compost per acre improved the physical and chemical properties of most soils without any phytotoxic effects. Also, composting improves physical waste handling by reducing weight, volume, and moisture content of raw waste materials. Almost complete pathogen and weed seed destruction is achieved through the composting process. Moreover, composting minimizes nitrogen losses in the form of ammonia gas compared to direct land application of animal wastes. Ammonia release has been identified to promote the wet depositions (Witter and Lopez-Real, 1988). Furthermore, composted wastes have lower risk of soil and water pollution than land application of untreated manure and sludges. Eventually, there is the possibility of earning revenue or financial credit from the produce or tipping fee for nontreated waste.

Compost is basically used as a soil conditioner. It can be used in horticulture, gardening, and landscaping. It can also be used as a base for biofilters (Mathur, 1991) and as a covering layer for composting pile.

The major drawbacks of composting include land requirements, odour problems, marketing the product, potential loss of nitrogen, interruption by bad weather conditions, and finally, the time and money required for equipment, bulking materials (in some cases), labour, energy and management.

Effective control of a composting process, like any other biological treatment, is based on understanding principles governing organic material utilization and microorganisms growth. The following sections deal with the characteristics of compostable raw materials, biochemical reactions involved, and dominant microorganisms.

2.3.2 Characteristics of compostable matter

Biodegradable materials, known as substrate in biological terminology, are utilized by microorganisms as the carbon and energy source. Any type of biodegradable material is suitable for composting such as manure, crop residuals, sewage sludge, yard waste, and putrescible portion of municipal solid waste (MSW). According to Haug (1980) the amount of collected organic fraction of urban refuse, agricultural waste, and manure in U.S. was over 100 million t/yr. A wide variety of wastes can be found in the literature which have been subjected to composting. Even composting of some hazardous and special wastes such as explosive and petroleum wastes has been documented. Williams *et al.* (1992) used composting as a bioremedation technology for treating sediments contaminated with explosives. They reported that extractable trinitrotoluene (TNT) was reduced from 11840 mg/kg to 3 mg/kg. Haug (1980) also referred to the composting of TNT, petroleum sludge, and certain pesticide residuals.

Although many elements serve to some extent as microbial nutrients, some are essential and required in larger amounts than others, for biological growth and maintenance of organisms. According to Golueke (1992) relatively large amounts of carbon, oxygen, nitrogen, and hydrogen must be available. About 50% of the microbial biomass consists of carbon, and 2 to 8% is nitrogen. Oxygen and hydrogen are present in a large percentage of microbial cell materials in the form of water. Microbial cell composition shows that the essential elements are required in proportion to each other, this is called nutrient balance. Shortage of any of the required nutrients becomes a limiting factor for biological growth. Therefore, in order to design a composting process, good knowledge of substrate composition and the availability of essential nutrients is necessary. The balance of carbon and nitrogen, expressed by their ratio (C/N), needs special attention, and it will be discussed in more detail in section 2.4.1.

Kirchmann and Witter (1992) measured the composition of fresh, aerobically and anaerobically decomposed cattle, pig, and poultry excreta. Results are shown in Table 2.1. The highest concentrations of nutrients were found in fresh poultry excreta. Analysis indicated that 61% of nitrogen in fresh poultry waste is present as uric acid and 92% of total nitrogen is in the organic form. For anaerobically decomposed poultry excreta, only 24% of total nitrogen is in the organic form and the rest is in the form of NH_4-N. And finally, 98% of nitrogen in aerobically decomposed waste is organic. Results from another study conducted by Mathur *et al.* (1990) on composition of raw poultry, dairy cow, and sheep manure are shown in Table 2.2. Characteristics of wastes from different sources are presented in Table 1 in Appendix A. These tables provide a good picture of the properties of different compostable substrate materials.

Table 2.1: Characteristics of animal excreta (Kirchmann and Witter, 1992)

Type of dung	*pH$_{H_2O}$*	*Ash (mg g^{-1} dry matter)*	*(mg g^{-1} ash free dry matter)* Organic matter			Water-soluble		*Organic matter losses (%)*	*C losses (%)*	*N losses (%)*
			Org.C	*Org.N*	*C/N*	*C*	*N*			
Cattle faeces										
Fresh	7·4	17·1	526·2	28·4	18·6	75·9	6·1	0	0	
Anaerobic	8·5	19·3	500·4	25·2	19·9	3·7	27·3	15·4	19·5	0^a
Aerobic	7·9	21·5	516·9	37·9	13·6	8·5	3·6	26·6	27·9	0·1
Pig faeces										
Fresh	6·5	17·6	541·9	34·2	15·8	117·0	10·3	0	0	0
Anaerobic	7·3	19·4	550·8	25·9	21·3	36·7	26·4	16·9	25·8	0^a
Aerobic	7·5	25·2	498·8	52·0	9·6	68·1	8·0	47·1	51·4	23·4
Poultry excreta										
Fresh	5·9	23·6	492·4	61·8	7·9	147·6	7·5	0	0	0
Anaerobic	7·8	34·7	452·1	25·2	17·9	20·7	73·2	40·1	43·7	7·5
Aerobic	7·9	42·9	478·1	40·8	11·7	60·9	10·1	57·9	58·0	76·5

Type of manure	*(mg g^{-1} dry matter)* P	K	Ca	Mg	S	*(µg g^{-1} dry matter)* Cu	Zn	Mn	Fe	B	Na	Al
Cattle faeces												
Fresh	9·0	7·3	19·6	6·0	3·6	40	127	154	2032	15	10	1440
Anaerobic	9·3	12·9	20·1	6·4	3·6	41	137	164	2028	20	30	1773
Aerobic	10·4	14·4	22·0	6·9	4·4	48	160	194	2462	22	34	1926
Pig faeces												
Fresh	29·0	11·4	26·4	9·8	4·3	114	1195	247	860	11	20	190
Anaerobic	19·7	17·8	34·2	12·2	4·6	121	1304	245	970	15	20	214
Aerobic	36·1	30·0	38·2	15·0	7·2	196	1998	436	1570	23	32	327
Poultry excreta												
Fresh	19·3	18·5	66·5	5·7	5·0	78	430	530	1050	10	80	430
Anaerobic	23·5	24·1	91·7	6·1	5·3	105	578	663	1782	17	73	689
Aerobic	33·5	40·7	118·7	9·5	8·2	134	778	947	2368	22	124	853

Table 2.2: Properties of animal manure slurries (Mathur et al., 1990)

Properties[a]	*Poultry manure*	*Dairy cow manure*	*Sheep manure*	*Peat*
Moisture (% of DM)	2870	1186	1566	100·0
Dry matter (% moist wt)	3·4	7·8	6·0	50·0
Organic matter (%)	68·4	80·7	63·9	96·0
Carbon (%)	34·6	40·0	31·3	43·7
Total nitrogen (%)	3·52	2·09	2·27	0·8
NH_4—N (mg kg^{-1})	5050	740	2650	300
NO_3—N (mg kg^{-1})	118	51	252	67
pH	6·52	8·35	7·41	3·0
C/N ratio	9·8	19·1	13·8	53·3
Phosphorus (%)	2·90	1·08	0·59	0·04
Potassium (%)	2·89	3·40	2·28	0·05
Calcium (%)	5·9	1·7	4·2	0·1
Magnesium (%)	0·74	0·53	0·63	0·1
Copper (mg kg^{-1})	50·4	52·9	23·4	2·8
Iron (%)	0·43	0·15	0·25	0·1
Manganese (mg kg^{-1})	380	120	115	78
Zinc (mg kg^{-1})	970	210	440	9

[a] On dry matter basis, unless indicated otherwise.

Besides the required amount, nutrients availability or biodegradability is also important. In fact organic materials with similar levels of moisture, carbon, bulk densities, and adequate nitrogen can compost at different rates (Motte and Griffis, 1980). Haug and Ellsworth (1991) stated that there is a tendency to use an assumed degradability for composting processes, whether or not it is correct. Thus, process design, like any other sanitary engineering practice, should be done in conjunction with laboratory testing for determination of substrate degradability. One measure of biodegradability is volatile solids (VS). Tchobanoglous *et al.* (1993) reported that VS content could be misleading, since some organic constitutes are highly volatile but low in biodegradability, especially for MSW. These authors suggested the use of lignin content to estimate the biodegradable fraction, using the following equation:

$$BF=0.83-0.028\ LC \qquad (2.2)$$

where: BF= biodegradable fraction expressed on VS basis.

LC= lignin content of VS expressed as a percent of dry weight.

Lignin is a difficult or recalcitrant material for microorganisms to metabolize. Therefore, lignin content is a good indicator of biodegradability. Gossett and McCarty (1975) measured no reduction in the lignin content during the composting of refuse. Another study showed only 15% lignin reduction in a cattle manure compost pile (Godden and Penninckx, 1986).

BF values for food wastes, yard wastes, and newsprint are 0.82, 0.72, and 0.22, respectively. Haug and Ellsworth (1991) suggested the use of respirometry for measuring biodegradability. Basically, respirometry measures oxygen consumption due to biological substrate utilization under conditions which eliminates any rate limitation from the lack of oxygen, nutrients, moisture, and imbalanced pH. By considering the oxygen uptake pattern it is possible to determine the rate constant of substrate decomposition.

2.3.3 Biochemical reactions

Any material of biological origin is a mixture of proteins, lipids, water soluble organic compounds, structural polysaccharides (starches and cellulose), and in the case of plants, phenylpropanoid compounds and their polymers such as lignin (Mathur, 1991). Tchobanoglous *et al.* (1993) reported that the organic fraction of MSW, except plastics, rubber, and leather, is composed of amino acids, proteins, lipids, carbohydrates, cellulose, lignin, and ash. Proteins and carbohydrates are easily biodegradable. According to Polprasert (1989), the break down pathways of proteins and carbohydrates are:

Proteins ==> peptides ==> amino acids ==> ammonium compounds ==> bacterial protoplasm and CO_2 (2.3)

Carbohydrates ==> simple sugars ==> organic acids ==> CO_2 and bacterial protoplasm (2.4)

Jakobsen (1992) described stoichiometric reactions for the decomposition of proteins and carbohydrates. These reactions are presented in Table 2.3. In the first step, carbohydrates decompose into monosaccharoses (simple sugars) by hydrolysis. Step 2 involves the fermentation of monosaccharide into ethanol. In the next two steps (3 and 4) ethanol is oxidized to acetaldehyde and then to acetic acid. In the final step oxidation of acetic acid into carbon dioxide occurs. If carbon dioxide is not removed in this step and accumulates, acetic acid will inhibit microbial decomposition. For every mole of simple sugar 6 moles of O_2 are consumed and 6 moles of CO_2 and H_2O are produced. In the case of protein, it is hydrolyzed into amino acids in the first step. The decomposition of amino acids yields hydrogen carbonate ion and ammonia. Ammonia is an alkanity agent, which results in a pH increase.

2.3.4 Microorganisms

As mentioned above, microorganisms need a carbon source, energy source, and nutrients to reproduce and to maintain themselves. The microorganisms that use organic carbon as carbon source are called heterotrophs and those that use CO_2 are known as autotrophs. As energy source, microorganisms can use either sunlight or energy derived from chemical reactions and they are known as phototrophs and chemotrophs, respectively. Phototrophs and chemotrophs can be either heterotrophic or autotrophic. Chemoheterotrophs are the dominant microorganisms in biodegradation (Tchobanoglous and Schroeder, 1985). Protozoa, fungi, and most bacteria belong to this group. Based on optimal temperature range for their function, microorganisms in each group can be

Table 2.3: Decomposition of carbohydrates and proteins (Jackobsen, 1992)

Chemical reactions during decomposition of carbohydrates

$(C_6H_{10}O_5)_n + n\,H_2O$	→	$n\,C_6H_{12}O_6$
$C_6H_{12}O_6$	→	$2\,CH_3CH_2OH + 2\,CO_2$
fermentation into ethanol		
$2\,CH_3CH_2OH + O_2$	→	$2\,CH_3CHO + 2\,H_2O$
oxidation into acetaldehyde		
$2\,CH_3CHO + O_2$	→	$2\,CH_3COOH$
oxidation into acetic acid		
$2\,CH_3COOH + 4\,O_2$	→	$4\,CO_2 + 4\,H_2O$
oxidation into carbon dioxide and water		
$C_6H_{12}O_6 + 6\,O_2$	→	$6\,CO_2 + 6\,H_2O$
gross reaction		
$CO_2 + H_2O + CaCO_3$	=	$Ca\,(HCO_3)_2$
CH_3COOH	→	$CH_4 + CO_2$
decarboxylation into methane		
$C_6H_{10}O_5 + 6\,O_2$	→	$6\,CO_2 + 5\,H_2O$

Chemical reactions during decomposition of amino acids

R			
|			
$HCNH_2 + O_2 + H_2O$	→	$RH + CO_2 + HCO_3^- + NH_3$	
|			
COO–			
$CH_4 + 2\,O_2$	→	$CO_2 + 2\,H_2O$ methane	
amino acid $+ 3\,O_2$	→	$2CO_2 + HCO_3^- + NH_3 + H_2O$	
		$H_2O + CO_2$	
		⇅	
$2\,HCO_3$	⇌	$H_2CO_3 + CO_3^{2-}$	
$CO_3^{2-} + H^+$	⇌	HCO_3^-	pH increases
$CO_3^{2-} + Ca^{2+}$	⇌	$CaCO_3$	activity of Ca decreases
NH_4^+	⇌	$NH_3 + H^+$	at 24 °C pKa = 9.3
			at 60 °C pKa = 8.3
$NH_3 + CO_2 + H_2O$	⇌	NH_4HCO_3	
$2\,NH_4HCO_3 + CaCl_2$	⇌	$2\,NH_4Cl + CaCO_3$	

further classified into psychrophillic, mesophyllic, and thermophilic species.

Composting involves a diverse group of microorganisms. Because conditions vary with time and location, different types of microorganisms dominate at different time steps and positions within the composting pile. The major groups that participate in this process are bacteria, fungi, and actinomycetes. Fig. 2.2 shows their typical shapes.

Bacteria are small, simple unicellular organisms. They usually reproduce by binary fission. The optimum pH level for bacteria is around neutral (6.5 to 7.5). Bacteria are the largest group of microorganisms participating in composting. Actinomycetes are technically classified as bacteria because of their small size and cell structure (Haug, 1980). They have low tolerance for low pH conditions. Fungi are larger organisms. Many of them form filaments, networks of individual cells in strands. They are more tolerant of low moisture and low pH conditions, but severely affected by low oxygen conditions. Fungi are important in the decomposition of woody materials.

Fungi and actinomycetes are more important in the final stages of composting. Results from a study on composted urban refuse showed that bacteria predominated, but actinomycetes and fungi were also in high densities (Diaz-Ravina *et al.*, 1989). Based on experiments of composting agricultural and forest residues,Falcon *et al.*(1987) reported that the fungi were mainly thermophilic and most bacteria were detected during mesophilic phases. According to Poincelot (1972), both mesophilic and thermophilic

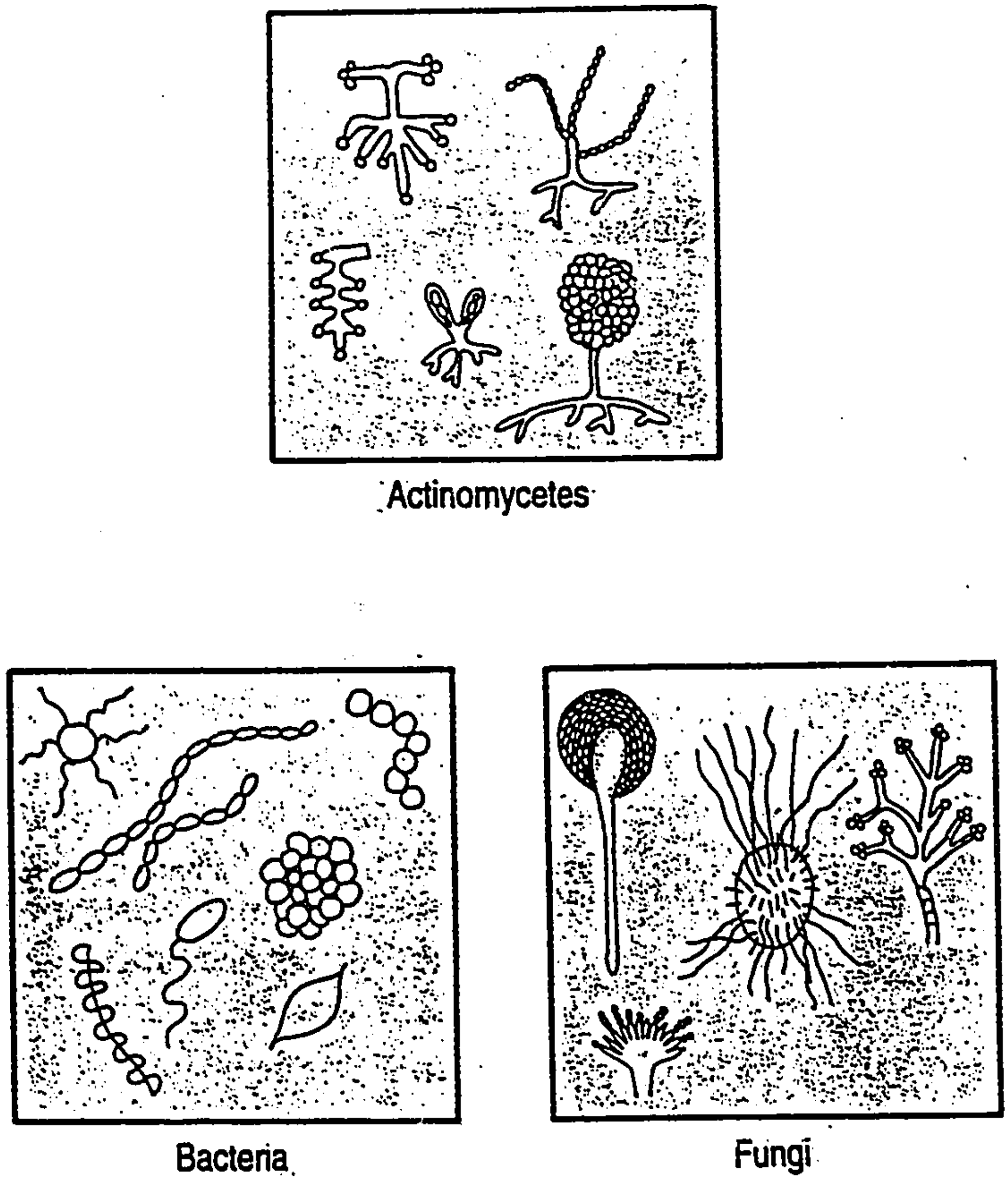


Figure 2.2: Microorganisms involved in composting (Rynk, 1992)

microorganisms can be found throughout the composting process. Davis *et al.* (1992) enumerated the microorganisms associated with pine bark composting, and found that the numbers of bacterial colony forming units (CFU) were higher than fungal CFU throughout the composting process. In an experiment with sewage sludge compost, twelve strains of thermophilic bacteria were isolated. These isolates were able to grow in the temperature range from 40 to 78°C; optimum range being 60 to 65°C (Fujio and Kume, 1991). In contrast to the above findings, some researchers believe that thermophilic bacteria can develop at temperature below 65°C. (Beaudet *et al.*, 1990 and Gray, 1970).

Inoculation is the act of deliberately adding microorganisms to improve composting. Most studies have shown that inoculation is not advantageous to composting. Faure and Deschamps (1991) demonstrated that the addition of an inocolum rich in cellulolytic and lignilolytic bacteria had no effect on grape pulp biodegradation. The main reason being that sufficient quantity of bacteria were present in the grape pulp already. Golueke (1977) also stated that inoculation was not effective for composting. However, depending on the nature of the material (e.g. processed wood pulp) inoculation may be beneficial if initial microbial populations are low.

2.4 Control And Design Considerations

Since composting is essentially a biological process, its efficiency depends on various environmental conditions. Hansen *et al.* (1989a) counted as many as 20 factors having the potential to affect composting. Among the more important factors are C/N ratio, physical state of material, moisture content (MC), temperature, degree of aeration, and pH. In addition, special consideration should be given to the control of odour, pathogens, and nitrogen loss.

2.4.1 C/N

Microbial protoplasm contains about 50% carbon, 5% nitrogen, and 0.25-1% phosphorous on a dry basis (Mathur, 1991). It means that for biomass accumulation, the need for carbon is ten times that of nitrogen. As already stated, microorganisms also need carbon for energy. Mathur (1991) stated that about two atoms of carbon as energy source are needed for assimilation of each atom of carbon. Therefore, approximately for every part of nitrogen, 10 parts of carbon are required as carbon source and another 20 parts as energy source, which brings the total carbon requirement to 30 parts, or a C/N ratio of 30 approximately. A lot of research has been directed at finding the optimum range of C/N values for composting.

Polprasert (1989) suggested a range of 20 to 40 as the optimum C/N for composting. Gotaas (1956) found that optimum C/N ratios for different organic materials were between 26 to 35. According to Golueke (1992) a ratio of 30 is optimum for most types of wastes, especially MSW and food waste. Typical C/N values for poultry manure and some other types of wastes are presented in Tables 2.1 and 2.2.

When C/N ratio is below the optimum range, available carbon is fully utilized and nitrogen in excess will be lost to the atmosphere as NH_3. On the other hand, if C/N ratio is above the optimum range, nitrogen will become a limiting factor for biological growth. The process slows down, less heat is generated, and longer composting time is required.

Kubota and Nakasaki (1991) examined the effect of C/N ratio on composting of garbage. They conducted experiments with three different C/N ratio, 13.9, 22.4, and 30.9 as run A, B, and C respectively. The evolution of CO_2 and NH_3 gases was monitored. The results are shown in Fig. 2.3. Higher peaks of CO_2, an indication of biological activity, were achieved in runs B and C. Also much lower NH_3 emissions were observed in run C. Considering both CO_2 and NH_3 evolution rates, it appears that optimum condition is somewhere between 22.4 and 30.9 for C/N ratio. Hansen *et al.* (1989b) measured NH_3 emissions from compost piles of poultry manure with initial C/N values of 15 and 20. Cumulative quantities of emitted NH_3 are shown in Fig 2.4. The significant effect of low C/N values on NH_3 emissions is obvious. Although C/N is a useful guide, it needs special attention if the carbon is in a form that is difficult to decompose. In this case, biodegradable carbon should be used for determination of C/N.

As the composting proceeds the amount of carbon is reduced. With each cycle of biological growth two-thirds of utilized carbon is given off as CO_2 while nitrogen is

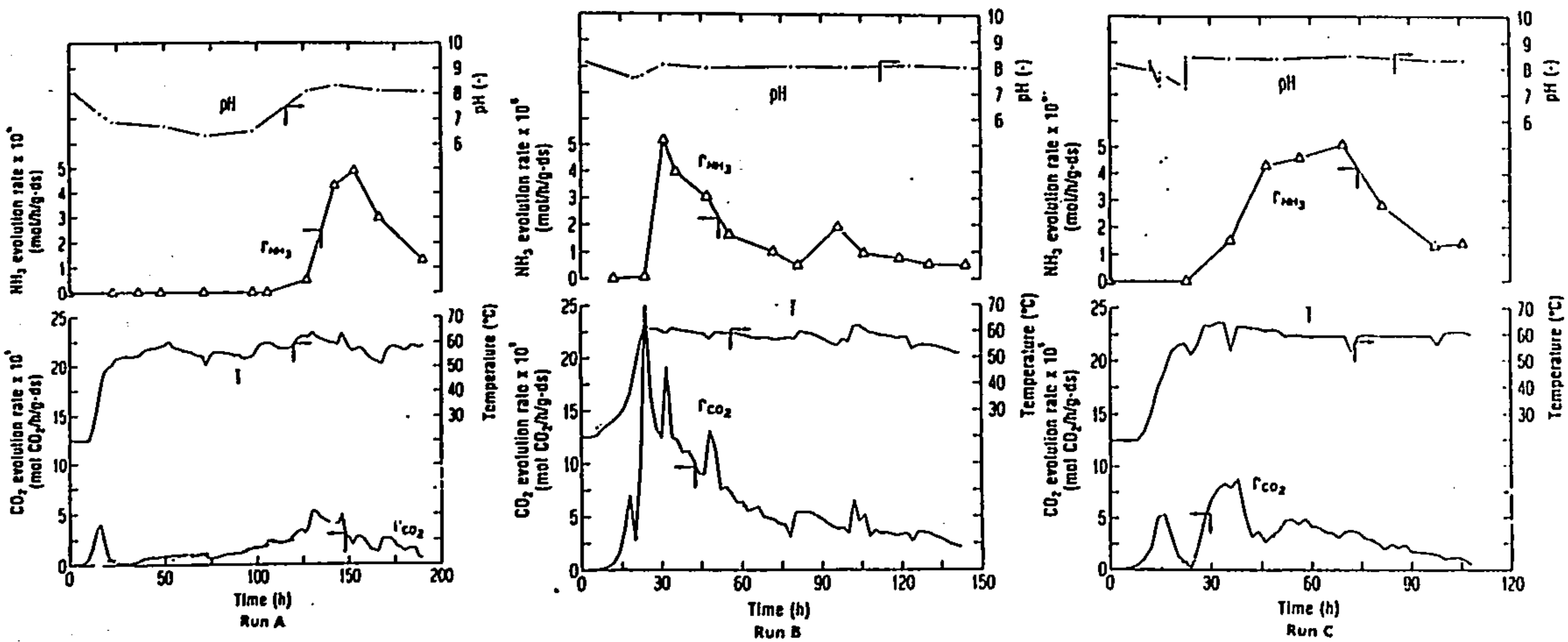


Figure 2.3: Evolution of CO_2 and NH_3 (Kubota and Nakasaki, 1991)

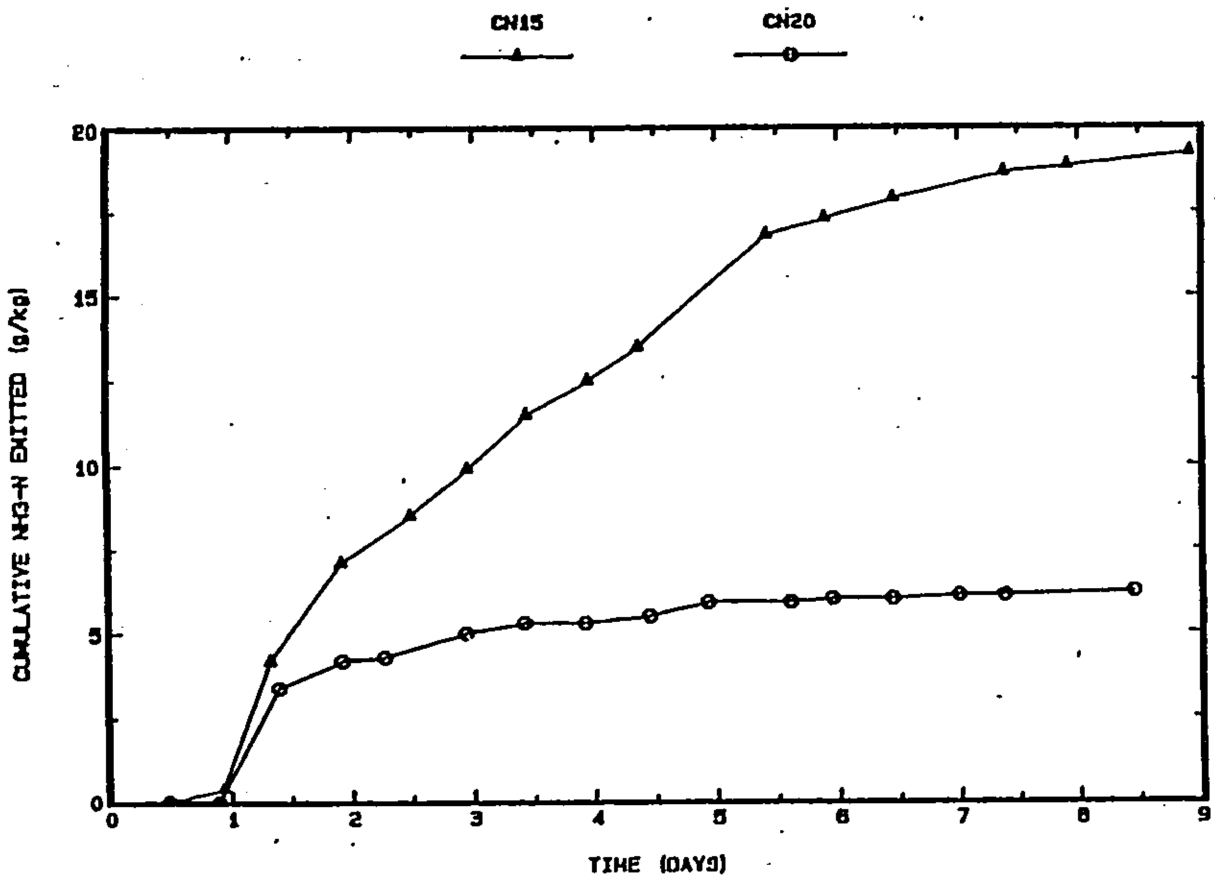


Figure 2.4: Cumulative NH_3 emission (Hansen *et al.*, 1989)

mostly recycled. This results in lower C/N ratios. If initial C/N ratio is lower than optimum, it increases during the process due to volatilization of NH_3.

2.4.2 Physical state of raw compost

Porosity, structure, and particle size of composting material are important physical properties that affect the process of composting. They have a direct influence on aeration and biological activities. Porosity refers to the air space within the composting materials and is influenced by particle size, size distribution and moisture. Structure is a measure of a material's ability to resist settling and compaction. Smaller particle size increases the particle surface area on which most aerobic decomposition occurs. Therefore, smaller particle sizes accelerate decomposition rate. But too small particles also decrease the porosity which in turn restricts air movement, so a compromise is needed. Particle size range from 0.003 to 0.05 m was suggested by Rynk (1992) to give the best results. Mathur (1991) stated that a mixture of various sizes, in which the largest size is not greater than 0.05 m, is optimal. For woody materials a maximum particle size of 0.01 m was recommended by Golueke (1977).

2.4.3 Moisture content (MC)

A proper MC is necessary to support microbial metabolic processes. Water is the medium in which chemical reactions, nutrients transport, and biological activities occur.

In theory, optimal biological activities occur when materials are saturated. In practice, relatively, lower MC levels should be maintained because, 1) high MC restricts air movement, 2) high temperatures can not be achieved, and 3) composting pile construction at high MC levels is not feasible. The optimum MC depends on the porosity and raw materials ability to adsorb water. Optimum MC for a highly adsorbent and porous material is greater than that of a densely packed material with low absorbency. The ability to adsorb water is expressed by the water holding capacity (WHC). It is reported that maximum aerobic microbial activity in soil occurs when the MC is two-thirds of its WHC (Mathur, 1991). Although 50 to 60% MC is generally recommended for composting (Poincelot, 1974), it is found by some researchers that proper composting with MC higher than this range is feasible. Mathur (1991) reported on effective peat-based composting of manure with 70-90% MC. Thostrup (1985) stated that MC for solid manure should be between 70 to 80%. Zhan (1993) demonstrated effective composting of poultry manure plus peat with MC levels up to 80%. Poultry manure is high in MC, about 90%, and is adjusted by adding bulking material that is low in MC. One advantage of composting at high MC levels is the lower need for bulking materials.

During composting, a portion of water evaporates due to high temperatures in the pile. Since water is produced during biological reactions, a part of the water loss is compensated for, and MC change over the whole process period might be insignificant in some cases.

2.4.4 Temperature

As shown in eq. 2.1, during microbial substrate decomposition some energy in the form of heat is released. It accumulates within the composting pile and causes the temperature to rise. High temperatures, in the thermophilic range, help composting function in three ways: 1) water vapour and other gases like CO_2 are carried away by the movement of warm air; 2) pathogens and weed seeds destruction is achieved; and 3) rates of microbial activity are faster. Since heat is generated by decomposition of organic matter it is also the most important indicator of composting progress. Haug (1980) calculated that each mole (180 g) of glucose ($C_6H_{12}O_6$) would release 673 kcal of energy. A portion is captured by microbes and the rest is released as heat.

As a general rule microorganism activity doubles for each 10°C rise in temperature. However, there is an upper limit beyond which many microorganisms are inactivated. Optimum values found by different investigators range from 45 to 70°C (Haug, 1980). Temperatures higher than 70 are not appropriate because few organisms are active at these levels and rates of reactions are severely affected (Mathur, 1991 and Haug 1980). Hong *et al.* (1983) concluded that maximum decomposition rate for composting of dairy manure occurred at a temperature between 65 and 75°C. McKinley and Vestal (1985) investigated the effect of temperature on microbial activity during composting of municipal sewage sludge. In one set of experiments, the mean temperatures were kept below 58°C while in the other, mean temperatures reached 84°C. The results showed that significantly greater microbial activity were found at moderate temperatures below 58°C.

Mathur (1991) stated " recently, heightening awareness of (a) the dependence of pathogen inactivation on both the period and temperature of exposure rather than the latter alone, (b) bioinhibitory properties of certain intermediate products of decomposition, and (c) the need for odour control, as well as detailed observations of maximal decomposition at near 55°C, have seemingly led to a consensus that 55-60°C is the optimal temperature range for composting."

Thermal death points for some pathogenic organisms are shown in Table 2.4. It is apparent that inactivation is a function of both time and temperature. For pathogen control, U.S. Environmental Protection Agency (EPA) has set specific requirements, processes to significantly reduce pathogens (PSRP) and processes to further reduce pathogens (PFRP). These regulatory requirements are also shown in Table 2.4. Temperature patterns for different composting technologies will be discussed in later sections.

2.4.5 Aeration

The main purposes for supplying air are: 1) to provide oxygen for aerobic biodegradation; and 2) to remove heat, water vapour, and other gases generated during composting. Aeration plays a vital role in composting. As a matter of fact, composting technologies are classified based on the way they introduce air into the materials.

Table 2.4: Thermal death points of pathogenic organisms and EPA requirements (Tchobanoglous et al, 1993)

Temperature and time of exposure required for destruction of some common pathogens and parasites

Organism	Observations
Salmonella typhosa	No growth beyond 46°C; death within 30 minutes at 55–60°C and within 20 minutes at 60°C; destroyed in a short time in compost environment.
Salmonella sp.	Death within 1 hour at 55°C and within 15–20 minutes at 60°C.
Shigella sp.	Death within 1 hour at 55°C.
Escherichia coli	Most die within 1 hour at 55°C and within 15–20 minutes at 60°C.
Entamoeba histolytica cysts	Death within a few minutes at 45°C and within a few seconds at 55°C.
Taenia saginata	Death within a few minutes at 55°C.
Trichinella spiralis larvae	Quickly killed at 55°C; instantly killed at 60°C.
Brucella abortus or *Br. suis*	Death within 3 minutes at 62–63°C and within 1 hour at 55°C.
Micrococcus pyogenes var. *aureus*	Death within 10 minutes at 50°C.
Streptococcus pyogenes	Death within 10 minutes at 54°C.
Mycobacterium tuberculosis var. *hominis*	Death within 15–20 minutes at 66°C or after momentary heating at 67°C.
Corynebacterium diphtheriae	Death within 45 minutes at 55°C.
Necator americanus	Death within 50 minutes at 45°C.
Ascaris lumbricoides eggs	Death in less than 1 hour at temperatures over 50°C.

EPA requirements for pathogen control in compost processes

Requirement	Remarks
Processes to significantly reduce pathogens (PSRP)	Using the in-vessel, aerated static pile, or windrow composting methods, the solid waste is maintained at minimum operating conditions of 40°C for 5 days. For four hours during this period, the temperature exceeds 55°C.
Processes to further reduce pathogens (PFRP)	Using the in-vessel or aerated static pile composting methods, the solid waste is maintained at operating conditions of 55°C or greater for three days.
	Using the windrow composting method, the solid waste is maintained at operating conditions of 55°C or greater for at least 15 days during the composting period. Also, during the high-temperature period there will be a minimum of five turnings of the windrow.

The need for aeration is much greater in the early stages of composting. Without sufficient oxygen, the process becomes anaerobic and slows down. In addition, anaerobic process does not produce enough heat for inactivation of pathogens and weed seeds. Furthermore, offensive odours are associated with anaerobic biodegradation of organic matter. Principal end products of this process are CO_2, CH_4, NH_3, H_2S, and stable organic matter.

The amount and frequency of aeration is controlled by temperature. The required rate of aeration for heat removal is reported to be ten times higher than that for supplying oxygen (Rynk, 1992).

According to Jeris and Regan (1973), for each kg of volatile organic matter in MSW, 0.144 kg of oxygen are needed. Lossin (1971) reported that the range of 263 to 306 l air/kg VS /hr is an appropriate range for aeration rates. Mathur (1991) reported that optimal aeration is 0.6 to 1.8 m^3 air/kg VS/day during the thermophilic range. If the chemical and physical composition of waste is known, it is possible to calculate the amount of oxygen required to oxidize the organic portion. Tchobanoglous *et al.* (1993) presented the following equation for the complete conversion of organic material:

$$C_aH_bO_cN_d+\left(\frac{4a+b-2c-3d}{4}\right)O_2 \rightarrow aCO_2+\left(\frac{b-3d}{2}\right)H_2O+dNH_3 \qquad (2.4)$$

Rynk (1992) and Mathur (1991) advised that a minimum oxygen concentration of 5%

should be maintained in the gas phase. But Tchobanoglous *et al.* (1993) suggested that air with a minimum of 50% of initial oxygen concentration (about 10%) must be available within the composting pile. More about aeration will be said in the section on composting technologies.

2.4.6 pH

Although ideal pH for most microorganisms is in the neutral range (6.5 to 8), composting can proceed at a wider range, from 5.5 to 9.0. However, at a pH of 8.5 or more, excess OH^- ions will encourage the conversion of ammonium to ammonia gas. Therefore, it is important to keep the pH below 8 in order to reduce ammonia loss.

As the process proceeds, the pH first drops due to production of intermediate organic acids, CO_2, and amino acids. Then, with the production of ammonia, calcium carbonate, and hydrogen carbonate ions it rises to values around neutral. It was thought that adjusting the pH upward by adding some additives like lime is useful, but as reported this action is not advisable due to potential effect on ammonia volatilization.

2.4.7 Bulking agent

Often the raw waste material does not have all the required characteristics for composting. In this case, bulking agents or amendments are added to adjust waste properties. Bulking agents are usually added to adjust the MC and/or the C/N ratio, and to provide a good structure so that materials can be piled up and maintain sufficient porosity. Commonly used bulking agents are woodchips, straw, sawdust, peat and finished compost.

According to Mathur *et al.* (1990), a good bulking agent for composting manure should: 1) absorb large amounts of water because manure has a high MC; 2) be acidic to prevent ammonia loss; 3) be porous enough to prevent anaerobic conditions; 4) be free of pathogen and weed seeds so that an outer layer of it does not have to be sanitized; 5) have a high cation exchange capacity (CEC); and 6) have the ability to deodorize. These authors also reported that peat had all of these properties, a pH of 3 to 4, bulk density of 0.06 g/cm^3, CEC of 130 meq/100 g, ability of absorbing water up to 20 times its weight and NH_3 up to 3% of its weight.

Peat is a partially fossilized plant matter which occurs in wetlands. Peat passes through the composting process virtually unchanged. ASTM (1983) defines peat as organic matter of geological origin, excluding coal, formed from dead plant remains in water and in the absence of air, that has an ash content less than 25% of dry weight.

Martin *et al.* (1993) reported that peat had fibrous and granular characteristics which aided air flow circulation by creating vertical channels. Working with poultry manure, Zhan (1993) concluded that peat performed better than straw, as a bulking agent, in terms of final quality and prevention of nitrogen loss.

2.4.8 Nitrogen loss

In composting it is important to keep nitrogen losses as low as possible for two main reasons: 1) since nitrogen is a valuable fertilizer, its loss reduces the agronomic value of the final product; and 2) odour problems are associated with the nitrogen loss in the form of NH_3.

Mineralization, the conversion of organic nitrogen to inorganic nitrogen, volatilization NH_3-N, denitrification which is the reduction of NO_3-N to N gases, and immobilization by microbial assimilation are the principal processes for conversion of nitrogen in composting (Edwards and Daniel, 1992). The rates of these processes depend on environmental conditions. It is claimed that nearly all losses of nitrogen occur through mineralization-volatilization during initial stages of composting (Hansen *et al.*, 1989b and Witter and Lopez-Real, 1988). These authors measured over 85% of total NH_3-N production during the first 4 days of composting poultry manure. Martins and Dewes (1992) measured nitrogen loss during composting of liquid manure mixed with straw. Results showed that between 46.8 and 77.4% of total nitrogen was lost in the form of NH_3 and less than 5% in the form of NO_x. Hansen *et al.* (1989a) used Taguchi's method to investigate the effects of amendment, mixing method, initial dry solids, C/N ratio, particle size, temperature set point, and stirring frequency on poultry manure composting.

They concluded that C/N ratio, stirring frequency, and particle size had the greatest impact on nitrogen loss.

2.4.9 Odour

During the initial stages of composting, offensive odours are often produced due to the release of NH_3 and some other gases. Hansen *et al.* (1989b) and Witter and Lopez-Real (1988) have found that NH_3 is the main component of odour emissions. Termeer and Warman (1993) reported that a strong correlation existed between odour and NH_3 emissions from dairy and pig manure. Soil filters, compost filters, addition of odour adsorbent amendments, and collection and/or treatment of odorous gases have been practised to control odour problems.

2.5 Composting Technologies

Based on the aeration methods, composting technologies can be classified into five groups as 1) natural composting, 2) turned windrow composting, 3) passively aerated (passive) method, 4) aerated static pile or forced aeration (FA) system, and 5) in-vessel technology. In the following sections, these methods will be explained.

2.5.1 Natural composting

After properties of raw materials are adjusted, these are stacked in piles. Aeration is provided by natural movement of air around and within the pile through diffusion and updraft convection resulting from the temperature gradient. The mixture should be porous enough to enhance aeration. Since porosity is reduced as MC increases, this method is not recommended for high MC conditions. Schuchardt (1987) detected anaerobic conditions in a study on natural composting of liquid manure and straw with 75% MC. As the outer surface is exposed to ambient temperature, it is necessary to cover the surface with a layer of sanitized material like finished compost or peat. Fig. 2.5-a shows the aeration mechanism in this method. Overall, this method is slow and has greater potential for creating odour problems, but it demands minimum labour and equipment. It takes between 2 to 12 months for the completion of the composting process.

Emerton *et al.* (1988) stated that if air permeability of material is great enough, natural aeration may supply adequate oxygen for composting. In their study on naturally aerated composting of dairy manure, piles achieved adequate temperatures for good composting. The only disadvantage was the slow rate of the process. Ishii *et al.* (1991) also reported on successful natural composting of sewage sludge with initial MC of 50%.

2.5.2 Turned windrow

In this method, materials are placed manually or mechanically in long narrow piles a)

b)

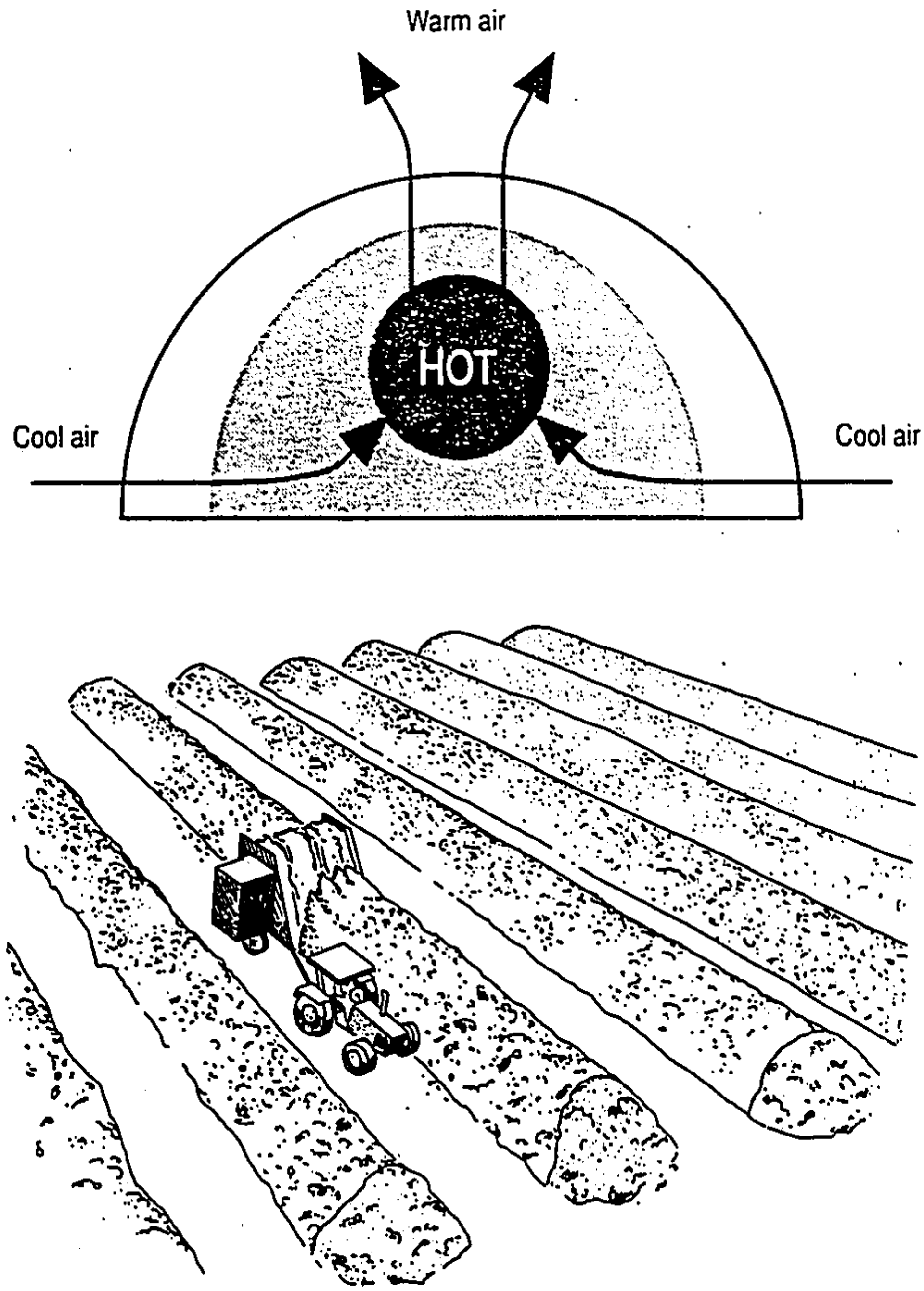


Figure 2.5: Natural (a) and turned windrow composting (b) (Rynk, 1992)

or windrows. Air is mostly supplied by natural aeration and to some extent by turning the piles. The windrows are between 1 and 2.5 m high and 3 to 6 m wide. If turning is done mechanically, the equipment used for turning determines the exact size, shape, and spacing of windrows. The most important objectives of turning are to rebuild porosity and to remove excess heat, water vapour, and gases. The other objective is to exchange the materials from outer layer with those in the pile core. This exposes all materials equally to the high temperatures inside the pile which is necessary for pathogen inactivation. As the composting ages, the frequency of turning decreases. The process is completed in 1 to 4 months. The operation of a mechanically turned windrow composting is shown in Fig. 2.5-b. This method is simple and has low capital cost, but it demands high labour. Odour problems is another big disadvantage associated with turned windrow system.

2.5.3 Passively aerated (PA) composting

This method is similar to natural composting with regard to aeration, *i.e.* air is supplied by the movement of warm air, but it is accelerated by introducing additional air into the pile core by placing open ended perforated pipes at the pile base. The pile height is 1 to 1.5 m. Guidelines for this method, suggest making at least two rows of 0.0125 m diameter holes on top of pipes with 0.3 m spacing between holes in each row (Rynk, 1992). Like natural composting, it is necessary to use a covering layer. Fig. 2.6 shows the guidelines for construction of passively aerated compost pile. After compost maturation, the pipes are pulled out and used to construct new piles.

Passively aerated composting is faster than natural composting, it takes 8 to 12 weeks and eliminates the need for turning as required in turned windrow system. As a result, it performs better in terms of elimination of odour problems and NH_3 loss. Simplicity and low cost are other advantages of this system.

Probably this method was used for the first time by McGarry and Stainforth (1978) with little success. They inserted perforated wooden poles inside the compost piles. Mathur *et al* (1988, 1990) reported on successful composting of seafood wastes and manure slurries using this method, which they named static pile passive aeration composting (SPPAC). Zhan (1993) used this method successfully for composting poultry manure under high MC conditions. PA method has not been used in full scale yet.

2.5.4 Aerated static pile

Aerated static pile, also known as forced aeration (FA), was developed by U.S. Department of Agriculture (USDA) at Beltsville station, Maryland. It is sometimes referred to as the Beltsville process. Using a blower or fan, aerobic conditions are maintained by forcing air movement. Fig. 2.7 shows a typical FA composting system. The blower is operated either to pull (negative pressure) or to push (positive pressure) air into the pile through perforated pipes placed at the base. Initial pile height is 1.5 to

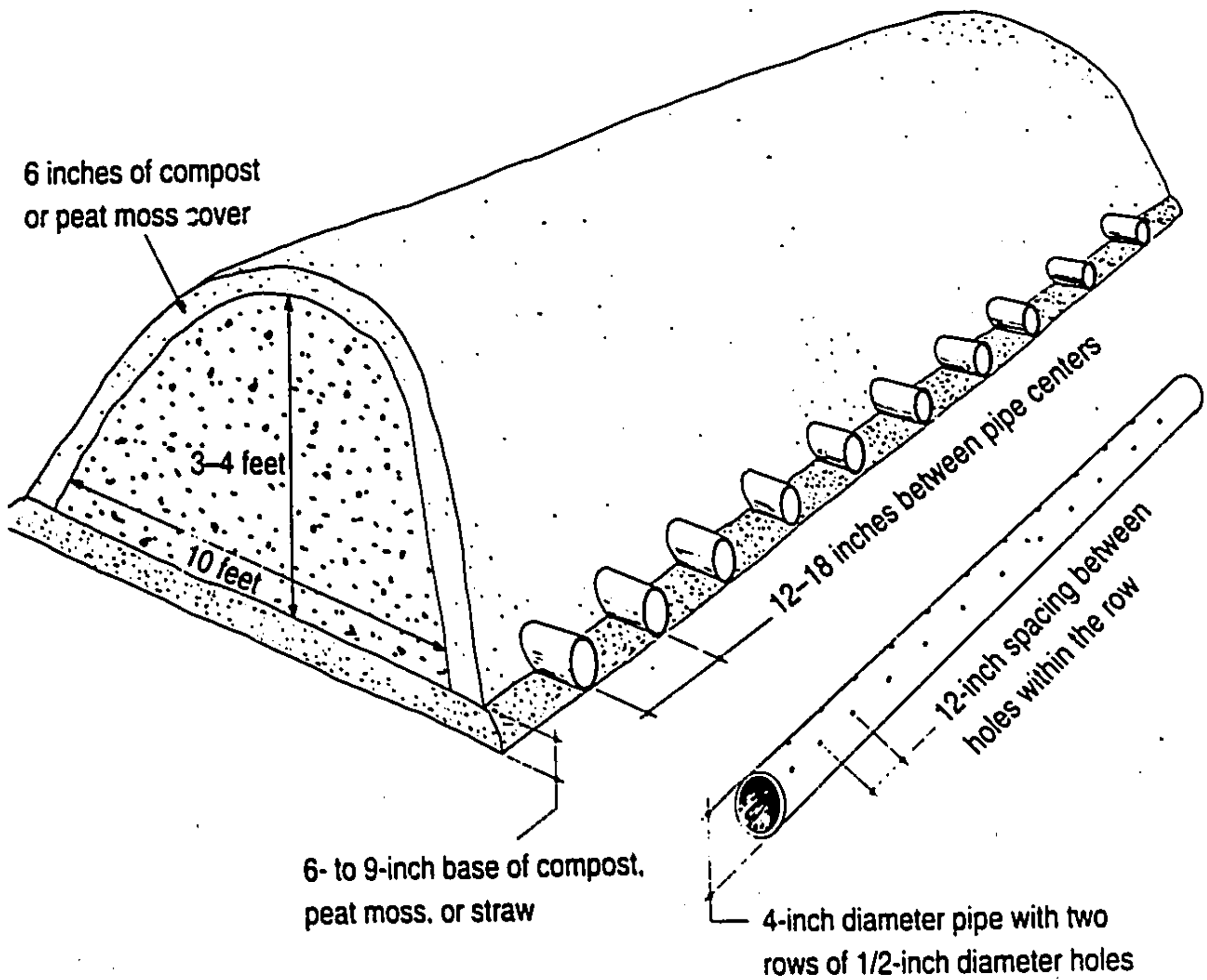


Figure 2.6: Guidelines for passively aerated composting (Rynk, 1992)

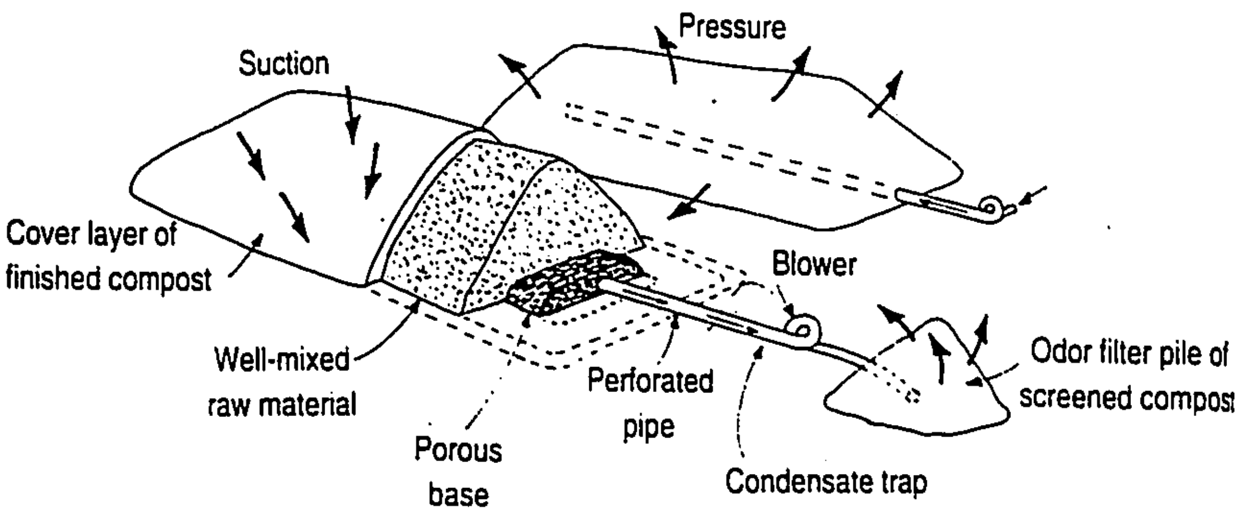
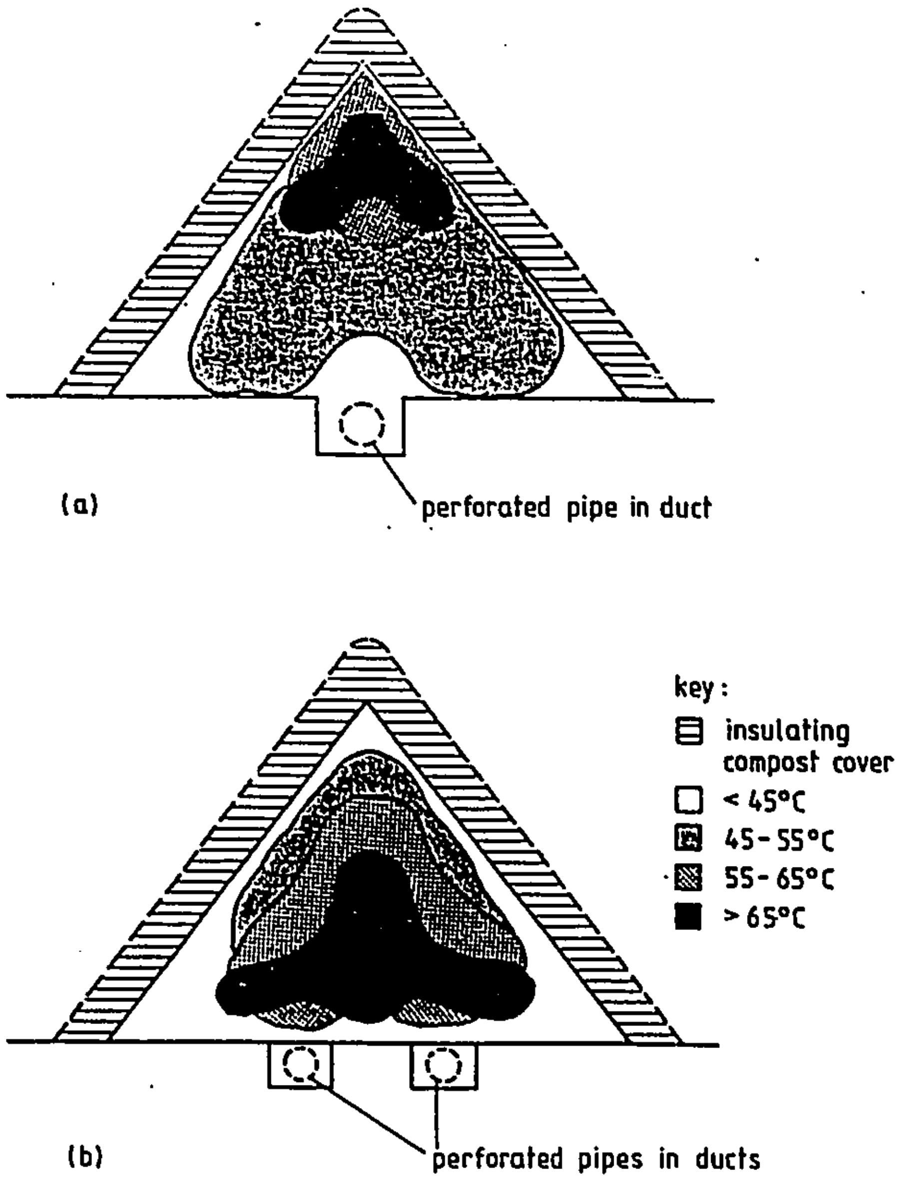


Figure 2.7: Forced aeration composting (Rynk, 1992)

2.5 m and a covering layer is necessary. The active composting period is completed in 3 to 5 weeks. This system requires less land area than windrow or passively aerated methods. It is also more effective in conserving NH_3 than windrow composting, but less effective than passively aerated and natural composting methods.

Epstein *et al.* (1976) reported that negative pressure or suction is the predominant pattern of air flow. Air is drawn into the pile through the large outer surface at low velocities and is preheated before reaching the active zone. This is useful in cold regions and during initial stages of composting when temperatures in the active zone are not very high. The other advantage is the possibility of collecting odorous compounds and passing them through a scrubber or filter. Disadvantages of suction pattern include the necessity of collecting condensed water in aeration line and less uniform distribution of airflow along the perforated pipe (Higgins *et al.*, 1982). Positive pressure has its own advantages and disadvantages. The area near aeration pipes will not reach suitable pasteurizing temperatures unless the air is preheated and exhaust gases are not captured (Higgins, 1984). But air is distributed more uniformly and it is more efficient for heat removal (Finstein and Miller, 1985). Fig. 2.8 shows temperature distribution in positive and negative pressure aeration systems of co-composting of domestic and sewage sludge (Stentiford *et al.*, 1985).

Higgins (1984) used a directional valve to switch between these two systems. During initial stages, aeration is done by suction to introduce preheated air into the pile core.



(a) positive pressure (blowing) aeration; and
(b) negative pressure (sucking) aeration.

Figure 2.8: Temp. distribution in negative and positive pressure aeration (Stentiford et al., 1985)

When the initial stage is over and elevated temperatures are observed, the system is switched to positive pressure ventilation to enhance uniformity of air distribution.

The blower can be run either continuously or intermittently. In continuous operation lower air flow rates are required. This method is not recommended since it leads to less uniform temperatures and it keeps the area around the pipes cooler than the rest of the pile. There are two approaches to control intermittent aeration: time control and temperature control. In the first one, the blower is turned on and off based on a fixed schedule using a timer, while in the other approach the blower is turned on and off in order to keep the temperature within an optimum range. It can be done by putting an electronic temperature sensor such as thermocouples inside the pile. The blower is turned on when the temperature reaches the upper limit. After the temperature drops to the lower limit, the system is shut off. Rynk (1992) suggested to place the sensor at least 45 cm (18 inches) below the pile surface and at two-thirds the length of pile measured from the blower end.

There are two basic control strategies for FA composting: 1) Beltsville strategy and 2) Rutgers strategy. In the first one, suction is the mode of aeration and fixed schedule is the control approach. In the second one positive pressure is the aeration mode and temperature feed back is the control approach.

Higgins *et al.* (1982), Higgins (1982), and Steele and Shove (1969) presented design charts for airflow and pressure distribution in composting aeration systems. Rynk (1993) suggested that as a rough estimate, aeration piping should be sized to maintain air velocity in the pipe below 10 m/sec. The holes should be located in two rows facing downward. The number and size of holes should provide a total area equal to twice the cross-sectional area of the pipe. Hole spacing should not be greater than 0.3 m.

Lau *et al.* (1992) conducted experiments on aeration for swine waste composting. Their recommendation was to use 0.04 to 0.08 l air/min/kg VS and an intermittent mode of aeration should be adopted. Hong *et al.* (1983) studied composting of dairy manure, and concluded that maximum decomposition occurred with an aeration rate between 0.87 and 1.87 l/min/kg VS, which is significantly different from the rate recommended above. Finstein and Miller (1985) measured the range of peak demand for air from 57 to 134 m^3/h/wet tonne of waste. Rynk (1992) suggested airflow rates of 12 l/h/dry ton of manure and 47 l/h/dry ton of manure for time and temperature based control aeration, respectively.

By comparing constant aeration with temperature control aeration, Sikora and Sowers (1985) observed that in the latter case where temperatures were not allowed to exceed 55°C, up to 2.5 times more CO_2 evolved. Since the CO_2 evolution is a direct result of biodegradation, it shows that temperature control aeration is more effective than constant aeration.

Emerton *et al.* (1988) compared forced and naturally aerated composting of dairy manure solids. They monitored changes in moisture content and internal temperature of 10 piles, with 5 piles for each method. The temperature was measured by positioning 3 thermocouples at the centre of the pile, 30 cm apart in vertical direction. They concluded that even though the analysis of variance showed that higher temperatures were achieved by the FA in less time, the temperatures developed in naturally aerated piles were in the range to be considered adequate for good composting. FA appeared to be superior if, for some reason, high maximum temperatures and rapid temperature rise are the process goals. They also conducted the analysis of variance for the mean drying rates. Results showed that the compost piles with forced aeration dried more rapidly than did the naturally aerated compost piles. The reliability of the above conclusion is under question because FA and NA composting piles were monitored under different ambient temperatures.

2.5.5 In-vessel composting

In-vessel technology refers to a group of methods in which composting is confined to a container or vessel. Several such systems were developed in a variety of shapes and sizes. In-vessel composting systems can be classified into two major groups: agitated (dynamic) and not agitated (plug flow) systems. These systems are very fast. The detention time for in-vessel systems is about 10 to 15 days. The process is controlled mainly by mechanical devices and microcomputers. Mechanical systems are designed to control environmental conditions such as temperature, air flow and oxygen concentration. They usually carry very high capital and operating costs. Also a higher level of operational knowledge is required.

2.6 Compost Maturity

Effective composting process should convert the raw material into a product in which the readily decomposable material are broken down to stable substances, plant nutrients are in a usable form, and no phytotoxic substances and pathogens are present. The use of immature compost causes many adverse effects on soil environment, such as N immobilization resulting in N deficiencies in soil (Inbar *et al.*, 1990 and Duggan, 1973). It was pointed out that rapid decomposition of immature compost results in a decrease in O_2 concentrations in soils (Jimenez and Garcia, 1989). The presence of phytotoxic compounds is another consequence of the application of immature compost to the soil (Maureen *et al.*, 1982). Golueke (1977) stated that the phytotoxic effects of insufficiently composted materials are due to the emission of NH_3. He *et al.* (1992) reported that phytotoxicity due to the application of compost is attributed to the presence of organic acids.

Many parameters have been proposed to evaluate compost maturity such as C/N ratio, CEC, adenosine triphosphate (ATP), phytotoxicity, and humus composition. However, a universal method has not yet been adapted. Jimenez and Garcia (1989) classified techniques proposed for this subject into five groups: physical tests, study of microbial activity, study of humic fractions, chemical methods, and biological methods.

Physical tests include the assessment of temperature, odour, colour and reheating. If during the composting, the temperature reaches thermophilic values and then decreases gradually to ambient temperature, it will be a good indication of maturity. Unpleasant odours disappear by the end of process. And the final product has a dark brown colour. Reheating is reported by many researchers as being an easy and more practical way to assess maturity (Mathur *et al.*, 1990, Rynk, 1992, Martin *et al.*, 1993). At the end of the process composted materials are remixed and reheaped. If the pile reheats, it will show that there is still enough easily biodegradable material to support biological activity and thus the temperature rise, otherwise the compost has maturated.

Total microorganisms count, respirometric studies, biochemical parameters, and analysis of biodegradable constituents are some of the procedures for the study of microbial activity. In respirometric studies, O_2 consumption is measured. Immature compost is a compost with strong O_2 consumption. ATP was measured as one of the biochemical parameters by some researchers. Riffaldi *et al.* (1992) reported on maturity evaluation by measuring humic substances and the humification index. Germination tests are more often used in biological tests.

Chemical parameters of interest are C/N ratio, pH, CEC, COD, nitrites, and nitrates. Low C/N ratios of 14 to 20 are indicative of acceptable maturity (Mathur, 1991 and Golueke, 1981). The ratio of final C/N ratio to initial C/N ratio also could be used as an indicator. The reported values for this parameter vary from 0.49 to 0.85 with the mean value of 0.63 (Jimenez and Garcia, 1989). During initial stages of composting, pH drops and later rises to values between 7 and 8. Low pH values at the end of composting indicate lack of maturity. COD can be used as a parameter to measure the degree of stabilization of organig matter. According to Finstein and Miller (1985), appreciable quantities of NO_2 and/or NO_3 appear at the end of composting and measurement of these oxides could be used as an indicator. Gonzalez *et al.* (1989) followed the variation of NO_2 and NO_3 in the composting process.

If the finished compost has a good structure, it can be used as bulking agent. Mathur *et al.* (1990) reported that the finished compost from peat-based composting looked like peat and had a similar WHC. They suggested that compost be recharged with manure for repeated use. It should be noted, however, that the final product has a low C/N ratio while peat is rich in carbon (high C/N ratio). Therefore, it might be necessary to blend compost with fresh peat to increase the C/N ratio for repeated use. The use of finished compost as a bedding material is another possibility which is very attractive to dairy farmers (Emerton *et al.*, 1988).

2.7 Summary

Interest in composting has increased significantly in recent years. It is a simple method in practice, but very complicated in nature. It has many benefits including the ability to reduce environmental impacts resulting from direct land application of farm animal wastes. Many factors affect its performance. Among the more important are C/N ratio, physical state of raw material, moisture content, temperature, aeration, and pH. Bulking agents are usually added to adjust raw material properties. Since nitrogen is a valuable nutrient, a special attention is given to nitrogen loss during the composting process. Several types of composting processes have been used. They are classified into five general groups as natural composting, turned windrow, passively aerated, aerated static pile, and in-vessel systems. Aeration condition is extremely important, in fact, aeration method is the basis of above classification. Since composting involves exothermic reactions with accompanying production of CO_2, the most important indicators of composting progress are temperature and CO_2 production. Many parameters have been proposed to evaluate compost maturity. Among them, the most practical is to assess reheating. Compost is mainly used as a soil conditioner.

Despite the significant amount of research about composting, many aspects of the process are yet to be determined. No information is available on the effectiveness of perforated pipes in passively aerated composting or influence zones of the pipes. There is a lack of research conducted on comparison of natural, passive and forced aeration composting of poultry manure. And limited work has been done on composting under high initial MC.

Chapter 3

MATERIALS AND METHODS

To accomplish the objectives outlined in this thesis, 9 composting piles, on a large scale, were built and monitored for a period of 90 days from September to November, 1993. The experiments were conducted under a roofed barn at the Greenbelt Farm, Agriculture Canada, Nepean, Ontario. Average ambient temperature during this study varied from 25°C at the beginning to 4°C at the end. Forced, passive, and natural aeration modes were examined. These modes of aeration are designated by FA, PA, and NA, respectively. For each of these three treatments, three replicated piles were built. Positive pressure mode was chosen for FA because it gives a more uniform distribution of air. For each treatment, one pile referred as the main pile was monitored intensively. Throughout the rest of this thesis, the letters F, P, and N will be used to refer to the main piles of forced, passive and natural aeration treatments, respectively. The other two replicates are denoted by prefixes R1 and R2. For example, R1F, P, R2N refer to replicate 1 of forced, main pile of passive and replicate 2 of natural aeration treatments, respectively. The layout of composting piles, FA system, and the positions of data loggers are shown in Fig. 3.1.

3.1 Materials

3.1.1 Raw materials

The raw materials used in this study were poultry manure slurry as the waste and sphagnum peat as the bulking agent and pile cover material. Manure was obtained from a poultry house located at the Greenbelt Farm. Peat was purchased in 0.170 m^3 bags. The bulk density of peat was measured to be 130 kg/m^3. Physical and chemical properties of the poultry manure and peat are shown in Table 3.1.

3.1.2 Aeration pipes

ABS pipes, 0.10 m i.d., were chosen for PA. Two rows of holes, 0.022 m in diameter and 0.125 m spacing between the holes, were made on the upper surface of the pipes. The holes were covered with a mesh. The holes provided a total area of 0.0175 m^2, which is 2.3 times the pipe's cross sectional area.

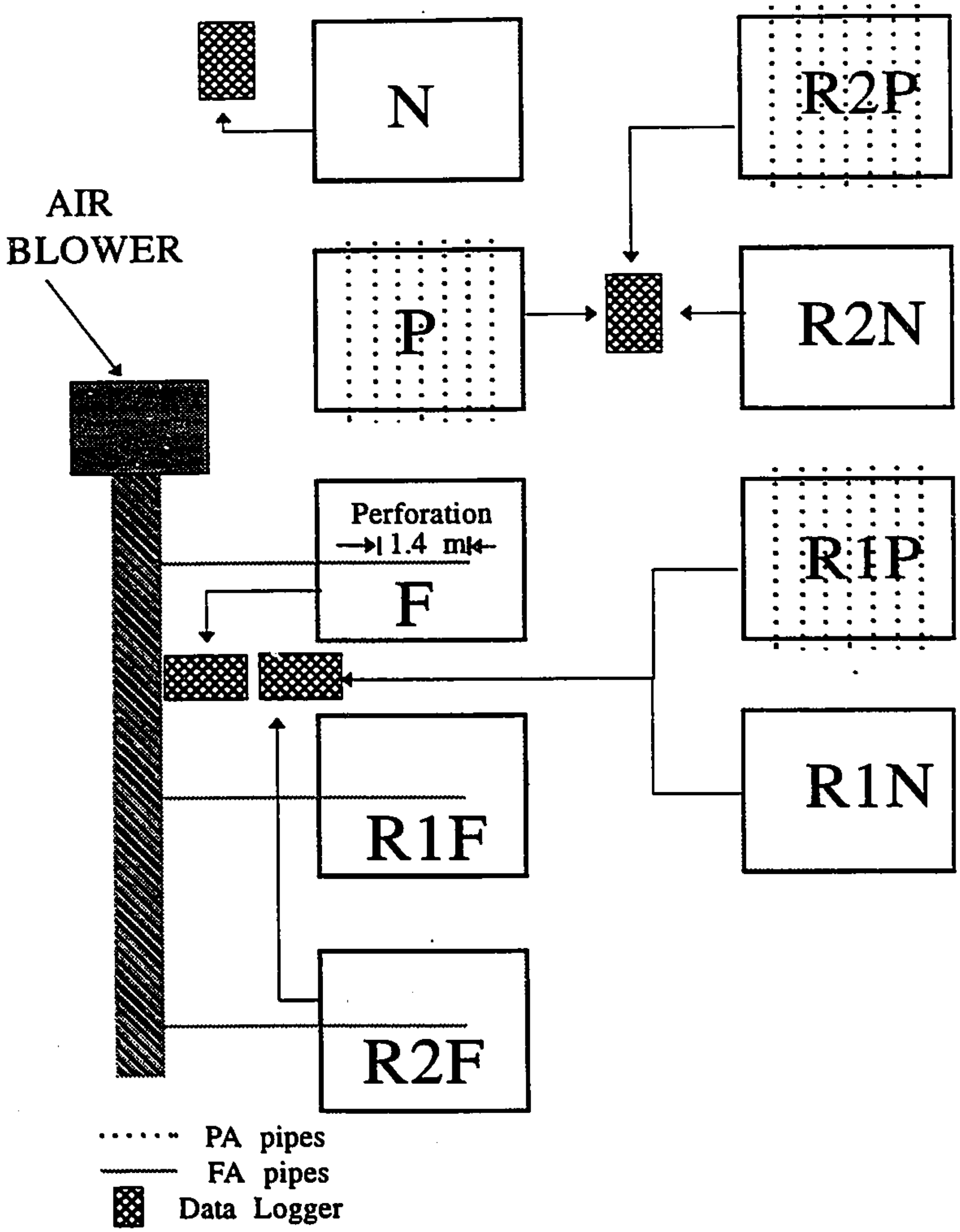


Figure 3.1: Layout of composting piles and FA system

Table 3.1: Physical and chemical properties of raw materials

PROPERTIES	PEAT	POULTRY MANURE	RAW COMPOST
MC (%)	65.6	88.0	76.0
VS% (DM)	94.0	77.0	88.5
ASH% (DM)	6.0	23.0	11.5
TC (DM)	49.2	33.4	42.7
TN (DM)	1.0	2.9	2.0
C/N	51.8	11.5	21.9
pH[a]	3.0	7.3	5.4
TP% (DM)	---	---	0.9
BD	130	N/A	250[b] 360[c]

DM = Dry matter
BD = Bulk density (kg/m^3)
N/A= Not applicable
a: in 0.01 M $CaCl_2$
b: before pile construction
c: after pile construction

Galvanized pipes, 0.10 m i.d., were connected to an air duct, 0.3 m x 0.5 m x 10.0 m, and used as part of the FA system as shown in Fig. 3.1. One end of the pipe inside the pile was closed, while the other end was open to the duct, which was connected to an 1/2 hp air blower (type 122 u/s Sheldons Eng., Ont.). Two rows of holes, 0.029 m in diameter and with 0.15 m spacing between the holes, were made on the lower surface of the pipes for a length of 1.4 m from the inside end of the pipe. The FA pipe was placed in the middle of the pile leaving a 1 meter distance from its edges. Total area of the holes was 1.28 x 10^{-4} m^2 which is 1.6 times the pipe's cross sectional area. These pipes were equipped with a valve in order to control the airflow. The pipes were covered with mesh to prevent the holes from being clogged and provide a more uniform distribution of the air.

3.1.3 Temperature measurement

A total of 233 thermocouples were manufactured using type K thermocouple wire. The theory of temperature measurement with thermocouple wire is explained in Appendix B. Wooden frames, 3 mm thick, were used to support the thermocouples and locate them inside the piles. For intensive monitoring of the temperature, the main piles were instrumented with a total of 59 thermocouples distributed in four layers. Figs. 3.2 and 3.3 show the position of thermocouples with respect to passive and forced aeration pipes in the main compost piles. The vertical position of each thermocouple layer is also shown in these figures. The thermocouple positions were chosen in such a way that they

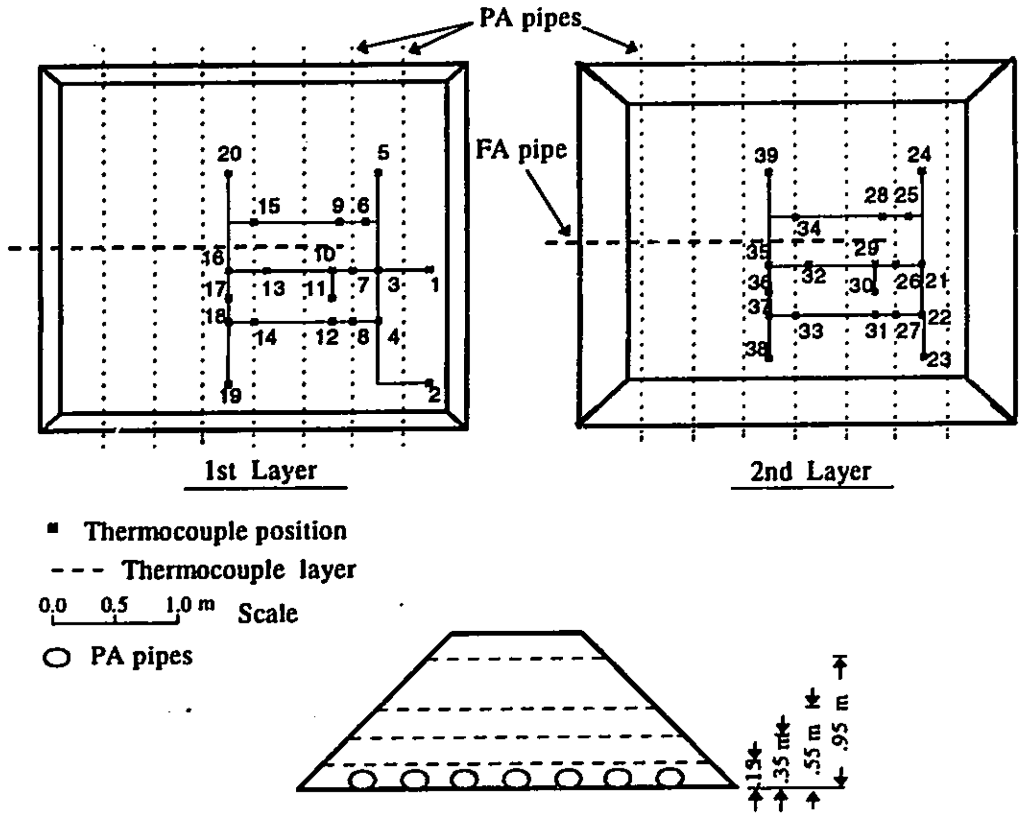


Figure 3.2: Thermocouple layers 1 and 2 in the main piles

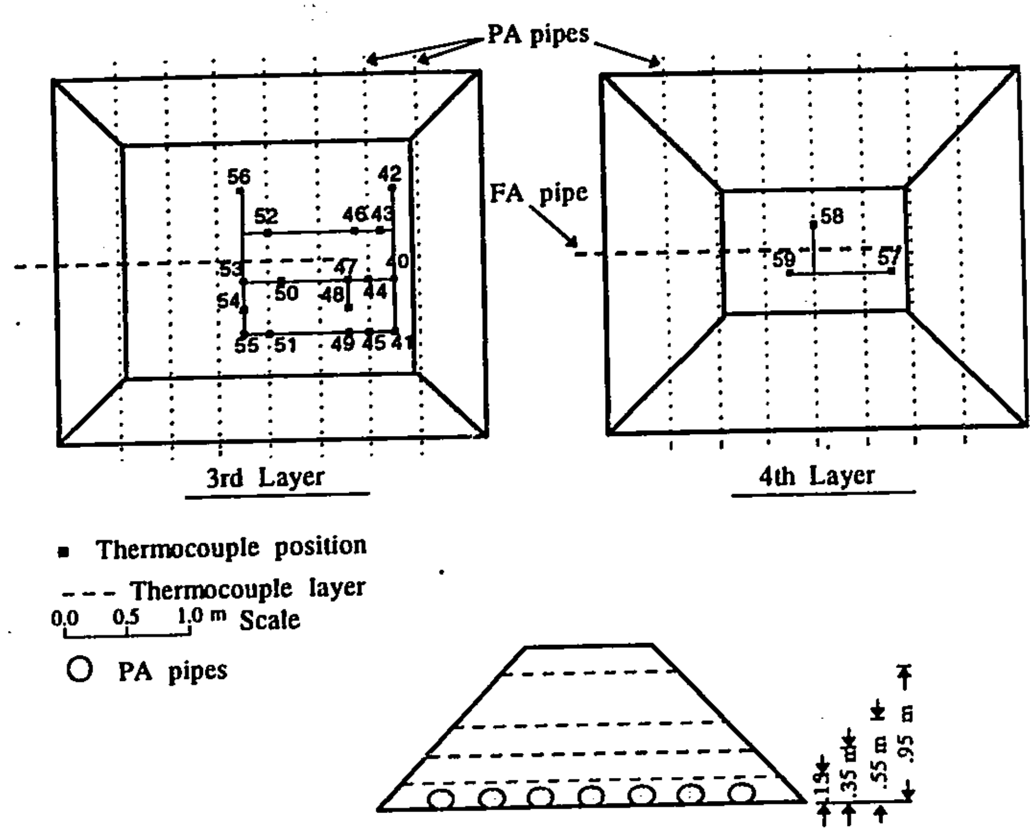


Figure 3.3: Thermocouple layers 3 and 4 in the main piles

formed a grid around the FA and PA pipes. Some thermocouples were located in a manner that allowed to check for symmetry in temperature distribution. The thermocouples were numbered from 1 to 59. For replicated piles, 9 thermocouples of the main piles were reproduced, namely no. 1, 8, 10, 13, 14, 45, 47, 50, and 51, and these are shown in Fig. 1, Appendix A. Two thermocouples were used to measure the ambient temperature. All the thermocouples were connected to 4 data loggers, Digi II, Digi III, Digi IV, and Fluke 2240C.

3.2 Methods

3.2.1 Construction of compost piles

An auger mixing truck (Fig. 3.4-a), equipped with a weighing scale, was used to mix the raw materials. First, the mixing truck was loaded with peat. Then, based on the peat weight reading and the initial MC of the peat and poultry manure, which were 66% and 88% respectively, the amount of required poultry manure was calculated to obtain a raw compost with a MC of 76%. After addition of manure, mixing continued for 30 minutes in order to achieve a uniform compost. The bulk density of the mixture before construction of the piles was measured to be 250 kg/m^3. This procedure was repeated for subsequent batches. Table 2 in Appendix A shows the amount of materials used for each batch. A total quantity of 16,500 kg raw compost was used. A larger amount of peat was required because of its high MC. If the peat had been supplied in more drier a)

b)

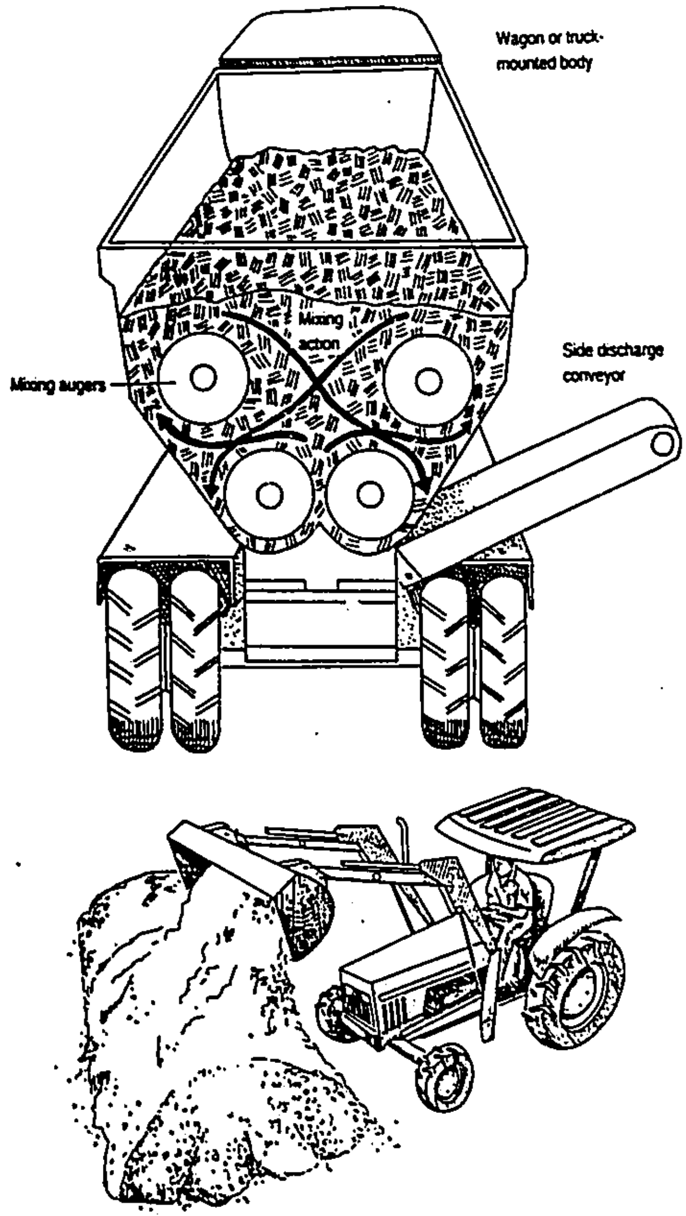


Figure 3.4: Auger mixing truck (a) and bucket loader (b) (Rynk, 1992)

conditions, 50% MC, then a greater quantity of poultry manure, as much as 260% more, could have been processed.

A 0.10 m thick base of peat was prepared on the ground. According to the applicable treatments aeration pipes were placed at the desired positions. For PA piles, a total of 7 perforated pipes, with 0.4 m spacing between them, were placed on the peat base. The first and the last pipes were located at a distance of 0.5 m from the pile edges. For FA piles, a single perforated pipe was placed at the pile's centre. The location of forced and passive pipes are shown in Figs. 3.2 and 3.3. Pipes were not used for natural aeration piles.

In the next step, the raw compost was discharged from the side chute of the mixing truck into a bucket loader (Fig. 3.4-b), used for transportation of raw compost and to build the piles. To shape and size the piles, a wooden frame was placed on a peat base. Whenever the height of the pile reached the thermocouple layers' levels, the surface was levelled and the thermocouple frame was placed. The piles were trapezoidal in section with bottom and top dimensions of 3.4 m x 2.9 m and 1.0 m x 0.5 m, respectively. The initial height was 1.2 m, which worked out to a pile volume of:

$$
\begin{aligned}
V &= 1/3*h*[\,A_1 + A_2 + (A_1A_2)^{1/2}\,] \\
&= 1/3*1.2*[9.86 + 0.5 + (9.86*0.5)^{1/2}] \\
&= 5.03\ m^3
\end{aligned}
$$

where h is height, and A_1 and A_2 are bottom and top areas, respectively. Considering the total amount of the raw mixture used (16500 kg) and the total volume of the nine piles

(45.3 m^3), the overall bulk density was calculated to be 360 kg/m^3. This implies a compaction factor of 1.4 based on the bulk densities of raw compost before (250 kg/m^3) and after (360 kg/m^3) the piles construction. When the pile construction was complete, it was covered with 0.03 to 0.05 m thick layer of peat.

3.2.2 Monitoring of compost piles

<u>Temperature</u>

All data loggers were calibrated in ice bath and programmed to register temperature with a 6 h time step. Two of the data loggers were connected to two computers (PCs). The other two data loggers transferred the data to cassette recording devices. Finally, all temperature readings were compiled as spreadsheet (Lotus) files. Temperature monitoring was carried out until the temperatures in the piles dropped to ambient level. At this time, the piles were remixed and reheaped and were monitored for another 10 days.

<u>CO_2, NH_3, and O_2 measurement</u>

For each of the 3 main piles, three tygon tubes were extended into the middle of the pile at the first, third, and fourth levels for air sampling. After stagnant air was pumped out (until hot steam was observed), air samples were taken by syringes and analyzed with a gas chromatograph (GC) for CO_2, CH_4, and H_2S. Dragger pump and tubes were used to measure CO_2 and NH_3 gases inside the piles and NH_3 gas at the surface of the piles during the first week. The measuring ranges of Dragger tubes for CO_2 and NH_3 were 0.01 to 6 % (vol.) and 5 to 700 ppm respectively.

An oxygen probe was used to measure the available oxygen at the bottom, middle, and top layers of piles F and N. For pile P, the available oxygen was measured at four locations: top, middle, and two at the bottom, right above the middle pipe and between the middle pipe and the adjacent pipe. A hot wire velometer was used to measure the airflow velocity inside the FA pipes. Whenever necessary, the flow rate was adjusted using the valve in order to have equal airflow rates in all FA pipes. The forced aeration system was started when the temperatures inside the FA piles reached about 40°C. The air blower was controlled by a timer. The time schedule was adjusted based on the temperatures inside the FA piles. Table 3.2 shows the measured values of the flowrate for each FA pile and the time schedule for blower operation.

<u>Physical and Chemical analysis</u>

During the experimental period, samples from the bottom, middle, and top of the piles were taken and kept in a freezer. Samples were taken from inside the piles by using a small showel. Then, samples were analyzed for MC, total solids (TS), volatile solids (VS), total carbon (TC), total nitrogen (TN), NH_3 and pH. Total Phosphorous (TP) was measured at the beginning and at the end of the process.

MC and TS were measured by drying the sample in an oven at 105°C for 24 hrs,

Table 3.2: Time schedule for forced aeration system

Day	Velocity (m/s)	Flow rate (l/s)	Time Schedule	Flow rate (l/kg of waste /day)
3	---	---	off	----
4	0.83	6.52	0.5 hr on/0.5 hr off	154
5	0.81	6.36	0.5 hr on/0.5 hr off	150
6	0.80	6.28	0.5 hr on/1.0 hr off	99
7	0.34	2.67	0.5 hr on/1.0 hr off	42
10	0.32	2.51	0.5 hr on/1.5 hr off	30
13	0.32	2.51	0.5 hr on/3.5 hr off	15
15	0.30	2.36	0.5 hr on/11.5 hr off	5
19	---	---	off	----

while the sample for VS determination was ignited in a muffle furnace at 550°C for 30 min (AWWA, Standard Methods, 1992). pH was measured in 0.01 M $CaCl_2$ solution (Mckeague, 1978). Measurement of pH in $CaCl_2$ solution is preferred over measuring pH in water, for pH measured using this solution is independent of dilution over a wide range and it is virtually independent of the initial amount of salts in the sample. pH values obtained in $CaCl_2$ solution are usually 0.5 to 0.8 pH unit lower than measurement in water. For TC and TN determination, the samples were freeze dried, ground in a lab mill, and then analyzed with a LECO analyzer. In order to prevent NH_3 volatilization, it is necessary to freeze dry the samples. TP was determined using an spectrophotometric analyzer, Spectronic 70. An ammonia electrode, Orion, model 95-10, was used to measure NH_3 in 2 N KCl solution.

A complete list of equipment and instruments used during this study is presented in Table 3.3.

Table 3.3: List of materials and equipments used

Material/Equipment	quantity	purpose
ABS pipes	21	passive aeration pipes
Ammonia electrode	1	NH_3 measurement
Blower	1	forced aeration system
Bucket loader	1	construction of piles
$CaCl_2$ solution	-	pH measurement
Cassette recorder device	2	temperature measurement
Data logger	4	temperature measurement
Dragger pumps	2	gas measurement
Dragger tubes	60	gas measurement
Feed (auger) mixing truck	1	mixing raw material
Galvanized pipes	10 m	FA system
Gas chromatograph	1	gascomposition determination
Hot wire velometer	1	air velocity measurement
KCl solution	-	NH_3 measurement
Lab mill	1	grinding the samples
Leco analyzer	1	TN and TC determination
Muffle furnace	1	VS and ash measurement
Oxygen probe	1	measuring available oxygen
Pc (computer)	2	temperature reading
Peat	8844 kg	Raw material
pH meter	1	pH measurement
Poultry manure	8151 kg	Raw material
Spectrophotometric machine	1	TP measurement
Syringe	63	air sampling
Timer	2	forced aeration system
Thermocouple wire	-	temperature measurement
Tygon tubes	8 m	air sampling
Wooden frames (thin wood)	24	locating thermocouples
Wooden frame	1	shaping the piles

Chapter 4

Results And Discussions

4.1 General

In this Chapter, the experimental result are reported and discussed. As already mentioned, F, P, and N will continue to refer to the main piles of three modes of aeration, namely forced, passive and natural aeration, respectively, while replicates no.1 and no.2 of each treatment are denoted by prefixes R1 and R2. The temperature variations with time during composting process are designated as temperature profiles.

As stated in Chapter 2, composting process involves biochemical reactions during which energy in the form of heat is produced, and it is the main reason for temperature rise. To assess the effect of aeration on temperature, all other factors, MC, pH, C/N, and the availability of organic matter should be set at a constant level. For this reason, the same type and amount of waste and bulking material were used and a through mixing was carried out. Thus, air availability was the main factor causing temperature variations inside the composting piles. In Section 4.3, it will be demonstrated that good compost uniformity was achieved.

4.2 Average Temperature

Fig. 4.1 shows the arithmetic average temperature of the main piles based on the readings from 59 thermocouple positions inside each of them. Main characteristics of these average temperature profiles are shown in Table 4.1.

The fact that the average temperatures inside the piles reached the thermophilic range within 4 to 5 days shows that the initial compost composition was appropriate for quick start of the process. Also the average temperature of the piles reached to 55°C, which is the temperature limit for sanitization purpose, between 5 to 7 days. But, it should be noted that the average temperature inside piles P and N stayed above 55°C for 7.5 and 8.5 days, respectively while in pile F it stayed above 55°C less than 2 days. The USEPA standard requires that compost be sanitized at 55°C for at least 3 days.

Piles F and P reached the maximum temperatures of 57.5°C and 60.6°C, respectively on the 8th day. Pile N reached the maximum temperature of 58.4°C on the

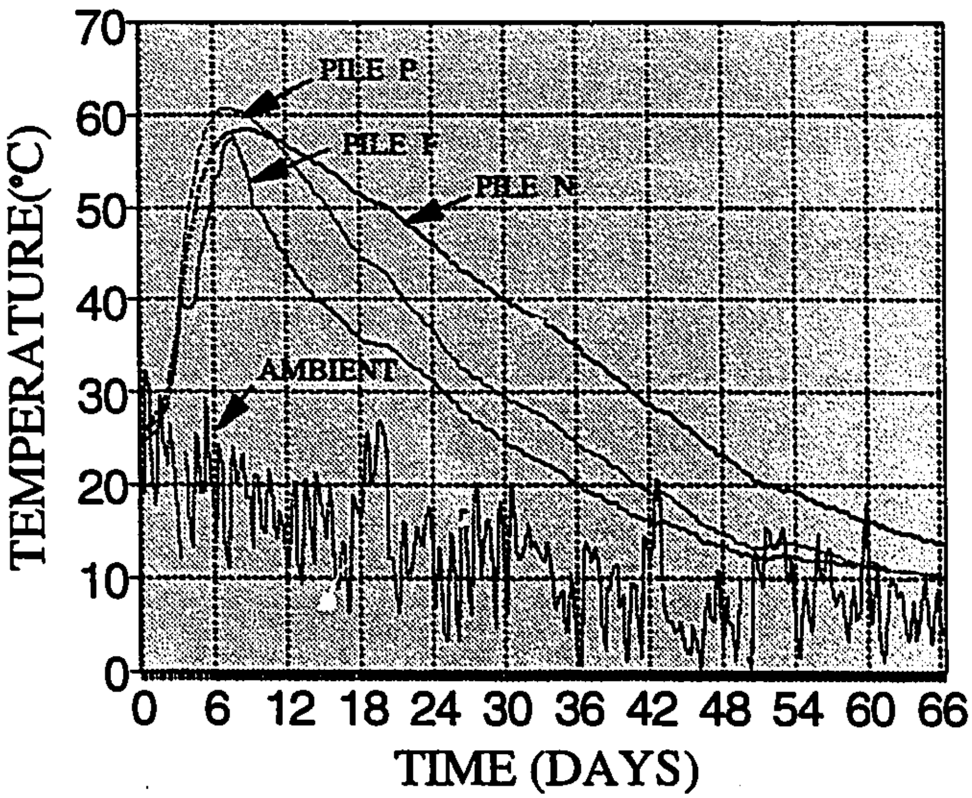


Figure 4.1: Average temperature of piles F, P and N

Table 4.1: Characteristics of average temp. profiles

Parameter	Pile F	Pile P	Pile N
Time to reach 45 °C (days)	5.0	3.75	4.0
Time to reach 55 °C (days)	7.0	5.0	6.0
Duration above 55 °C (days)	1.75	7.5	8.5
Cooling to 15 °C (days)	45.25	47.5	62.25
Peak Temp. (°C)	57.5	60.6	58.4
Time to reach peak (days)	8	8	9
Rate of temp. rise (°C/day)	4.0	4.6	3.7
Rate of temp. cooling (°C/day)	1.1	1.1	0.83

9th day. The rate of temperature rise was calculated by finding the slope of the line between the initial and maximum temperatures. The rate of temperature rise for piles F, P, and N were 4.0 °C/day, 4.6 °C/day, and 3.7 °C/day, respectively. This shows that pile P had the highest rate while pile N had the lowest rate. The reason is that air availability is a limiting factor for interior locations of natural aeration pile, which results in lower microbial activity and consequently lower rate of heat generation, which affects the temperature rise in the pile. But, PA pipes introduced more air into the interior zone of pile P and enhanced the rate of temperature rise. The rate of temperature rise for pile F is between those of piles N and P. Therefore, FA pipe enhanced the rate of temperature rise compared to NA pile, but not as effectively as PA pipes. The reason being that forced aeration introduced larger quantities of air in compost pile than passive pipes, which resulted in lowering the temperatures in areas around the FA pipe. This in turn lowered the rate of temperature rise compared to pile P.

Fig. 4.2 shows the temperature profiles of position 13 at the bottom of piles N, P and F. Position 13 is at a distance of 0.2 m and 0.1 m from FA and PA pipes, respectively. The fact that the temperature in pile F did not go above 45°C shows the cooling effect of forced aeration pipe on this position. Also, comparison of the temperature profiles of position 13 inside pile N and P reveals that PA pipe introduced more air into the pile which enhanced the rate of biodegradation and temperature rise. In fact, position 13 in pile P attained higher peak temperature, 63°C compared to 57°C, and it was achieved in less time *i.e.*, 14 days compared to 35 days in pile N.

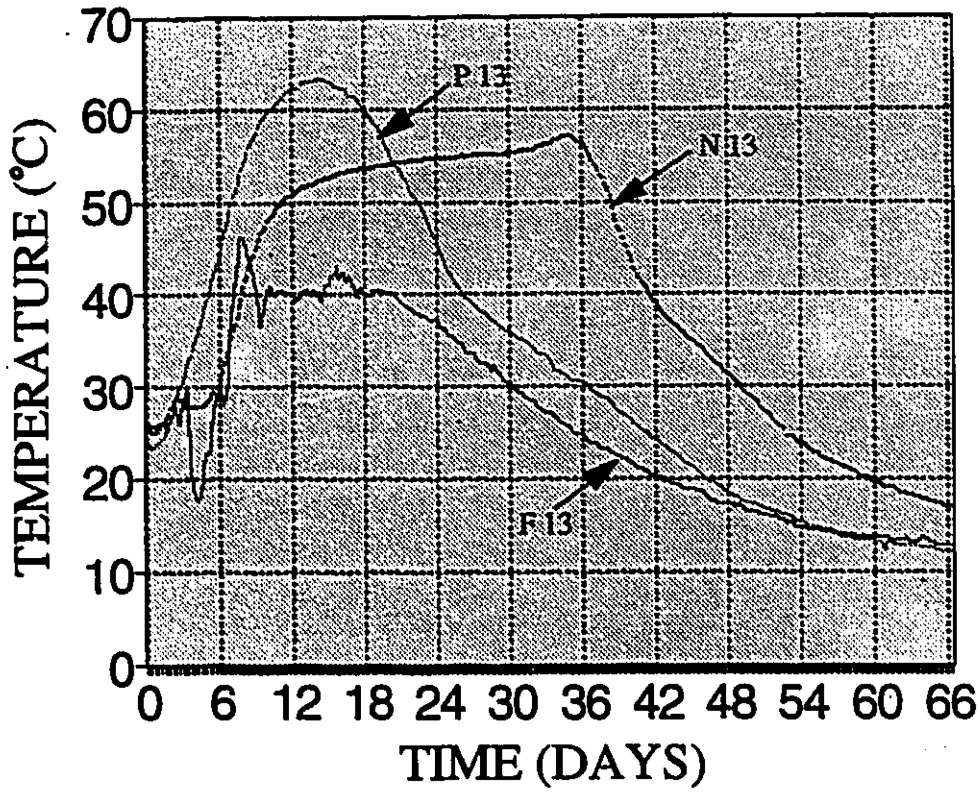


Figure 4.2:Temperature profiles of location 13 inside piles F, P and N

The temperature cooling rates presented in Table 4.1 show that piles F and P cooled down to the ambient temperature at the same rate of 1.1 °C/day, while pile N had the slowest cooling rate of 0.83 °C/day. Since the average temperature inside pile N reached to the maximum value and cooled down more slowly than the other two treatments, it can be said that the use of PA and FA enhanced the process in terms of time. The average temperature of piles F and P had dropped to 15°C by the 45th and 47th days, respectively. It took 62 days for average temperature of pile N to drop to 15°C, the reason being the slower rate of this process.

4.3 Influence Zone of Aeration Pipes

The main goal of this section is to develop a procedure to determine the influence zone of PA and FA pipes. The procedure is based on the comparative study of forced and passive aeration treatments with NA treatment used as the control. Generally, comparative experiments are executed to assess the effect of a treatment on a sample group. In an ideal experiment, one or more treatments are applied to the same group. Outcomes measured from these studies would then be direct consequences of the treatments, and therefore be the measure of their effects. But in reality, this ideal experiment is impossible. In practice, a similar group is chosen which does not receive the treatment and is called the control group. To be effective, it should be an adequate proxy for the performance of those receiving the treatment.

Unfortunately, the use of a control group does not itself ensure an adequate comparison, since the groups may differ in factors other than the treatment, factors that may introduce a bias into the estimation of the treatment effect, these are called confounding factors. In this study, aeration methods, FA or PA, are the treatments whose effects are being determined. Natural aeration piles act as the control group. And outcomes are temperature readings.

The average of absolute differences (AAD) is the parameter used to find the influence zones of aeration pipes. AAD of two positions is defined as:

$$AAD_{1,2}=\frac{1}{n}\sum |T_{1i}-T_{2i}| \qquad (4.1)$$

Where: $T_{1,i}$= temperature readings of position 1 at time step i
$T_{1,i}$= temperature readings of position 1 at time step i
n= total number of readings.

The procedure used here involves two steps. In the first step, the degree of similarity between replicated positions, or reproducibility, for NA, FA and PA treatments is investigated. Distribution of the AAD of temperature readings for 9 replicated positions in all treatments is determined. And confounding factors, if any, and their nature are assessed.

Based on the findings from the first step, all the thermocouple positions in the main piles F and P will be compared to those of pile N, to see which ones are affected or influenced by the treatment and those which are not. For each position, if the AAD between the control and the treatment lies within the distribution obtained in the first step, it shows that there in no real difference between this AAD value and the AAD values of replicated positions. This is to say that the position inside the treatment pile has performed like a replicated position of the similar location inside the control group. In other words, that specific position in the compost pile is not influenced by the treatment.

However, if the AAD between the control and the treatment for a given position does not lie within the distribution obtained for replicated positions in the first step, then it shows that there is a real difference between this AAD value and the AAD values of replicated positions. Hence this position is influenced by the treatment. And in this way, it is possible to detect the influence zones. The rational behind the above procedure can be explained as that by providing the same conditions such as same initial MC, pH, pile size, it is possible to detect any effect on temperature due to the presence of passive and forced aeration pipes.

To assess the degree of similarity, or reproducibility, 9 thermocouple positions, 5 in the first layer and 4 in the third layer, were triplicated for each treatment. Figs. 4.3 through 4.5 show typical examples of the temperature profiles of replicated positions. Temperature profiles for all replicated positions showed high correlation which means a good uniformity in raw compost was achieved.

Correlation factors between temperature readings of each pair of replicated positions were calculated and are presented in Table 4.2. Correlation factor was clculated using the following equation;

$$r_{x,y}=\frac{\sum xy-nXY}{\{(\sum x^2-nX^2)(\sum y^2-nY^2)\}^{1/2}} \tag{4.2}$$

Where: X= average of x values
Y= average of y values
n= total number of values

The correlation factors varied from 0.897 to 0.999. The closeness of these values to 1 shows a very strong correlation between the temperature readings of replicated positions. Also, within each pile, the temperature readings for symmetrical points show good similarities. This effect is illustrated in Fig. 4.6 for the temperature profiles of symmetrical positions 4 and 5 as well as 18 and 20 in the pile N. The correlation factors were 0.998 and 0.992, respectively.

The AAD of temperature readings of each pair of replicated positions was calculated. Table 4.3 shows these average values of absolute differences between each pair of 9 replicated positions for the three treatments, which totals to 81 AAD values. The result of the one-way Analysis of Variance (ANOVA) for each treatment is also shown in Table 4.3.

In ANOVA, two estimates of variance (σ^2) of mean value are calculated. One based

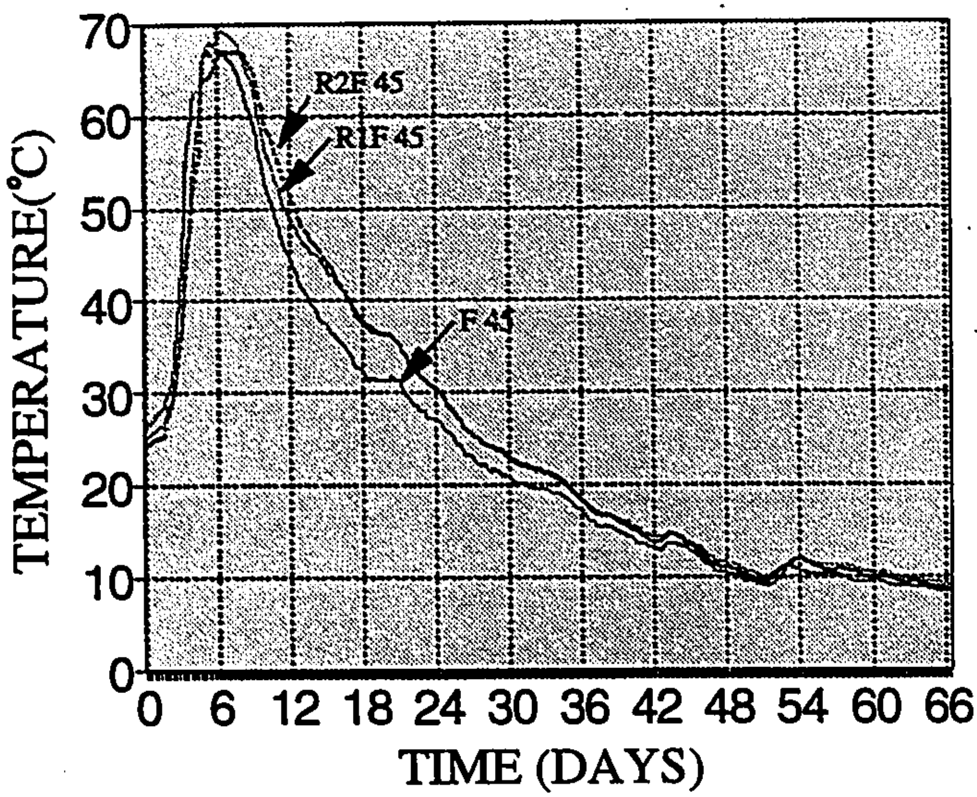


Figure 4.3:Temperature profiles of position 45 in piles F, R1F and R2F

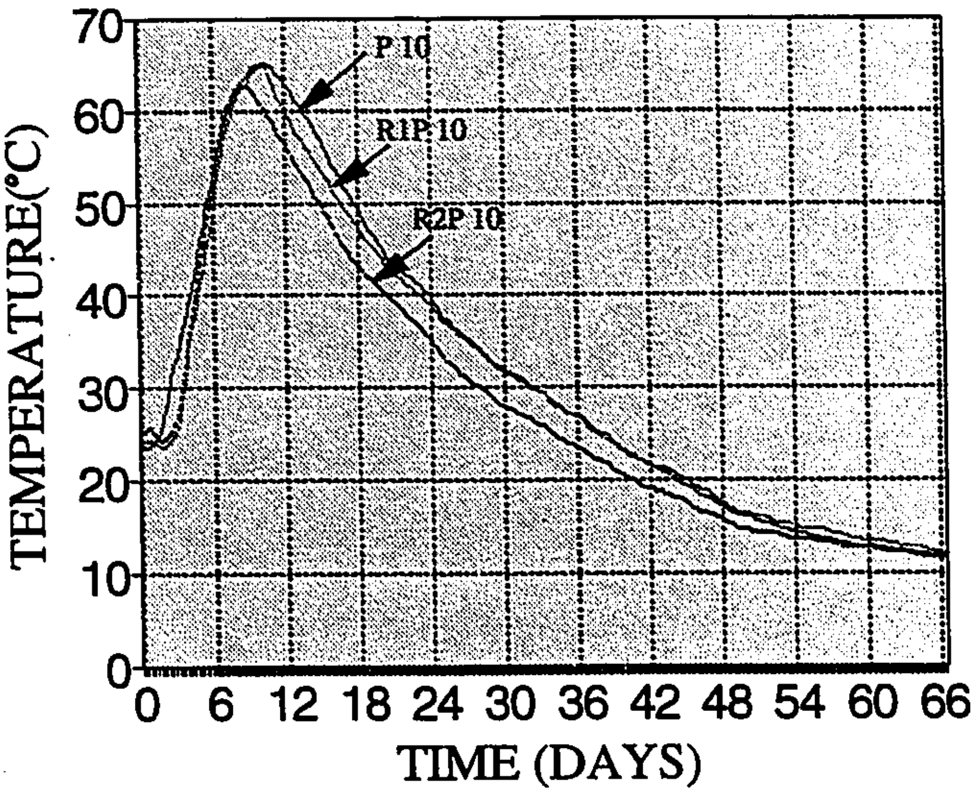


Figure 4.4:Temperature profiles of position 10 in piles P, R1P and R2P

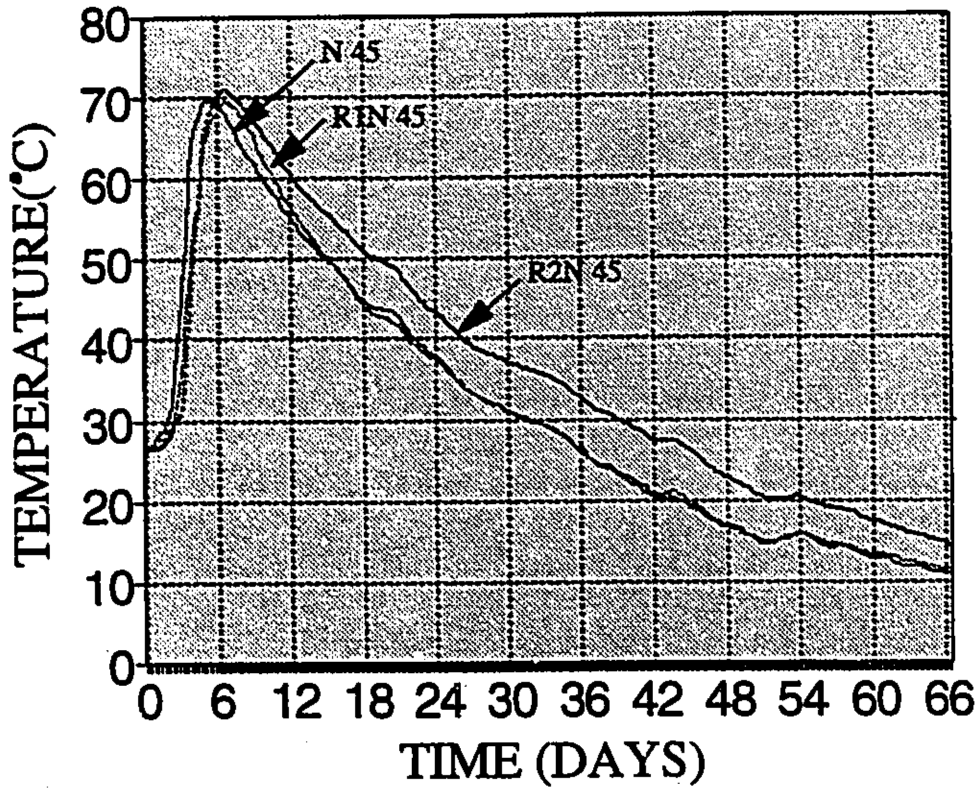


Figure 4.5:Temperature profiles of position 45 in piles N, R1N and R2N

Table 4.2 Correlation factors between replicated positions

Position	$r_{F,R1F}$	$r_{F,R2F}$	$r_{R1F,R2F}$	$r_{P,R1P}$	$r_{P,R2P}$	$r_{R1P,R2P}$	$r_{N,R1N}$	$r_{N,R2N}$	$r_{R1N,R2N}$
1	0.979	0.979	0.998	0.934	0.905	0.952	0.905	0.988	0.945
8	0.986	0.997	0.990	0.942	0.897	0.986	0.992	0.985	0.996
10	0.986	0.990	0.984	0.996	0.994	0.994	0.996	0.995	0.995
13	0.979	0.988	0.982	0.996	0.986	0.986	0.978	0.932	0.969
14	0.989	0.988	0.995	0.995	0.987	0.987	0.992	0.984	0.992
45	0.990	0.986	0.999	0.996	0.999	0.992	0.992	0.990	0.974
47	0.992	0.987	0.997	0.998	0.998	0.996	0.992	0.980	0.974
50	0.995	0.994	0.996	0.978	0.990	0.994	0.989	0.971	0.964
51	0.995	0.986	0.996	0.965	0.963	0.998	0.996	0.995	0.997

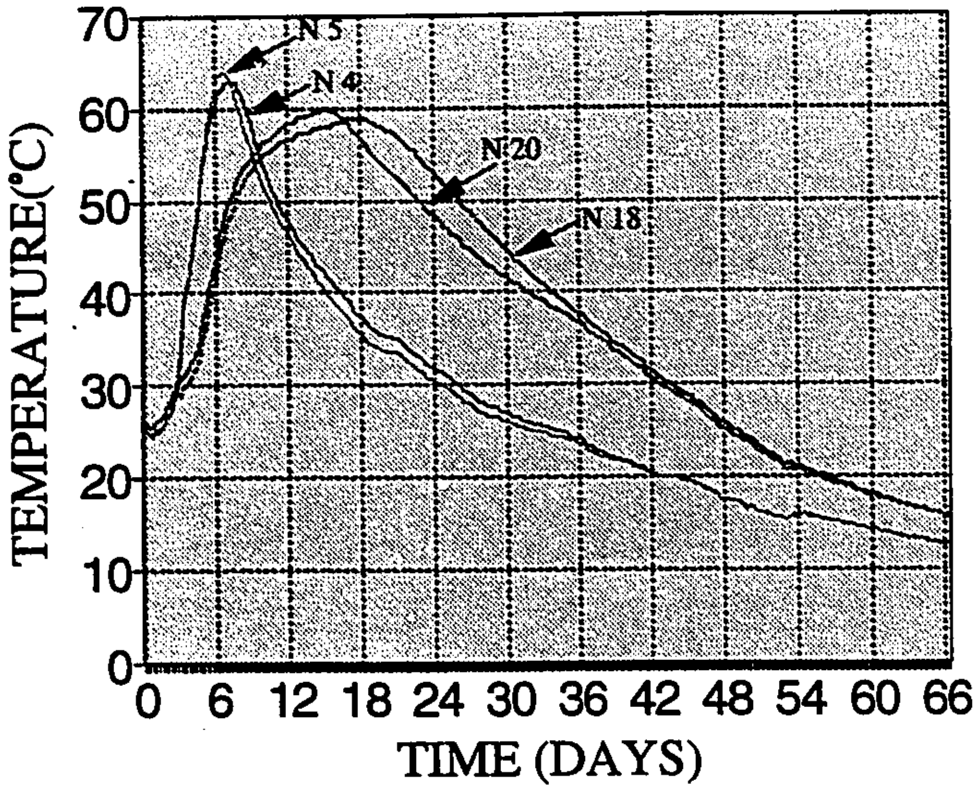


Figure 4.6:Temperature profiles of positions 4, 5, 18 and 20 inside pile N

Table 4.3 One-way ANOVA of average of absolute differences values of replicated positions

				Position					
Treat.	1	8	10	13	14	45	47	50	51
F,R1F	3.677	2.456	1.647	1.367	1.745	1.741	1.497	1.698	1.569
F,R2F	3.583	3.504	3.322	2.727	3.251	1.655	1.703	2.327	2.407
R1F,R2F	0.723	1.783	1.890	2.096	2.236	0.574	0.889	1.754	1.445
Y	2.661	2.581	2.286	2.063	2.411	1.323	1.363	1.926	1.807

Y_{GA} = 2.047, σ^2_R = 0.716, σ^2_T = 0.719, f = 1.004, $CI_{\alpha=0.90}$=[0.316 to 2.520]

Treat.	1	8	10	13	14	45	47	50	51
P,R1P	1.364	4.991	1.542	1.594	1.189	1.774	1.244	2.489	8.209
P,R2P	1.862	3.849	3.738	4.370	5.215	1.169	1.636	1.771	1.396
R1P,R2P	0.669	8.379	2.460	3.764	4.325	1.014	1.733	3.527	7.373
Y	1.298	5.740	2.580	3.243	3.576	1.319	1.538	2.596	5.659

Y_{GA} = 3.061, σ^2_R = 3.106, σ^2_T = 8.676, f = 2.793, $CI_{\alpha=0.90}$=[0.878 to 7.010]

Treat.	1	8	10	13	14	45	47	50	51
N,R1N	1.808	2.970	3.897	4.275	3.707	1.105	2.601	3.084	1.669
N,R2N	1.669	1.808	3.008	3.639	3.312	4.300	4.539	3.966	3.124
R1N,R2N	1.596	4.139	6.644	7.800	6.840	5.014	7.037	6.949	3.294
Y	1.691	2.972	4.516	5.238	4.620	3.473	4.726	4.666	2.696

Y_{GA} = 3.844, σ^2_R = 3.100, σ^2_T = 4.238, f = 1.367, $CI_{\alpha=0.90}$=[0.430 to 3.431]

on the values obtained for each position, called the residual estimate (σ^2_R), and the other based on the mean values (Y) of each triplicated position designated as σ^2_T. Then the hypothesis that there are no differences between mean values (Y), *i.e.*, $\sigma^2_R = \sigma^2_T$, is tested by making a confidence interval for the ratio $\mathbf{f}=\sigma^2_T/\sigma^2_R$. The average of all mean values of each treatment is called the grand average, denoted by Y_{GA}. The confidence interval for **f** is denoted by CI_α=[a,b], where **a** and **b** are lower and upper limit of the interval and α is the percent probability associated with the confidence interval. If the confidence interval includes 1, then it shows that 1 is a plausible value for the **f** ratio and that Y values have the same distribution. This is to say there is no real difference between the mean values, and the observed variations are just due to random errors. More details about the ANOVA, can be obtained from Box (1978) and Mendenhall *et al.* (1990).

As shown in Table 4.3, all three confidence intervals include 1, hence it can be concluded that within each treatment, the AAD values of the 9 replicated positions follow the same distribution. This is to say that there is no position-to-position effect on the variations of AAD in each treatment, and the position of thermocouples is not a confounding factor within each treatment.

To investigate the effect of treatments on the variations of AAD, a two-way ANOVA was carried out. The result is shown in Table 4.4. Data include the mean values of each triplicated positions, presented in Table 4.3. Y_T and Y_B are the averages for the treatments (columns) and positions (rows), respectively. σ^2_B and σ^2_r refer to between

Table 4.4: Two-way ANOVA of average of absolute differences values

	TREATMENT			
POSITION	FA	PA	NA	Y_B
1	2.661	1.298	1.691	1.883
8	2.581	5.740	2.972	3.764
10	2.286	2.580	4.516	3.217
13	2.063	3.243	5.238	3.515
14	2.411	3.576	4.620	3.536
45	1.323	1.319	3.473	2.038
47	1.363	1.538	4.726	2.542
50	1.926	2.596	4.666	3.063
51	1.807	5.659	2.696	3.387
Y_T	2.047	3.060	3.844	

Y_{GA} =2.984, σ^2_B =1.395, σ^2_T =7.305, σ^2_r =1.583, f_B =0.881, $CI_{\alpha=0.90}$ =[0.435 TO 3.613]
f_T =4.615, $CI_{\alpha=0.90}$ =[0.376 TO 26.517]

position and residual estimates of variance, respectively. Confidence intervals for the two ratios of σ^2_B/σ^2_r and σ^2_T/σ^2_r were calculated and are shown in Table 4.4. It is seen that 1 lies within the confidence interval for both ratios. This shows that there is neither a position-to-position effect nor a treatment-to-treatment effect on the variations of AAD. This means that the distributions of the AAD of all the replicated positions for the three treatments are the same. It can also be concluded that neither the position of thermocouples nor the treatment is a confounding factor.

It should be noted that the fact that all AAD values of replicated positions in the three treatments that were studied followed the same distribution does not reflect that the temperature profiles of these positions are similar or have the same pattern. It strictly shows that the differences between the reproduced positions are the same.

With the knowledge that all AAD values follow the same distribution, an estimate of the mean and standard deviation of the AAD can be found. AAD of replicated positions has a distribution with a mean of μ =2.983 and a standard deviation of σ =1.866. This distribution will be used in the next step to determine the influence zones of aeration pipes. The percentage points of F distribution which are used in the ANOVA are presented in Appendix C.

To determine which of the 59 positions in the main piles are affected by the treatments, for each position the AAD between F and N piles as well as between P and

N piles were calculated. The result is shown in Table 4.5.

If the AAD value between the two treatments for a given position is greater than $\mu+3\sigma$ (2.983+3*1.866) of the distribution of the AAD values found in the previous step, it shows that this value does not belong to the distribution. In statistical terminology such a value is called an outlier. In this case, the AAD between the temperature readings from two treatments is really different from those obtained for replicated positions, thus the position inside the treatment pile is not acting like a replicated position. This could be interpreted as that the position is influenced by the treatment.

On the other hand, if the AAD between the treatment and control piles for a position is less than $\mu+3\sigma$, it shows that in the light of available data there is no real difference between the AAD for this position in these two piles and the AAD values of replicated positions. Therefore, this position is not influenced by the treatment. In Table 4.5, the positions which are affected by the treatment are denoted by a + sign and those which are not affected by a - sign. AAD values for some positions are very close to $\mu+3\sigma$. These positions can not be entirely denoted by a + or a - and are therefore distinguished by a * sign.

In Figs. 4.7 through 4.9, the temperature profiles of some of the positions in the main piles are shown. It is seen that for the positions which are not affected by the forced or passive aeration treatments, for example 42 in Fig. 4.7, 19 in Fig. 4.8 and 57 in Fig. 4.9,

Table 4.5: AAD values between each pair of treatments

POSITION	AAD (F & N)	AAD (P & N)	POSITION	AAD (F and N)	AAD (P and N)
1	5.2 -	2.0 -	20	12.0 +	8.8 +
2	2.0 -	2.0 -	21	9.6 +	8.9 +
3	10.6 +	5.3 -	22	6.1 -	7.8 -
4	6.4 -	4.2 -	23	2.9 -	5.2 -
5	6.8 -	4.5 -	24	6.1 -	6.7 -
6	11.1 +	6.7 -	25	10.4 +	8.8 +
7	12.3 +	7.7 -	26	12.2 +	9.4 +
8	7.9 -	5.7 -	27	8.1 -	7.5 -
9	12.3 +	8.6 *	28	12.8 +	9.7 +
10	13.1 +	9.1 +	29	14.0 +	10.2 +
11	10.4 +	8.3 -	30	12.1 +	9.5 +
12	8.8 +	6.5 -	31	9.8 +	7.5 -
13	13.7 +	11.5 +	32	15.9 +	11.1 +
14	11.2 +	8.5 *	33	12.6 +	8.1 -
15	14.2 +	12.6 +	34	16.2 +	11.0 +
16	13.3 +	10.8 +	35	----	9.8 +
17	13.0 +	10.4 +	36	15.0 +	9.7 +
18	11.8 +	9.0 +	37	12.8 +	8.2 -
19	5.4 -	3.0 -	38	7.2 -	5.2 -

+ influenced - not influenced * on the boarder

Table 4.5: AAD values between each pair of treatments (continued)

POSITION	AAD (F & N)		AAD (P & N)		POSITION	AAD (F and N)		AAD (P and N)	
39	12.7	+	8.0	-	50	15.9	+	5.5	-
40	7.2	-	5.8	-	51	11.1	+	3.9	-
41	4.6	-	4.9	-	52	16.1	+	9.7	+
42	3.8	-	3.1	-	53	14.9	+	8.5	*
43	8.6	*	6.0	-	54	13.8	+	8.6	*
44	10.6	+	6.1	-	55	11.0	+	7.9	-
45	7.1	-	5.5	-	56	12.3	+	7.4	-
46	12.0	+	6.5	-	57	5.1	-	2.8	-
47	12.9	+	7.3	-	58	11.1	+	9.0	+
48	12.0	+	7.0	-	59	10.4	+	7.3	-
49	9.3	+	6.2	-					

\+ influenced - not influenced * on the boarder

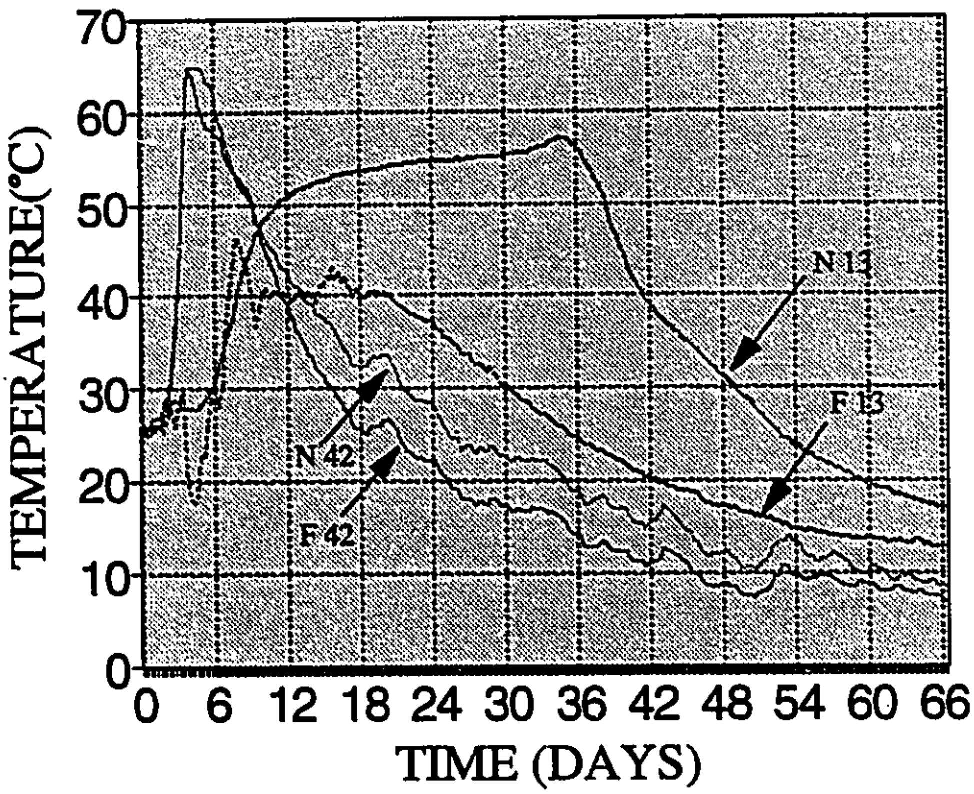


Figure 4.7 Temperature profiles of positions 13 and 42 in piles F and N

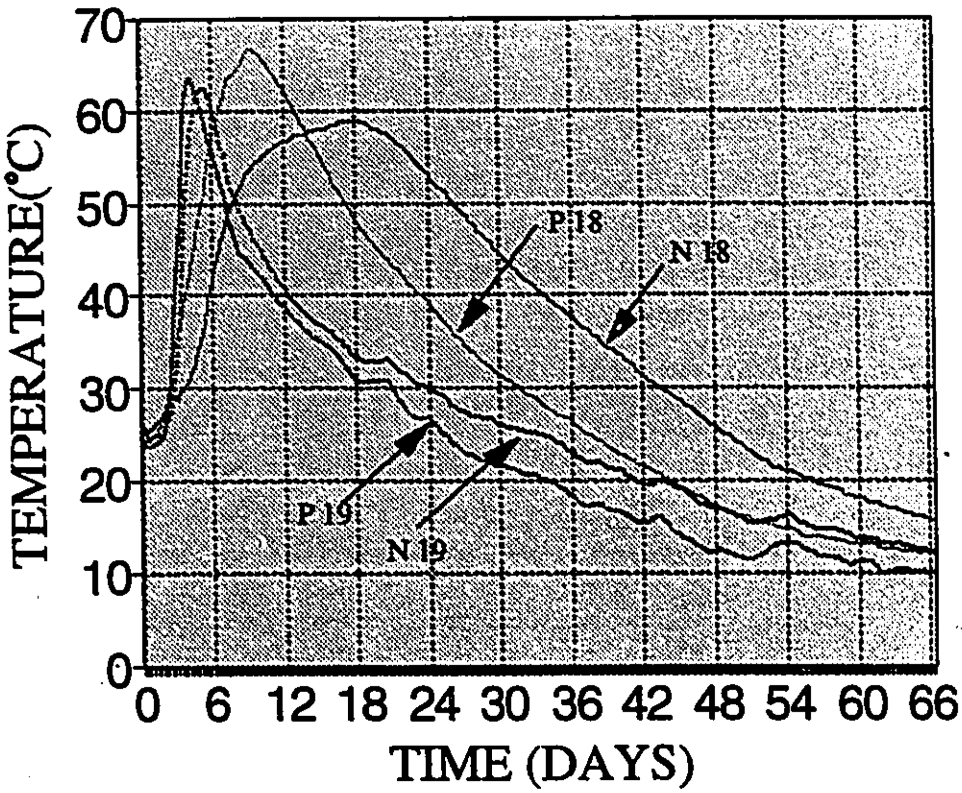


Figure 4.8:Temperature profiles of positions 18 and 19 in piles P and N

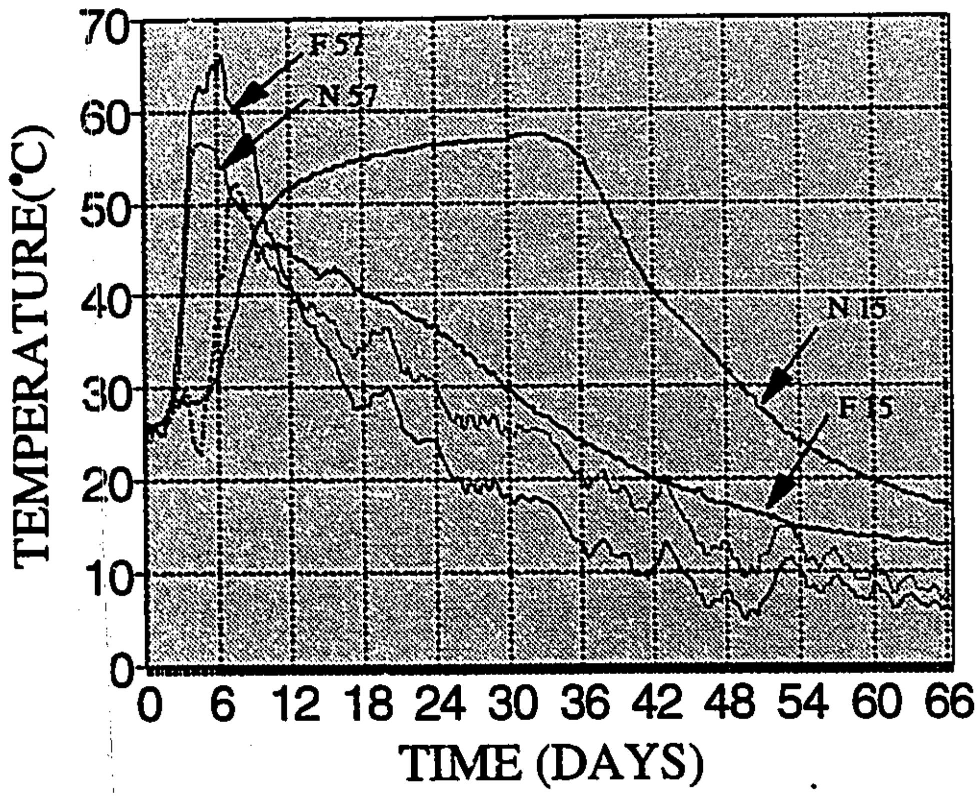


Figure 4.9:Temperature profiles of positions 15 and 57 in piles F and N

temperature profiles for the treatment and control are almost the same, and a good similarity exists. In fact, they look like the temperature profiles of replicated positions for these locations. However, for positions influenced by the treatment, for example 13 in Fig. 4.7, 18 in Fig. 4.8 and 15 in Fig. 4.9, the temperature profiles are significantly different.

It should be noted that being influenced does not necessarily mean an improvement. It means that the temperature readings for the designated treatment and position is different from the equivalent position in the control pile. By comparing the temperature profiles of a given position in the treatment and the control piles it can be investigated whether there is any improvement. For example, temperature profiles of positions 13 in pile F and N, in Fig. 4.7, show that although there is an improvement in term of time, the temperature in pile F reached to the ambient level sooner than in pile N, but FA had a negative effect on temperature. For position 13, in the forced aeration pile the temperature is significantly lower, a peak of 45°C vs. 57°C in the natural aeration pile. Comparison of temperature profiles of position 18 in piles P and N in Fig. 4.8, reveals that the passive aeration enhanced the process since higher maximum temperature (67°C) was achieved in less time (8 days) and the process finished about 14 days sooner than the natural aeration treatment.

Based on the above findings, the influence zones for PA and FA pipes are shown in Figs. 4.10 and 4.11. Fig. 4.10 shows that the interior part of the bottom half of the pile

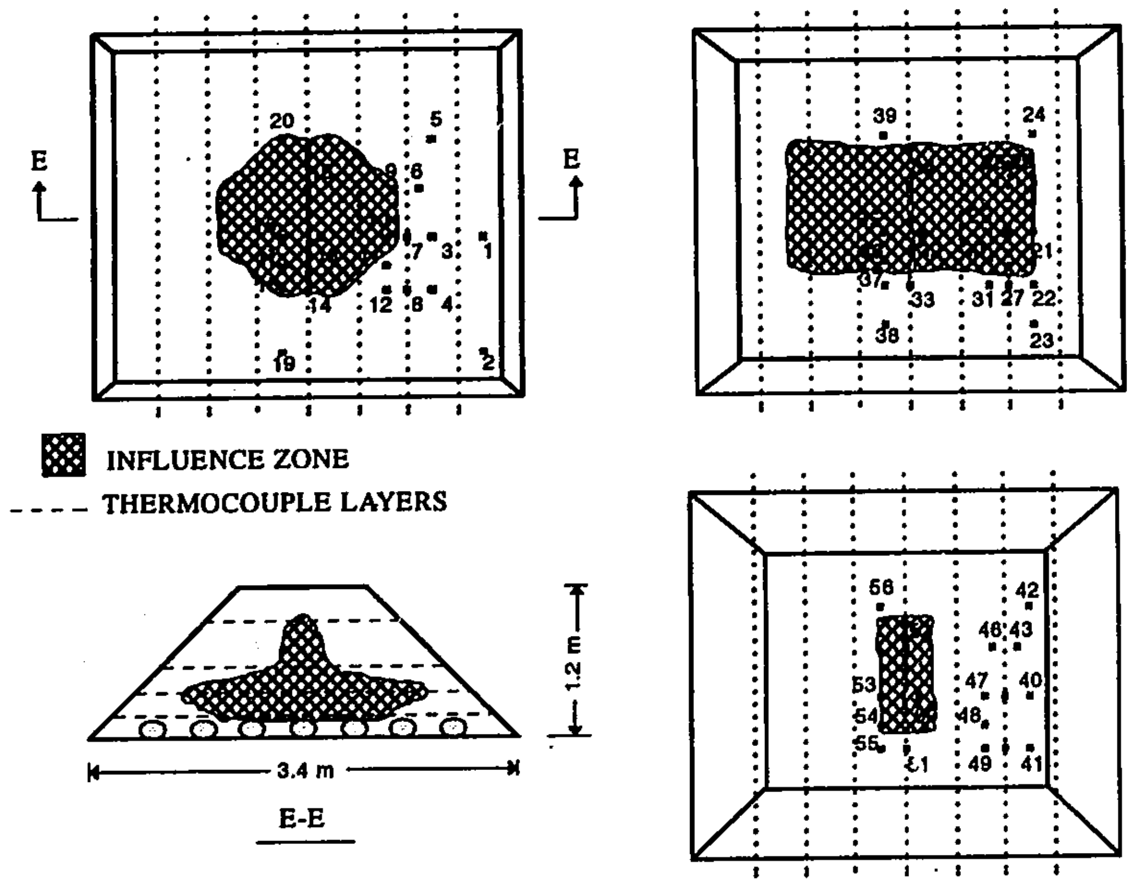


Figure 4.10: Influence zone of PA pipes

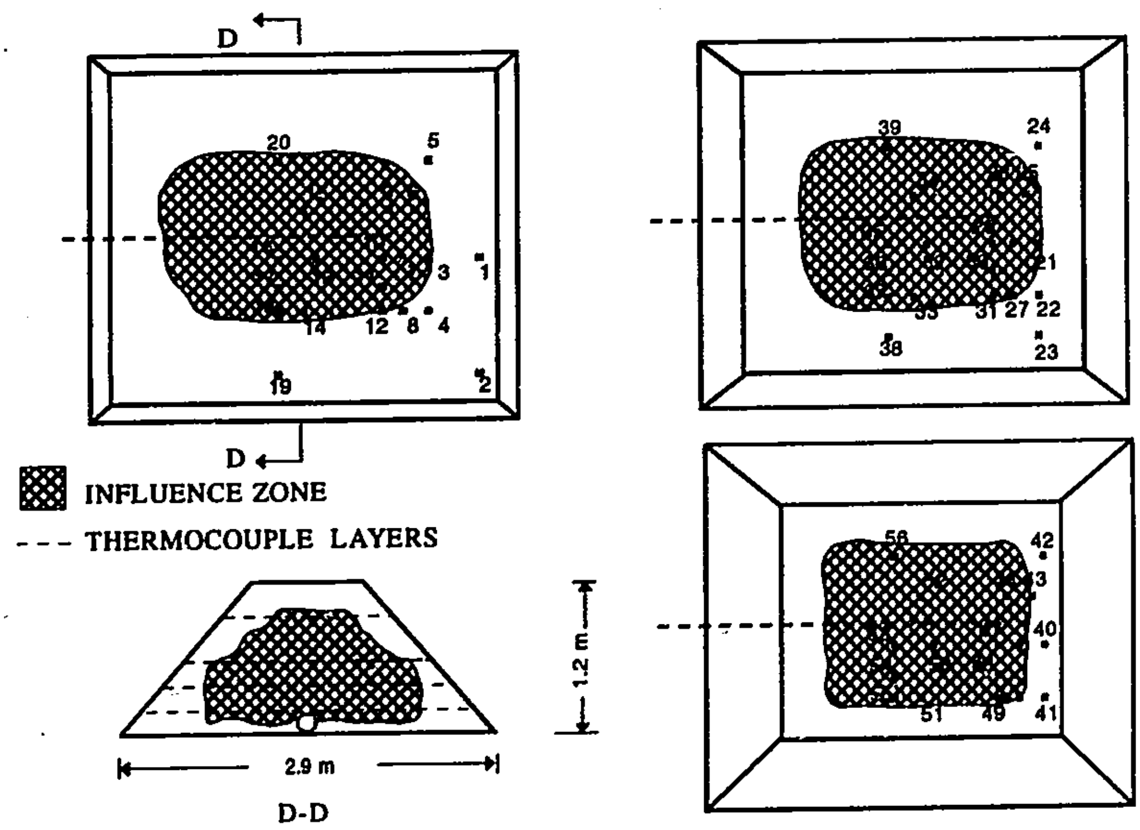


Figure 4.11: Influence zone of FA pipe

was influenced by the passive aeration pipes. For locations near the pile surface, especially at the top of the pile, the ambient air diffusion into the pile was predominant and the perforated pipe did not affect the temperature performance. In other words, temperature performance was the same as in NA pile. For the top part of the pile, a greater surface area is exposed to ambient air and as a result the effect of air diffusion is more significant. The outer two pipes at the sides appeared to be of no use, again the corner effect *i.e.* large surface exposure and ambient air diffusion prevailed. For the FA pipe, as shown in Fig. 4.11, the interior part of the pile was affected. As in the previous case, air diffusion was predominant in locations near the pile surface. The temperature variations inside the piles will be discussed in section 4.5.

4.4 Cluster Analysis

To verify the result obtained in previous section, a cluster analysis was carried out. Cluster analysis is a generic name for a variety of mathematical methods that can be used to find out which objects in a set are similar. Hierarchical methods are the ones most frequently used. The data are arranged in a matrix and a clustering method is used to process the data, which results in a diagram, called a tree, that shows the hierarchy of similarities. More details on cluster analysis are given by Everitt (1980).

Data used for clustering analysis, include the AAD between each pair of replicated positions (AAD values in Table 4.2) and AAD between F and N as well as between P and N for all 59 positions inside the main piles (AAD values in Table 4.5). The cluster analysis was carried out using SAS program. The result are shown in Figs. 4.12 and 4.13.

Data are denoted as a combination of two letters followed by a number. The number refers to the position and the two letters refer to the two treatments for which the AAD was calculated. For example, FN13 refer to the AAD value between the forced and natural piles for position 13 and PP14 refer to the AAD of replicated position 14 of passive aeration piles. The rational behind this study is that by applying cluster analysis, the AAD values of replicated positions and those positions which are not affected by the treatment should be classified in the same group. And the AAD values for positions affected by the treatment should be classified in another group.

Fig. 4.12 shows the result of cluster analysis for AAD values of replicated positions and AAD values between piles F and N. Group A includes replicated positions and those positions which are not affected by FA. Group B includes those positions which are influenced by FA. With the exception of position 12, the results are exactly the same as those results shown in Table 4.5. For position 12, the AAD value (8.8) is very closed to $\mu+3\sigma=$ 8.6 and hence it is classified with the positions which are not affected by the treatment.

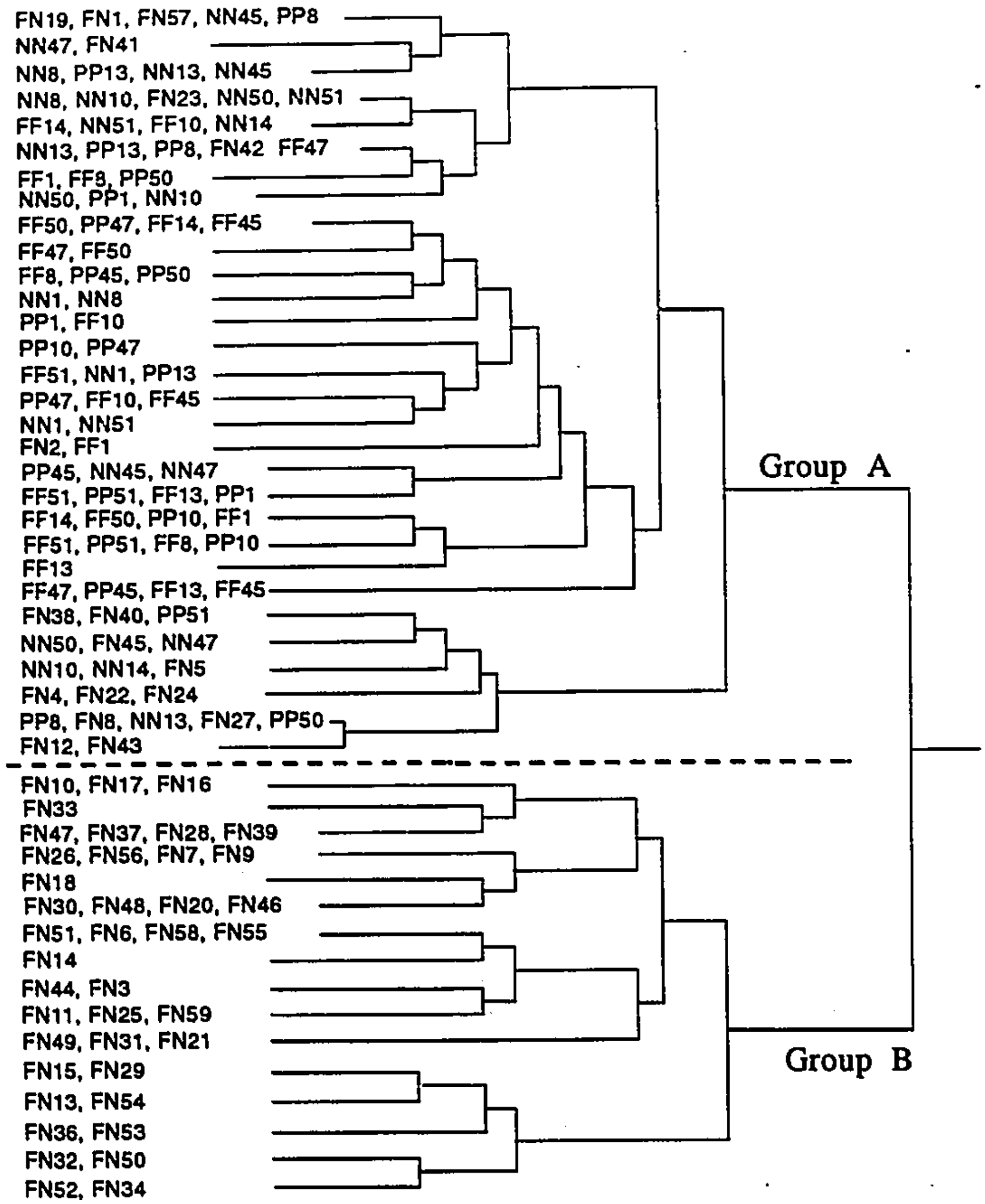


Figure 4.12 Cluster analysis for pile F

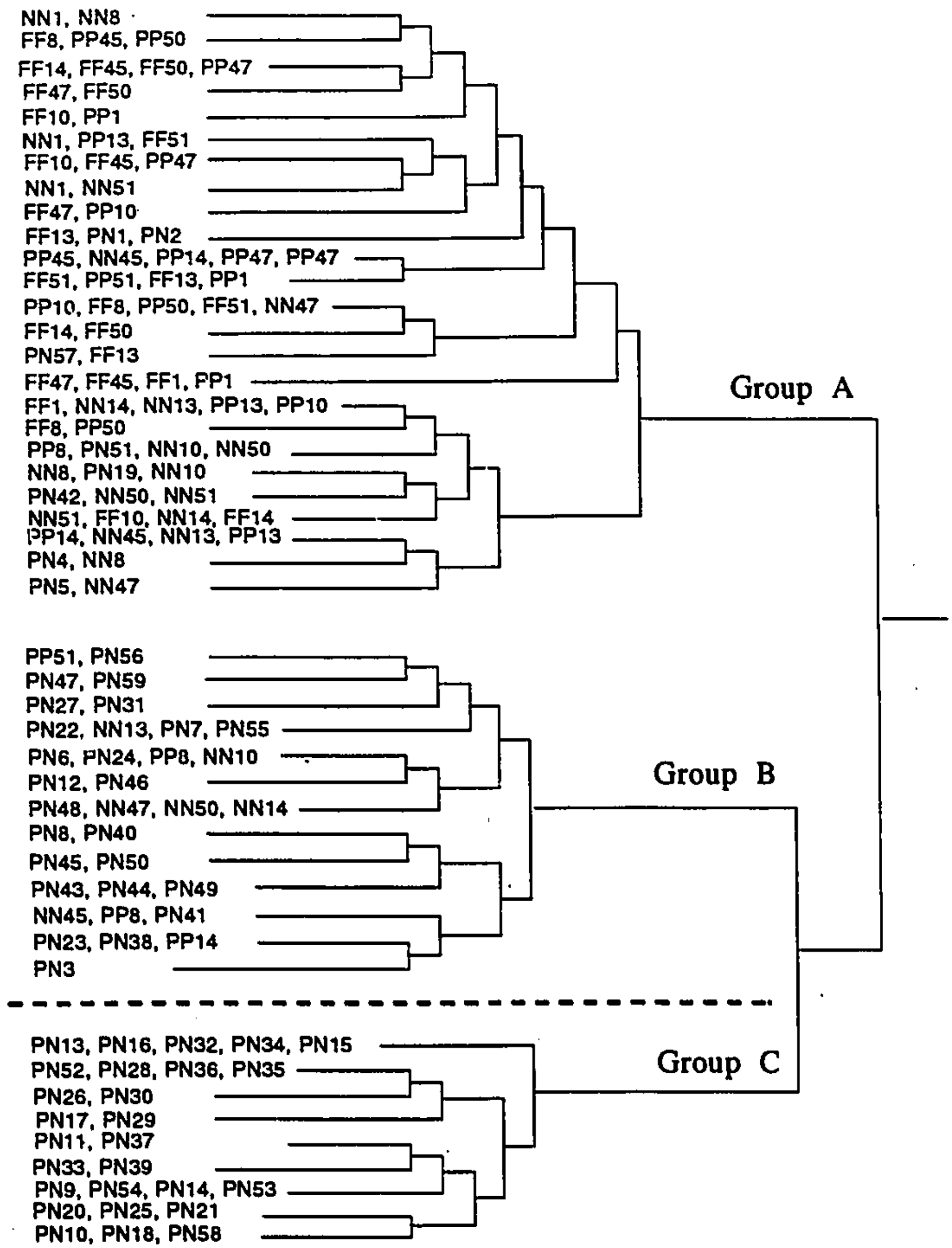


Figure 4.13 Cluster analysis for pile P

The same procedure was followed for the passive aeration pile. As shown in Fig.4.13, data are classified into three groups. Both groups A and B include the AAD values of replicated positions and AAD of positions which were not affected. Group C includes the AAD of the positions influenced by passive aeration, which is relatively small compared to groups A and B. According to Cluster analysis, groups B and C are at the same hierarchy level, and there is a greater similarity between these two than group A. However, group B includes some of the replicated positions, which makes this group part of the domain of replicated positions. Therefore, group B should be at the outer limits of the domain of replicated position, which shows similarity to group C and at the same time includes some replicated positions and positions which are not affected by the treatment. These results are in good agreement with those obtained in Table 4.5.

4.5 Temperature Distribution

Typical temperature distribution inside the main piles were determined on the 3rd, 7th, 14th, and 28th day. Temperature readings were classified into five temperature ranges, $T < 35°C$, $35°C < T < 45°C$, $45°C < T < 55°C$, $55°C < T < 65°C$, and $T > 65°C$. Temperature distribution was found for two cross sectional views, along the pile length and width.

For pile N, as shown in Fig. 4.14, temperature values between 35 and 45°C developed

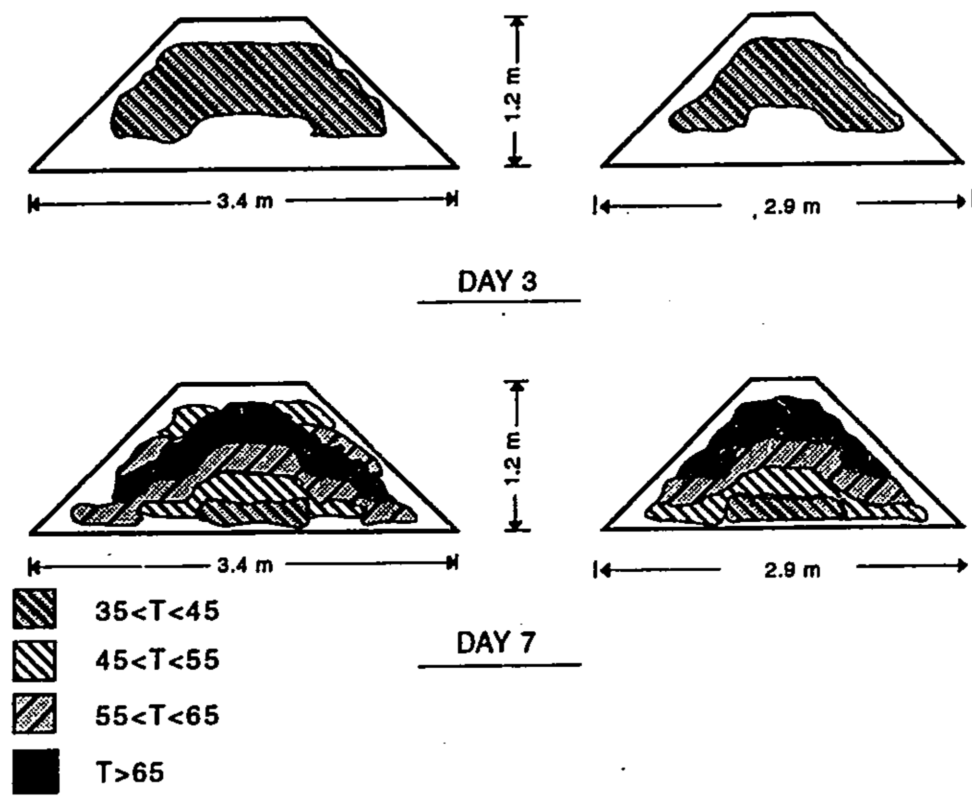


Figure 4.14: Temperature distribution inside pile N

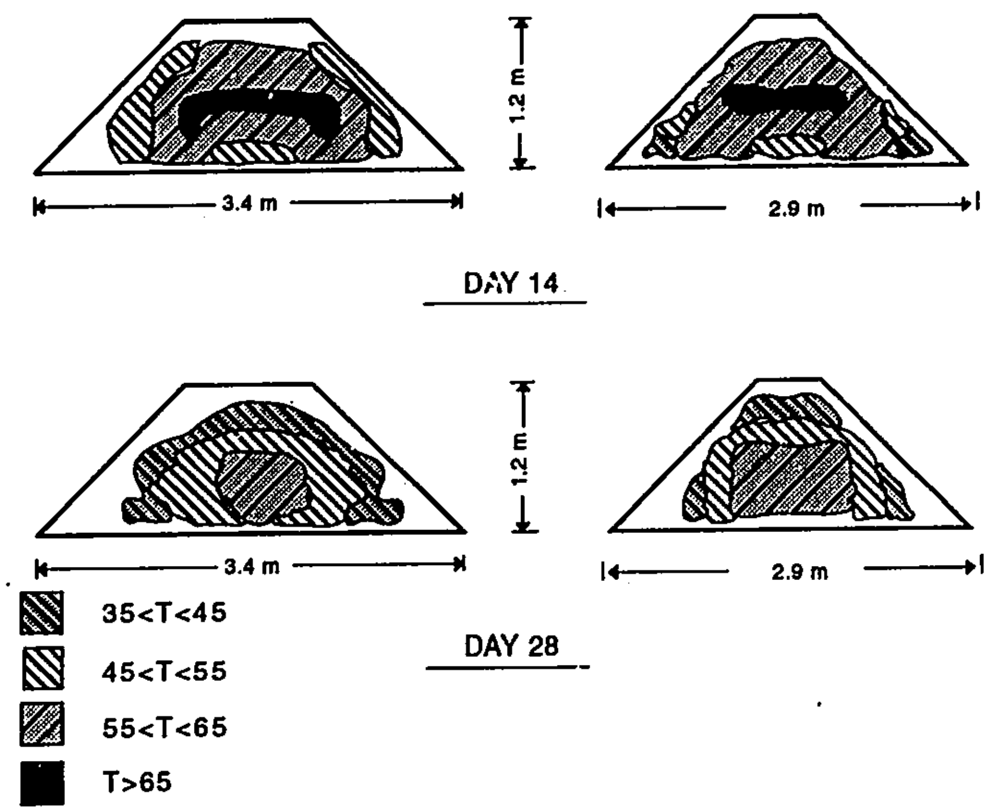


Figure 4.14:Temperature distribution inside pile N (continued)

on the 3rd day of composting. On the 7th day, layers of different temperatures ranges were observed, with the lowest temperature values at the bottom of the pile and the highest temperatures at the top near the pile surface. By the 14th day, the maximum temperature zone (T>65°C) had moved into the centre of the pile surrounded by a zone with temperatures between 55 and 65°C. By the 28th day, the pile core was still hot and registered temperatures were between 55 and 65°C, while the temperatures in the regions near the pile surface dropped to values between 35 and 45°C. This pattern of temperatures rising to maximum values over 65°C near the pile surface with subsequent shift into the pile core confirms the results reported by Zhan (1993).

The above pattern can be explained as the result of air diffusion phenomena. At the beginning, most of the diffused ambient oxygen is consumed by biochemical reactions in the region near the surface. With time, oxygen diffusion extends into the core and enhances the exothermic biochemical reactions which causes the temperature to rise above 65°C. Hence, distance from a given location to the pile surface is an important factor affecting oxygen availability, microbial activity and hence the rate of temperature rise.

This could be verified by evaluating the temperature profiles of positions 3, 10, and 13 in the bottom layer of pile N. These are located 0.55 m, 0.95 m, and 1.1 m from the piles surface, respectively. As shown in Fig. 4.15, position 13 took a longer time, twice as much as position 3, to reach 50°C. It reached the maximum of 57.4°C on the 35th day while position 3 reached the maximum temperature of 62.6°C in only 7 days. It is worth

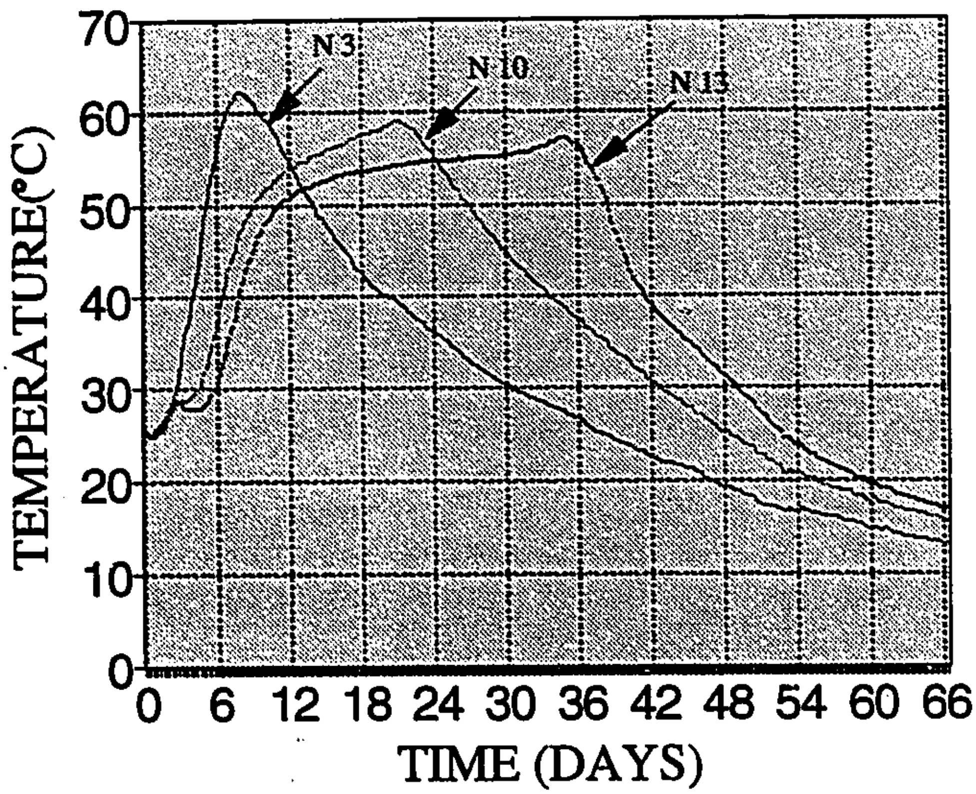


Figure 4.15: Temperature profiles of 3, 10 and 13 inside pile N

noting that position 13 stayed at temperatures above 50°C for more than 27 days, a reason for this might be that heat exchange was low at this location. Position 13 is located at the bottom which is more compacted by the overburden material. Since position 10 is at a distance from pile surface which lies between those for positions 3 and 13, its performance in terms of temperature also lies between 3 and 13.

Time schedule for the operation of forced aeration system was presented in Table 3.2. Forced air was started on the 4th day after the temperature inside the pile reached above 40°C and shut off on 19th day. For pile F, as shown in Fig. 4.16, regions near the exterior surface reached temperature values between 35 and 45°C on the 3rd day. By the 7th day, maximum temperature values (T>65°C) developed at the top part of the pile above the perforated portion of the FA pipe. By the 14th day, only a small zone at the middle had temperatures between 55 and 65°C. And by the 28th day, except for a very small zone at the middle, temperatures dropped to values below 35°C in the pile. It should be noticed that the temperature in the pile bottom around the FA pipe did not reach over 55°C (positions 10 and 13 in Fig. 4.2). This result show that the EPA requirement for pathogens inactivation by means of high temperature is not satisfied in this area. Comparing Figs. 4.14 and 4.16 it can be seen that, by the 28th day, while most of the temperatures in pile F dropped to values below 35°C, temperatures over 55°C were observed in pile N. Thus, temperatures inside pile F cooled down at a faster rate than in pile N. This is in agreement with the result derived from the comparison of temperature decreasing rates in Section 4.2, showing the effect of FA on heat removal.

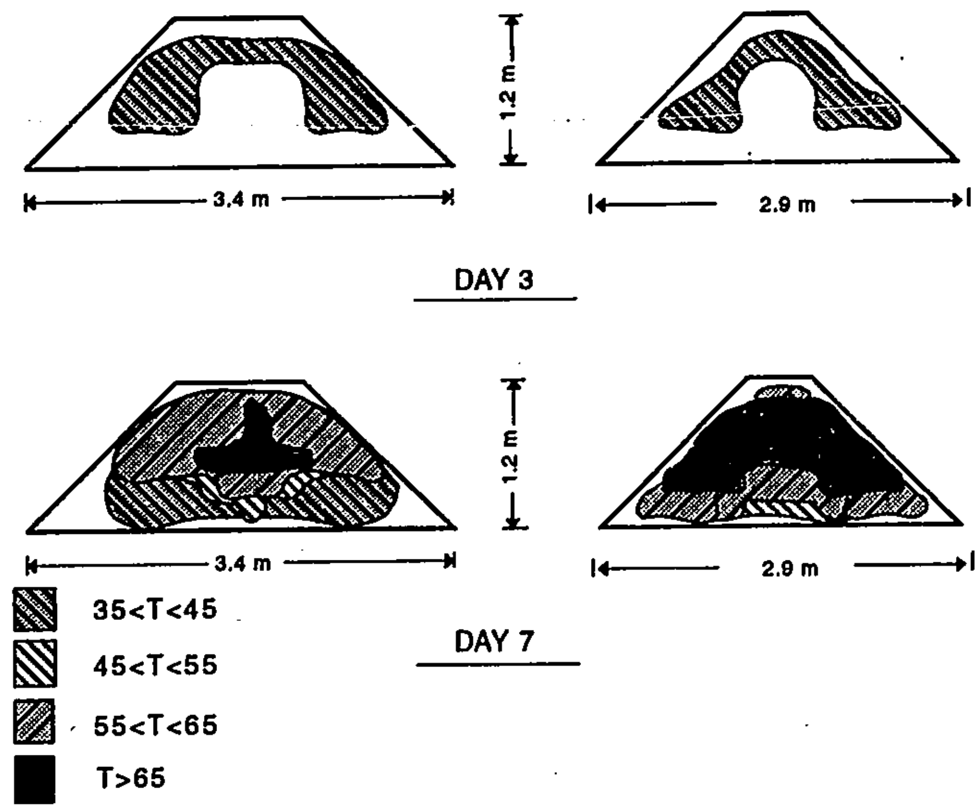


Figure 4.16: Temperature distribution inside pile F

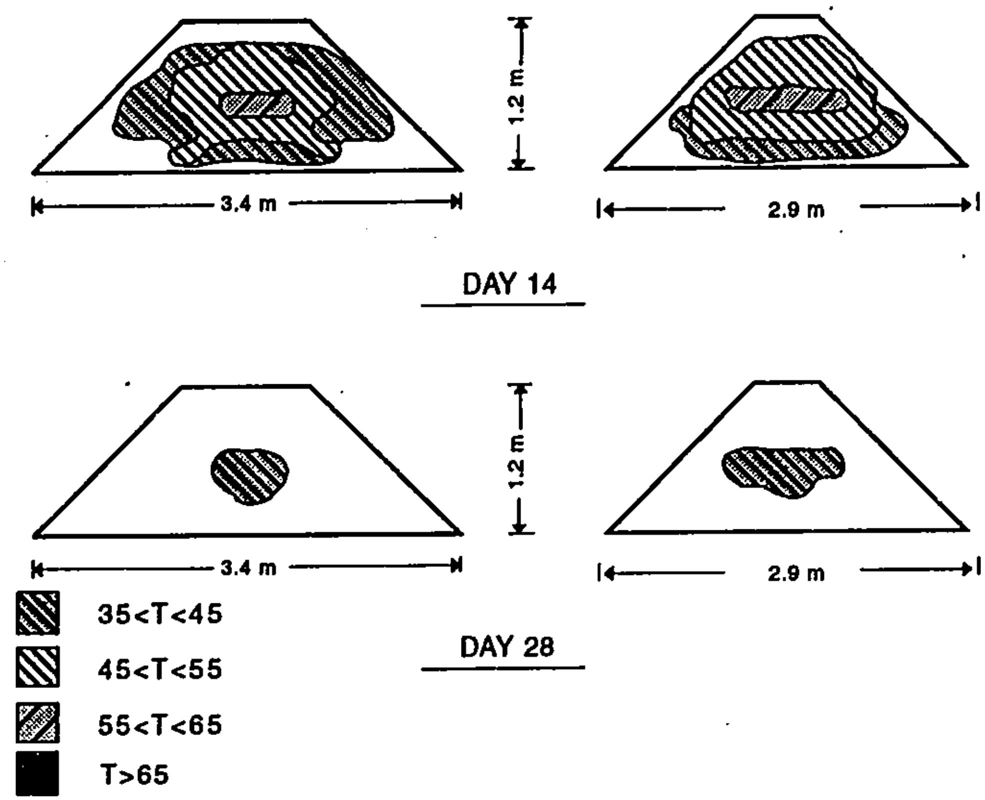


Figure 4.16: Temperature distribution inside pile F (continued)

By the 3rd day, temperature values between 35 and 45°C were recorded inside pile P. Fig. 4.17 shows that on the 7th day, temperature in most parts of the pile were between 55 and 65°C. Temperatures above 65°C were observed at positions located about half way between the pile centre and the pile edges. These positions received air from PA pipes as well as air diffusion through pile surface. But, positions at the pile core received air just from PA pipes during early stages, the first week, of composting and as a result temperatures did not reach above 65°C until the air diffusion extended into the pile core, which was around the 14th day. And by the 28th day, a small central zone with temperatures between 45 and 55°C surrounded by another zone of lower temperatures between 35 and 45°C was observed.

Fig. 4.18 shows the temperature profiles of positions 14 and 15 in piles P and N. It is apparent that the use of PA pipes increased air availability which in turn enhanced the biodegradation of organic matter at positions near the PA pipes. Since the temperature profiles of position 15 in piles P and N differ more than those of position 14, it can be concluded that the effect of the PA pipe on position 15 is more significant than on position 14. The reason is that position 15 is at a distance of 1.25 m from the pile surface while position 14 is located 0.85 m from the pile surface. Consequently, the effect of air diffusion on position 14 is greater than position 15, and the latter was more influenced by the PA pipes.

Comparison of the temperature distributions inside the three piles on the 7th day

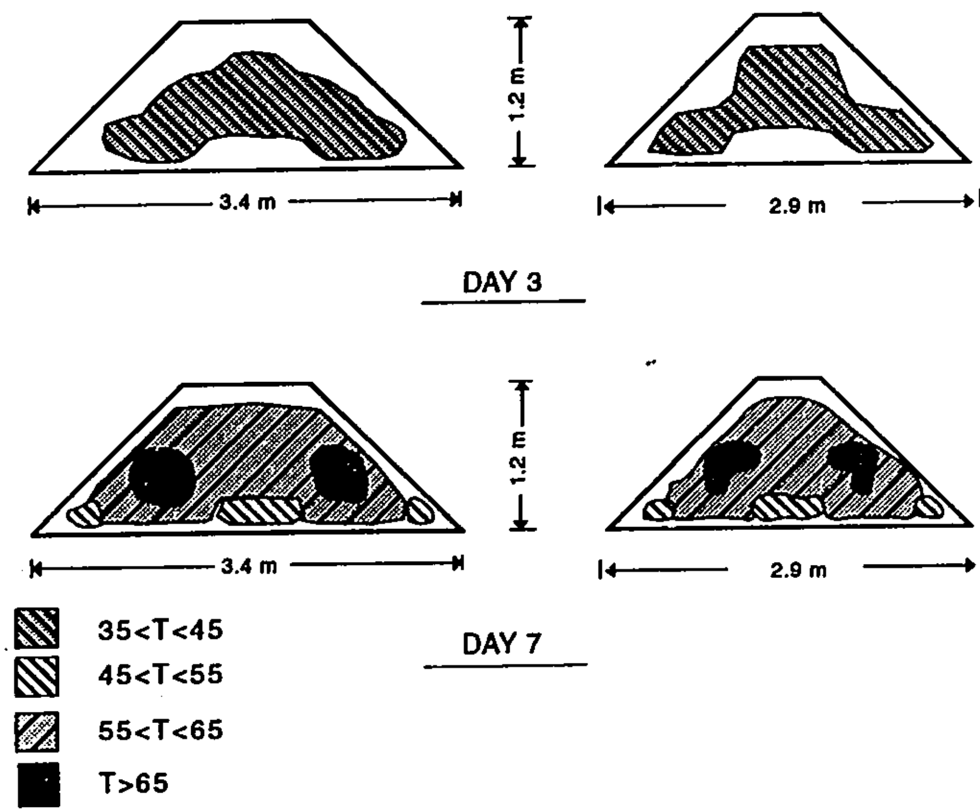


Figure 4.17: Temperature distribution inside pile P

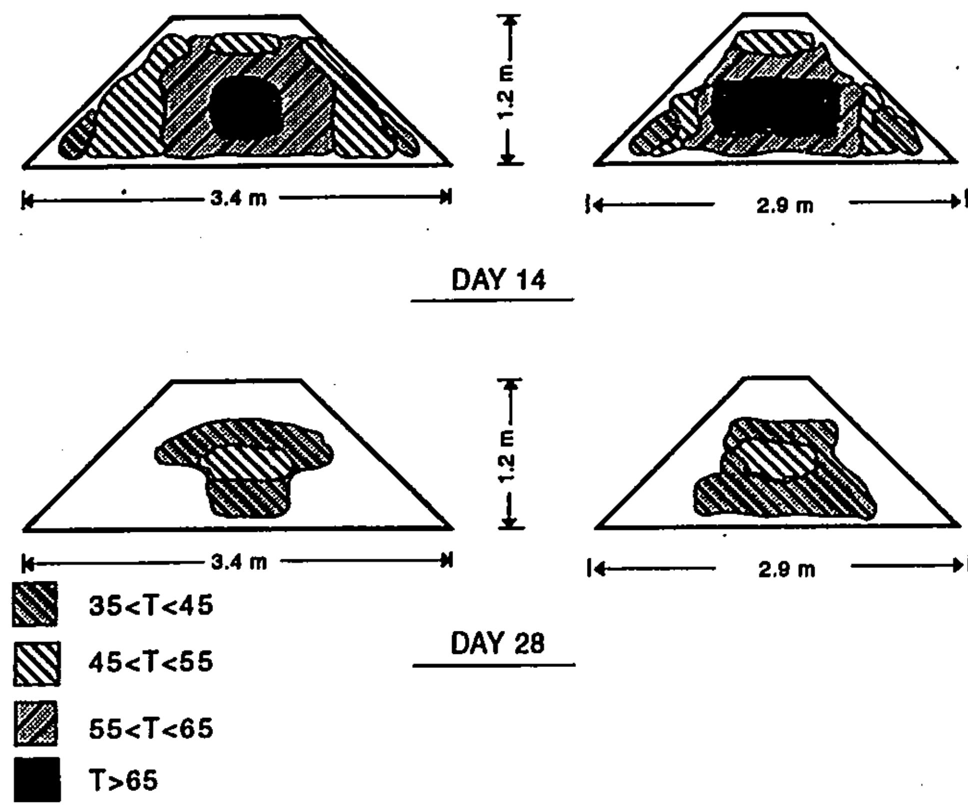


Figure 4.17: Temperature distribution inside pile P (continued)

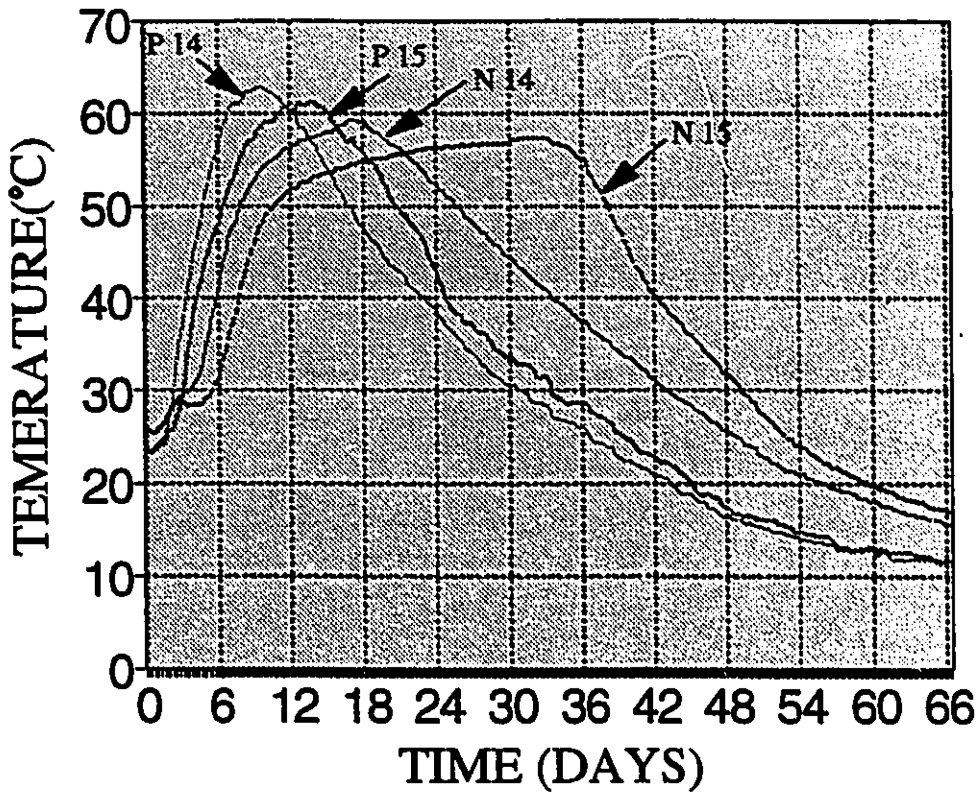


Figure 4.18:Temperature profiles of positions 14 and 15 in piles N and P

(Figs. 4.14, 4.16 and 4.17) shows that a more uniform pattern was achieved in pile P where most parts of the pile had a temperature between 55 and 65°C. But, in pile N layers with different temperatures were observed and in pile F, temperatures at the bottom did not go above 45°C while temperatures above 65°C were observed at the top.

Temperature distribution study in the main piles shows that in the areas near the piles surfaces and the corners the temperature did not reached above 35°C, mainly due to the heat loss to the ambient. Therefore, to satisfy the EPA requirement for pathogens inactivation it is necessary to provide better ticker insulation at the pile surface and corners.

4.6 Comparison of the Treatments

In this section, the three modes of aeration that were studied will be compared in terms of the peak temperature, time to attain the peak temperature, increasing and decreasing temperature rates, temperature duration above 55°C, and time for temperature to drop to 15°C. The comparison will be based on a new parameter which will be introduced as geometric average.

A more realistic approach to calculate the average temperature is to assign a weight to the portion of the pile volume covered by each thermocouple position, and then calculate the weighted average. This average is called the geometric average. The geometric average of all piles was calculated based on temperature readings from 10 thermocouple positions, namely 1, 8, 10, 13, 14, 45, 47, 50, 51, and 58. The reason for choosing these positions was that it was necessary to have some replications in order to support the statistical analysis for the comparison of the treatments. The above positions, except 58, are located at the bottom and middle section of the pile and were replicated in all 9 compost piles. Since no position was replicated at the top part of the piles, and considering the high degree of similarity among the replicated positions which was demonstrated in previous section, it is reasonable to use readings for position 58 inside the main piles for calculating the geometric averages of the replicated piles. By passing vertical and horizental planes between the replicated positions, the assigned volume and weight to each of these 10 positions were calculated and shown in Table 9.

The geometric averages of the main piles F, P and N are shown in Fig. 4.19. Comparing Fig. 4.19 with Fig. 4.1, it can be seen that the configurations are essentially the same but the geometric averages displayed lower temperature values than the arithmetic averages based on the data from 59 thermocouple positions in each pile. Peak temperatures were 52.9 vs. 57.5 for pile F, 56 vs. 60.6 for pile P and 55.8 vs. 58.4 for pile N. Also the time to cool down to 15°C is less when using geometric averages, for example 40.5 vs. 45.25 for pile F, 46.25 vs. 47.5 for pile P, and 59.25 vs. 62.5 for pile N. The reason is that most of thermocouples are located in the interior part of the pile, where the temperature is higher than at locations near the surface. Thus, the arithmetic

Table 4.6: Assigned volume and weight to each position

POSITION	ASSIGNED VOL.(m^3)	ASSIGNED WEIGHT
1	1.383	0.273
8	0.532	0.105
10	0.392	0.077
13	0.196	0.039
14	0.233	0.046
45	0.589	0.116
47	0.480	0.095
50	0.256	0.051
51	0.352	0.070
58	0.647	0.128
	$\Sigma = 5.06$	$\Sigma = 1.00$

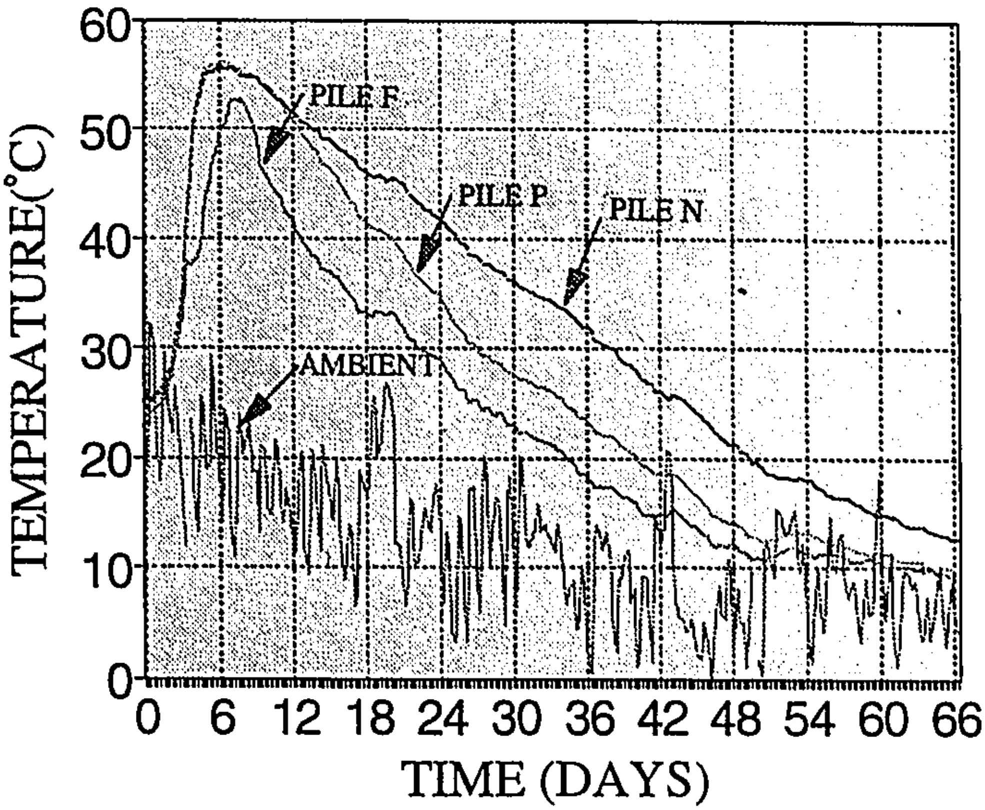


Figure 4.19: Geometric average temperatures of the main piles

average of 59 positions gives a higher value. Depending on the distribution of thermocouples inside the pile the arithmetic average may not be a good representative for temperature performance in composting.

Figs. 4.20 and 4.21 show the geometric temperature averages of PA and NA piles. A high degree of similarity exists between the replicated piles. Calculated correlation factors also support this similarity. The correlation factors ranged from 0.995 to 0.999, 0.992 to 0.997, and 0.988 to 0.996 for forced, passive, and natural aeration piles, respectively.

For each pile, a regression analysis was carried out in order to find the best fitting straight lines on either sides of the maximum point of the geometric average temperature profiles. Fig. 4.22 shows one of the geometric average profile for pile P, with the accompanying fitted straight lines. The slopes of these lines represent the temperature increasing rate up to the maximum temperature and temperature decreasing rate to the ambient level. The temperature increasing and decreasing rates of all piles are presented in Table 4.7. Other results included in this table are peak temperature, time to reach the peak temperature, length of time that the temperature stayed above 55°C, and time for temperature to drop to 15°C.

As explained before, the geometric average displays lower temperature values. This can be seen by comparing the figures in Table 4.7 with those in Table 4.1. The

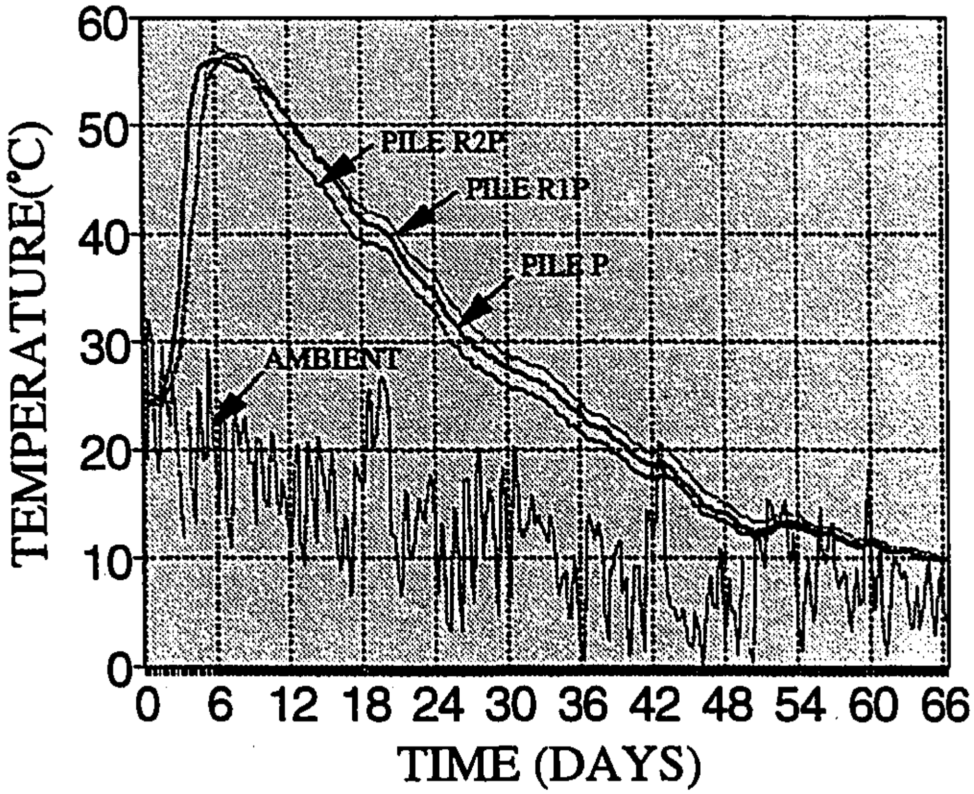


Figure 4.20:Geometric average temperature of piles P, R1P and R2P

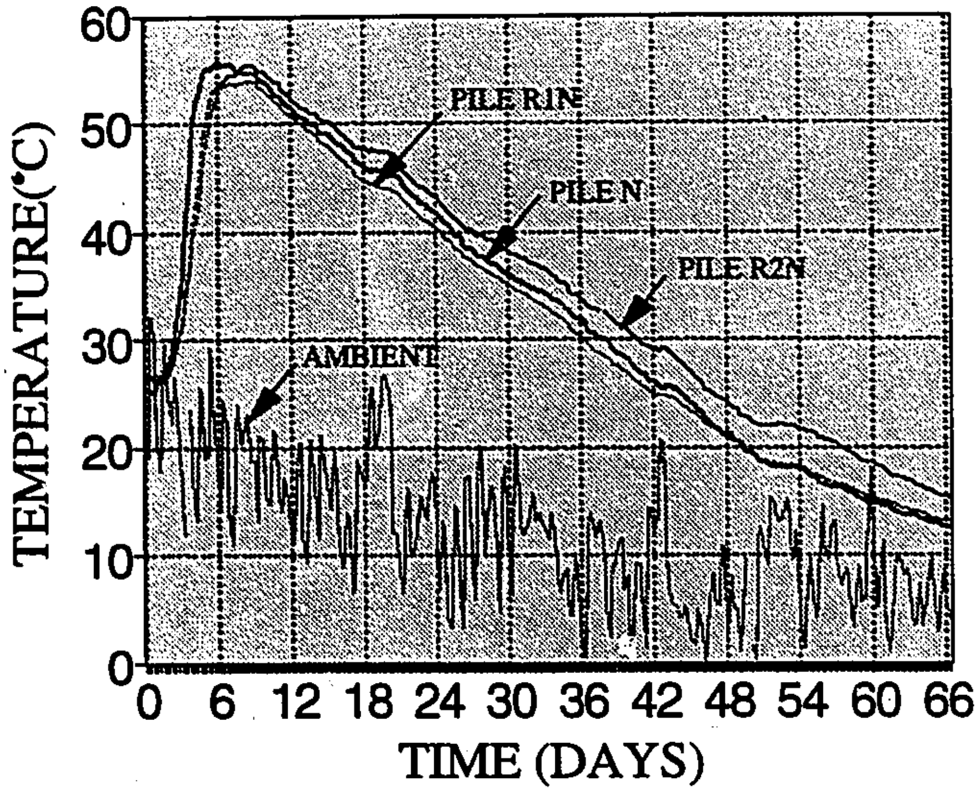


Figure 4.21:Geometric average temperature of piles N, R1N and R2N

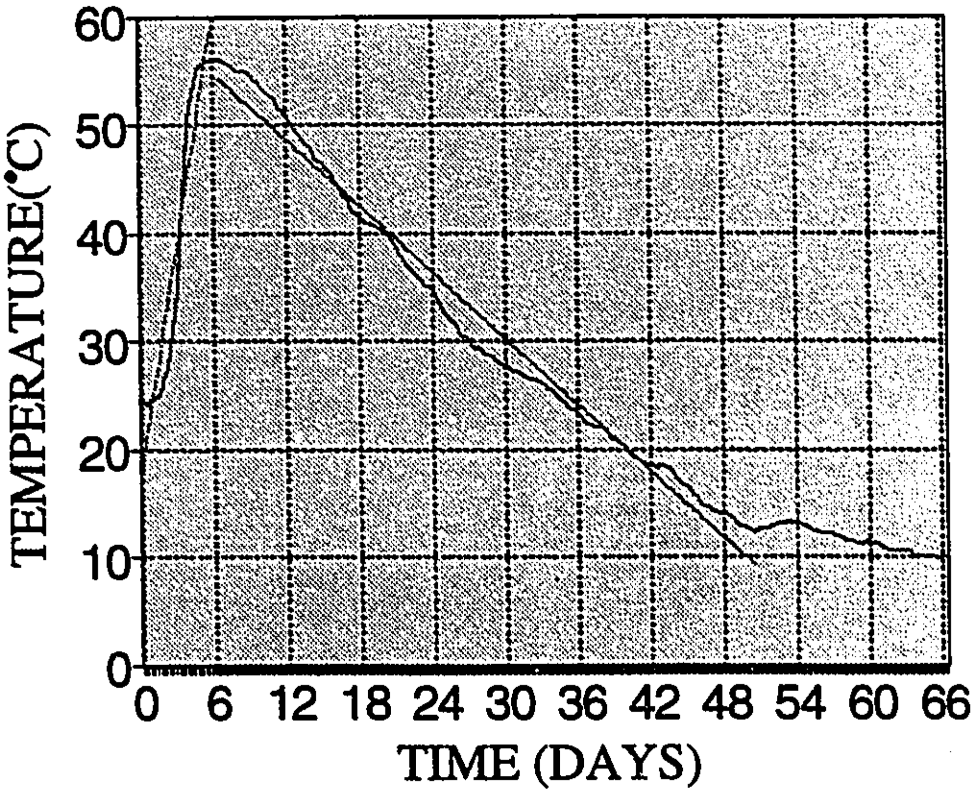


Figure 4.22:Geometric average temperature and fitted straight lines for pile P

Table 4.7: Characteristics of geometric average temp. of all piles

Pile	Peak (°C)	Time to reach peak (day)	Dur. above 55 °C (day)	Inc. rate (°C/day)	Dec. rate (°C/day)	Time to reach 15 °
F	52.9	7.75	0.0	4.3	0.9	40.5
R1F	55.0	7.25	0.25	4.5	0.9	45.0
R2F	55.4	6.25	0.50	4.8	1.0	45.0
Y_F	54.4	7.08	0.25	4.53	0.93	43.5
P	56.0	6.25	4.00	7.0	1.0	46.25
R1P	57.4	6.00	4.25	6.1	1.1	48.25
R2P	56.4	7.00	3.25	5.8	1.0	45.5
Y_P	56.6	6.42	3.83	6.3	1.03	46.67
N	55.8	6.25	2.5	6.5	0.8	59.25
R1N	54.0	8.50	0.0	4.4	0.8	61.25
R2N	55.6	8.75	1.75	4.5	0.7	66.0
Y_N	55.1	7.83	1.42	5.13	0.77	62.17

Y_i = Average of each column

difference is shown more significantly in the duration above 55°C, 0.0 vs. 1.75 for pile F, 4.0 vs. 7.5 fore pile P and 2.5 vs. 8.5 for pile N.

A t-test was carried out to compare each pair of the three modes of aeration in terms of the parameters presented in Table 4.8. In the t-test, a confidence interval for the absolute difference of the treatments average (Y_i) of the parameter is made. If this interval includes zero, then it shows that in the light of available data there is no real difference between the averages of the parameter analyzed from the two treatments. The percentage points required for carrying out the t-test are presented in Appendix C. The results of the t-test and associated confidence intervals for each parameter are shown in Table 4.8. The results of the t-test is based on 3 replicates for each treatment. As in the ANOVA, α is the percent probability associated with the confidence interval.

The results show that there is no real difference between FA and PA in terms of the time to reach peak value and the temperature decreasing rate. However, the peak temperature, duration above 55°C, the temperature increasing rate and time to reach 15°C for the passive aeration are 2.2°C, 3.58 days, 1.8 °C/day and 3.17 days greater than that of forced aeration, respectively. Above findings show that PA reached higher peak temperature more quickly than FA. PA is also superior in term of sanitization because it stayed above 55°C for a longer time. From Table 4.7, it can be seen that the temperature in PA stayed above 55°C for 3.83 days on average, which is greater than 3 days required be EPA. Forced aeration is superior only in term of time for process to

Table 4.8: Results of t-test

Parameter	FA and PA	FA and NA	PA and NA
PEAK TEMP.	$\lvert Y_F - Y_P \rvert = 2.2$ $\sigma^2 = 1.03$ $CI_\alpha = [0.43, 3.97]$	$\lvert Y_F - Y_N \rvert = 0.7$ $\sigma^2 = 1.17$ $CI_\alpha = [-1.18, 2.58]$	$\lvert Y_P - Y_N \rvert = 1.5$ $\sigma^2 = 0.854$ $CI_\alpha = [-0.11, 3.11]$
TIME TO REACH PEAK	$\lvert Y_F - Y_P \rvert = 0.66$ $\sigma^2 = 0.64$ $CI_\alpha = [-0.73, 2.05]$	$\lvert Y_F - Y_N \rvert = 0.75$ $\sigma^2 = 1.07$ $CI_\alpha = [-1.05, 2.55]$	$\lvert Y_P - Y_N \rvert = 1.41$ $\sigma^2 = 0.95$ $CI_\alpha = [-0.29, 3.11]$
DURATION ABOVE 55°C	$\lvert Y_F - Y_P \rvert = 3.58$ $\sigma^2 = 0.39$ $CI_\alpha = [2.49, 4.67]$	$\lvert Y_F - Y_N \rvert = 1.17$ $\sigma^2 = 0.77$ $CI_\alpha = [-0.36, 2.70]$	$\lvert Y_P - Y_N \rvert = 2.41$ $\sigma^2 = 0.90$ $CI_\alpha = [0.76, 4.06]$
INCREASING RATE	$\lvert Y_F - Y_P \rvert = 1.77$ $\sigma^2 = 0.44$ $CI_\alpha = [0.62, 2.92]$	$\lvert Y_F - Y_N \rvert = 0.60$ $\sigma^2 = 0.72$ $CI_\alpha = [-0.88, 2.08]$	$\lvert Y_P - Y_N \rvert = 1.17$ $\sigma^2 = 0.90$ $CI_\alpha = [-0.48, 2.82]$
DECREASING RATE	$\lvert Y_F - Y_P \rvert = 0.10$ $\sigma^2 = 0.06$ $CI_\alpha = [-0.33, 0.53]$	$\lvert Y_F - Y_N \rvert = 0.17$ $\sigma^2 = 0.06$ $CI_\alpha = [-0.26, 0.60]$	$\lvert Y_P - Y_N \rvert = 0.27$ $\sigma^2 = 0.06$ $CI_\alpha = [-0.17, 0.69]$
TIME TO REACH 15 °C	$\lvert Y_F - Y_P \rvert = 3.17$ $\sigma^2 = 2.01$ $CI_\alpha = [0.70, 5.64]$	$\lvert Y_F - Y_N \rvert = 18.67$ $\sigma^2 = 3.04$ $CI_\alpha = [15.63, 21.72]$	$\lvert Y_P - Y_N \rvert = 15.50$ $\sigma^2 = 2.45$ $CI_\alpha = [12.78, 18.22]$

$\alpha = 90\%$
σ_2 = pooled estimate of variance

finish, which was 3.6 days less than PA.

Comparison of the values for the forced and natural aeration, second column in Table 4.8, shows that they displayed the same performance in terms of peak temperature, time to reach the peak temperature, and the temperature increasing and decreasing rates. But, FA reached to 15°C in less time, 18.7 days sooner than NA. For duration above 55°C, since the lower limit of confidence interval is very close to zero, a= -0.36, it can not be rigidly interpreted whether the two treatments worked in the same way or not. In fact, if α = 80% is used for calculating the limits of the confidence interval, the lower limit will be 0.07 and the interval will not include zero. Above result show that FA is superior to NA only in term of the time for the process to finish.

Third column in Table 4.8 shows that the PA and NA performed equally in terms of temperature increasing and decreasing rates. The duration above 55°C for PA was 2.4 days longer than that of the NA and for NA it took 15.5 more days to drop to 15°C. For peak temperature and the time to reach peak it can not be interpreted whether these two treatments performed equally or not because the lower limit of confidence interval is very close to zero.

4.7 Process Monitoring

4.7.1 Moisture content (MC)

Composting under high initial MC was chosen to reduce the consumption of bulking agent. Water evaporation during the early stages of composting process was apparent. By day 5 the surfaces of all 9 piles became wet and remained wet until the end of the fourth week. The reason being that water evaporated due to high temperatures inside the piles and condensed on the surface after reaching the cold ambient air. Also, during the second and third weeks hot steam was coming out from the gas sampling tubes. At the end of composting process, the MC at the piles surfaces was measured to be between 45% and 55%.

Fig. 4.23 shows the variations of the MC in time for bottom, middle, and top of pile F. All nine piles behaved almost in the same manner. The initial and final MC of the piles were around 76% and 70-71%, respectively. This implies 6.5-8% reduction in the MC percentage which is not very significant. One reason for this is that a part of water evaporation is compensated by the production of water through biodegradation. High capacity of peat for absorbing and holding water could be another reason for this retention of moisture. Fig. 4.24 shows the average of MC, average of MC at bottom, middle, and top of the piles, of piles F, R1F, and R2F. The figure shows that there is a good similarity among the replicated piles.

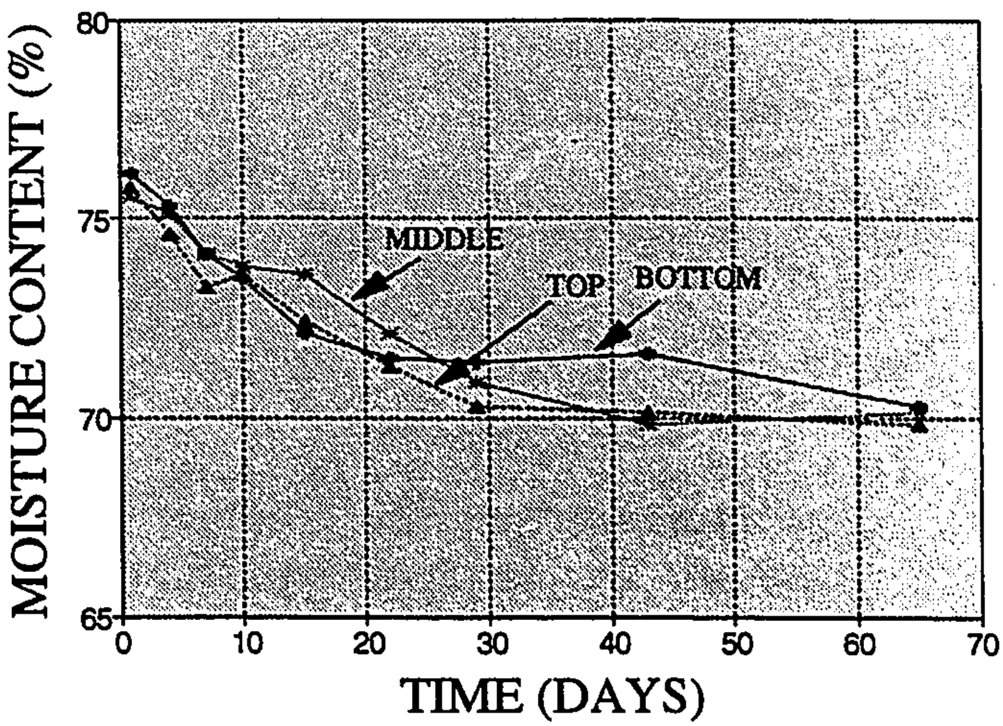


Figure 4.23: MC at the bottom, middle and top of pile F

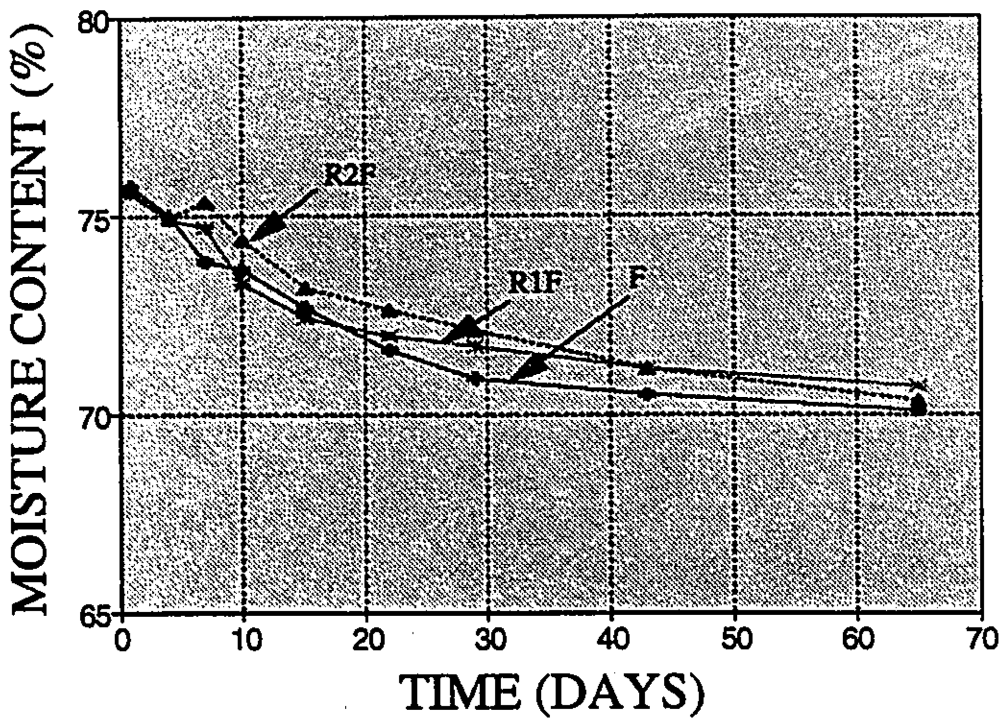


Figure 4.24: Average MC of pile F, R1F and R2F

It should be noted that most of MC decrease occurred during the first four weeks. It is worth noting that throughout the composting process MCs were high enough, 70-76%, to support the microbial activities. As mentioned in Chapter 2, the optimum range is reported to be between 50% and 60%. Thus, MC was not a limiting factor in this sense. But, high MC could restrict the air movement which results in anaerobic conditions. Low temperatures, below 35°C, and production of CH_4 and H_2S are symptoms of anaerobic conditions. This will be discussed in Section 4.7.4.

4.7.2 pH

Variations of the pH at the bottom, middle, and top of the pile F is presented in Fig. 4.25. For all piles there was a sharp increase in pH from initial values around 5.3 to values above 6.0. According to Zhan (1993), production of NH_3/NH_4^+, release of CO_2 and decomposition of amino acids are the main reasons for pH increase during early stages of composting.

In pile F, aftrer the initial increase the pH slightly dropped followed by an slight increase to final values between 6.6 and 6.7 as show in Fig. 4.25. For pile P, after reaching peak, pH stayed between 6.2 and 6.6. And for pile N, after reaching peak, pH drop was more significant than the other two treatments, the pH values were between 6.0 and 6.2. Eventually the pH in pile N increased slightly to values between 6.2 and 6.4.

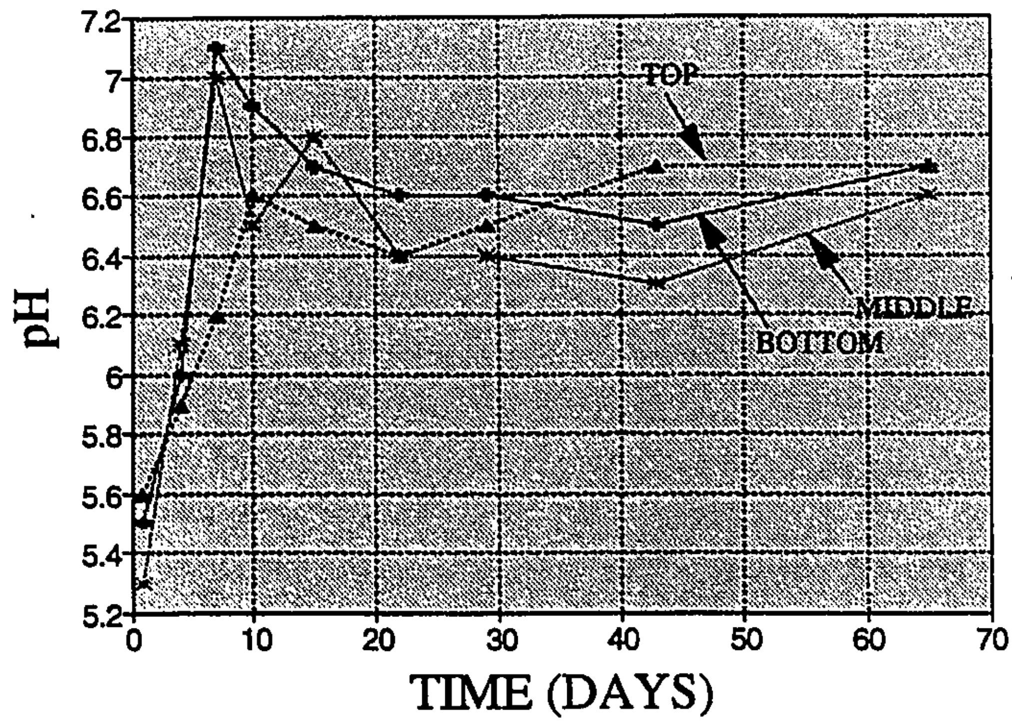


Figure 4.25: pH at the bottom, middle and top of pile F

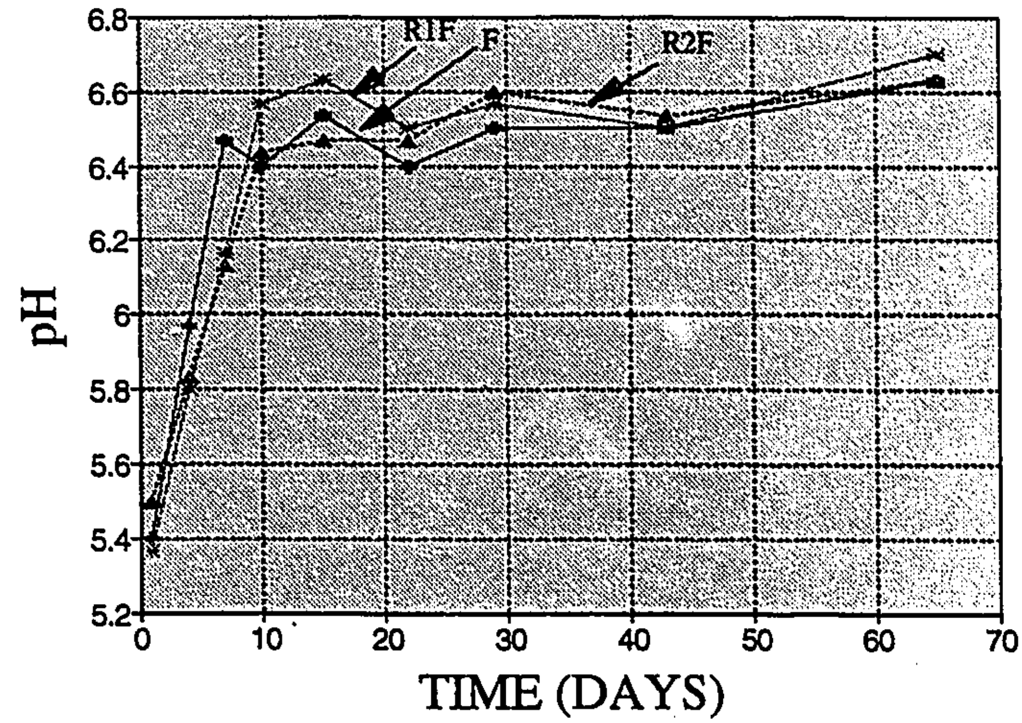


Figure 4.26: Average pH of piles F, R1F and R2F

Fig. 4.26 shows the average pH, based on the average values of pH at bottom, middle, and top of the piles F, R1F, and R2F. The figure displays a good similarity among the replicated piles.

4.7.3 Oxygen

Oxygen concentrations was measured at the top, middle, and bottom of the main piles using an oxygen probe and results are reported as % vol. Figs. 4.27 to 4.29 show the oxygen concentrations inside the main piles.

The first readings on the 9th day (the equipement was not available before day 9) for FA pile showed values between 12% and 17% which were much higher than those observed in PA and NA piles. In fact, throughout the composting process, higher oxygen concentrations were measured in the FA pile. This shows the effectiveness of FA in providing more oxygen. The effectiveness of passive pipes can be verified by considering Figs. 4.28 and 4.29. While the oxygen concentrations inside pile N varied between 0.0% and 4.0%, values between 1.0% and 12% were measured inside pile P on the 9th day. Also, higher oxygen levels were measured inside pile P than pile N throughout the process. It should be noted that the effect of passive pipes is more significant at the bottom level compared to natural aeration compost pile. In pile N, bottom layer shows a better performance than middle layer.

The effect of FA and passive pipes can be seen more clearly in Fig. 4.30, which

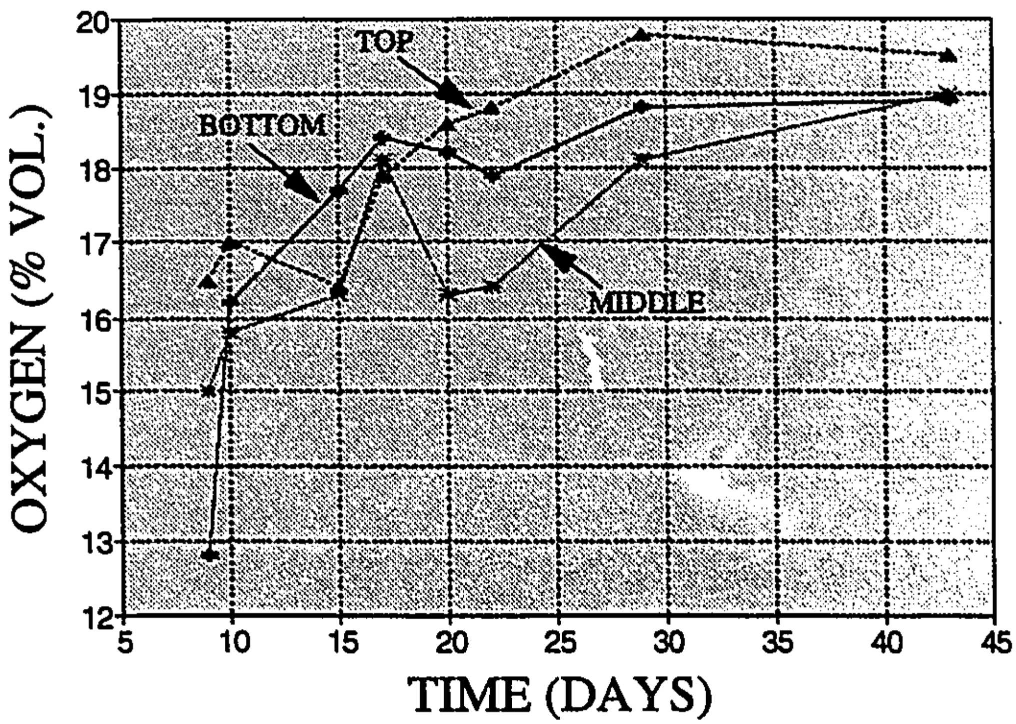


Figure 4.27: Oxygen concentrations inside pile F

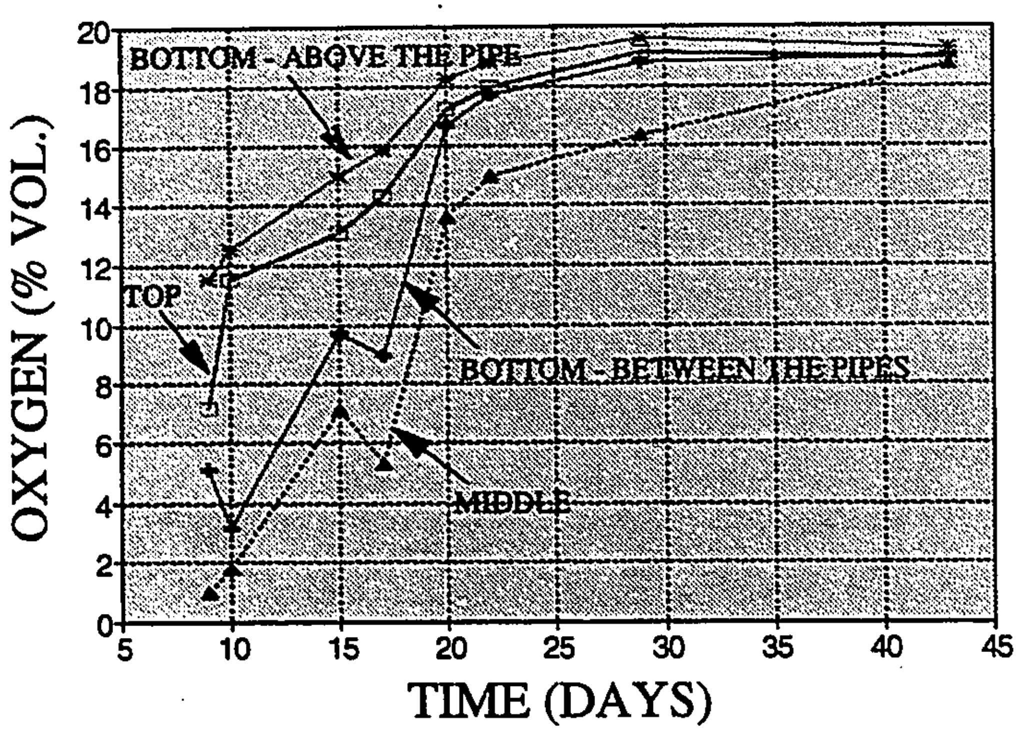


Figure 4.28: Oxygen concentrations inside pile P

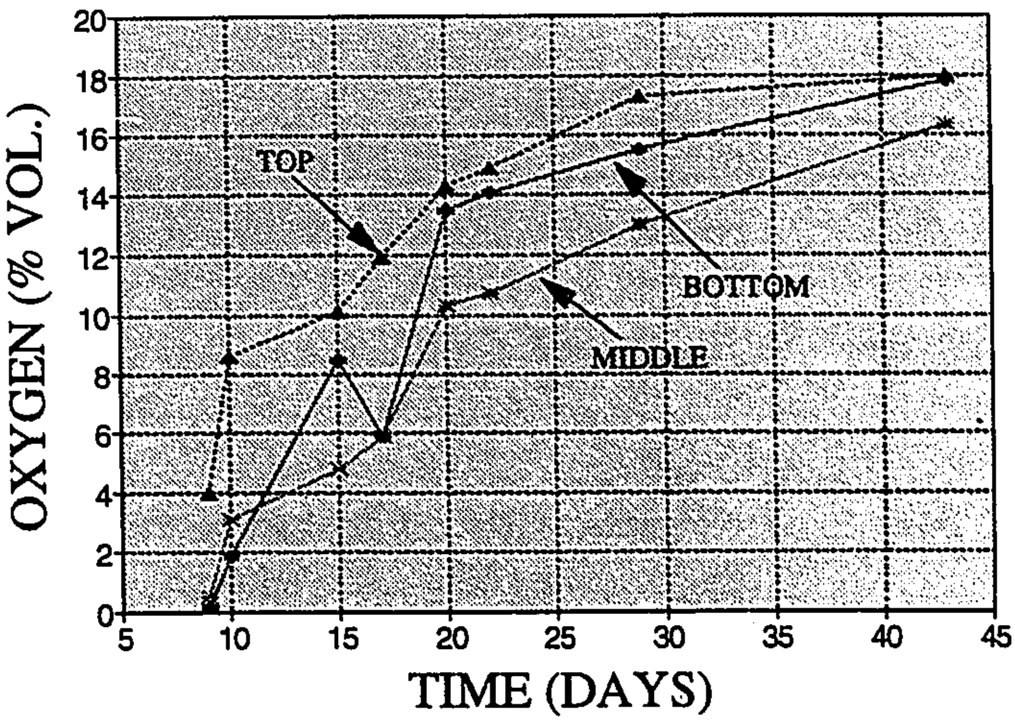


Figure 4.29: Oxygen concentrations inside pile N

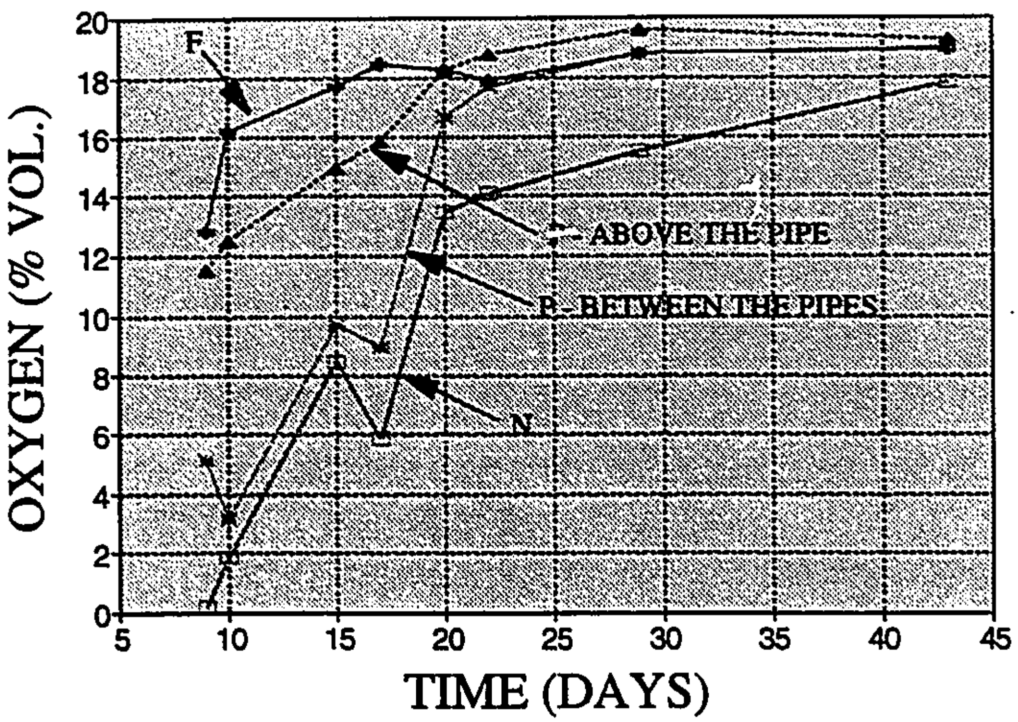


Figure 4.30: Oxygen concentrations at the bottom of piles F, P and N

shows the oxygen concentrations at the bottom of piles F, N, and P. FA and PA pipes provided more oxygen at the bottom of the piles. The oxygen concentrations measured above the passive pipe are comparable to those measured in forced aeration pile and are much higher than those values in pile N. This shows that the passive aeration pipes introduced extra air at the bottom of the pile. It might be due to the use of 0.1 m thick peat layer at the base. Peat was porous and enhanced the air difusion.

By considering the shapes of the oxygen concentration versus time curves, it is seen that after the 30th day, the oxygen concentrations in piles F and P reached a constant level of about 18% by volume. This shows that the active composting period was finished in less than 30 days.

4.7.4 NH_3, CO_2, and H_2S

Since a limited number of Dragger tubes for measuring NH_3 was available, NH_3 at the surfaces of the main piles was monitored only during the first week. Also, NH_3 concentrations inside the main piles at the bottom were measured on the 5th and 7th days. NH_3 gas was not detected at the surfaces of the piles P and N during the first week. NH_3 tends to volatile at high pH values, above 8.0. The acidic characteristic of peat helped to conserve ammonia in the ionic form NH_4^+-N. For pile F, NH_3 concentrations between 40 to 55 ppm were detected at the pile surface. NH_3 concentrations at the bottom of piles F, P, and N were 35, 0.0, and 0.0 ppm on the 5th day and 260, 90, and 32 ppm on the 7th day, respectively, which shows the effect of FA on NH_3 volatilization was quite significant.

Dragger tubes that were used for CO_2 measurement inside the piles P and N were over ranged *i.e.*, CO_2 concentrations were highre than the Dragger tube's range. This shows that CO_2 concentrations inside the piles P and N were more than 6% by volume. For pile F, concentrations of CO_2 between 0.05 to 0.24%, 0.95 to 2.25%, and 1.5 to 6% were measured at the bottom, middle, and top of the pile during the first week.

From the second week onward, a GC was used for determining CO_2. Air samples from bottom, middle and top of the three main piles were taken and analyzed by GC for determination of CO_2, H_2S, and CH_4. Figs. 4.31 to 4.33 show the concentrations of CO_2 and H_2S gases at bottom, middle, and top of the three main piles. CH_4 was not detected in any of the piles.

Low concentrations of CO_2 and no H_2S were measured in pile F. The peak concentrations for CO_2 inside pile F occurred on the 22th day, after the FA system had been shut off. CO_2 values ranged between 5.5 and 9.0%. Pile P started with CO_2 concentrations between 15 and 30% and followed by a gradual drop to zero on the 43th day. Atmospheric air contains 0.03% CO_2, but the GC was not able to detect low CO_2 concentrations near zero. H_2S was only detected (3%) on the 29th day at the middle of pile P. For pile N, higher concentrations of CO_2 and H_2S were measured. Peak values

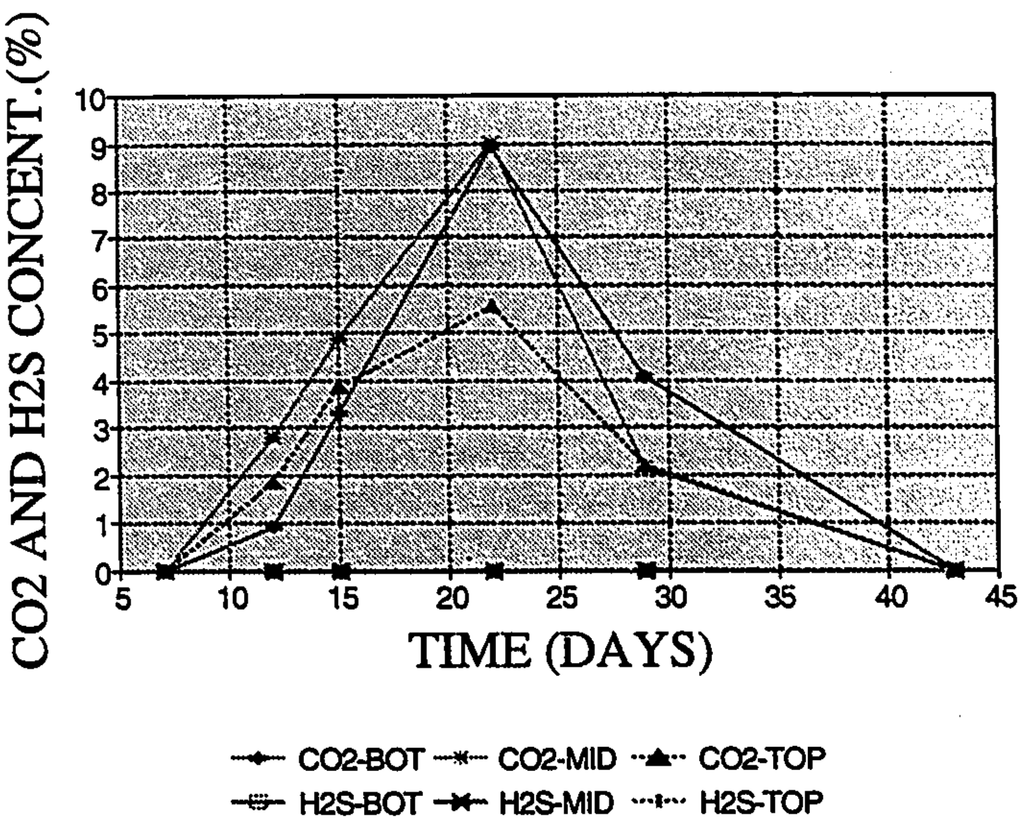


Figure 4.31: Concentrations of CO_2 and H_2S inside pile F

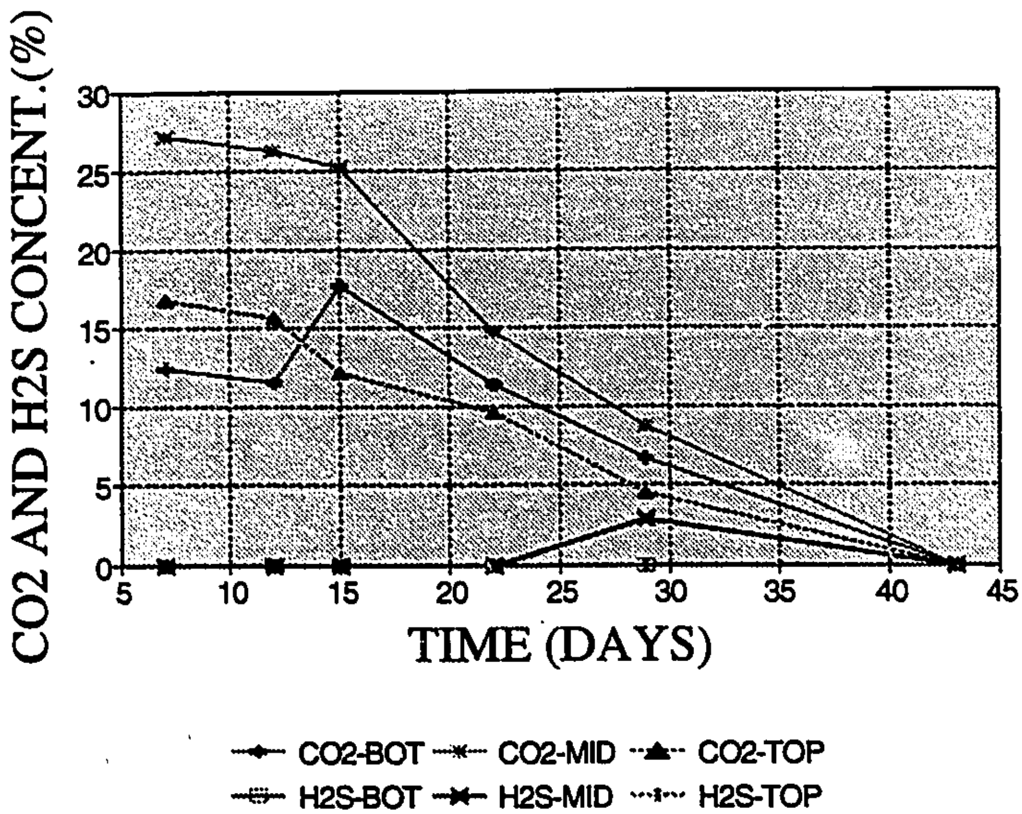


Figure 4.32: Concentrations of CO_2 and H_2S inside pile P

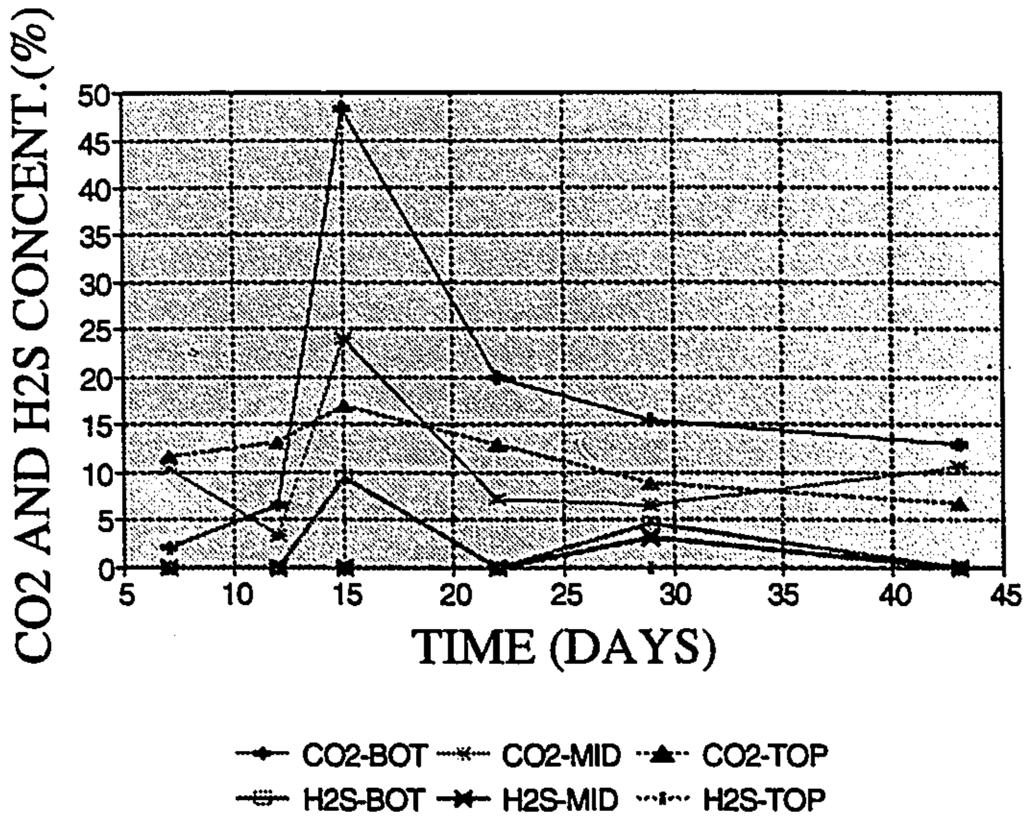


Figure 4.33: Concentrations of CO_2 and H_2S inside pile N

for CO_2 were 48, 24, and 17% at bottom, middle, and top of the pile, respectively. The maximum H_2S concentrations at bottom and middle were 9.6% and 3.0%, respectively. H_2S was not detected at the top of pile N.

Since occurrence of H_2S is a symptom of anaerobic conditions, thus, it appears that anaerobic conditions occurred at the bottom and middle of pile N and to a less extent at the middle of pile P. High moisture content, low oxygen concentrations and compaction, especially at the bottom, are the main reasons for this problem. Above findings shows that the use of PA pipes improved the aerobic conditions at the bottom.

Comparison of CO_2 concentrations inside three piles shows the significant effect of forced aeration on CO_2 removal. CO_2 concentrations inside pile N are up to 5 times of those inside pile F. As explained in Chapter 2, if the CO_2 produced in biochemical reactions is not removed, it could result in lowering pH. Therefore, lower pH values reported in section 4.7.2 for pile N are associated with high CO_2 concentrations.

CO_2 in piles P and F were reduced to trace concentrations by the 43th day. This shows that the active composting was finished by that time.

4.7.5 C/N, NH_3, VS, TP and ash

Changes in C/N, VS, and ash content during the process was very small. The final

C/N values were 20.9, 19.8 and 18.9 for piles F, P and N, respectively, compared to initial C/N value of 22.1. VS and ash content ranged between 87 to 88% and 11.8 to 12.6%, respectively. The main reason for small changes in C/N, VS and ash content is that a large amount of peat was used in raw compost. Peat passes through the process virtually unchanged, which masks the changes of these parameters in manure.

TP increased from the initial value of 0.9 to 1.1, 1.0 and 1.1% for piles F, P and N, respectively, the reason being that the total amount of phosphorous does not change during the composting process (Jackobsen, 1992 and Zhan, 1993), which results in an increase in the percentage of TP due to mass reduction.

Fig. 4.34 presents the variations of NH_3 concentrations (% dry basis) inside the main piles. The initial values were between 0.36 and 0.57%. Then, it decreased slightly because NH_3-N is the available form of nitrogen and it was consumed by the microorganisms. Then, by breaking down of organic matter some of nitrogen is converted to ammonia and as a result the NH_3 concentration increased to final values of 1.25, 1.48 and 1.76 % for piles F, P and N, respectively. Comparison of the final NH_3 concentrations shows that natural pile was more effective in conserving NH_3. The main reason for this are the lesser air striping effect and lower rate of biochemical reactions affecting conversion of organic nitrogen to reduced inorganic form.

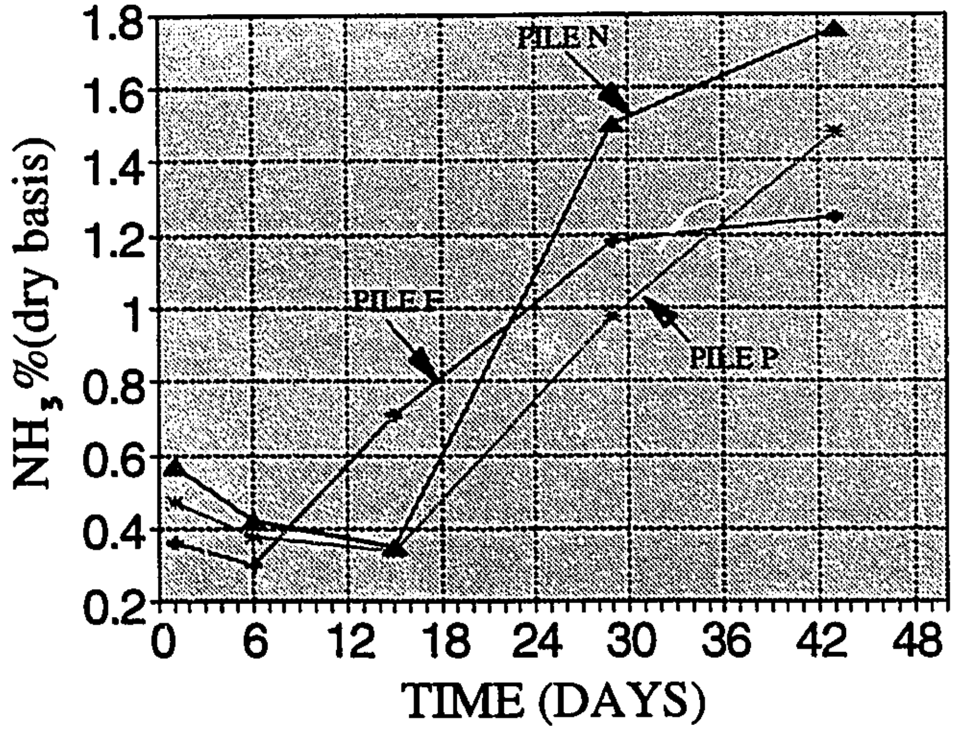


Figure 4.34: NH_3 concentrations inside the main piles

4.8 Final Product

Table 4.9 shows the physical and chemical properties of the final products from the main piles. The final product looked like peat. It had all physical characteristics of a mature compost, *i.e.* dark brown colour and an earthy smell. It was rich in total nitrogen, 2.1- 2.2% on dry mass basis, and total phosphorous, 1.0-1.1% on dry mass basis. The shape of the temperature profiles also support the idea that the final product was mature. The temperatures rose to the maximum and then gradually dropped to ambient level. Furthermore, at the end of the process the compost piles were remixed, reheaped, and temperatures inside the piles were monitored for another 10 days. Temperatures did not go above 9°C. The fact that no reheating occurred also shows that the compost was mature.

The volume of the main piles was measured at the end of process. It varied from initial volume of 5.0 m^m to the final values of 3.9 m^3, 4.0 m^3, and 4.2 m^3 for forced, passive, and natural aeration piles, respectively. This implies a volume reduction between 16 to 22%. Since the total amount of phosphorous does not change during the composting process, the mass reduction can be calculated by carrying out a mass balance. The mass reduction was between 28 to 34.5 %.

MC of final product was high, around 70%. But, it's C/N was relatively low, between 18.9 to 20.9, compared to raw peat. These characteristics should be considered

Table 4.9: Properties of the final products

PROPERTY	INITIAL	PILE F FINAL	PILE P FINAL	PILE N FINAL
MC (%)	76.0	70.1	70.3	70.8
VS% (DM)	88.5	87.2	88.0	87.0
ASH% (DM)	11.0	12.5	11.8	12.6
TC (DM)	44.2	44.0	43.6	43.9
TN (DM)	2.1	2.1	2.2	2.2
C/N	22.1	20.9	19.8	18.9
pH[a]	5.4	6.7	6.3	6.2
NH_3[b]% (DM)	0.45	1.3	1.5	1.8
TP% (DM)	0.9	1.1	1.0	1.1

DM = Dry matter
a: in 0.01 M $CaCl_2$
b: 2 N KCl extract

if the final product is to be used as bulking agent material. A good bulking agent for composting of manure should be low in MC and high in C/N.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A total amount of 16,500 kg raw compost, composed of poultry manure and peat, was successfully composted under high moisture content (76%) conditions using forced, passive, and natural aeration treatments. All treatments progressed stably and ended in less than 10 weeks. By applying statistical analysis to temperature monitoring results, information on the performance of these three treatments, influence zones of forced and passive aeration pipes and comparison of each pair of the treatments was derived. Also, the physical and chemical characteristics of compost as well as concentrations of oxygen, CO_2, NH_3 and H_2S were monitored during compost processing.

Correlation factors for temperature readings of replicated positions showed that a good similarity existed among these positions. These results clearly supports that the process was quite stable and reproducible.

The influence zone of passive aeration pipes included positions in the interior part of the bottom half of the pile. Forced aeration pipe influenced the interior part of the pile. Positions near the pile surface were not affected by the aeration pipes. And the passive aeartion pipes placed at the outer side of the pile appeared to not be of great use. The results on influence zones were also verified by Cluster analysis.

Temperature distribution pattern inside the piles showed that: 1) for natural aeration pile, air diffusion into the pile was the predominant aeration mechanism and the amount of available air in each position was affected by its distance from the pile surface. Consideration of temperature profiles of positions with different distances from the pile surface also supported this assertion; 2) temperatures inside the forced aeration pile dropped to the ambient level at a faster rate than the other two treatments; 3) at positions around the forced aeration pipe temperatures did not go above 55°C.; 4) a more uniform temperature distribution was observed inside passive aeration pile; and 5) the temperatures at the corners and near the surface of all piles did not rise above 35°C. Thus, these locations require more insulating material.

Three treatments were compared, using geometric average temperature, in terms of their peak temperature, the time to reach peak, the time duration above 55°C, time to drop to 15°C and the temperature rising and falling rates using a t-test. The comparison revealed that passive aeration was superior to forced and natural aeration. Higher peak temperatures were achieved at a faster rate, temperature stayed above 55°C for longer time and it finished quickly. Forced aeration performed better than natural aeration only in terms of time to mature.

Variations in MC and pH was almost the same for all treatments, 6.5-8% reduction in percentage of MC and final pH values between 6.2 and 6.7. TP changed from initial value of 0.9% (dry mass basis) to the final value of 1.0-1.1% (dry mass basis). Temperature profiles and variations in moisture content and pH also showed that the composting process is quite stable and reproducible.

Oxygen measurements showed that forced and passive aeration were effective in providing more oxygen. Oxygen concentrations above the passive pipe were comparable to those at the bottom of the forced aeration pile. The shape of the oxygen concentration curves showed that the active composting period in forced and passive piles finished in less than 30 days. Oxygen concentrations had reached to values around 18% by the 30th day.

Forced aeration was more effective in CO_2 removal, but promoted NH_3 volatilization. H_2S was not detected in forced aeration pile. The use of passive pipes improved the aerobic conditions inside the pile.

C/N, volatile solids and ash content did not change significantly because a large amount of peat was used, which does not change during the composting process. NH_3 (on dry basis) varied from initial values of 0.36-0.57% to final values of 1.25-1.76%. Natural aeration was more effective in conserving ammonia than the other two treatments.

At the end of the process, the compost were remixed and reheaped. But, no reheating occurred showing that the compost from all treatments were mature. The volume of the piles were reduced by 16 to 22% and the mass reductions were calculated to be 28-34.5%. The final product had a dark brown colour, an earthy smell, and a loose structure with a moisture content of 70%, and a pH of 6.2 to 6.6.

5.2 Recommendations for future studies

Based on the results from this work, the followings topics are recommended for future study on composting:

1) determination of the influence zones of passive aeration pipes under the following conditions:

a) different types of wastes and bulking agents;

b) different moisture contents;

c) different pile sizes and shapes; and

d) different configurations and spacing of pipes;

2) the optimum thickness of covering material for insulation purposes;

3) An in depth study of the volatilization of NH_3 and the production of CO_2, H_2S, and CH_4 gases in different composting methods.

4) composting of manure slurries under winter conditions.

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APPENDICES

Appendix A: Figures and Tables

Appendix B: Temperature Measurement with Thermocouples

Appendix C: Percentage points for F and t distributions

Appendix A: Figures and Tables

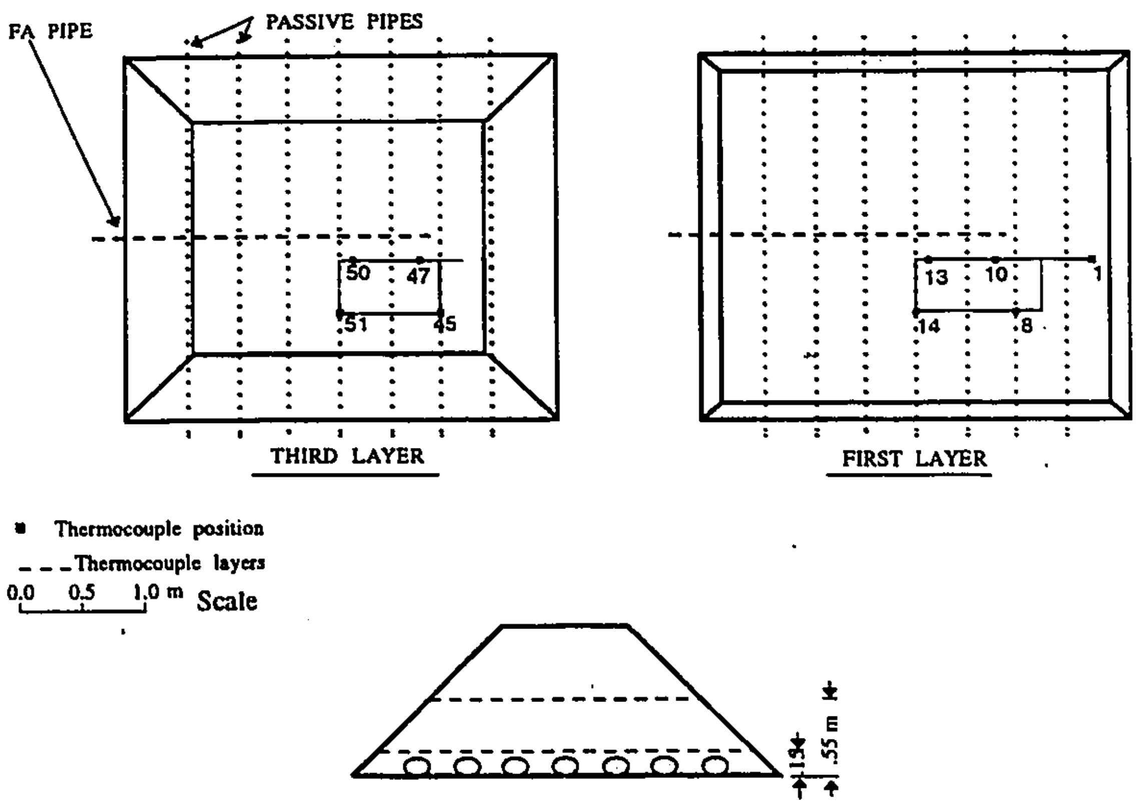


Figure A-1: Thermocouple layers of replicated positions

Table A-1: Characteristics of wastes from different sources (Rynk, 1992)

Material	% N (dry weight)	C/N ratio	MC (%)	Bulk Density (kg/m^3)
Manures				
Broiler litter	1.6-3.9	12-15	22-46	448-608
Cattle	1.5-4.2	11-30	67-87	784-992
Horse	1.4-2.3	22-50	59-79	720-960
Laying hens	4.0-10	3-10	62-75	816-960
Sheep	1.3-3.9	13-20	60-75	----
Swine	1.9-4.3	9-19	65-91	----
Food and meat processing				
Crab and lobster	4.6-8.2	4.0-5.4	35-61	----
Shrimp wastes	9.5	3.4	78	----
Mussel wastes	3.6	2.2	63	----
Municipal Wastes				
Food wastes	1.9-2.9	14-16	69	----
Sewage sludge	2-6.9	5-16	72-84	637-1040
Leaves	0.5-1.3	40-80	----	----
Newsprint	0.06-0.14	398-852	3-8	116-143
Night soil	5.5-6.5	6-10	----	----

Table A-2: **Amount of peat and manure used in each batch**

BATCH #	PEAT(KG)	MANURE(KG)	TOTAL(KG)	CALCULATED MC (%)
1	920	840	1760	76.2
2	1263	1175	2438	76.0
3	846	776	1622	76.0
4	965	895	1860	76.0
5	995	930	1925	76.0
6	965	900	1865	76.1
7	945	860	1805	76.0
8	1005	915	1920	76.0
9	940	860	1800	76.0
TOTAL	8844	8151	16995	----

APPENDIX B:
THEORY OF TEMPERATURE MEASUREMENT WITH THERMOCOUPLES

(The material in this section is directly taken from *Methods of Soil Analysis. Part 1. Physical and Mineralogical methods, Ch. 37,* by S.A.Taylor and R.D.Jackson)

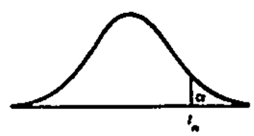
Temperature cannot be measured directly. It can only be estimated by its influence on some property of matter that responds to variation in the intensity of heat in the body of matter. Instruments built to take the advantage of the response of any property of the matter to the variation of temperature are called thermometers. The influence of temperature on thermal electromotive force is the property used in measuring temperature with thermocouples.

Thermoelectric junctions, called thermocouples, are made by joining two dissimilar metals at two different points, to form two junctions. If the entire circuit is composed of only two metals, the total electromotive force in the circuit is proportional to the difference in temperature of the two junctions. One junction is called ***measuring (or hot) junction***, and the other, the ***reference (or cold) junction***. For measurement of temperature , the reference junction is kept at a constant temperature, for example, in melting ice. The electrical potential produced is usually measured with a potentiometer when precise measurements are desired. Also, a galvanometer or millivoltmeter can be used. Some commercially available potentiometers have a built-in correction for the temperature of the reference junction, thus eliminating the need of an ice bath or other constant-temperature source.

One great advantage to thermocouples, in addition to their adaptiblity to automatic recording, is their small size and almost instantaneous response to temperature changes. They may be placed precisely, and therefore indicate the temperature at a given point.

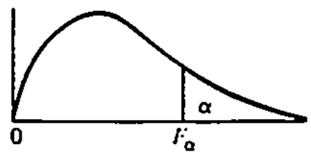
Appendix C:

Table C.1: Percentage points of t distribution



$t_{.100}$	$t_{.050}$	$t_{.025}$	$t_{.010}$	$t_{.005}$	d.f.
3.078	6.314	12.706	31.821	63.657	1
1.886	2.920	4.303	6.965	9.925	2
1.638	2.353	3.182	4.541	5.841	3
1.533	2.132	2.776	3.747	4.604	4
1.476	2.015	2.571	3.365	4.032	5
1.440	1.943	2.447	3.143	3.707	6
1.415	1.895	2.365	2.998	3.499	7
1.397	1.860	2.306	2.896	3.355	8
1.383	1.833	2.262	2.821	3.250	9
1.372	1.812	2.228	2.764	3.169	10
1.363	1.796	2.201	2.718	3.106	11
1.356	1.782	2.179	2.681	3.055	12
1.350	1.771	2.160	2.650	3.012	13
1.345	1.761	2.145	2.624	2.977	14
1.341	1.753	2.131	2.602	2.947	15
1.337	1.746	2.120	2.583	2.921	16
1.333	1.740	2.110	2.567	2.898	17
1.330	1.734	2.101	2.552	2.878	18
1.328	1.729	2.093	2.539	2.861	19
1.325	1.725	2.086	2.528	2.845	20
1.323	1.721	2.080	2.518	2.831	21
1.321	1.717	2.074	2.508	2.819	22
1.319	1.714	2.069	2.500	2.807	23
1.318	1.711	2.064	2.492	2.797	24
1.316	1.708	2.060	2.485	2.787	25
1.315	1.706	2.056	2.479	2.779	26
1.314	1.703	2.052	2.473	2.771	27
1.313	1.701	2.048	2.467	2.763	28
1.311	1.699	2.045	2.462	2.756	29
1.282	1.645	1.960	2.326	2.576	inf.

Table C-2: Percentage points of F distribution



Denominator d.f.	α	Numerator d.f. 1	2	3	4	5	6	7	8	9
1	.100	39.86	49.50	53.59	55.83	57.24	58.20	58.91	59.44	59.86
	.050	161.4	199.5	215.7	224.6	230.2	234.0	236.8	238.9	240.5
	.025	647.8	799.5	864.2	899.6	921.8	937.1	948.2	956.7	963.3
	.010	4052	4999.5	5403	5625	5764	5859	5928	5982	6022
	.005	16211	20000	21615	22500	23056	23437	23715	23925	24091
2	.100	8.53	9.00	9.16	9.24	9.29	9.33	9.35	9.37	9.38
	.050	18.51	19.00	19.16	19.25	19.30	19.33	19.35	19.37	19.38
	.025	38.51	39.00	39.17	39.25	39.30	39.33	39.36	39.37	39.39
	.010	98.50	99.00	99.17	99.25	99.30	99.33	99.36	99.37	99.39
	.005	198.5	199.0	199.2	199.2	199.3	199.3	199.4	199.4	199.4
3	.100	5.54	5.46	5.39	5.34	5.31	5.28	5.27	5.25	5.24
	.050	10.13	9.55	9.28	9.12	9.01	8.94	8.89	8.85	8.81
	.025	17.44	16.04	15.44	15.10	14.88	14.73	14.62	14.54	14.47
	.010	34.12	30.82	29.46	28.71	28.24	27.91	27.67	27.49	27.35
	.005	55.55	49.80	47.47	46.19	45.39	44.84	44.43	44.13	43.88
4	.100	4.54	4.32	4.19	4.11	4.05	4.01	3.98	3.95	3.94
	.050	7.71	6.94	6.59	6.39	6.26	6.16	6.09	6.04	6.00
	.025	12.22	10.65	9.98	9.60	9.36	9.20	9.07	8.98	8.90
	.010	21.20	18.00	16.69	15.98	15.52	15.21	14.98	14.80	14.66
	.005	31.33	26.28	24.26	23.15	22.46	21.97	21.62	21.35	21.14
5	.100	4.06	3.78	3.62	3.52	3.45	3.40	3.37	3.34	3.32
	.050	6.61	5.79	5.41	5.19	5.05	4.95	4.88	4.82	4.77
	.025	10.01	8.43	7.76	7.39	7.15	6.98	6.85	6.76	6.68
	.010	16.26	13.27	12.06	11.39	10.97	10.67	10.46	10.29	10.16
	.005	22.78	18.31	16.53	15.56	14.94	14.51	14.20	13.96	13.77
6	.100	3.78	3.46	3.29	3.18	3.11	3.05	3.01	2.98	2.96
	.050	5.99	5.14	4.76	4.53	4.39	4.28	4.21	4.15	4.10
	.025	8.81	7.26	6.60	6.23	5.99	5.82	5.70	5.60	5.52
	.010	13.75	10.92	9.78	9.15	8.75	8.47	8.26	8.10	7.98
	.005	18.63	14.54	12.92	12.03	11.46	11.07	10.79	10.57	10.39
7	.100	3.59	3.26	3.07	2.96	2.88	2.83	2.78	2.75	2.72
	.050	5.59	4.74	4.35	4.12	3.97	3.87	3.79	3.73	3.68
	.025	8.07	6.54	5.89	5.52	5.29	5.12	4.99	4.90	4.82
	.010	12.25	9.55	8.45	7.85	7.46	7.19	6.99	6.84	6.72
	.005	16.24	12.40	10.88	10.05	9.52	9.16	8.89	8.68	8.51

F_α

Numerator d.f.											
10	*12*	*15*	*20*	*24*	*30*	*40*	*60*	*120*	∞	α	d.f.
60.19	60.71	61.22	61.74	62.00	62.26	62.53	62.79	63.06	63.33	.100	1
241.9	243.9	245.9	248.0	249.1	250.1	251.1	252.2	253.3	254.3	.050	
968.6	976.7	984.9	993.1	997.2	1001	1006	1010	1014	1018	.025	
6056	6106	6157	6209	6235	6261	6287	6313	6339	6366	.010	
24224	24426	24630	24836	24940	25044	25148	25253	25359	25465	.005	
9.39	9.41	9.42	9.44	9.45	9.46	9.47	9.47	9.48	9.49	.100	2
19.40	19.41	19.43	19.45	19.45	19.46	19.47	19.48	19.49	19.50	.050	
39.40	39.41	39.43	39.45	39.46	39.46	39.47	39.48	39.49	39.50	.025	
99.40	99.42	99.43	99.45	99.46	99.47	99.47	99.48	99.49	99.50	.010	
199.4	199.4	199.4	199.4	199.5	199.5	199.5	199.5	199.5	199.5	.005	
5.23	5.22	5.20	5.18	5.18	5.17	5.16	5.15	5.14	5.13	.100	3
8.79	8.74	8.70	8.66	8.64	8.62	8.59	8.57	8.55	8.53	.050	
14.42	14.34	14.25	14.17	14.12	14.08	14.04	13.99	13.95	13.90	.025	
27.23	27.05	26.87	26.69	26.60	26.50	26.41	26.32	26.22	26.13	.010	
43.69	43.39	43.08	42.78	42.62	42.47	42.31	42.15	41.99	41.83	.005	
3.92	3.90	3.87	3.84	3.83	3.82	3.80	3.79	3.78	3.76	.100	4
5.96	5.91	5.86	5.80	5.77	5.75	5.72	5.69	5.66	5.63	.050	
8.84	8.75	8.66	8.56	8.51	8.46	8.41	8.36	8.31	8.26	.025	
14.55	14.37	14.20	14.02	13.93	13.84	13.75	13.65	13.56	13.46	.010	
20.97	20.70	20.44	20.17	20.03	19.89	19.75	19.61	19.47	19.32	.005	
3.30	3.27	3.24	3.21	3.19	3.17	3.16	3.14	3.12	3.10	.100	5
4.74	4.68	4.62	4.56	4.53	4.50	4.46	4.43	4.40	4.36	.050	
6.62	6.52	6.43	6.33	6.28	6.23	6.18	6.12	6.07	6.02	.025	
10.05	9.89	9.72	9.55	9.47	9.38	9.29	9.20	9.11	9.02	.010	
13.62	13.38	13.15	12.90	12.78	12.66	12.53	12.40	12.27	12.14	.005	
2.94	2.90	2.87	2.84	2.82	2.80	2.78	2.76	2.74	2.72	.100	6
4.06	4.00	3.94	3.87	3.84	3.81	3.77	3.74	3.70	3.67	.050	
5.46	5.37	5.27	5.17	5.12	5.07	5.01	4.96	4.90	4.85	.025	
7.87	7.72	7.56	7.40	7.31	7.23	7.14	7.06	6.97	6.88	.010	
10.25	10.03	9.81	9.59	9.47	9.36	9.24	9.12	9.00	8.88	.005	
2.70	2.67	2.63	2.59	2.58	2.56	2.54	2.51	2.49	2.47	.100	7
3.64	3.57	3.51	3.44	3.41	3.38	3.34	3.30	3.27	3.23	.050	
4.76	4.67	4.57	4.47	4.42	4.36	4.31	4.25	4.20	4.14	.025	
6.62	6.47	6.31	6.16	6.07	5.99	5.91	5.82	5.74	5.65	.010	
8.38	8.18	7.97	7.75	7.65	7.53	7.42	7.31	7.19	7.08	.005	

F_{α}

Denominator d.f.	Numerator d.f.									
	α	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
8	.100	3.46	3.11	2.92	2.81	2.73	2.67	2.62	2.59	2.56
	.050	5.32	4.46	4.07	3.84	3.69	3.58	3.50	3.44	3.39
	.025	7.57	6.06	5.42	5.05	4.82	4.65	4.53	4.43	4.36
	.010	11.26	8.65	7.59	7.01	6.63	6.37	6.18	6.03	5.91
	.005	14.69	11.04	9.60	8.81	8.30	7.95	7.69	7.50	7.34
9	.100	3.36	3.01	2.81	2.69	2.61	2.55	2.51	2.47	2.44
	.050	5.12	4.26	3.86	3.63	3.48	3.37	3.29	3.23	3.18
	.025	7.21	5.71	5.08	4.72	4.48	4.32	4.20	4.10	4.03
	.010	10.56	8.02	6.99	6.42	6.06	5.80	5.61	5.47	5.35
	.005	13.61	10.11	8.72	7.96	7.47	7.13	6.88	6.69	6.54
10	.100	3.29	2.92	2.73	2.61	2.52	2.46	2.41	2.38	2.35
	.050	4.96	4.10	3.71	3.48	3.33	3.22	3.14	3.07	3.02
	.025	6.94	5.46	4.83	4.47	4.24	4.07	3.95	3.85	3.78
	.010	10.04	7.56	6.55	5.99	5.64	5.39	5.20	5.06	4.94
	.005	12.83	9.43	8.08	7.34	6.87	6.54	6.30	6.12	5.97
11	.100	3.23	2.86	2.66	2.54	2.45	2.39	2.34	2.30	2.27
	.050	4.84	3.98	3.59	3.36	3.20	3.09	3.01	2.95	2.90
	.025	6.72	5.26	4.63	4.28	4.04	3.88	3.76	3.66	3.59
	.010	9.65	7.21	6.22	5.67	5.32	5.07	4.89	4.74	4.63
	.005	12.23	8.91	7.60	6.88	6.42	6.10	5.86	5.68	5.54
12	.100	3.18	2.81	2.61	2.48	2.39	2.33	2.28	2.24	2.21
	.050	4.75	3.89	3.49	3.26	3.11	3.00	2.91	2.85	2.80
	.025	6.55	5.10	4.47	4.12	3.89	3.73	3.61	3.51	3.44
	.010	9.33	6.93	5.95	5.41	5.06	4.82	4.64	4.50	4.39
	.005	11.75	8.51	7.23	6.52	6.07	5.76	5.52	5.35	5.20
13	.100	3.14	2.76	2.56	2.43	2.35	2.28	2.23	2.20	2.16
	.050	4.67	3.81	3.41	3.18	3.03	2.92	2.83	2.77	2.71
	.025	6.41	4.97	4.35	4.00	3.77	3.60	3.48	3.39	3.31
	.010	9.07	6.70	5.74	5.21	4.86	4.62	4.44	4.30	4.19
	.005	11.37	8.19	6.93	6.23	5.79	5.48	5.25	5.08	4.94
14	.100	3.10	2.73	2.52	2.39	2.31	2.24	2.19	2.15	2.12
	.050	4.60	3.74	3.34	3.11	2.96	2.85	2.76	2.70	2.65
	.025	6.30	4.86	4.24	3.89	3.66	3.50	3.38	3.29	3.21
	.010	8.86	6.51	5.56	5.04	4.69	4.46	4.28	4.14	4.03
	.005	11.06	7.92	6.68	6.00	5.56	5.26	5.03	4.86	4.72

F_α

Numerator d.f.											
10	*12*	*15*	*20*	*24*	*30*	*40*	*60*	*120*	∞	α	d.f.
2.54	2.50	2.46	2.42	2.40	2.38	2.36	2.34	2.32	2.29	.100	8
3.35	3.28	3.22	3.15	3.12	3.08	3.04	3.01	2.97	2.93	.050	
4.30	4.20	4.10	4.00	3.95	3.89	3.84	3.78	3.73	3.67	.025	
5.81	5.67	5.52	5.36	5.28	5.20	5.12	5.03	4.95	4.86	.010	
7.21	7.01	6.81	6.61	6.50	6.40	6.29	6.18	6.06	5.95	.005	
2.42	2.38	2.34	2.30	2.28	2.25	2.23	2.21	2.18	2.16	.100	9
3.14	3.07	3.01	2.94	2.90	2.86	2.83	2.79	2.75	2.71	.050	
3.96	3.87	3.77	3.67	3.61	3.56	3.51	3.45	3.39	3.33	.025	
5.26	5.11	4.96	4.81	4.73	4.65	4.57	4.48	4.40	4.31	.010	
6.42	6.23	6.03	5.83	5.73	5.62	5.52	5.41	5.30	5.19	.005	
2.32	2.28	2.24	2.20	2.18	2.16	2.13	2.11	2.08	2.06	.100	10
2.98	2.91	2.85	2.74	2.77	2.70	2.66	2.62	2.58	2.54	.050	
3.72	3.62	3.52	3.42	3.37	3.31	3.26	3.20	3.14	3.08	.025	
4.85	4.71	4.56	4.41	4.33	4.25	4.17	4.08	4.00	3.91	.010	
5.85	5.66	5.47	5.27	5.17	5.07	4.97	4.86	4.75	4.64	.005	
2.25	2.21	2.17	2.12	2.10	2.08	2.05	2.03	2.00	1.97	.100	11
2.85	2.79	2.72	2.65	2.61	2.57	2.53	2.49	2.45	2.40	.050	
3.53	3.43	3.33	3.23	3.17	3.12	3.06	3.00	2.94	2.88	.025	
4.54	4.40	4.25	4.10	4.02	3.94	3.86	3.78	3.69	3.60	.010	
5.42	5.24	5.05	4.86	4.76	4.65	4.55	4.44	4.34	4.23	.005	
2.19	2.15	2.10	2.06	2.04	2.01	1.99	1.96	1.93	1.90	.100	12
2.75	2.69	2.62	2.54	2.51	2.47	2.43	2.38	2.34	2.30	.050	
3.37	3.28	3.18	3.07	3.02	2.96	2.91	2.85	2.79	2.72	.025	
4.30	4.16	4.01	3.86	3.78	3.70	3.62	3.54	3.45	3.36	.010	
5.09	4.91	4.72	4.53	4.43	4.33	4.23	4.12	4.01	3.90	.005	
2.14	2.10	2.05	2.01	1.98	1.96	1.93	1.90	1.88	1.85	.100	13
2.67	2.60	2.53	2.46	2.42	2.38	2.34	2.30	2.25	2.21	.050	
3.25	3.15	3.05	2.95	2.89	2.84	2.78	2.72	2.66	2.60	.025	
4.10	3.96	3.82	3.66	3.59	3.51	3.43	3.34	3.25	3.17	.010	
4.82	4.64	4.46	4.27	4.17	4.07	3.97	3.87	3.76	3.65	.005	
2.10	2.05	2.01	1.96	1.94	1.91	1.89	1.86	1.83	1.80	.100	14
2.60	2.53	2.46	2.39	2.35	2.31	2.27	2.22	2.18	2.13	.050	
3.15	3.05	2.95	2.84	2.79	2.73	2.67	2.61	2.55	2.49	.025	
3.94	3.80	3.66	3.51	3.43	3.35	3.27	3.18	3.09	3.00	.010	
4.60	4.43	4.25	4.06	3.96	3.86	3.76	3.66	3.55	3.44	.005	

F_{α}

Denominator d.f.	α	Numerator d.f. 1	2	3	4	5	6	7	8	9
15	.100	3.07	2.70	2.49	2.36	2.27	2.21	2.16	2.12	2.09
	.050	4.54	3.68	3.29	3.06	2.90	2.79	2.71	2.64	2.59
	.025	6.20	4.77	4.15	3.80	3.58	3.41	3.29	3.20	3.12
	.010	8.68	6.36	5.42	4.89	4.56	4.32	4.14	4.00	3.89
	.005	10.80	7.70	6.48	5.80	5.37	5.07	4.85	4.67	4.54
16	.100	3.05	2.67	2.46	2.33	2.24	2.18	2.13	2.09	2.06
	.050	4.49	3.63	3.24	3.01	2.85	2.74	2.66	2.59	2.54
	.025	6.12	4.69	4.08	3.73	3.50	3.34	3.22	3.12	3.05
	.010	8.53	6.23	5.29	4.77	4.44	4.20	4.03	3.89	3.78
	.005	10.58	7.51	6.30	5.64	5.21	4.91	4.69	4.52	4.38
17	.100	3.03	2.64	2.44	2.31	2.22	2.15	2.10	2.06	2.03
	.050	4.45	3.59	3.20	2.96	2.81	2.70	2.61	2.55	2.49
	.025	6.04	4.62	4.01	3.66	3.44	3.28	3.16	3.06	2.98
	.010	8.40	6.11	5.18	4.67	4.34	4.10	3.93	3.79	3.68
	.005	10.38	7.35	6.16	5.50	5.07	4.78	4.56	4.39	4.25
18	.100	3.01	2.62	2.42	2.29	2.20	2.13	2.08	2.04	2.00
	.050	4.41	3.55	3.16	2.93	2.77	2.66	2.58	2.51	2.46
	.025	5.98	4.56	3.95	3.61	3.38	3.22	3.10	3.01	2.93
	.010	8.29	6.01	5.09	4.58	4.25	4.01	3.84	3.71	3.60
	.005	10.22	7.21	6.03	5.37	4.96	4.66	4.44	4.28	4.14
19	.100	2.99	2.61	2.40	2.27	2.18	2.11	2.06	2.02	1.98
	.050	4.38	3.52	3.13	2.90	2.74	2.63	2.54	2.48	2.42
	.025	5.92	4.51	3.90	3.56	3.33	3.17	3.05	2.96	2.88
	.010	8.18	5.93	5.01	4.50	4.17	3.94	3.77	3.63	3.52
	.005	10.07	7.09	5.92	5.27	4.85	4.56	4.34	4.18	4.04
20	.100	2.97	2.59	2.38	2.25	2.16	2.09	2.04	2.00	1.96
	.050	4.35	3.49	3.10	2.87	2.71	2.60	2.51	2.45	2.39
	.025	5.87	4.46	3.86	3.51	3.29	3.13	3.01	2.91	2.84
	.010	8.10	5.85	4.94	4.43	4.10	3.87	3.70	3.56	3.46
	.005	9.94	6.99	5.82	5.17	4.76	4.47	4.26	4.09	3.96
21	.100	2.96	2.57	2.36	2.23	2.14	2.08	2.02	1.98	1.95
	.050	4.32	3.47	3.07	2.84	2.68	2.57	2.49	2.42	2.37
	.025	5.83	4.42	3.82	3.48	3.25	3.09	2.97	2.87	2.80
	.010	8.02	5.78	4.87	4.37	4.04	3.81	3.64	3.51	3.40
	.005	9.83	6.89	5.73	5.09	4.68	4.39	4.18	4.01	3.88

F_α

Numerator d.f.											
10	12	15	20	24	30	40	60	120	∞	α	d.f.
2.06	2.02	1.97	1.92	1.90	1.87	1.85	1.82	1.79	1.76	.100	15
2.54	2.48	2.40	2.33	2.29	2.25	2.20	2.16	2.11	2.07	.050	
3.06	2.96	2.86	2.76	2.70	2.64	2.59	2.52	2.46	2.40	.025	
3.80	3.67	3.52	3.37	3.29	3.21	3.13	3.05	2.96	2.87	.010	
4.42	4.25	4.07	3.88	3.79	3.69	3.58	3.48	3.37	3.26	.005	
2.03	1.99	1.94	1.89	1.87	1.84	1.81	1.78	1.75	1.72	.100	16
2.49	2.42	2.35	2.28	2.24	2.19	2.15	2.11	2.06	2.01	.050	
2.99	2.89	2.79	2.68	2.63	2.57	2.51	2.45	2.38	2.32	.025	
3.69	3.55	3.41	3.26	3.18	3.10	3.02	2.93	2.84	2.75	.010	
4.27	4.10	3.92	3.73	3.64	3.54	3.44	3.33	3.22	3.11	.005	
2.00	1.96	1.91	1.86	1.84	1.81	1.78	1.75	1.72	1.69	.100	17
2.45	2.38	2.31	2.23	2.19	2.15	2.10	2.06	2.01	1.96	.050	
2.92	2.82	2.72	2.62	2.56	2.50	2.44	2.38	2.32	2.25	.025	
3.59	3.46	3.31	3.16	3.08	3.00	2.92	2.83	2.75	2.65	.010	
4.14	3.97	3.79	3.61	3.51	3.41	3.31	3.21	3.10	2.98	.005	
1.98	1.93	1.89	1.84	1.81	1.78	1.75	1.72	1.69	1.66	.100	18
2.41	2.34	2.27	2.19	2.15	2.11	2.06	2.02	1.97	1.92	.050	
2.87	2.77	2.67	2.56	2.50	2.44	2.38	2.32	2.26	2.19	.025	
3.51	3.37	3.23	3.08	3.00	2.92	2.84	2.75	2.66	2.57	.010	
4.03	3.86	3.68	3.50	3.40	3.30	3.20	3.10	2.99	2.87	.005	
1.96	1.91	1.86	1.81	1.79	1.76	1.73	1.70	1.67	1.63	.100	19
2.38	2.31	2.23	2.16	2.11	2.07	2.03	1.98	1.93	1.88	.050	
2.82	2.72	2.62	2.51	2.45	2.39	2.33	2.27	2.20	2.13	.025	
3.43	3.30	3.15	3.00	2.92	2.84	2.76	2.67	2.58	2.49	.010	
3.93	3.76	3.59	3.40	3.31	3.21	3.11	3.00	2.89	2.78	.005	
1.94	1.89	1.84	1.79	1.77	1.74	1.71	1.68	1.64	1.61	.100	20
2.35	2.28	2.20	2.12	2.08	2.04	1.99	1.95	1.90	1.84	.050	
2.77	2.68	2.57	2.46	2.41	2.35	2.29	2.22	2.16	2.09	.025	
3.37	3.23	3.09	2.94	2.86	2.78	2.69	2.61	2.52	2.42	.010	
3.85	3.68	3.50	3.32	3.22	3.12	3.02	2.92	2.81	2.69	.005	
1.92	1.87	1.83	1.78	1.75	1.72	1.69	1.66	1.62	1.59	.100	21
2.32	2.25	2.18	2.10	2.05	2.01	1.96	1.92	1.87	1.81	.050	
2.73	2.64	2.53	2.42	2.37	2.31	2.25	2.18	2.11	2.04	.025	
3.31	3.17	3.03	2.88	2.80	2.72	2.64	2.55	2.46	2.36	.010	
3.77	3.60	3.43	3.24	3.15	3.05	2.95	2.84	2.73	2.61	.005	