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**COMPOSTING OF HIGH MOISTURE DAIRY MANURE  
USING SAWDUST OR MIXED PAPER AS AMENDMENTS  
AND WOOD CHIPS AS THE BULKING AGENT.**

**MD. SHAHJAHAN MOLLAH**

**2002**

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USING SAWDUST OR MIXED PAPER AS AMENDMENTS  
AND WOOD CHIPS AS THE BULKING AGENT.**

A thesis  
presented in partial fulfillment of the requirements  
for the degree of

**MASTER OF TECHNOLOGY**

in

**ENVIRONMENTAL ENGINEERING**

at the

Institute of Technology and Engineering  
College of Science  
**Massey University**  
Palmerston North  
**New Zealand**

**BY**

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**2002**

## ABSTRACT

The agricultural industry in New Zealand is a major source of waste generation and about 84% of the country's point source pollution comes from dairy sector alone. Dairy farm effluent in New Zealand is most commonly treated via waste stabilization ponds. Two-pond systems which are frequently used, are not sufficient to make the dairy shed effluent suitable for discharging to surface water, thus there is a need for investigation and development of treatment/disposal technologies, especially where land treatment is not a practical option. Composting is a process whereby the heat that is liberated from the decomposition of organics drives the evaporation of water. By reducing the large amount of water in the slurry, its mass, bulk weight & volume through composting, there is a large potential to reduce associated transportation and handling costs of disposal as well as minimising the area of land required for manure application. Composting can further reduce the risk of pollution from runoff, odour, and nitrate contamination of ground water.

A passively aerated composting system was used to treat high moisture (90%) dairy manure slurry. Both sawdust and mixed paper were investigated as amendments with wood chips as the bulking agent. Two identical piles (1.2m×1.2m×1.2m) for the sawdust investigation and another two for the mixed paper experiment were established. Passive aeration was achieved with three horizontal aeration pipes in the base of each pile. The piles were monitored for about 70 days for all the experiments.

During the active phase of composting, piles reached above 60°C and thermophilic temperatures were sustained for more than three weeks. The importance of pile cooling because of excessive wind flow was demonstrated suggesting the advisability of a wind barrier to protect piles.

Moisture content in the piles decreased over the period of study. Initial moisture content varied from 67% to 71% but diminished to between 47% and 58% by the

conclusions of the experiments. Results of these studies suggest that composting can remove water by virtue of the biologically produced heat.

The results of this study also suggest that the amount of heat energy generated from composting depends on the amount of volatile solids degraded. Energy rich feed materials were shown to be converted to energy poor materials due to reduced volatile solids degradation and energy poor feed materials emerged as energy rich due to the greater amount of volatile solids degradation. In this study from 47.2% to 76% of produced heat was lost as latent heat through convective (evaporative drying).

From the comparison of results using two different amendments, mixed paper was found better than sawdust as an amendment in terms of biodegradability, heat development, heat accumulation, evaporative drying, moisture removal, volume reduction and weight reduction.

The results of this study also indicated that the required extent of total coliforms destruction was not achieved within the period of composting using the materials and method undertaken. A longer maturation or curing phase may be helpful in achieving the recommended level of total coliform inactivation.

## TECHNICAL ABBREVIATIONS

%	Percentile values unless otherwise stated will be expressed as weight per unit weight
Amb Air T	Ambient air temperature
ASH	Inert fraction after combustion (kg)
BVS	Biodegradable Volatile Solids
BW	Bulk Weight (kg / m <sup>3</sup> )
C	Carbon
C:N	Carbon to Nitrogen ratio
D sa	Bulk Density (sawdust and manure) Or Combined bulk density of substrate and amendment.
DGASO	Dry exhaust gas from composting process
DM	Dry matter expressed as % (w/w)
Ds	Bulk Density (manure and sawdust or manure plus mixed paper)
Dw	Density of water at ambient conditions
E	Energy ratio (calories / g.water); also exponential symbol ( Ratio of biological heat released from oxidation of organics to the weight of water present in the substrate.
EI	Experiment I
EII	Experiment II
FAS	Free air space (% v/v), The ratio of gas volume to total volume of material.
Fb	Free air space (FAS) within interstices of bulking agent
Fm	Free air space (FAS) within interstices of final mixture of substrate, amendment and bulking agent.
G sa	Specific Gravity (sawdust and manure) or Combined Sp. Gravity of substrate and amendment.
Gs	Specific gravity of substrate (manure).
HORG	Heat of combustion of substrates, kg/g. VS)
HSWVI	Sensible heat with water vapour (input air) (k cal)
L	Distance in mm from floor of compost pile; also used to indicate Litre.
Mbs	Volumetric mixing ratio
Mbs	Volumetric Mixing Ratio (manure and sawdust to wood chips or manure and mixed paper to wood chips).
MC	Moisture Content (% w/w). Also expressed as g/g
MIC	Microns (10 <sup>-6</sup> M)
Mmb	Factor for volume increase after mixing
MPN	Most Probable Number (index per g dry solids)
N	Nitrogen
N.paper	Un-used newsprint paper
NBVS	Non-biodegradable volatile solids
Off paper	Office Paper
P-1	Compost Pile number 1
P-2	Compost pile number 2
PAIR	Atmospheric pressure (m m Hg)
PAN	Particles < 250 microns collecting in fractionation pan
PV	Actual vapour pressure of water
PVS	Saturation vapour pressure
RHAIR	Relative humidity (air), a fraction of the saturated vapour pressure
S sa	Solid Contact (sawdust and manure) or Combined solid content of substrate and amendment.
Ss	Solids (total) Content of substrate (manure).
S <sub>Sm(m)</sub>	Maximum total solids content achievable (manure and sawdust or manure and mixed paper)
Ta	Absolute Temperature (°K)
TC	Total Carbon (% DW)
TN	Total Nitrogen (% DW)
TS	Total Solids (kg)
VS	Volatile solids (kg). May also be expressed as % DM
W	Specific humidity of inlet and outlet gases, g-water/g-dry air. Also water ratio in Haug equation.
W	Water Ratio (g. water/ g. BVS)
WAT	Water content (g) in raw compost mixture
WATSO	Water component in final compost
WATVI	Water vapour associated with input air
WATVO	Water vapour associated with output air

### AMENDMENTS

READER'S SHOULD NOTE THE FOLLOWING MINOR CORRECTIONS TO THE PAGES AS INDICATED.

PAGE 112: PARA 4: LAST LINE:- READ "AREAS UNDER CURVES" & NOT "AREAS".  
 PAGE 128: FIG. 5. 17:- FOR "TOTAL WEIGHT" READ: 138.00; & 87.34.  
 PAGE 128: FIG 5. 18:- FOR "TOTAL WEIGHT" READ: 134.76 & 46.03.  
 PAGE 129: FIG. 5.19:- FOR "TOTAL WEIGHT" READ: 128.07 & 51.38.  
 PAGE 129: FIG 5. 20:- FOR "TOTAL WEIGHT" READ: 134.75 & 58.73.  
 PAGE 131: PARA 1: LINE 1:- READ "INITIAL TOTAL COLIFORM COUNTS" & LATER, " FINAL TOTAL COLIFORM COUNTS" AND NOT, "TOTAL INITIAL COLIFORM COUNTS" & " TOTAL FINAL COLIFORM COUNTS" RESPECTIVELY.  
 PAGE 141: SECTION 6.4: PARA 1: LINE 5:- READ "HEAT LOSSES" & NOT "HEAT LOSS".  
 PAGE 141: " PARA 4:-LINE 2:- READ "TABLES WERE DEVELOPED" NOT "TABLES WAS DEVELOPED".

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## CHAPTER-1

### GENERAL INTRODUCTION

#### 1.1 DAIRY FARMING IN NEW ZEALAND

The rapid development of the dairy industry in New Zealand started in 1882 with the successful demonstration of refrigerated transportation to distant markets of perishable food products on ocean steamers. The remarkable development of the dairy industry in New Zealand is mainly due to a natural temperate climate with plenty of rainfall and sunshine, the application of science in the manufacture of dairy products and the progressive spirit of the dairy-farming community. Also, the pasture-growing period in New Zealand is from 10 months to possibly 12 months (in the far north) whereas it is only 6 months in competing dairying countries in Europe and America (Duncan, 1933). These natural advantages have led to the development of a strong pastoral-based dairy industry.

The total stock of dairy cattle in 1962 was 3.1 million including 2.0 million cattle in milk production producing an average of 2,728 kg of milk per head (or 128 kg milkfat/head). By 1975, the number of cattle in milk production had risen to 2.1 million and an average yield was 6,071 litres of milk per head (135 kg milkfat/head). In 1983, although the number of cattle remained 2.1 million, the average milk yield was 3,240 kg per head (149 kg milkfat/head). Thus 28% more milk and 19% more yield per head obtained in 1983 than that of 1962 (Rae *et al.*, 1985). This progressive trend in terms of milk production and average yield of milk fat per head has been observed up to the present time (Fig.1.1 and Table 1.1). Table 1.1 shows for the period from 1974 to 2000 that the total number of cattle, the total milk processed, average yield of milk fat per head have been showing an upward trend over the years.

Table 1.1 also shows that the increasing number of cattle is reflected in an increase in the stocking rate (number of cattle/ha) of grazing. The stocking rate is highest in the South Island at 3 cattle/hectare in South Canterbury, 2.9 cattle/hectare in North Canterbury and Otago. In the North Island, stocking rate is 2.8 cattle/hectare in South



Auckland, Bay of Plenty, Taranaki, Wellington and 2.9 cattle/hectare is for the East Coast. Although the Auckland region is the main milk production region (43% of the national total) and the next biggest milk-producing region is Taranaki and Wellington (26%); in recent years production in the South Island has grown at above the national average. In 1999-2000 the production in the South Island was 22% of the national total which is 72% more than production in 1994-95. In terms of milk production New Zealand is the 4<sup>th</sup> highest producing country in the world but in terms of milk product manufacturing New Zealand is the number one country in the world with 97% of total production being used in manufacturing by-products (Dairy statistics, 1999-2000).

Table 1.1 Summary of dairy cattle, milk production, herd size, stocking rate.

Season	Total cattle	Herds	Herd size (av)	Milk Processed. (million litres)	Milksolids Processed (million kg)	Milk fat/cattle(av) in kg	Effective hectares (av)	Cattle/ha. (av)
74/75	2,079,886	18,540	112	5,222	425	128	-	-
75/76	2,091,950	18,442	113	5,403	466	137	-	-
76/77	2,074,443	17,924	116	5,775	479	143	-	-
77/78	2,052,624	17,363	118	5,238	437	131	-	-
78/79	2,039,902	16,907	121	5,655	477	142	-	-
79/80	2,045,808	16,506	124	5,997	506	151	-	-
80/81	2,027,096	16,089	126	5,868	491	147	-	-
81/82	2,060,898	15,821	130	5,979	491	144	63	2.1
82/83	2,128,199	15,816	135	6,096	505	143	64	2.2
83/84	2,209,725	15,932	139	6,733	564	154	65	2.2
84/85	2,280,273	15,881	144	6,965	578	152	64	2.4
85/86	2,321,012	15,753	147	7,326	609	157	64	2.4
86/87	2,281,894	15,315	149	6,385	524	138	65	2.4
87/88	2,236,290	14,818	151	6,921	579	154	65	2.4
88/89	2,269,073	14,744	154	6,533	541	143	66	2.4
89/90	2,313,822	14,595	159	6,868	572	147	67	2.4
90/91	2,402,145	14,685	164	7,077	599	148	70	2.4
91/92	2,438,641	14,452	169	7,454	637	157	-	-
92/93	2,603,049	14,458	180	7,629	651	148	74	2.5
93/94	2,736,452	14,597	188	8,603	736	160	77	2.5
94/95	2,830,977	14,649	193	8,633	733	156	80	2.5
95/96	2,935,759	14,736	199	9,325	788	163	82	2.5
96/97	3,064,523	14,741	208	10,339	880	173	86	2.5
97/98	3,222,591	14,673	220	10,651	891	168	87	2.6
98/99	3,289,319	14,362	229	10,168	850	147	91	2.7
99/00	3,269,362	13,861	236	11,480	970	165	93	2.7

Source: Dairy statistics (1999-2000).

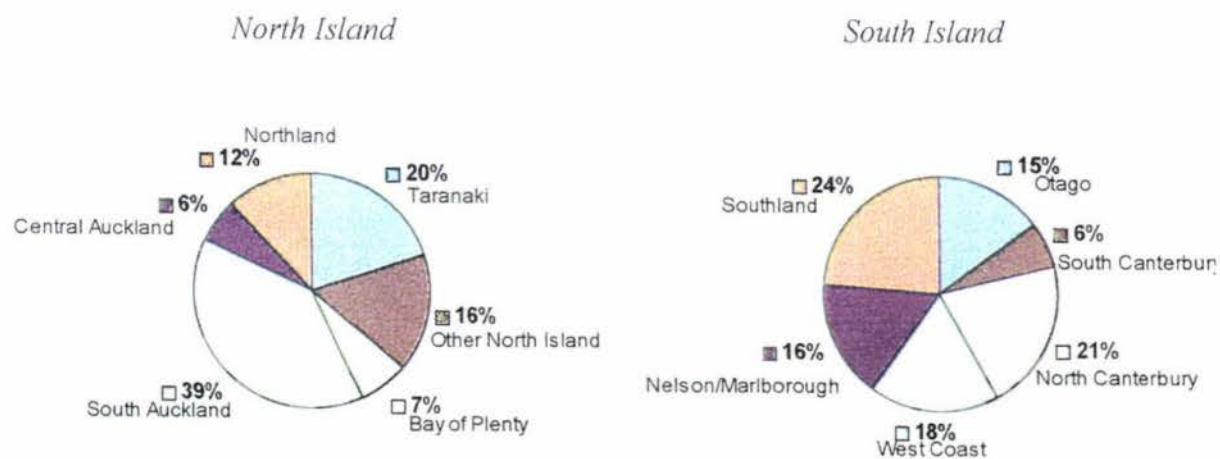


Fig. 1.1 Regional Distribution of Dairy Farms, 1999-2000.  
(Dairy Statistics, 1999-2000)

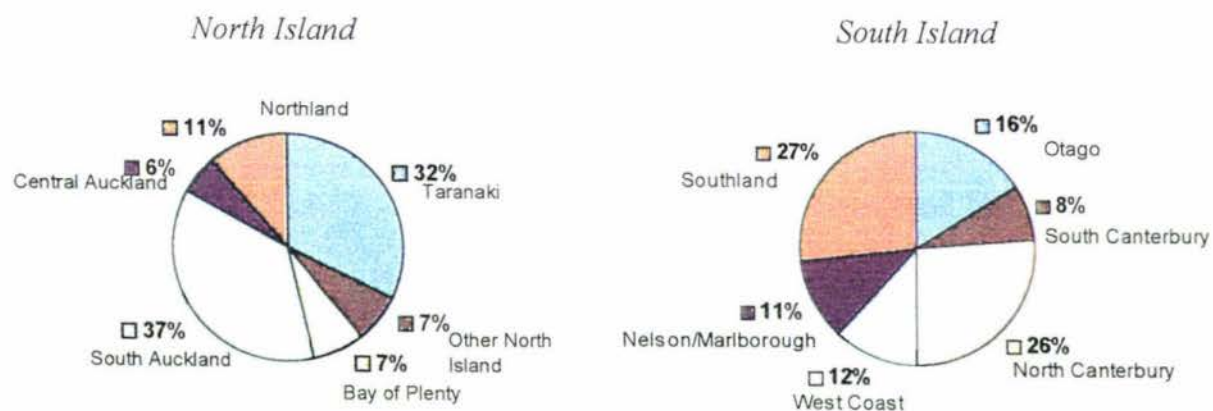


Fig. 1.2 Regional Distribution of Dairy Cattle in 1999-2000.  
(Dairy Statistics, 1999-2000)

The regional distribution of dairy farm and dairy cattle in the North Island and the South Island are shown in Figs.1.1 and 1.2 above. The distribution of dairy farms is

highest (39%) in South Auckland (Auckland, Waikato and Bay of Plenty) and Taranaki (20%) is the next in the North Island. Southland (24%) and North Canterbury (21%) are the main dairy farm regions in the South Island. The population of dairy cattle is also highest in South Auckland (37%) and Taranaki (32%) in the North Island. Southland (27%) and North Canterbury (26%) are also the main regions of dairy cattle in the South Island. Thus, South Auckland, Taranaki, Southland and North Canterbury are the potential regions of greatest productivity in terms of dairy herd size. Table 1.2. shows the trend in volume and value of New Zealand dairy exports in the last five years and it can be seen that the total volume and value of dairy exports are increasing annually.

Table 1.2 Total volume (000 tonnes) and value (NZ\$Million) for dairy exports.

Season	Skimmilk power	Wholemilk powder	Cheese	Casein	Butter	AMF	Other	Total
Export volume (000 tonnes)								
95/96	127	278	173	72	193	44	120	1,007
96/97	183	347	236	83	250	64	190	1,353
97/98	166	359	232	94	232	82	181	1,346
98/99	174	362	240	103	188	89	202	1,358
99/00	172	393	249	106	249	87	191	1,447
Export value ( NZ\$ Millions)								
95/96	425.7	942.6	617.4	557.1	703.7	155.6	390.1	3,792.2
96/97	545.8	1,051.5	838.5	569.4	752.4	163.1	404.9	4,325.6
97/98	486.2	1,126.2	892.5	651.7	787.3	233.1	441.3	4,618.3
98/99	481.7	1,199.9	983.4	763.0	677.0	303.9	528.3	4,937.2
99/00	509.5	1,269.9	987.4	802.6	736.5	259.8	536.9	5,102.6

Source:Dairy Facts and Figures (1999-2000).

The average dairy farm cash revenue has increased from \$159,750 in 1990-91 to \$268,894 in 1999-2000 and during this time the number of cattle, effective hectares and variable expenses (81%) have also increased. Average farm profit before tax increased by 76% from \$38,554 to \$68,011 between 1998-99 and 1999-2000 ( Economic Survey,1999-2000).

From the above information and discussion it has become evident that the dairy sector in New Zealand has been playing a vital role in foreign currency earnings (Table 1.2) and the economic development of the country. Therefore, for the betterment of people and to safeguard the life support capacity of air, water, soil and ecosystems, the

dairy industry sector must be kept free from any environmental hazard and obstacle that may cause negative impacts on the natural and physical resources of the country.

## 1.2 LEGISLATION

In New Zealand, The Resource Management Act 1991 received its Royal Assent from the Governor General on 22 July 1991. The act brought together the laws governing New Zealand's land, air and water resources. The act established a common purpose and framework for dealing with the effects of disposal activities on the environment. The purpose of the Resources Management Act is sustainable management of New Zealand's natural and physical resources. The definition of sustainable management described in the Act reads as:

“ Managing the use, development and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic and cultural wellbeing, and for their health and safety while-

- (a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations;
- (b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems;
- (c) avoiding, remedying, or mitigating any adverse effects of activities on the environment.”

One of the key changes the Act introduced, was to focus decisions on the effects of activities rather than the activities themselves. This was expected to lead to tighter and more effective targeting of regulatory controls. Regional councils are the consent authority for all activities involving discharges to water, land and air. Section 15 of the Act requires every person who discharges a contaminant into water to obtain a discharge permit from the regional council. However, provision was made that where, prior to 1 October 1991, any activity discharging contaminants into or onto land did not require any license or authorization to do so, those activities were exempted from the requirement to obtain a discharge permits to discharge contaminants to land for three years or sooner if a regional plan provided otherwise. Thus, from 1991 permits to discharge contaminated materials became universally applicable.

The type of activities related with discharge consent are divided into five categories permitted, controlled, discretionary, non-complying and prohibited. The permitted activities are allowed as of right, controlled activities are non-notified which are allowed by delegated staff with conditions, discretionary activities are notified/non-notified and are allowed/declined by delegated staff, non-complying activities are notified and granted/declined by the council and prohibited activities are never permitted. For example, if ponds are located and operated to avoid odour and spray drift and if their sealing permeability does not exceed  $10^{-9}$ m/sec then land application (25mm/application) of dairy effluent at a loading rate 150kg-N/ha/yr is a permitted activity. But if the treatment systems do not comply with the above conditions or if the effluent is discharged to surface water then they will be categorized as discretionary activity. But that is not always automatically applicable because the notification requirements and decision on consent are determined on a case by case basis according to Part-VI of RMA (Environment Waikato, 1994). Every regional council in New Zealand has different guidelines based on scientific criteria about concentrations or numerical values of different parameters of various waste. Heatley (1996) prepared a summary of different regional council and unitary authority requirements for discharges of dairyshed and piggery wastewater.

It is expected that public concern about odour potential following land and surface water application of dairy waste would result in promoting waste disposal systems in an effective manner and that has been the case The Resource Management Act 1991 has been a turning point towards the implementation of new technologies for dealing with waste in New Zealand.

### **1.3 AGRICULTURAL WASTES AND IMPACTS IN NZ**

“If you look at what you feed cattle, about one-third becomes meat or milk, the other two-thirds is manure.”(Glenn,1998). The agricultural industry in New Zealand itself is a major source of waste generation and the bulk of it comes from animals. Waste produced from agricultural crops has not been considered in this discussion. Animal waste is a highly variable material with its properties dependent on animal age, species, type of ration, production practices and environment. Animal waste is commonly referred

to as manure with added wash down water, bedding, soil, hair or spilled feed (Vanderholm,1984). A study was carried out for 10 days on 152 Friesian cattle during milking period in Palmerston North, New Zealand in January 1998. Undiluted dairy manure was collected and it was found that on average 2.0 kg manure/head/day is deposited in the holding area. This represented 3.7% of the average daily bovine manure production. The collected material comprised 60% faeces and 40% urine and the moisture content of that slurry was 92.6% (Mason & Reijnen, 1999).

This volume varied from 30-70 litres/head/day if wash water is included (Dakers,1979). For most dairies about 2 hrs/day and approximately 8% of the total manure (may vary & depends on holding time, amount of stress on the cattle) will be found in farm dairy wastes (Vanderholm,1984) but Drysdale (1977) suggested that 3.6% of total daily production of manure can be collected on cowshed yard, which is very close to the figure (3.7%) given by Mason & Reijnen (1999). Composition of the manure is neither liquid nor solid but a plastic slurry which is difficult to handle. Dickinson (1974) reported that "the amount excreta (dung and urine) produced per day by beef and dairy cattle is approximately 10% of their own weight and contain 85-90% water".

When cattle graze freely over pasture, their excretions are returned directly to the land and under normal conditions of good husbandry no particular problem either of waste disposal or of water pollution arises. However, problems develop when these animals are housed in a farm building or enclosure. During grazing, livestock deposit manure directly on the land where it is recycled naturally and does not cause significant pollution (Vanderholm, 1984). However, with increasing stock numbers the potential for pollution increases and subsequent environmental damage is of concern.

Currently, there are major concerns about the negative effects of nutrient losses (increased nutrients entering surface and ground water) due to non-point source of pollution from the manure of large dairy herds maintained on small acreages (Van Horn *et al.*,1994). "Sheep and cattle grazing can be a major cause of non-point source of pollution of ground and surface water in New Zealand. Contaminants can include

sediment derived from erosion, nutrients such as N & P and pathogens. High levels of orthophosphate or dissolved reactive phosphorus and nitrate can cause eutrophication of warm, slow moving water” (Caruso & Jensen, 2000).

Much of the hill country on New Zealand’s North Island is particularly sensitive because of deforestation, steep terrain and thin, unstable soils (Crozier *et al.*, 1980; Merz & Mosley, 1998). Kruskal-Wallis tests showed that soil water had a significantly higher value for  $\text{NO}_3^-$ -N concentrations than streams, surface runoff and subsurface water. This indicated that soil water is a reservoir and significant source of  $\text{NO}_3^-$ -N entering streams (Caruso & Jensen, 2000).

Animal waste can also be a significant source of organic nitrogen and ammoniacal nitrogen both of which is toxic to many species of fish at very low concentration. Some organic-N is oxidized to  $\text{NO}_3^-$ -N through nitrification. Transportation of N through a hillslope to stream water is predominantly as dissolved  $\text{NO}_3^-$ -N. Transport mechanisms include overland flow during storms and nitrate saturated watersubsurface flow (Burt *et al.*, 1993). Nitrogen concentrations in soil water are affected by these transport pathways and the residence time of water in contaminated soil (Cooper & Cooke, 1984; Goulding *et al.*, 1996).

Temporarily confined animals such as dairy cattle and such permanently confined livestock as pigs and chickens also generate significant quantities of wastes which may lead to disposal problems (Vanderholm, 1984) of a point source and non-point nature. Dairy cattle are confined only during milking and controllable manure waste comes from this period. The manure produced comprises 6 to 12% of total daily manure production (MAF Agriculture policy, 1994)

The estimated contributions from dairy, pig & sheep sectors in terms of point and non-point source pollution are given in the Table 1.3 where it is indicated that only 2.88 percent of generated waste from these animals can cause point source of pollution and needs management by human intervention. Table 1.3 also shows that about 84% of the

point source of pollution comes from dairy sector alone and remaining 16% from pigs. The dairy sector is the major source of both point and non-point source of pollution in New Zealand.

The animal population and associated waste generation in New Zealand during the period of 1952 to 1980 is given in Table 1.4. Also according to Statistics New Zealand, Agricultural Production Survey (1999-2000), an analysis of livestock populations of New Zealand and the respective animal waste generation is presented in Tables 1.3 and 1.5 respectively. From the data of Tables 1.4 and 1.5 it is evident that the total quantity and strength of animal wastes in New Zealand represents significant polluting potential, especially the quantity to be handled manually, i.e. these quantities of wastes coming from milking yards and feed pad.

Table 1.3 The estimated point and non-point pollution from dairy cows, pigs & sheep

Animal	Population (millions <sup>1</sup> )	Waste generation (tonnes/day <sup>2</sup> )	Pollution sources <sup>3</sup> (tonnes/day)		Point and non-point pollution (%)		Contribution to pollution (%)	
			Non-point	Point	Non-point	Point	Non-point	Point
Dairy cattle	3.26	176,040	169,527	6,513	65	84.3	97.12	2.88
Pigs	0.368	1,214	-	1,214	-	15.7		
Sheep	45.67	91,340	91,340	-	35	-		
Total	49.298	268,594	260,867	7,727	100	100		

Waste: Undiluted mixture of urine and faeces considered by Vanderholm (1984) for calculating waste generation of different livestock in New Zealand.

1. Statistics New Zealand, Agricultural Production Survey (1999-2000), where population of different animal in 1999-2000 is given.
2. Vanderholm (1984), where characteristics of different animal manure is presented.
3. Mason & Reijnen (1999), where 3.7% of the average daily bovine manure production was found in the farm dairy waste.

The estimated dairy animal population for 1999-2000 was 3.26 millions (Dairy Statistics, 1999-2000). On a BOD<sub>5</sub> basis the farm dairy (dairyshed and milking parlour) produced waste, (based on 1999 numbers) equivalent to a human population of 1.97 million. The average herd size has increased steadily over the past 27 years from approximately 110 in 1974/75 to 236 in 1999-2000 and the number of farm dairies in 1999 was reported to be 13,861 (Dairy Facts and Figures, 1999-2000).



Some studies (Dakers,1979; Vanderholm,1984 and Mason & Reijnen,1999) have been carried out in New Zealand to investigate the basic characteristics of raw animal wastes. Table.1.6 has been prepared on the basis of data obtained from such investigations and shows some of these characteristics of freshly voided animal manure.

Table 1.4 National animal population equivalent and manually handled waste from 1952 – 1980

Farm Type <sup>a</sup>	Dairy	Beef	Pig	Sheep	Total P.E. (Millions)	Total <sup>c</sup> Manually handled
1952 Population (thousands)	2882	2282	566	35384		
P.E. <sup>b</sup> (millions)	36.6	29.0	0.74	14.9	81.2	2.6
1960 Population (thousands)	2933	30.2	660	32632		
P.E. (millions)	37.3	38.3	0.87	13.7	90	2.7
1970 Population (thousands)	3729	5048	578	60276		
P.E. (millions)	47.4	64.1	0.75	25.3	138	3.1
1980 Population (thousands)	2969	5162	68772			
P.E. (millions)	37.7	65.6	0.56	28.9	133	2.4

Source: Dakers & Painter (1983).

- a. 75% of gross income is derived from this activity.  
 b. 1 Population Equivalent (P.E.) = 0.077kg-BOD<sub>5</sub>/Day.  
 c. Only pig waste and 5% of dairy waste considered.

Table 1.5 The quantity and strength of agricultural wastes in New Zealand

Animal	Population (millions)	Total Wastes		Collected Wastes	
		Daily BOD <sub>5</sub> <sup>1</sup> (tonne)	Population Equivalent <sup>2</sup> (millions)	Daily BOD (tonne)	Population Equivalent (millions)
Dairy cattle	3.26	2510	32.6	100.4	1.30
Sheep	45.67	1462	18.98	nil	nil
Pigs	0.368	51.52	0.67	51.52	0.67
Beef	4.64	3155	40.98	nil	nil
Total		7178.52	93.23	151.92	1.97

- Daily BOD<sub>5</sub> per capita, 0.077kg.
- 4% of total waste production is considered to be collected in yards (Drysdale,1977).
- All pigs and poultry are permanently housed and penned.

Table 1.6 Characteristics of freshly voided animal wastes.

Animal	Raw			
	Dairy Cattle	Pig	Poultry	
			Layer	Broiler
Animal Weight (kg)	500	50	2	1
Raw Manure (kg/day)	54	3.3	0.11	0.071
Faeces, % RM	60	55	-	-
Total Solids (kg/day)	4.4	0.30	0.027	0.018
Volatile Solids (kg/day)	3.2	0.24	0.019	0.012
BOD <sub>5</sub> (kg/day)	0.77	0.14	0.007	-
COD (kg/day)	4.3	0.29	0.024	-
Total N (kg/day)	0.24	0.023	0.0014	0.0012
Total P (kg/day)	0.025	0.075	0.0056	0.0026
Total K (kg/day)	0.31	0.015	0.00062	0.00036
Solid content (%)	13	9.2	25.3	24.1

Source: Dakers (1979) & Vanderholm (1984).

There are eleven different types of pollutants referred to or implied in the standards of the RMA (1991) and of those eleven, nine pollutants (excluding heat, acids & bases) have been found in lagoon treated dairy and piggery effluents. These pollutants are: oxygen demanding substances, suspended solids, infectious microbiota, toxic materials, nutrients, odour-producing substances, tainting substances, light-attenuating materials, and unsightly (visually-degrading) materials among which faecal indicators, ammoniacal-N (toxic, oxygen-demanding and a nutrient), suspended solids and other light-attenuating materials in dairymshed lagoon effluents have been identified as priority pollutants (Davis-Colley, 1996). Therefore, these effluents represent a significant point source of pollution in New Zealand.

The characteristics of two-pond (anaerobic-aerobic) treated dairy effluent was investigated in New Zealand by Hickey *et al.* (1989) on 11 dairymshed oxidation ponds in two regions (Manawatu and Southland) which were designed according to national specifications. The results of that study have confirmed that the traditional two-pond systems are not sufficient to achieve the desirable level of treatment to protect the quality

of receiving water and obviously these effluents need greater dilution. The results of that investigation of six priority pollutants and the relevant guideline values are given in the Table 1.7

Table 1.7 Characteristics of two- pond treated dairy effluent, stream guideline & dilution in New Zealand.

Variable	Stream Guideline	Effluent concentration		Dilution factor		Remarks
		Median	95%ile	Median	95%ile	
Faecal coliforms.	200  1000	70,000	540,000	350	2700	Health risk for bathing (DoH, 1992) stock watering, crop irrigation.
Nutrients						
DIN	0.040-0.1	75	216	750-1875	2160-5400	Promoting nuisance algal growths (MfE, 1992)
DRP	0.015-0.03	12	17	407-813	570-1140	Promoting nuisance algal growths (MfE, 1992)
NH <sub>4</sub> <sup>+</sup> -N (toxic)	0.22  0.77	75	191	341  97	868  248	Toxicity to NZ invertibrates, pH 8 (Hickey & Vickers, 1994) Toxicity to salmonids, pH 8 (USEPA, 1985)
Visual clarity (light attenuation)	50%	0.03m	-	213	-	Visual water clarity impact (MfE, 1994) (for a stream with median visibility, 3.2m).
CBOD + NBOD (O <sub>2</sub> demand)	5	413	1068	83	214	O <sub>2</sub> stress on aquatic life (Hickey <i>et al.</i> , 1989; Cooper, 1986)
Suspended solids (organics)	4	198	804	50	201	Ecological impact (Quinn & Hickey, 1993).

Notes: Effluent data from Hickey *et al.* (1989), except for visibility data (from Sukias *et al.*, 1995).

1. DIN = Dissolved Inorganic Nitrogen.
2. DRP = Dissolved Reactive Phosphorus.
3. CBOD = Carbonaceous BOD.
4. NBOD = Nitrogenous BOD.

#### 1.4 ANIMAL WASTE TREATMENT OVERVIEW IN NEW ZEALAND

For the first century of livestock farming in New Zealand, the small proportion of total dairy waste concentrated in confined areas was usually discharged into streams and rivers. Before 1967, the farmers were generally reluctant to spend money for waste management. Beyond that, the simple and economic technology of animal waste management was also unknown (Dakers & Painter,1983). Due to the concern about natural environment particularly natural water, The Water and Soil Conservation Act,1976 through Regional Water Boards first imposed a “water right” to people-who desired to discharge wastewater into natural water or to land. But at that time there was a lack of technical expertise and understanding for planning, design, operation, monitoring and evaluation of treatment systems and what standards of effluent after treatment should be specified. Initially the land application of dairy shed wash down effluent by tanker or spray irrigation was considered satisfactory but pump and sprinkler blockages, seal and bearing failures in pumps, soil saturation and plugging in winter, the unpleasant and labour intensive task of sprinkler shifting, spread of weeds, and ground water pollution due to critical  $\text{NO}_3^-$  leaching induced farmers’ disenchantment with these systems. The rate of sprinkler irrigation of waste was recommended by Ministry of Works and Development on the basis of hydraulic loading criteria rather than nutrient loading criteria. Hills (1975) noted that N was the critical for water pollution because of its higher mobility relative to P and K and recommended N loading rates on pasture based on 400 kg-N/ha/yr as given in the Table 1.8.

Table 1.8 Recommended area of land in hectares for land application based on N loading of 400kg-N/ha/yr.

Livestock	Fresh manure	Anaerobic winter storage	Anaerobic Lagoon	Aerobic treatment effluent.
100 cattle	0.64	0.88	0.44	0.22
500 pigs	3.7	5.1	2.6	1.3
10,000 poultry	10.1	14	7	3.5

Source: Dakers (1979).

Consequently, organic loading per hectare for land disposal became less meaningful than nutrient loading and due to this concept farmers and associated people looked for a satisfactory arrangement for economic disposal or management of the wastes. During the period between 1952 and 1980 the livestock population equivalent was increased about 60% with a corresponding 25% increase in grazing land area which indicates an increased intensity of animal population over a small area of land than previously used for waste disposal (Dakers,1979; Dakers & Painter,1983)

Before 1973-75, two stage anaerobic aerobic lagoon systems were not considered viable alternatives. In 1972, Ministry of Works first specified lagoon systems which have received wide acceptance with regional water boards for permitting discharge from these lagoons into natural waters. Lagoon systems consist of two ponds in series, an anaerobic pond 3 to 4m deep with a design capacity of  $42\text{m}^3/\text{kg BOD}_5$ , followed by a aerobic pond 1.2m deep with a surface area of  $120\text{ m}^2/\text{kg BOD}_5$ . A 70% BOD reduction occurred in the anaerobic pond and over-all 94% BOD reduction from the wastes were measured (Dawn,1973).

There are some other systems such as trickling filters, sequencing batch reactors, anaerobic digester for biogas production and composting that have been tried in pilot scale by the New Zealand farmers and scientists but still none of them has been accepted for wide scale implementation. Although there are several anaerobic digester biogas plants installed in piggery and poultry farms they still need further technical development. Generally, the farmer is offered two alternatives; ponds or land disposal or a combination of these two (Dakers,1979) and even today these practices continuing to be used.

Dairy farm effluent in New Zealand is most commonly treated via waste stabilization ponds (two-pond system). The final effluent may then be released into streams or rivers or on to land. According to one estimate in 1985, half of the approximately 14000 dairy sheds in New Zealand were using pond systems (Hickey and Quinn,1992). In the Taranaki region, 1200 out of 2700 dairy sheds (44%) utilized pond

systems in 1992 (Mason,1996).There were approximately 6000 dairy farms in Waikato region, 70% discharge their effluent to surface waters with 30% discharging to land (Environment Waikato,1994). The system is popular because of low operation and maintenance costs and the production of high quality effluents in terms of BOD and coliform level. However, their nutrient removal ability is not satisfactory (Mason,1996). The nutrient removal, particularly N by the two-pond system is proving insufficient to protect the quality of receiving waters. The effluent of two-pond oxidation systems offers additional benefit when it is applied to land, because much of its N is converted to  $\text{NH}_3$  during the treatment process and this form of N is readily available for plant uptake (Taranaki Regional Council,2000).

Hickey *et al.*(1989) has reported that pond effluent has been found to vary widely in terms of Suspended Solids (52-804  $\text{g}/\text{m}^3$ ),  $\text{BOD}_5$  (32-241  $\text{g}/\text{m}^3$ ), Nitrogen (7.2-216  $\text{g-N}/\text{m}^3$ ) and Phosphorus (4.6-17.1  $\text{g-DRP}/\text{m}^3$ ) and for the sake of water quality the effluents need 500-fold dilution for  $\text{NH}_3$  criteria, >2700-fold dilution for faecal coliforms (bathing criterion), >67-fold dilution for coliforms (post-treatment drinking criterion) and >2700-fold dilution for nuisance control (algal proliferation). The organic matter, nutrients and Suspended Solids (SS) of effluent can cause river deoxygenation, nuisance growth of algae and macrophytes, depletion of Dissolved Oxygen (DO) levels.  $\text{NH}_3$  are toxic to fish and invertebrates. Nitrification of  $\text{NH}_3$  may also decrease DO levels. SS and dissolved organic matter reduce water clarity. Direct discharges of treated dairymshed effluent to surface water introduce contaminants such as  $\text{NH}_3$ , P, Faecal Coliform (FC), pathogenic bacteria and SS (Taranaki regional Council,1995).

Under the RMA 1991 regional councils are required to consider the Maori cultural concerns. Maori culture does not allow direct discharge of farm effluent to waterways but the purification of effluents through the land is much more acceptable to Maori and accordingly some Iwi and other Maori representatives favour pond, ditch or wetland systems which are land based treatment of effluent. That is why Waikato regional council has been encouraging the re-use of dairy effluent through land treatment

systems as a permitted activity and providing financial incentives (Environment Waikato,1994).

For the above reasons most of the councils are moving towards managing effluent discharges in regard to  $\text{NH}_3$ , and pathogens. Land disposal of treated or untreated dairy effluent is encouraged by regional councils as a treatment/disposal/reuse option, where it is well managed ( MAF policy,1994). From the above information it has become evident that two-pond systems are not sufficient to make the dairy shed effluent suitable for discharge to surface water and the existing systems need additional tertiary level of treatment to meet the criteria. There is a need for investigation and development of treatment/disposal technologies especially where land treatment is not a practical option. Technologies to consider are an additional maturation pond, use of zeolites, filtration, overland flow treatment bed, constructed wetland, rotating biological contactor and land application. One or more maturation ponds followed by a facultative pond can provide further polishing of effluent and especially they can remove coliforms significantly. Sukius *et al.*(1996) noted that four equal size ponds for treating domestic wastewater each having 2.5 day retention time achieved 3 decades reduction of faecal coliforms (0.1% remaining), whereas a single pond the same retention time (10 days) removed only 95% (5% remaining). Zeolites are crystalline hydrated alumino-silicates which are known to have an affinity for  $\text{NH}_4^+$  and other cations (Nguyen,1996). Natural New Zealand zeolites (clinoptilolite and mordenite) can be used at the end of two-pond system or pond-constructed wetland sequence as a filtering bed to remove ammoniacal-N of dairy pond effluent, where clogging may not be a problem. Wetlands also commonly remove 70% SS of wastewater (Nguyen & Tanner,1998). The study carried out by Nguyen & Tanner (1998) suggested that although both clinoptilolite and mordenite are potential for  $\text{NH}_4^+$  removal (87-98%), mordenite is more effective for  $\text{NH}_4^+$  removal from dairy and piggery wastewater and this removal capacity was not influenced by the source of zeolite used and zeolite particle size.

Rock filters and back-flushable sand filters can remove a considerable proportion of SS and  $\text{BOD}_5$  associated with algae in pond discharges, but to maintain through flow

sand filters needs frequent back-flushing which is expensive and likely to provide insufficient benefit. In contrast, rock filters can be used with dairy effluent as biofilm can develop on the rock surfaces, nitrification and BOD conversion occur but these filters need periodic cleaning and rebuilding to remove clogging (Mason,1996). A by-product called ecoflow produced from the steel making process at BHP New Zealand Steel has been used to remove the nutrients in dairy pond effluent and an 80% reduction in SS and 90% removal of P was obtained. Removal through physical and chemical reaction processes has been proposed (Mason,1996).

Dairy effluent can be applied to soil for over land flow in the riparian zone before reaching a surface water body where a suitable slope of soil is available (2-10%). Effluent flows as a thin sheet, water saturates the upper soil layer than further effluent additions pass through the litter layer and grass sward. Suspended solids (SS) can be removed by settling and filtration. Nutrients are sorbed by the soil and microbial biofilm. Plants also assimilate nutrients. Aerobic degradation of organic matter and nitrification of  $\text{NH}_3$  occurs. Denitrification of accumulated nitrate may also occur during flooding (Mason,1996). Results of laboratory-scale Rotating Biological Contactors (RBC) experiments carried out at National Institute of Water & Atmospheric Research Ltd, Hamilton, (NIWA) have shown that over 90% removal of ammoniacal-N is possible from dairy pond effluent with an initial concentration of 60 g/m<sup>3</sup> at residence times of < 1 day (Mason,1996). Where land application is preferred, effluent may be passed through zeolite beds before land application.

Constructed wetlands can be used to reduce the organic pollutants from pond pre-treated dairy effluent through nutrient uptaking and storage by aquatic plants, sediments, detritus, microbes and fauna. Both surface and subsurface flow system can be used. Taranaki Regional Council prefers surface flow systems because they are simple to design, construct and operate and have the potential to produce a high quality effluent. However, subsurface flow wetlands require accurate and detailed engineering design and construction which may be difficult to achieve. For example, up-flow wetlands will often clog due to excessive algal inputs (Taranaki Regional Council,2000).



A study of dairy effluent treated through subsurface flow (SF) wetland (Tanner *et al.*,1995) concluded that planted wetlands are better than unplanted ones in terms of Total Nitrogen (TN) (0.15-1.4g/m<sup>2</sup>/d) and Total Phosphorus (TP) (0.13-0.32g/m<sup>2</sup>/d) removal. With gradually increasing mass loading rates the plants have the capacity to store N (3-20% of greater N removal) and P (3-60% of greater P removal). Final removal is achieved by harvesting the plants in the first year. Most studies of constructed wetlands performance have been carried out over limited time periods. Results from a 4 year long monitoring program of SF wetlands suggested that annual mean removal of Carbonaceous Biochemical Oxygen Demand (CBOD), SS, TP, and Total Kjeldahl Nitrogen (TKN) did not vary significantly over the years but soluble P removal declined markedly after second year and NH<sub>4</sub>-N removal varied from year to year, ranging from 5-35% (P) and 31-51% (N) respectively (Tanner *et al.*,1998).

The gradual reduction of P removal in subsurface gravel bed constructed wetlands has been observed (Tanner *et al.*,1998). Tanner *et al.*,(1998) reported that the wetlands maintained their performance about CBOD, CNBOD, TN and Faecal Coliform (FC) removal over a period of five years but overall removal performance of TP and SS declined significantly over the years and the reasons could be the saturation of the key P removal processes (precipitation reactions and adsorption to detritus, humic materials, and soil minerals) and clogging. Since there are a finite numbers of P sorption sites in a wetland environment, these sites eventually saturated and when this happens, no further P removal will occur. If desorption of P occurs then the output could be greater than the input (Faulkner & Richardson,1989). Therefore, since the different regional councils are now looking for NH<sub>3</sub> and pathogen removal before discharging to a water body, constructed wetlands may offer an alternative tertiary treatment option because of their high pathogen removal capacity (92-99%) as observed by Tanner *et al.*(1998) and sustainable N removal through nitrification and denitrification processes. Maximum N removal in wetlands could be obtained when the NO<sub>3</sub>-N concentration in the influent was high. However, the wetland was not efficient for removing ammoniacal-N.

Currently, land based systems are being actively promoted by various Regional Councils in New Zealand as the most preferred option for disposal of dairyshed effluents onto land (Taranaki Regional Council,1995). Land treatment of effluent after solid liquid separation is becoming more widespread. Irrigation of dairy-shed effluent on to pastures and cropping lands is being practiced increasingly by dairy farmers in New Zealand (Roygard,1999). The application of manure to land has been accepted because of its nutritive value as it offers a source of N,P,K and S fertilisers and trace elements which increase pasture and crop production and improves soil water holding capacity, soil aeration, drainage and soil tillage characteristics ( Taranaki Regional Council,2000). One of the problems with this practice, however, is the potential for contaminants, such as pathogens and heavy metals in the effluent to enter the food chain (Di *et al.*,1998; Silva *et al.*,1999).

Fertilizer nutrients in manure can be recycled through land application but salt nutrients (Na and Cl) in manure are a potential limitation where the soils salt content is high especially in dry or low rainfall areas (Van Horn *et al.*,1994). Land application of effluent causes release of inorganic N in the form of  $\text{NO}_2^-$  &  $\text{NO}_3^-$ . Nitrite ( $\text{NO}_2^-$ ) is usually transitory in soils as it is microbially converted to nitrate ( $\text{NO}_3^-$ ) but it may accumulate in soil under certain conditions and it is toxic to higher plants even in very small quantities. Nitrate ( $\text{NO}_3^-$ ) is a highly mobile anion, readily utilized by plants and microorganisms but it may readily be leached from the soil and thus contaminate ground water thus representing a potential human health hazard.

Nuisance problems in the vicinity of land application actually may occur. Its operation and maintenance cost is medium to high and extra attention has to be given to separated solids which need to be removed and hauled off the dairy farm. Also, control of K concentration during application is required in order to ensure edible crop production (Mason & Young,1999). This implies higher land areas, greater pipe systems and increased pumping costs. Sometimes, land application may not be possible due to weather conditions or mechanical failure. Extra costs subsequently are borne for storage facilities in high rainfall areas. Land application technology involves transportation of

effluent and some sort of mechanical devices for irrigation which are also costly. In addition, both pond and land treatments produce some solids during solid-liquid separation in anaerobic pond or holding pond which has to be managed either by landfill or composting. Thus, neither of these systems is able to treat solid and liquid fractions in a single phase of treatment and pose therefore, medium to high management costs. One major limitation of land treatment is the lack of required acreage for disposing manure nutrients from large dairy farms. Here, nutrients cannot be applied in excess of crop requirements and off farm disposal of excess nutrients must be considered. Therefore, there is a great need to utilize technology that partitions fertilizer nutrients from manure and water so that surplus nutrients can be transported economically to other farms or regions where there are in deficits (Van Horn *et al.*,1994).

### **1.5 IS COMPOSTING AN ANSWER?**

Rather than thinking of manure management as a burden, it can be viewed as an opportunity with which the dairy farmer must deal so as not to waste the nutrients in the manure. That's why composting makes so much sense. The economic viability of composting is predicted on the fact that the feed stock for the operation is generated on the farm. There are no hauling costs and no need to collect it (Glenn,1998). Dairy manure slurry contains a high water content (around 90%). Composting is a method of processing manure slurry whereby heat is liberated from the decomposition of organic substances and this released heat drives the evaporation of water, which is removed in exhaust gases (Patni & Kinsman,1997). Reducing the large amount of water in the slurry leads to a reduction in mass, bulk weight & volume. Thus, there is a large potential to reduce transportation and handling costs for disposal as well as the area of land required for manure application. Composting can also reduce the risk of pollution from runoff, odour, and nitrate contamination of ground water (Patni & Kinsman,1997). These ideas are reviewed in the next chapter of this work.

## CHAPTER 2

### REVIEW OF LITERATURE.

#### 2.1 DEFINITION

Composting is defined as the process of making into a mixed manure of organic origin (Crawford,1983). Biddlestone & Gray (1973) define composting as “the decomposition of heterogeneous organic matter by a mixed microbial population in a moist warm aerobic environment”. Bell & Pos (1971) define it as an aerobic thermophilic decomposition process while Muller (1967) states that “composting may be defined as incomplete microbial degradation of organic waste, where the microbial processes may vary from aerobic to anaerobic”. Although there is no universally accepted definition of composting and many have been given as mentioned above, a suitable one is given by Haug (1993) as follows:

*“Composting is the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land.”*

Composting differs from other waste stabilization systems in that the temperature and rate of decomposition are usually altered directly by human intervention. During aerobic decomposition processes microorganisms consume oxygen ( $O_2$ ), feed on organic matter and generate heat, large quantities of carbon dioxide ( $CO_2$ ) and water vapour (Rynk,1992). Anaerobic decomposition processes generate  $CH_4$ ,  $CO_2$ , organic acid, alcohol and some odourous compounds. Anaerobic composting produces significantly less energy per weight of organic decomposed compared to aerobic composting (Haug,1993). Composting is usually encouraged under aerobic conditions. During the composting process, the amount of humus increases, the C:N ratio decreases, pH neutralizes and the cation exchange capacity of the compost increases. The weight of compostable materials is also reduced by 40-80% (w/w) because of water loss through evaporation plus carbon (C) lost as  $CO_2$ . The C:N ratio gradually falls because of further loss of  $CO_2$  in comparison with nitrogen (N) loss during

composting, but where N losses exceed those of C, the change of C:N ratio would be insignificant (Rynk,1992).

Chemical energy is stored in organic materials through the transformation of solar energy during photosynthesis. During the composting process, the chemical bonds are broken and microorganisms obtain some energy for growth and some energy is transformed into heat energy which increases the pile temperature. During aerobic decomposition, the available nutrients used by the microbes remain in the cells of new microbes as humus (Rynk,1992).

## 2.2 ROLE OF COMPOSTING

Composting can play a beneficial role as it is a method of biorecycling of livestock wastes as renewable resources because it reduces the weight, moisture content, and bioactivity of manure as well as destroying pathogens (Rynk,1992). Composting reduces landfilling of organic wastes and limits green house gas emissions (Pare *et al.*,1997). The end product of composting is a stabilized, low nuisance, solid materials which could be beneficially applied to land. It has lower N levels due to NH<sub>3</sub> losses by volatilization during composting and allows slow release of other nutrients to soil (Mason & Reijnen,1999; Crawford,1983). Crawford (1983) also reported that composting recycles organic waste and improves soil texture, structure, organic content, aeration, permeability, cation exchange capacity and water holding capacity. According to Hong *et al.*(1983), importance of composting arises from the following: (a) The need to dispose of wastes, (b) the need of humus to replace that loss from soil and (c) prevention of any environmental pollution caused by using chemical fertilizer.

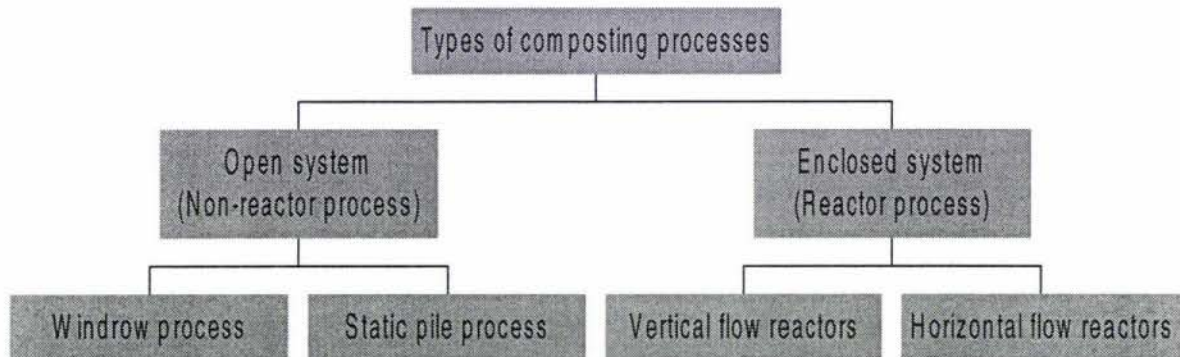
The aerobic, thermophilic conditions in composting systems are inhibitory to most of the pathogenic organisms, weed seeds and insects (Vanderholm,1984). Composting can virtually kill weed seeds completely. It can be uniformly spread on land with a side delivery spreader as a part of a soil fertility program and if produced from dairy manure can provide approximately 1.2% N, 1%P and 1.2%K (Lufkin *et al.*,1995).

Crawford (1983) argues that agricultural wastes contain highly soluble N compounds which can be easily washed into watercourses if directly applied to land whereas, composting offers two additional advantages. It conserves increasingly expensive fertilizers (on a dry weight basis compost contains 0.4-3.5%N, 0.3-3.5%P as  $P_2O_5$  and 0.5-2.0%K as  $K_2O$ ) and reduces the risks of polluting water-courses because the process reduces the soluble N content from raw agricultural wastes while P compounds become incorporated into new microbial cells. Higher crop yields have also been claimed in trials that examine compost versus directly applied animal manure. According to Pare *et al.* (1997), composting of animal manure proceeds with the removal of  $NH_3$  gas by volatilization. Thus, there is a decrease in the water-soluble  $NH_4^+$ -N concentrations throughout the composting period with a concomitant rise in water-soluble  $NO_3^-$ -N, which usually starts after the thermophilic stage. Nitrate concentrations continue to increase towards the ends of the composting. After application to soil, the N from this water-soluble  $NO_3^-$ -N may be lost to the atmosphere through the denitrification processes in the soil-plant root zone environment.

Therefore, composting could be the only method of partitioning fertilizer nutrients and the recovered nutrients can be economically transported to other farms to off-set nutrient deficits. However, field scale on-farm non-waterborne composting needs some extra infra-structural facilities such as covered farm dairy yards and covered composting pads to avoid rain water. The costs are associated with the initial investment and maintenance and can be recovered over a reasonable period of time through sale of a useful end product to gardeners and other customers. Non-waterborne collection and composting can reduce the major pollutants in wastewater significantly and can reduce the generation of wastewater to some extent (Mason & Reijnen, 1999 assumed 70% removal of N,P,K and 30% reduction in water consumption) but cannot eliminate the generation of wastewater in a farm dairy completely. This is because an amount of water must be used for the final cleaning of yards. Recent animal manure composting research has introduced the possibility of fitting together the water and non-waterborne collection of manure slurry especially from dairy sheds and the subsequent composting of manure with irrigation of final washdown water from yard cleaning (Mason & Reijnen, 1999; Biddlestone & Gray, 1985 & Patni & Kinsman, 1997). Operations such as these offer further advancement towards acceptability and sustainability

of composting processes as a farm waste management option in New Zealand and other dairying countries.

### 2.3 TYPES OF COMPOSTING PROCESSES



There are two types of composting systems, enclosed and open. Enclosed systems use a reactor or an in-vessel process but the open systems do not use any container and are thus termed nonreactor systems.

**Non-reactor processes:** Non-reactor systems are primarily of two types, namely the agitated solid bed (Windrow) process and the static solid bed (Static pile) process.

In a windrow system, mixed feed stocks are placed in rows often in large open fields and turned periodically usually by mechanical equipment. Oxygen is supplied naturally due to the buoyancy of hot gases in the pile. Oxygen can also be introduced by forced aeration with the aid of blowers. Alternatively, turning can provide both restructuring of the pile and some oxygen re-supply.

In a static pile process, substrate is mixed with a bulking agent such as wood chips and large piles are formed. Bulking material provides structural stability of the pile matrix and maintains enough free air space without the need of periodic agitation. An air distribution system is provided for induced aeration. This aeration system can be positive or negative.

Negative induced aeration reduces odour problems as an earth filter is often used through which exhaust gases are passed.<sup>1</sup>

**Reactor processes:** Reactor processes are primarily classified on the basis of flow direction of materials as vertical flow reactors and horizontal flow reactors.

Vertical flow reactors are again classified according to the bed conditions, if agitation is provided during the movement of materials down the reactor then it is called “**moving agitated bed reactors**” but if the materials occupies the entire bed volume and is not agitated during single passing then it is called “**moving packed bed reactors**”. The vertical “moving packed bed reactors” are widely used for sludge composting along with sawdust and other amendments.

Horizontal flow reactors are divided into a number of varieties such as rotating drum, which use bins of varying geometric shapes with varying agitation methods and a bin without agitation. Rotary drums can be dispersed flow systems and plug flow systems which can be compartmented into a number of cells in series. An agitated horizontal bin reactor can be circular or rectangular where forced or mechanical agitation is provided. This is uncovered at the top and usually installed in a building for operation throughout the year and to control odour. The horizontal static bed reactor was developed in about 1979 which could be tubular or tunnel of rectangular cross section and has been using for composting of sludge, manure and Municipal Solid Waste (MSW) fractions. Its volume ranges from 10 to 500m<sup>3</sup> and operated under plug-flow conditions. The larger size units are constructed of reinforced concrete while smaller ones are made of fabricated steel. It has a pusher plate which hydraulically pushes the new materials from feed end and simultaneously expels un-matured compost through the exit end. The product is then taken off-site for maturation.

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<sup>1</sup> A “positive” aeration pump flows air into and through the pile. Whereas, a “negative” aeration pump sucks atmospheric air down through the pile.



### 2.3.1 DIFFERENT METHODS OF AERATION

Composting technologies can be classified according to their methods of aeration which are: (1) turned windrow systems; (2) in-vessel systems; (3) naturally aerated systems; (4) passively aerated systems; and (5) forced aeration (Beltsville process).

Turned windrow systems are labour & energy intensive and result in high  $\text{NH}_3$  loss and odour production which often make composting an unattractive waste handling technology for small businesses and dairy farmers (Rynk,1992; Lynch & Cherry,1996). In-vessel systems have the advantage of high rate and excellent control of the process variables, but involve costly capital outlay, maintenance and trained operators (Haug,1993). Naturally aerated systems do not facilitate air delivery to the composting material and the processes are dependent only on the diffusion phenomena of aeration. These systems are not recommended for very wet materials (Sartaj *et al.*,1997; Fernandes & Sartaj,1997). Passively aerated systems are similar to natural aeration, except that a set of perforated pipes are used to facilitate air delivery to the material. Air is drawn into the pipes and through the perforations by convection currents developed due to spatial temperature gradients from the point of air entry to the warm decomposing mass (Fernandes & Sartaj,1997). Forced aeration has the biggest advantage over other methods. Operated in either positive or negative mode with a controlled air delivery program by time or temperature feedback. Although air distribution is more uniform and efficient for heat removal but its capital outlay, operation and maintenance costs are high and areas near aeration pipes do not reach suitable pasteurizing temperature unless the air is preheated (Fernandes & Sartaj,1997).

The results of a comparison of forced and natural aeration for dairy manure composting has concluded that naturally aerated static piles can achieve temperatures high enough for optimum composting and can maintain elevated temperatures longer than forced aeration static piles, although forced aeration appears to be superior to natural aeration because materials dry more rapidly (0.362%/day) by forced aeration than by natural aeration (0.188%/day) but the drying rate by forced aeration was still quite low with an estimated duration of 55 days to dry from 80% to 60% moisture content. Thus if the air permeability of the material within the compost pile is sufficient, natural aeration may provide an adequate

O<sub>2</sub> supply for the composting process and composting costs can be expected to be low (Emerton *et al.*,1988).

### 2.3.2 METHOD OF PASSIVE AERATION

Passive aeration composting has been used in a variety of applications (Mathur *et al.*,1990; Lynch & Cherry,1996; Sartaj *et al.*,1997; and Fernandes *et al.*,1994). This method of aeration can eliminate the need for turning of pile materials by supplying air to the composting materials through open ended 10cm dia. perforated PVC pipes extended to the atmosphere with two rows of 12mm (½ inch) diameter holes at 300mm (12 inches) intervals along the pipe in a staggered pattern placed at a 300-450mm (12-18 inches) interval perpendicularly by keeping the holes upward or downward beneath the compost pile, built on top of a base of porous materials like straw, peat moss, wood chips (Rynk,1992) as shown in Fig.2.1 below.

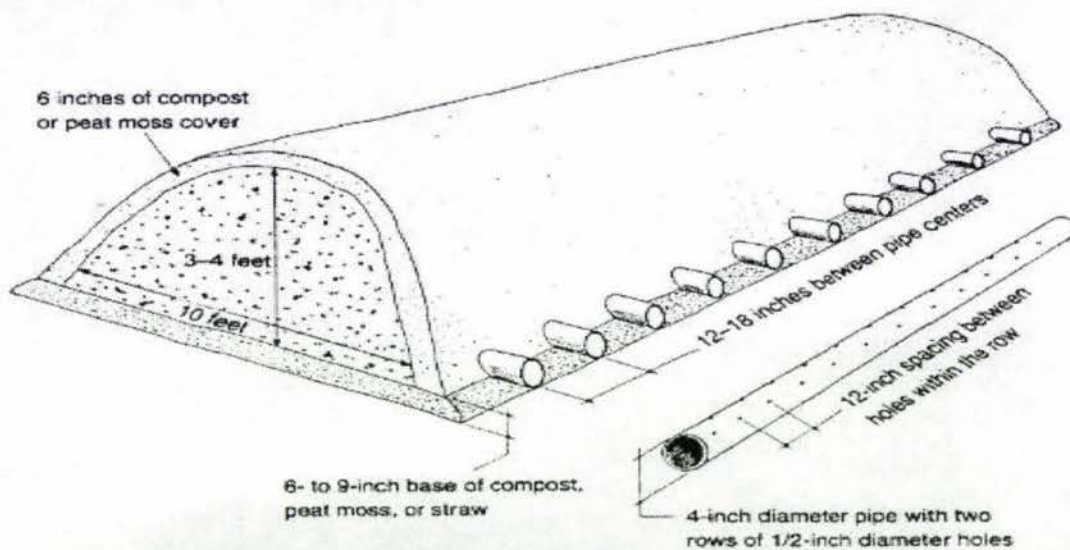


Figure 2.1 Passively aerated windrow method for composting manure (Rynk,1992).

A covering and insulating layer is provided on top of the pile to minimize the loss of heat, moisture, NH<sub>3</sub> and to work as a biofilter to control odours that otherwise attract flies. The covering materials could be peat moss, finished compost, sawdust or any other suitable materials (Lynch & Cherry, 1996). Since the materials are not turned after pile formation,

adequate initial mixing is important. This method can successfully compost manure mixtures within 7-10 weeks and has been found to retain odours and conserve N effectively (Rynk,1992). As the warm air in the pile rises it pulls in fresh air flows through the pile via free convection (Lynch & Cherry,1996). The air exits the pipe by traveling upwards and outwards through the compost pile's surface cover. Sartaj *et al.*(1997) had compared the performance of force aeration (FA), passive aeration (PA) and natural aeration (NA) and reported that PA is superior to FA & NA in terms of duration of temperatures above 55°C. On average PA was 3.8 days while FA & NA were 0.25 and 1.4 days respectively. Thus, only PA met the EPA (1979) criteria for pathogen destruction. PA was also superior to NA in terms of O<sub>2</sub> concentration inside the pile. For NA it was between 0 – 4% saturation and for PA it was in between 1 – 12%. NH<sub>3</sub> was not detected at the surface of NA and PA systems, but FA had the highest NH<sub>3</sub> emission. Sartaj *et al.*(1995) studied the influence zone of aeration pipes under passive aeration and concluded that (1) For PA, positions near the compost pile surface were not affected by the aeration pipes. (2) For NA, air diffusion was the predominant aeration mechanism and amount of air depends on the distance from pile surface. (3) PA is more effective in providing air at core area than the NA. (4) Composting under PA could be completed more early than NA and more uniform temperature distribution should be achieved under PA. The static pile, passive aeration method of composting requires minimal labour and equipment and furthermore, the method is effective for composting animal manure slurries containing up to 80% water (Mathur *et al.*,1990); Sartaj *et al.*,1997 and Fernandes *et al.*,1994).

## **2.4 IMPORTANT FACTORS IN COMPOSTING**

Since composting is essentially a biological process, its efficiency depends on various factors. Hansen *et al.*(1989a) counted as many as 20 various factors that might potentially affect the process. Some of the most important factors are discussed below:

### **2.4.1 OXYGEN AND AERATION**

As composting is considered an aerobic environment so oxygen is needed within the pore spaces of the composting pile. Aeration is provided for aerobic biodegradation as well as to remove excess water vapour, heat, and gases. A minimum 5%(w/w) O<sub>2</sub> in the air inside the

matrix is necessary to keep the process aerobic. Cold weather and small piles increase heat loss (Rynk,1992). The aeration rate required for heat removal is much greater than the stoichiometric demand (MacGregor *et al.*,1981; Haug,1986) and enthalpy change associated with the mass transport of water through evaporation is the major mechanism for heat removal. This evaporation can represent as much as 90% of the heat lost from the process ( Walker *et al.*,1999). The recommended aeration range quoted in literature varies significantly, with suggested rates as low as 0.04-0.08 L-air/min-kg of VS (Lau *et al.*, 1992) and as high as to 0.87-1.87 L-air/min-kg of VS (Hong *et al.*,1983).

Composting needs air, but too much aeration can retard the process. High air flow rates can remove moisture by developing air channels within the piles. Another consequences of excessive aeration is NH<sub>3</sub> loss, especially with high N wastes. As the material dries out, more NH<sub>3</sub> volatilizes and more N is lost (Seekins,1999).

Oxygen migrates through the pore spaces into the interior of compost pile by any one of two natural mechanisms: (1) by molecular diffusion (2) by mass movement of air through the pores due to the energy gradient in the pile. Molecular diffusion occurs due to a concentration gradient of molecules and molecules move from a zone of higher concentration to a zone of lower concentration. However, migration rates decrease as moisture content increases. This is common in wet substrates and molecular diffusion rates are usually extremely slow in comparison to the metabolic consumption rates of required oxygen during composting. If oxygen is depleted inside the pile, then a net movement of oxygen will occur from outside. Similarly, CO<sub>2</sub> and water vapour will diffuse from the inside to the outside because their concentrations are higher internally. The second mechanism is air movement through pores. A mass movement of air into the pile can be expected to meet the required oxygen demands due to an energy gradient inside the pile. Convective air movement occurs due to the high temperature of gases inside the pile. The effect is called natural draft ventilation. As temperature increases, the density of dry air decreases and saturation vapour pressure increases exponentially. Thus molecular weight of H<sub>2</sub>O vapour is considerably less than those of O<sub>2</sub> and N which it displaces (Haug,1993; Miller *et al.*,1982; Willson & Hummel, 1972)

## 2.4.2 CARBON AND NITROGEN RATIOS

Carbon (C), Nitrogen (N), Phosphorus (P), Potassium (K) are the primary nutrients required for the microorganisms responsible for decomposition in the composting process. Microorganisms use C for both energy and growth and N is essential for protein and reproduction (Rynk,1992). A balanced C:N ratio is very important to ensure the required nutrients in addition of other trace nutrients. Although many organic materials contain ample quantities of nutrients but usually excessive or insufficient C or N are most likely. That is why it is almost always necessary to adjust the C:N ratio by adding amendment<sup>2</sup> material for efficient composting processing in terms of time, quality, stability and maturity. According to Rynk (1992) “a range of 20:1 to 40:1 is considered to be workable, although for many applications 50:1 and higher are acceptable. Usually 25:1 to 30:1 is an ideal range for active composting process design. In case of low C:N ratios, available C is fully utilized before stabilizing all N and excess N may be lost as NH<sub>3</sub> or nitrous oxide and odour is produced. But for higher C:N ratios, the process requires longer times to use the excess C”.

Carbon serves primarily as an energy source for the microorganisms, while a small fraction of the C is incorporated into their cells. N is a critical element for microorganisms because it is a component of the proteins, nucleic acids, amino acids, enzymes and co-enzymes necessary for cell growth and functioning. If N is a limiting factor, then degradation will be slow but if it is in excess, then losses as NH<sub>3</sub> or other N compounds can occur (Tuomela *et al.*,2000). The C:N ratios in urine containing slurries of farm dairy manure are often so low that during decomposition much of the N is lost, as it exceeds the requirement for all the microbial biomass synthesis possible from the amount of C present (Witter & Lopez-Real,1987)

## 2.4.3 BIODEGRADABILITY

Most of the organic substrates and amendments such as wood, sawdust, yard trimmings, paper, manure and sludge are directly or indirectly derived from plant materials. Manure and sludge are called “once used” biomass because they are composed of undigested plant or

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<sup>2</sup> Amendment: An amendment is a material added to the other substrates to condition the feed mixture (Haug,1993).

animal materials. In plant derived materials, cellulose, hemicellulose and lignin are the three materials used to form wood where cellulose is a course structural part or skeleton, hemicellulose is a filler material and lignin acts as a cementing or binding material in the woody mass (Haug,1993). Tuomela *et al.*(2000) reported that “lignocellulose accounts for the major part of biomass. Lignocellulose such as wood, is mainly composed of a mixture of cellulose (ca.40%), hemicellulose (ca.20-30%) and lignin (ca.20-30%). Lignin is an integral cell wall constituent which provides plant strength and resistance to microbial degradation”. However, Haug (1993) noted that a typical wood composition was cellulose 30-60%, hemicellulose 10-30% and lignin 10-20%. While the cellulose part is highly degradable (90%), hemicellulose and other sugars are moderately degradable (70%), lipids and proteins have low degradability (50%) and the lignin is difficult to break down in the typical time span of a composting process. Cellulose is composed of simple sugars including glucose whereas hemicellulose is a combination of glucose, xylose, galactose and other sugars. Lignin is a complex, aromatic, three-dimensional polymer acting as a binder between cellulose fibers and protecting the cellulose from microbial enzymatic attack.

All organic materials are not equally decomposed in composting. The composition and degradability of organic materials affect the rate of decomposition. Therefore the materials containing a high proportion of cellulose induce a fast decomposition rate in composting whereas the materials containing a high proportion of lignin will induce a slow rate of decomposition. Lignin is not fully degradable but rather modified and contributes to final characteristics of the finished compost.

Only the volatile organic component of a material is considered as biodegradable but how much of its Volatile Solids (VS) biodegrades under aerobic composting conditions depend on the biodegradability. Decomposable VS components are lipids, carbohydrates and proteins. Sugar and starch are most readily utilized by microbes and lipids/fats are also readily degradable (Haug,1993).

Mesophilic organisms rapidly utilize the most readily available and decomposable carbohydrates and proteins leaving less easily degradable hemicellulose, cellulose and lignin.

These large molecules are unable to pass through cell walls of the microorganisms responsible for decomposition. They are hydrolysed by extracellular enzymes to basic sugar units which can be utilized by most of the microorganisms. Initially the decomposition rates of both hemicellulose and cellulose are exponential and remain similar for at least 20 days but eventually the rate for hemicellulose decomposition becomes slower than that of cellulose. Finally the percentage cellulose lost is greater than that of the initial hemicellulose lost. Hemicellulose decomposition was faster at 65°C than at 28°C while cellulose decomposition was faster at 28°C than at 65°C. The initial thermophilic phase is thus important for hemicellulose degradation although cellulose decomposition begins around the peak temperature and continues in the post peak phase while the temperature is still relatively high. Lignin shows little evidence of being decomposed in the first 2 to 3 months but it may be modified as soon as composting starts. Higher basidiomycetes possess phenoloxidase enzymes which are able to breakdown the altered lignin. After 480 days at ambient temperatures about 50% of the lignin had been degraded (Crawford,1983).

During composting organic materials are modified by decomposition and humification through a wide variety of biological and biochemical processes. Microorganisms play a key role in this transformation. Microbial enzymes in compost are intracellular and extracellular. Intracellular enzymes catalyze biochemical reactions occurring within cells but extracellular enzymes are released exterior to cells to catalyze the degradation of polymeric substances which are too large to cross the cellular membrane. In N transformation, ammonium ions are produced from water soluble nitrogenous organic matter within microbial cells, through the action of intracellular enzymes. Since bacteria cannot metabolize insoluble particles of organic matter, they produce hydrolytic extracellular enzymes to depolymerize larger compounds such as proteins, aminopolysaccharides and nucleic acids to smaller fragments. These water soluble products are subsequently absorbed by a variety of microbial cells (Tiquia *et al.*,2001).

Chandler *et al.*(1983) investigated the biodegradability of various substrates under anaerobic fermentation and found that degradability of cattle manure ranged from 52.8 to 58.8% depending on the cattle feed energy content. If feed energy content is high then

degradability is also high. These authors reported that the degradability of newsprint was 28.1%, pig manure 72.2% and chicken manure 75.6%. They also found that the following equation provided the best predictive model for substrate biodegradability.

$$B = 0.83 - (0.028) X. \text{-----} (2.1)$$

Where, B = biodegradable fraction of the volatile solids.

X = lignin content and expressed as % of VS.

#### 2.4.3.1 PARTITIONING OF CARBON AND NITROGEN COMPOUNDS

In a composting system, C and N can be partitioned into four fraction: (1) Compounds lost to the atmosphere and leachate (2) Water-soluble (3) Acid-hydrolyzable and (4) Non-hydrolyzable. The biological transformation of organic matter from animal manures or other sources by composting results in a decrease of total, water-soluble and acid-hydrolyzable C, but non-hydrolyzable C remains relatively constant during composting. On the other hand, it reduces the total, water soluble and acid-hydrolyzable N, but the non-hydrolyzable N increases as the process proceeds and forms stabilized complex organic N (linked with humus formation) which is not readily available to microbes and considered as long term reserve of N in compost. The water-soluble and acid-hydrolyzable C & N are bio-available. Therefore, C:N ratios for the design of co-composting materials should be based on water-soluble and acid-hydrolyzable C and N, rather than on total C and N ( Pare *et al.*,1998). Mathur *et al.*(1990) found that 90.7% of the total N in dairy manure slurries was in hydrolyzable form but Pare *et al.*(1998) found 65-73% of total N of dairy manure is hydrolyzable which could be due to the difference of biodegradable fraction in manure.

#### 2.4.3.2 BIODEGRADABILITY OF WOODY MATERIALS

Sawdust degradability depends on its source. If it is sourced from soft wood then degradability is low but if it is from hard wood then degradability is relatively high. Haug (1993) studied the decomposition of papermill sludges and other substrates and divided the VS content into fast and slow fractions and partitioned also the total degradability into fast and slow rates. He reported that 20% VS of sawdust degraded quickly and the remaining



80% degrade only slowly. A case study carried out by the city of Plattsburgh, New York indicated that the degradability of sawdust from the soft wood, white pine, was 11.2% after 90 days whereas sawdust from hardwood degraded more than 50% within the same period of time and was finally degraded by 78% after 350 days (Haug,1993). Atkinson *et al.* (1996) reported that after 29 days of composting a poultry litter, sawdust mix, the sawdust had degraded to 29% of its VS.

There are some differences between the wood fibers which constitute the basic raw materials of newsprint and office paper. Wood fibers divide into two major categories, softwood and hardwood. Softwoods generally have long fibers which provide strength and a rough surface whereas hardwoods have short fibers and can act as a filler material and provide a smooth surface. Most office paper and paperboard is made from a combination of the two fibers. For newsprint and other publication paper, mostly mechanically produced softwood long fibers are used and lignin is not removed.

In Kraft processing, chemically produced fibers from softwood and hardwood are combined to make office paper in which a major part of lignin is chemically dissolved and removed (Kline,1982). Kayhanian & Tchobanoglous (1992) determined the lignin content and then calculated the biodegradability of newsprint, office paper and mixed paper ( 25% newsprint + 75% office paper) using Equation 2.1 (Chandler *et al.*,1983). Calculation results are given in Table 2.1.

Table 2.1 The biodegradable fraction and lignin contents of papers.

Component	Lignin content (% of VS)	Biodegradable fraction (% of VS)
Newsprint	21.9	21.7
Office paper	0.4	81.9
Mixed paper (25% Newsprint+75% office paper)	5.8	66.7

Source: Kayhanian & Tchobanoglous (1992). Values based upon  $w/w \times 100$ .

These results suggest that the hardwood fraction of office paper contributes to its biodegradability.

#### 2.4.4 PARTICLE SIZE AND FREE AIR SPACE

Particle size is a critical factor in composting. When the particle size is small the rate of decomposition is enhanced because of the greater surface area available for microbial attack, facilitated also by a reduction of intraparticle depth for O<sub>2</sub> diffusion and microbial cell penetration. Small particle size improves the insulating properties of the compost thus retaining heat within the compost. However, too small a particle size can reduce the intraparticle voids significantly and can reduce the rate of O<sub>2</sub> & CO<sub>2</sub> diffusion, especially during the thermophilic stage of composting (Crawford,1983). Haug (1993) reported that “the particle size distribution of amendment is important for structural conditioning of a wet substrate. Too fine an amendment can provide the desired level of solid content but may not provide the desired level of Free Air Space (FAS). Satisfactory results can be obtained if the particle sizes ranges from 3mm to 50mm (1/8 to 2 inches) average diameter. The particle size distribution is also important to energy conditioning. Fine particles are undesirable from structural standpoint, but highly desirable for energy conditioning.” A suitable moisture content in fine particle size bulking agents<sup>3</sup> may be maintained at lower moisture levels such as 50% wet basis (Hong *et al.*,1983).

Free air space is important for determining the quantity and movement of air through the mixture. The optimum moisture content is related to maintenance of a certain minimum FAS. Different materials can hold different amounts of moisture at a particular FAS value. So moisture must be high enough to assure adequate rates of decomposition but that amount should not restrict the FAS which would eliminate or reduce air supply, thus diminishing the rate of biological activity. The FAS in the compost matrix is influenced by the moisture content and becomes limiting when the moisture is raised above 60% (Schulze,1961). FAS can be defined as the ratio of gas volume (the fraction of the total volume of material

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<sup>3</sup> Bulking agent: A bulking agent is a material, organic or inorganic, of sufficient size to provide structural support and maintain air spaces within the composting matrix (Haug,1993).

occupied by gas) to total volume of material (including solid, liquid and gas volume) and can be determined by the formula provided by Haug (1993):

$$f = 1 - \frac{\delta_m S_m}{G_m \delta_m} - \frac{\delta_m (1 - S_m)}{\delta_m} \text{ ----- 2.2}$$

Where,

$\delta_m$  = Unit bulk weight of the materials to be composted.

$S_m$  = fractional solids content of the mixture.

$G_m$  = Specific gravity of the mixture solids.

Optimum moisture contents usually fall in the range of FAS values between 30-35%. A minimum 30% FAS should be maintained but under constant tumbling or turning a lower FAS is acceptable. Free air space can be also determined by the following formula given by Hong *et al.*(1983):

$$\text{FAS (\%)} = \text{Porosity} [1 - \text{moisture content} / 100]. \text{ ----- 2.3}$$

According to Seekins (1999), bulk density is the mass of the compost mixture for a given volume in lbs/yd<sup>3</sup> or kg/m<sup>3</sup> which indirectly indicates how easily air can penetrate the material. If the material is too dense, no matter what system is provided, it would not compost adequately. The process will operate well if bulk density is between roughly 800-1000 lbs/yd<sup>3</sup> (475-600 kg/m<sup>3</sup>), if it is <800 lbs/yd<sup>3</sup> (475 kg/m<sup>3</sup>), it will compost well with little or no turning but may loss moisture rapidly. Whereas if it is > 1000 lbs/yd<sup>3</sup> (600 kg/m<sup>3</sup>) then it will be difficult to aerate the material.

Hong *et al.*(1983) reported that insufficient air supply causes a bulk weight increase and over aeration decreased the bulk weight sharply. An optimal FAS range from 32.7% to 40.8% is reported for composting of materials with a moisture content 55.6-64.6%. The optimum bulk weight should be maintained between 0.25 to 0.33 g/cm<sup>3</sup>.

The increased wet bulk density also causes higher compressive stresses and the compaction of the bed due to its own weight which can cause significant vertical profiles of free air space and permeability (Das & Keener,1997).

Most of the composting substrates are usually not fit for direct composting and that is why different types of remedial measures are required such as conditioning of wet substrates, conditioning of dry substrate, chemical conditioning and mass balance, water ratio and energy ratio adjustments.

#### **2.4.5 MOISTURE CONTENT**

Crawford (1983) reported that “moisture is essential for the metabolic processes of microorganisms. Water is used as the medium for chemical reactions, it transports nutrients and helps movement of microbes. More rigid materials like straw can be composted at higher moisture content than weak materials such as paper. Moisture level is linked with pore size and aeration. Decreasing the particle size will reduce the inter-particulate void size and will decrease O<sub>2</sub> diffusion and thus slowdown the rate of composting”. Rynk (1992) has suggested that “the acceptable range of moisture content is 40-65%. Moisture content below 40% will inhibit the biological activity of composting process and above 65% will displace the air from the pore spaces of matrix and will induce anaerobic processes. Since the composting process evaporates a large amount of water during composting so moisture content should be well above 40%. The acceptable upper limit depends on the porosity and absorbency of the raw materials”. Although the range of 50-60% is generally recommended for composting, Fernandes *et al.*(1994) found that composting with 80% moisture content was feasible. Although Haug (1993) recommended a moisture content for manure composting of 55-65%, it was possible to compost dairy manure with an initial moisture contents of 70-80% by adding small amounts of straw or dried compost using an aerated bin-type reactor and had temperature between 65-79°C, but at above 75% Moisture Content (MC) lower temperatures and extended process times occurred (Wilson,1971).

As the moisture is increased the material becomes more plastic and susceptible to compaction. A study by Das & Keener (1997) to quantify the influence of moisture on compaction and pressure drop for two types of compostable materials, namely biosolids and dairy manure, demonstrated that at higher MC, biosolids are more plastic in nature. Highly moist biosolids had a greater sensitivity to compressive stress reflected by increased pressure drop due to easy pore space compaction and blocking. The air permeability decreased exponentially with increasing compressive stress. However the dairy manure, even at high moisture content range of 57-73% (wet basis) was found to be fibrous, non-cohesive, less sensitive to compressive stress and did not exhibit plastic compactive behavior which was possibly due to the high moisture-absorbing capacity of dairy manure.

High moisture content mixtures need a large void volume to ensure adequate aeration but the higher moisture content lacks the porosity and induces a tendency to compact. For very wet substrates (like manure slurries), structural conditioning is essential to ensure a friable mixture that will promote the evaporation of moisture through temperature elevation. A number of approaches are available to overcome the problem of high moisture content in the feed materials. Firstly, dry mature compost can be recycled back into the system to condition the wet feed materials. Secondly, dry amendments like sawdust, rice hulls, newspaper, peat moss and similar amendment can be added to the wet feed materials. Thirdly, bulking agents such as wood chips, even shredded tires can be used to maintain structural integrity and to provide a more open structure to allow adequate aeration. Fourthly, wet substrate can be air or heat dried. Fifthly, constant agitation can be provided by mechanical means. Among the above five options the first three are reasonable but the last two are very difficult for large scale composting (Haug,1993).

#### **2.4.6 POROSITY, STRUCTURE & TEXTURE**

According to Rynk (1992), the three physical properties of porosity, structure & texture can affect the composting process by their influence on aeration. However, they can be adjusted by selection, grinding and mixing of raw materials. Materials added to adjust these properties are called amendment and bulking agents. Porosity is the total air space within the composting mass as determined by particle size and their size gradation and the continuity of

air in available spaces or in other words, “the ratio of void volume to total volume”. Larger and more uniform particles increase porosity. Porosity can be determined by the formula provided by Haug,(1993):

$$p = 1 - \frac{\delta_m S_m}{G_m \delta_m} \text{ ----- 2.4}$$

Where,

$\delta_m$  = Unit bulk weight of the materials to be composted.

$S_m$  = Fractional solids content of the mixture.

$G_m$  = Specific gravity of the mixture solids.

Porosity can be also determined by the following formula given by Hong *et al.*(1983):

$$\text{Porosity(\%)} = 100 \times [ 1 - \text{bulk density} / \text{Sp. gravity} ] \text{ ----- 2.5}$$

Structure is the rigidity of materials used in the matrix, i.e. their ability to resist settling and compaction over time. Good structure does not loose porosity and allows proper aeration. Texture is the total available surface area of the raw materials used in the pile for aerobic microbial activity. Therefore the greater the surface area, the greater will be decomposition without affecting the required porosity and structure (Rynk,1992).

#### 2.4.7 TEMPERATURE

Rates of chemical and biological reactions are a function of temperature. Over a limited temperature range suitable for living organisms the biologically mediated reaction rates increase exponentially with temperature increase, doubling with each 10°C rise. Like any other biochemical reaction, there is an upper limit to the exponential increase where the thermophilic microbes cannot overcome the effects of thermal denaturation of their enzymes and reaction rates then decrease with further increases in temperature. High temperature causes increased water vapor pressure and increased latent heat of evaporation resulting in drying of wet substrates. Microbial rates of reaction are markedly reduced as the temperature falls below 20°C. At low temperatures reaction rates become so slow that the rate of heat

generation is less than the rate of heat loss to the surrounding (Haug,1993). Air supply is the main factor causing temperature variations in the composting pile and the use of different aeration schedules result in different temperature regimes (Sartaj *et al.*,1997). According to Rynk (1992), “composting takes place within two ranges of biologically produced temperatures known as mesophilic (50-105°F or 10-40°C) and thermophilic (>105°F or 40°C). The thermophilic temperature is essential for destroying more pathogens, weed seeds, insects, insect eggs and fly larvae in composting materials. The critical temperature for destroying human pathogens is 131°F (55°C) and for plant pathogens it is 145°F (63°C). The thermophilic temperature can raise above 160°F (71°C) and at this temperature many microbes die or become dormant. Composting authorities suggest the maintenance of a temperature between 110-150°F (43-65°C)”. Hong *et al.*(1983) mentioned that “the mesophilic temperatures are between ambient and 40°C and above 40°C thermophilic microbes take over the process and continue up to 60-70°C ”. Pelczar *et al.*(1993) reported that mesophiles and thermophiles grow best within a temperature range of 25-40°C and 50-60°C respectively but most thermophiles grow at temperatures from 40-85°C “. Most authors consider the boundary between mesophilic and thermophilic to be 40°C but Haug (1993) claims 45°C. In the research to be discussed in this thesis the boundary is selected at 40°C to comply with majority of authors. Compost sometimes attains temperatures as high as 80°C which stops the growth of the thermoactinomyces until the temperature drops to 65°C or below (Hong *et al.*,1983). The temperature corresponding to the maximum reaction rate constant has been the subject of debate. Michel (1999) reported that the rate of organic matter conversion at 65°C was one third of that observed at 55°C and the microbial diversity was also reduced at 65°C. Temperature alone has a significant influence on respiratory activities and rate of decomposition during composting. From the study of Jackson & Line (1997) it had been found that composting occurred at a faster rate at 55°C than at 35°C because 35°C caused 30-50 days delay in maturation of compost. Hong *et al.*(1983) reported that “ majority of the decomposition in the composting process takes place in the 40 to 70°C region and the thermophilic range 55 to 70°C has been found to be the most efficient range for CO<sub>2</sub> production. A temperature of between 55 and 70°C was affected by the aeration rate, bulk weight, pH value, distribution of fine and coarse particle sizes and moisture content”.

A study by Nishida *et al.*(1998) in Japan to ascertain the relationship between the maximum temperature and survival (germinability or viability) of weed seeds in cattle manure compost showed that some species of weed seeds lost their germinability when temperatures rose above 46°C and all species lost their germinability when temperature rose above 57°C. The authors suggested that raising the temperature above 60°C for more than 142hrs enables the killing of non-dormant seeds to occur but dormant weed seeds could be more tolerant to heat. Hong *et al.*(1983) concluded from a study of dairy manure composting that the maximum decomposition rate occurred between 65 and 75°C, for an initial pH of 7.8-8.3 and with an aeration rate between 0.87-1.87 l/min kg VS.

#### **2.4.8 TIME -TEMPERATURE PATTERN**

In composting processes, the time needed to achieve maximum temperature and the shape of the time-temperature curve depends on various factors including nutrients, moisture, size of heap, aeration rate, agitation, particle size and FAS. A typical profile for the temperature and time curve of a batch windrow system is shown in Fig.2.2. Composting leads to biologically produced heat and there is a rise in temperature in the pile immediately after casting. The increase in temperature continues through the transition from mesophilic to thermophilic temperatures. For a small pile, this transition may show a clear but short declining trend (Haug,1993).

Temperature continues to increase to a peak temperature value and then a gradual decrease to ambient temperature over a period of time. This profile can be explained in terms of the rate of heat production being proportional to the rate of organic oxidation. A temperature decline to near ambient is a good indication that the process is nearing completion, if the temperature drop is not caused by thermal kill, oxygen shortage, low moisture, low FAS or lack of sufficient pile insulation (Haug,1993). According to Gray *et al.*(1971), The whole process can be divided into four stages- mesophilic, thermophilic, cooling down and maturing. At the beginning, the mass is at ambient temperature but as the indigenous mesophilic bacteria and fungi multiply, the temperature rises rapidly.



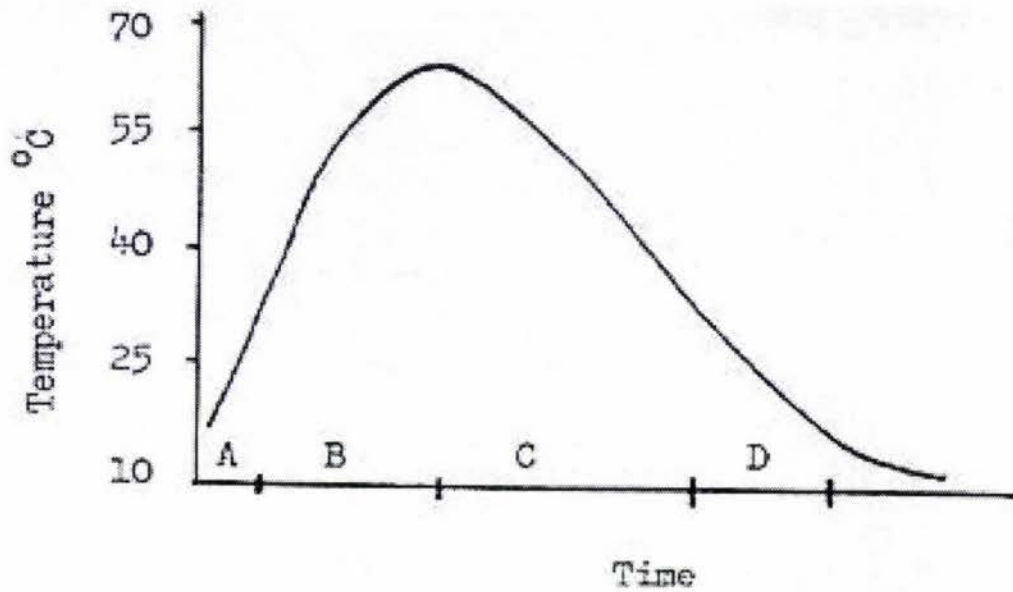


Figure 2.2 Temperature variation with time for a typical composting indicating the phases as A = mesophilic, B = thermophilic, C = cooling & D = maturing. (Source: Crawford, 1983).

At temperatures above 40°C the mesophilic activity decreases causing the end of the initial mesophilic phase and then the degradation is taken over by thermophilic microbes which can raise the temperature above 75°C a period called the thermophilic or high rate phase. At 60°C thermophilic fungi die off and the reaction is kept going by the thermophilic spore forming bacteria, the actinomycetes. As the readily available nutrients are exhausted, the reaction rate slows and the mass starts to cool down, called the cool down phase. Once the temperature falls below 60°C, the thermophilic fungi from the cooler outside mass re-invade the centre and start their attack on the cellulose. At temperatures around 40°C, surviving mesophilic organisms restart their activity either from heat resistant spores or by re-invasion as the temperature starts to fall towards ambient. This is called the maturation phase.

The time required for the desirable transformation of raw materials into compost depends upon many factors for example temperature and its duration, moisture, frequency of aeration and user requirements. Proper moisture content, thermophilic temperatures and its duration, balanced C:N ratio, particle size, materials composition, frequent aeration and composting

design & operational method can ensure the shortest possible composting period. The entire decomposition and stabilization of materials can be accomplished within a few weeks under favorable conditions and a period of more than 2 months is most commonly required (Rynk,1992).

Curing occurs at low mesophilic temperatures when the oxygen consumption, heat generation and moisture evaporation are much lower. Curing is essential to have a mature compost. Immature compost contains high organic acids, high C:N ratio which can adversely affect the plants in horticultural applications. Formation of nitrate-nitrogen becomes noticeable during the curing stage. Another advantage of curing is the recolonization of microorganisms in compost which can improve disease suppressing qualities. There is no specific point at which curing should start or end. When temperature increases cannot be regained after turning or aeration, then curing begins and when the pile temperature falls to ambient temperature then the curing is considered to be completed. A “rule of thumb” recommends a minimum curing time of one month (Rynk,1992).

#### **2.4.9 MICROORGANISMS**

According to Rynk (1992), “a diverse group of microorganisms are found in the composting process. The major groups of microorganisms are *bacteria, fungi and actinomycetes* and each of them have both mesophilic and thermophilic species. Among them, bacteria are the most numerous and faster decomposers than the others. Fungi are larger in size and more tolerant of low-moisture & low pH than bacteria but less tolerant of low-oxygen environments. Fungi are more beneficial for decomposition of decay-resistant materials”. Actinomycetes grow in filaments like fungi. Actinomycetes are able to degrade some cellulose and solubilize lignin but no more than fungi can and they tolerate higher temperatures and pH than fungi (Tuomela *et al.*,2000). Bacteria flourish in the early stages of composting but fungi and actinomycetes, feeding on decay-resistant materials become more important near the end of composting. At temperatures above 160°F (71°C), most of the active microbes die but the heat resistant species of some bacteria and actinomycetes form spores and when the pile cools enough they germinate as vegetative bacteria and actinomycetes (Rynk,1992). Some other organisms like protozoa, worms, insects, and mites

play an important role in the composting process. Some bacteria, e.g. *Bacillus* spp. are capable of producing thick-walled endospores which are very resistant to heat, radiation and chemical disinfection (Haug,1993). Staphylococci has been reported to be dominant during the mesophilic phase and at the beginning of the thermophilic phase and *Bacillus* appeared to be the dominant genus during the remainder of the composting cycle. The number of these bacteria increases at the middle of the thermophilic phase and this increase can persist until the end of the cycle. The late appearance of gram-negative rods (opportunistic pathogens) during the cooling phase could represent a serious risk for the sanitary quality of the finished compost for agricultural use (Hassen *et al.*, 2001). Sesay *et al.*(1997) reported that “an increase in faecal coliforms at the end of thermophilic phase was reduced during the maturation period and neither faecal coliforms nor streptococci were detected after five months of maturation, although temperatures in the maturation pile were near ambient levels”.

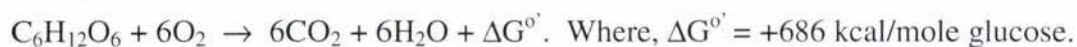
A wide range of bacteria have been isolated from different compost environments, including species of *Pseudomonas*, *Klebsiella* and *Bacillus* (Nakasaki *et al.*,1985; Strom, 1985). About 87% of the randomly selected colonies during the thermophilic phase of composting belong to the genus *Bacillus* (Strom, 1985).

#### **2.4.10 pH OF THE MATERIALS**

Composting process is relatively insensitive to pH values found in the usual mixture of organic materials. The preferable range of pH is 6.5-8.0 and composting can proceed effectively between 5.5 and 9.0 but it is likely to be less effective at these limits. Therefore it is wise to establish a pH greater than 5.5 and less than 9. When materials have a high N content, the loss of ammonia adds further alkalinity (Rynk,1992). The pH of manure is usually slightly above 7. As long as the environment is moist and the pH is close to neutral, most of the NH<sub>3</sub> remains in solution, where it can be used by the microorganisms. If the pile gets too dry or the pH goes too high, the gaseous NH<sub>3</sub> forms and is lost from the pile as it evaporates which is loss of valuable N and a source of potential odours (Seekins,1999). An initially low pH of substrates can prolong the composting process (Hong *et al.*,1983).

### 2.4.11 ENERGY

Living organisms are *autotrophic* and *heterotrophic* and are dependent on each other for their survival. Microorganisms found in compost populations which are responsible for the biodegradation of organic matter are heterotrophs. Furthermore, most heterotrophic cells use atmospheric O<sub>2</sub> for the oxidation of organic molecules like glucose to produce CO<sub>2</sub> and H<sub>2</sub>O. Organic compounds have a characteristic “heat of combustion”- the number of kcal of heat given up to the surroundings per 1 mole or gram of organic molecules burned completely at the expense of molecular O<sub>2</sub>. The complete combustion of 1 mole of glucose can yield a maximum of 686 Kcal heat energy according to the following glucose combustion equation (Lehninger, 1973).



The heat of combustion for molecules used by microorganisms as energy sources for growth are given in Table 2.2 below:

Table 2.2 The heat of combustion values for major energy substrates.

Energy substrates	Molecular Weight	Heat of combustion	
		kcal/mole	kcal/g
D-glucose	180	673	3.74
Tripalmitin	809	7510	9.3
Glycine	75	234	3.12

Source: Lehninger (1973).

The Table 2.2 above shows that combustion of a fat yields much more heat energy per gram than combustion of either a carbohydrates or an amino acid. Consequently, the oxidation of fatty materials require more O<sub>2</sub> to drive the respiratory metabolism needed for its mineralisation to CO<sub>2</sub>, H<sub>2</sub>O, heat and more molecules.

In composting systems, organic molecules contain chemical energy which is trapped as ATP (for cell biosynthesis) and released as heat energy during the mineralisation process. Heat is the form of energy that flows due to temperature differences between two bodies and heat released during metabolism, under constant pressure, is equal to the enthalpy change. Enthalpy is the heat of reaction required to form a compound from its elements. The specific heat difference between a solid and a liquid under constant pressure and constant volume is

small but dry gases and water vapour show greater specific heat values because of the added heat energy required to expand them against constant pressure (Haug,1993).

With respect to the composting process energy is the most apparent problem in very wet substrates (biosolids, manure) because of the high water content. Dewatering wet substrates from about 20%(w/w) solids to a final product with a 60%(w/w) solid content by driving off excess water, needs a significant amount of heat to be released from metabolic processes (Haug,1997).

Haug (1997) also notes that energy poor feedstocks cannot elevate temperatures sufficiently for evaporating the required amount of water, thus a soggy, unsuitable end-product will be produced. To make the wet and energy poor substrate suitable for composting, a supplemental source of energy needs to be added, which can be obtained from the addition of a degradable dry amendment like sawdust or some other biodegradable materials because they can provide energy/fuel for the process without adding a water burden. Whereas fairly dry materials are more likely energy rich and they will be capable of raising temperatures and driving off excess water. However, one problem is that if air is supplied to control the temperatures then it can cause extreme dryness.

Volatile solids have been used as an indirect measure of a material's energy content and it approximates the value for organic matter content (Seekins,1999). Both variables indicate how much material is available to the organisms as an energy source. The Volatile Solids (VS) content of the material must be greater than 40% on a dry basis to get adequate heating. Richard & Choi (1997) has reported that if the process is designed for optimizing the drying rates, a 0.75kg-H<sub>2</sub>O/kg.VS.day or greater removal rate can be achieved with a highly degradable substrate.

## **2.5 THERMODYNAMICS**

According to (Haug,1993), the application of thermodynamic principles and kinetics in composting has revealed much about the limitation and expectation of composting.

Thermodynamics deals with the transformation of energy in physical, chemical and biological systems while kinetics deals with the rate and speeds of reaction and one cannot be predicted from another.

Heat always flows due to temperature difference. The specific heat of composting materials can be measured under constant volume ( $C_v$ ) and constant pressure ( $C_p$ ) conditions and the difference between the two is small for both liquids and solids. For gases, however,  $C_p > C_v$ , because excess energy is required to expand the gas against constant pressure. Most composting processes operate under constant pressure, so dry gases and water vapor in composting are important for energy concern. According to the First Law of Thermodynamics, energy cannot be created or destroyed. In an open composting system, heat is either absorbed or released and therefore work is done by the system or on the system. Consequently,

Heat flow into the system = Change of internal energy + work done by the system.

$$\text{Or } q = \Delta E + w. \text{ ----- 2.6}$$

For constant volume, expansion or contraction is not possible. So  $w = 0$ , and  $q = \Delta E$ .

Now the heat per unit mass that can flow into the system,

$$\Delta q = m.C.\Delta T. \text{ ----- 2.7}$$

Where,  $C = \text{Sp. heat in Cal/g}^{\circ}\text{C}$ .

$m = \text{mass}$ .

At constant pressure, Equation 2.7 can be used to establish the composting energy balance. The enthalpy of a compound is the heat of reaction required to form the compound again from its elements. Now, from Equation 2.6,

$$q = \Delta E + w.$$

$$\text{Or } q = \Delta E + P.dV. [ w = \text{force} * \text{distance} = F. dL = P.A.dL. = P.dV ].$$

$$\text{Or } q = \Delta E + P.dV. = E_2 - E_1 + P.V_2 - P.V_1 = (E_2 + P.V_2) - (E_1 + P.V_1).$$

$$\text{Or } q = H_2 - H_1 = \Delta H, \text{ which is called enthalpy. -----2.8}$$

When heat is absorbed then  $q$  &  $H$  are +ve and endothermic and when it is released then  $q$  &  $H$  are -ve and exothermic. The change of enthalpy and the change in internal energy between two equilibrium states will be always same.

To understand the application of the Second Law of Thermodynamics in composting, when a solid substance dissolves in a liquid then the existence of different molecules in the solution are more random than its previous state. Thus the dissolution process tends to maximize randomness or entropy ( $\Delta S$ ) or in other words, all spontaneous changes in an isolated system occur with an increase in entropy or randomness.

According to J. W. Gibbs,

Change of enthalpy = Change of useful/available energy (free energy) + Change in entropy.

$$\text{Or } \Delta H = \Delta G + T \cdot \Delta S. \quad [T \text{ \& P constant}]$$

$$\text{Or } \Delta G = \Delta H - T \cdot \Delta S. \quad \text{----- 2.9}$$

In any spontaneous process, whether endothermic or exothermic, the entropy must increase (+ve) and the free energy must decrease and the reaction free energy must be zero at equilibrium.

It is often difficult to estimate heats of reaction for organic wastes from standard enthalpy values because wastes comprises a mixture of organics of unknown composition.

### 2.5.1 KINETICS

To describe the relation between temperature and reaction rate, Arrhenius proposed the following equation,

$$\frac{d(\ln k)}{dT} = \frac{E_a}{RT^2} \quad \text{----- 2.10}$$

Where,

$k$  = reaction rate constat.

$E_a$  = activation energy for the reaction, cal / mol.

$T$  = absolute temperature, °K.

Now by integration,

$$\ln \frac{k_2}{k_1} = \frac{E_a(T_2 - T_1)}{RT_1T_2} \text{ -----2.11}$$

Most biological processes operate under a limited temperature range, so the product of  $T_1$  and  $T_2$  changes slightly over that range and  $E_a/RT_1T_2$  can be assumed to be constant. Thus,

$$\ln \frac{k_2}{k_1} = \phi (T_1 - T_2).$$

$$\text{or } k_2 = k_1 \cdot e^{\phi(T_1 - T_2)} \quad [\text{for } Q_{10} = 2; \phi = 0.069]. \text{ -----2.12}$$

Most chemical and biological reaction rates approximately double for each 10°C rise in temperature ( $Q_{10}=2$ ). Most biological systems depend on the catalytic functioning of enzymes which are temperature sensitive. Above or below their optimal operating temperature rates will slow, to become inactive at extreme T values. Diffusion controlled reactions exhibit a  $Q_{10}<2$  because diffusion coefficients vary less with temperature.

Taking antilog of both side of Equation 2.12,

$$k_2 = [k_1 \cdot e^{(E_a/RT_1)}] \cdot e^{(-E_a/RT_2)}.$$

$$\text{Or } k_2 = C \cdot e^{(-E_a/RT_2)}. [\text{Since } k_1 \text{ correspond to } T_1, \text{ so all in bracket is constant}]. \text{ ---2.13}$$

## 2.5.2 HEAT ESTIMATION

According to (Haug,1993), the heating value ( A weighed sample is totally combusted in an insulated environment. The energy (KJ/g) released in oxidative combustion causes a temperature increase in the insulated system which is called heating value) of an organic waste can be determined by calorimetric measurements on the dry solids (ds). At constant pressure, the heat of reaction



can be determined using an open calorimeter but at constant volume, it is measured using a bomb calorimeter. Gaseous products of combustion during composting process are CO<sub>2</sub>, water vapour and N gas.

The degradation for any type of organic matter is given by Spoehr and Milner (1949):-

$$R = 100[2.66(C) + 7.94(H) - (O)] / 398.9 \text{ ----- } 2.14$$

Where C, H and O are the weight percentage of carbon, hydrogen and oxygen respectively on an ash free basis. The degree of combustion is

$$Q = 127R + 400 \text{ in Cal / g - ash free ds. ----- } 2.15$$

Another formula for Q, called Dulong's formula is,

$$Q = 145.4(C) + 620[H - (O/8)] + 41(S). \text{ ----- } 2.16$$

Where Q = heat of combustion in Btu/lb ash-free ds.

S = Sulfur content on ash free basis, weight %.

A rule of thumb is often used on the basis of COD of waste, as the COD test is often practiced by laboratories and because heat release per unit of COD is relatively constant. For most organics the heat released per gram COD of the waste is about 3.4±0.2 Kcal. According to Vanderholm (1984), the average COD of dairy cattle yard wash water is 0.33 kg/head/day or 6600mg COD/litre and the average raw manure slurry production in dairy shed is 50 Litre/head/day.

Therefore, amount of heat released = 3.4 kcal/g COD\*0.33\*1000 g COD/head/day.

$$= 1122 \text{ kcal/head/day.}$$

$$\text{Or } = 3.4 \text{ kcal} * 6.6 \text{g COD/L} * 50 \text{L/head/day.}$$

$$= 1122 \text{ kcal/head/day.}$$

The COD of dairy manure slurry is 98% of its total solids. Solid content of manure slurry is 8.1%(w/w), volatile solid content is 73%(w/w) and bulk density is 1 kg/Litre (Vanderholm,1984).

Therefore, the amount of heat released in usual unit Cal/g VS,

1 Litre Manure slurry = 1 kg manure slurry.

Or 1 kg manure slurry = 0.081 kg TS.

Or 0.081 kg TS = 0.98\* 0.081 kg COD.

Or 81 g dry solids = 79.38 g COD.

Or 1 g dry solids = 0.98 g COD. [ 0.98\*3.4 = 3.332 Kcal/g dry solids ].

Or Energy released = **3332** Cal/g dry solids.

Or 0.73\*0.081 kg VS = 79.38 g COD.

Or 59.13 g VS = 79.38 g COD.

Or 1 g VS = 1.34 g COD. ( i.e. 1.34 g COD/g VS ).

Therefore, Energy released = 3.4\*1.34 = 4.556 Kcal/g VS = **4556** Cal/g VS.

Now, the gross energy content determined in the laboratory and the theoretical energy content are given in the Table2.3 below:

Table.2.3 Comparison of theoretical and measured energy content of cow manure slurry

Sources	Energy content in Cal/g ds	Energy content in Cal/g VS.
Theoretically calculated on the basis of data from Vanderholm,(1984)	3332	4556
Laboratory experiment –I (Mollah, 2002) <sup>4</sup>	3990	6009
Laboratory experiment-II (Mollah, 2002) <sup>4</sup>	3480	5480

### 2.5.3 HEAT TRANSFER MECHANISMS IN COMPOSTING

In composting, heat can be transferred in three ways: conduction, convection and radiation. Conductive transfer occurs without mass movement due to the temperature difference between two points. In a compost pile heat can be transferred by conduction from one particle in contact with another and where a temperature difference between the two

<sup>4</sup> See Tables 5.1 and 5.2 presented in this thesis.

particles exists. The thermal conductivity of a material depends on its state (solid, liquid or gas). A large compost pile will tend to be self-insulating and heat losses by conduction may be negligible. The typical values of thermal conductivity for compost material ranges from 2 to 4 Cal/ (h cm<sup>2</sup> °C/cm) (Haug,1993).

Convective heat transfer occurs in liquids or gases by the mass movement of material between two different temperature zones and intermolecular heat transfer occurs. Movement of hot gases or water vapour in a compost pile is an example. Mass movement of ambient air across the compost pile will cause convective heat loss. In response to the temperature difference heat will be conducted from the interior of the pile to the pile wall (Haug,1993).

Heat can be also transferred as a result of radiant or electromagnetic energy exchange between two bodies of different temperatures. This transfer can occur in a vacuum and does not require any physical movement or contact. Radiant energy is always being exchanged, but a net exchange occurs in one direction when there is a temperature difference between two bodies. In composting, it is during the period when the pile is at a higher temperature than the surrounding ambient air temperature, then some radiative heat losses can be expected (Haug,1993).

#### **2.5.4 HEAT AND MASS TRANSFORMATION IN WET COMPOSTING SYSTEM**

The science of thermodynamics analyses energy differences between the initial total energy of the total raw compost mixture placed in a pile and all other matter (apart from the compost) in the surroundings and the final total energy of the system at equilibrium. Energy exchange is accompanied by either absorption or evolution of heat energy between the system and its surroundings. Composting occurs with loss of heat (exothermic) to the surroundings and the energy change can be calculated as kcal/g-molecular weight of biodegradable compound transformed. According to Lehninger (1973), organic compounds have a characteristic under composting called heat of combustion, defined as kcal of heat given up to the surroundings per mole or gram molecular weight of the substance is burned at the expense of molecular oxygen. Although heat is a medium of energy transformation it is

not the useful form of energy for doing biological work within the cell because living organisms are isothermal.

The physical and chemical processes in living microorganisms proceed in such a direction that the randomness (or entropy) of the system increases to a maximum due to concentration gradients under constant temperature and pressure (Lehninger,1973). This change in entropy is quantitatively related to total energy change of the system by a third function called free energy, thus entropy & free energy are related by the following equations.

$$\Delta G = \Delta E - T \cdot \Delta S$$

$$\text{Or } \Delta E = \Delta G + T \cdot \Delta S. \text{ -----} -2.17$$

Where,

$\Delta G$  = Change in free energy.

$\Delta E$  = Change in total energy.

$T$  = Absolute temperature.

$\Delta S$  = Change in entropy of the system plus surroundings.

Therefore, free energy change is that fraction of the total energy change which is available to do work within the cells under isothermal conditions.

When living organisms grow they decrease in entropy but this decrease in entropy can occur only if the surroundings increase in entropy (Lehninger,1973). For example, the end products of glucose microbial aerobic metabolism are  $\text{CO}_2$  and  $\text{H}_2\text{O}$  which are more "random" than the glucose molecule. Since the glucose is taken from the surroundings and end products are discharged back into it an increase in entropy of the surroundings will occur (Haug,1993).

Every chemical reaction has a equilibrium constant at its equilibrium state. If the equilibrium constant of a reaction is known then the standard free energy change of the reaction can be calculated using the following formula which gives the maximum amount of work that can be done at constant temperature and pressure:

$$\Delta G^{\circ}_R = -RT \ln K'_{eq} \text{ ----- 2.18}$$

Where,

$R$  = Gas constant (1.987 cal / mole – deg.)

$T$  = Absolute temperature (25 + 273 = 298° K).

$K'_{eq}$  = Natural Logarithm of the equilibrium constant at 25° C and  $p^H = 7$ .

$\Delta G^{\circ}_R$  = Standard free energy change

If the equilibrium constant is greater than 1 then the standard free energy change is negative (free energy reduced and heat energy released) which indicates that the reaction is exothermic and going towards completion. If it is less than 1 then the free energy change is positive and an energy input into the system from surroundings is required for reaction and also indicates that the reaction is endothermic (Lehninger, 1973).

During composting, some of the chemical bond energy will be captured by microbes for their own metabolic use and any remaining energy will be released as waste heat to the surroundings. All heat energy yielding reactions are conducted within the cell and produce CO<sub>2</sub> and H<sub>2</sub>O. If the produced H<sub>2</sub>O remains as water vapour, then the enthalpy changes cause a lower heat of combustion but if the H<sub>2</sub>O is condensed to liquid in the cell, additional heat is released and causes a higher heat of combustion (Haug, 1993). This produced heat accumulates in a wet compost pile and causes a temperature elevation of solids, water and air in the composting mixture. Drying of wet substrate by latent heat of evaporation thus becomes possible. The loss of moisture is desirable enabling the pile to proceed towards optimum moisture content and FAS and thus produce a relatively dry product .

Due to the temperature differences between the inside and outside of a compost pile, sensible heat moves towards low temperature zones from those of high temperature and fresh air will enter the pile through molecular diffusion and mass movement. This movement occurs due to the high temperature of gases inside the pile and the effect is called natural draft ventilation. As pile temperature increases, the density of dry air decreases and saturation vapor pressure increases exponentially. The molecular weight of H<sub>2</sub>O vapor is

considerably less than that of O<sub>2</sub> and N it displaces (Haug,1993; Miller *et al.*,1982; Willson & Hummel,1972). Air demand for heat removal is highest and that for biological oxidation is lowest (Haug,1993). When conductive heat transfer occurs due to temperature difference without mass movement then it is called sensible heat. The amount of conductive heat lost by a pile is governed by the surface area to volume ratio (Hogan *et al.*,1989). The specific heat and thermal conductivity are the two factors which affect conductive heat transfer and they vary linearly with MC. As MC increases, the value of specific heat and thermal conductivity of any material approaches as that of water (1cal/g °C, 5.62 cal/cm<sup>2</sup> h °C/cm). Specific heat and thermal conductivity of inorganic materials is greater than organic materials. During wet composting the value of specific heat and thermal conductivity (2 to 4cal/cm<sup>2</sup> h °C/cm) decreases since the loss of moisture through evaporation is compensated for by the effects of increased ash content (Haug,1993). The amount of sensible heat transfer can be determined by the following formula:

$$Q = mC_p \Delta T. \text{ -----}2.19$$

Where,

$Q$  = Amount of heat transfer in calories.

$m$  = Dry mass of materials.

$C_p$  = Specific heat of materials.

$\Delta T$  = Temperature difference.

When the heat is used to produce water vapour from water in wet compost at constant temperature and pressure then both heat and mass transfer occur simultaneously through latent heat of evaporation (540cal/g). Enthalpy change associated with this mass transport of water through evaporation is the major mechanism for heat removal which can represent as much as 90% of the heat loss from the process ( Walker *et al.*,1999) although some heat will be lost to the surroundings and in the output solids (Haug,1993). Therefore heat in wet composting decreases through sensible heat and latent heat of evaporation. According to Haug (1993), usually, energy released or energy output from a composting system is dominated by the latent heat of vaporization (range found from simulation models, 65-74%)

and sensible heat in the hot exhaust gases and water vapor are the next highest energy outputs. Sensible heat in the output solids and water is relatively minor.

The gas mixture exiting from the composting process is nearly saturated with water and has about the same temperature of composting materials. From standard psychometric charts and steam tables it can be seen that the quantity of moisture in saturated air increases exponentially with increasing air temperature and considerable water vapour can be removed from wet compost even at a high ambient relative humidity if the temperature difference between inlet and outlet air is more than 25°C (Haug,1993). Psychometric charts indicate that at a particular relative humidity, the amount of water vapour/kg dry air (specific humidity), volume of air vapour/kg dry air (Specific volume) and enthalpy (KJ/kg dry air) increase as temperature increases under constant pressure. Therefore, heat released through latent heat of evaporation in a wet composting process under constant pressure is equal to enthalpy change of initial and final state of exit gas mixture caused by the change in specific humidity as well as saturation vapour pressure with the increase of temperature which is the key process of heat and mass transfer. Also, it is to be noted that drying to a moisture level below 30% with heat of evaporation is difficult because microbial activity decreases below MC of 40-50% (Haug,1993). The enthalpy of dry air plus that of water vapour will be the enthalpy of air vapour mixture which can be determined from the following formula (Stoecker & Jones,1982).

$$h = C_p t + W h_g \text{ -----2.20}$$

Where,

$C_p$  = Specific heat of dry air at constant pressure = 1 kJ / kg °K.

$t$  = Temperature of air – vapor mixture, °C.

$W$  = Specific humidity, water vapor in kg / kg dry air.

$h_g$  = Enthalpy of saturated steam at temperature  $t$  of air vapor mixture, kJ / kg.

Although the specific humidity of air vapor mixture at different temperatures can be found from a psychometric chart it can also be determined mathematically with formulae which are available in Haug,(1993).

There are two common energy factors based on rules of thumb developed by Haug (1993) discussed below which are usually used to judge the need for energy conditioning of substrate for composting without doing a mass and energy balance of the system.

#### Water ratio (W):

Water ratio can be defined as the ratio of water to biodegradable organics.

$$W = \frac{\text{weight of water}}{\text{weight of degradable organics}} \text{ ----- 2.21}$$

Since the water evaporation through latent heat of evaporation uses the major part (almost 90%) of available total biologically produced heat energy, which is a product of Biodegradable Volatile Solids (BVS) oxidation. Therefore, the ratio of the water to be evaporated to the available BVS indicates the capability of the feed materials to evaporate water from the system. A water ratio value 8 to 10 g H<sub>2</sub>O/g BVS is used to judge the availability of energy for temperature elevation and subsequent water evaporation. If W < 8, sufficient energy should be available for temperature elevation and evaporative drying of wet materials. But if W > 10, then wet substrate alone may not provide sufficient energy, lower process temperatures or less drying may have occurred.

#### Energy Ratio (E):

Energy ratio can be defined as the ratio of biological heat released from oxidation of organics to the weight of water present in the substrate.

$$E = \frac{\text{heat released}}{\text{weight of water}} \text{ ----- 2.22}$$

Energy ratio is another energy factor used for the prediction of capability of feed materials to produce heat from biological oxidation of organics and subsequent evaporation of water. If E is greater than 700 cal/g, sufficient energy should be available both for composting and evaporative drying. But if E is less than 600 cal/g, then a lower level of drying and lower temperature can be expected during composting.



Where materials to be composted do not contain sufficient energy to drive the composting, then further energy conditioning can be obtained in three ways (Haug,1993).

Limiting drying: Energy can be balanced by reducing the evaporation of water to reduce the total heat demand but with wet substrate this approach results in most cases in a very wet final product which is unsuitable for reuse. This approach could be viable if air drying or heat drying is used to remove moisture from the final wet product.

Dewatering: An optimal energy balance can be obtained by maximizing the solid content by mechanically dewatering of the wet substrates prior to composting. This is the most effective approach.

Amendment addition: Amendment use alone can provide both energy and structural conditioning but it needs a considerable quantity of amendment which is costly. The amount and costs of amendment can be minimized by a combination of amendment addition and product recycling. Although the end product recycling does not provide any energy conditioning, it does provide structural conditioning.

## **2.6 DISINFECTION**

According to (Haug,1993), "sterilization is the process of destroying all life forms. Bacterial spores and certain protozoan cysts are microbial forms particularly resistant to elevated temperatures. Cysts and spores resist exposure to dry heat of over 100°C. Dry sterilization, therefore, requires a temperature of about 180°C for 2-3hrs to assure complete destruction. Moist sterilization needs only 15 minutes at 115°C. Boiling at 100°C kills some cysts and spores, but induces germination in others. After a time lapse, a second boiling is necessary to kill bacteria or protozoa that have emerged from the spores or cysts. Pasteurization at 70°C for 30 minutes can destroy pathogens in sludge. For example, *Entamoeba histolytica* can be pasteurized at relatively low temperatures. Temperatures of 75°C for 1 hr can destroy enteric pathogens and usually reduce coliform indicator concentrations to <1000/100ml. However, from the data of thermal inactivation of pathogens

given in Haug (1993), it is apparent that a high temperature for a short period of time or a lower temperature for longer duration may be equally effective.

Destruction of virus by heat inactivation is more complicated than for other microbes. Enteric bacterial pathogens cannot form spores and they are less heat tolerant than protozoan cyst or helminth eggs. Certain vegetative bacterial cells such as *Mycobacterium tuberculosis* are comparatively heat resistant. The conditions which can disinfect the intestinal worm *Ascaris* will ultimately destroy protozoan cysts. *Ascaris* is a nematode indicator organism because of its heat tolerance relative to other enteric parasites. A minimum temperature of 50°C for 60 minutes is required for rapid reduction of *Ascaris* density in compost.

However, there are some other spore forming bacteria that are more heat tolerant than *Ascaris*. These bacteria include *Bacillus subtilis*, *Clostridium tetani* and *C. botulinum* which require greater than 100°C for destruction. Thus composting temperatures are effective for inactivating vegetative cells of enteric bacterial pathogens as well as viruses, protozoans and metazoans but not bacterial endspores. During composting obligate pathogens, indicator bacteria and nonobligate bacterial pathogens can be reduced to a very low numbers. Regrowth of nonobligate bacterial pathogens can be suppressed by ensuring a diverse microbial flora. The microbial flora is enhanced at ambient temperatures in the pile. Therefore, all materials should be consistently exposed to inactivating time and temperature conditions (Haug,1993).

In composting, solid wastes are maintained at 40°C for 5 days and at above 55°C for 4 hours to kill the pathogens. For in-vessel systems solids are maintained above 55°C for more than 3 days, for static aerated pile, above 55°C for 3 days and for the windrow method usually solid attains more than 55°C for at least 15 days (Haug,1993).

## **2.7 HYGIENE**

When viewing the hygienic aspects for composting plants, one has to consider not only the microbial load of the product, but also the possibility of airborne contaminants. This is very important since microbial air pollution represents a possible occupational health hazard.

Environmental health risks of both natural and human origin, are an ever-present feature of human life. The perception of hygiene in the composting process has also been evaluated through several studies. During composting, bioaerosols are organisms or biological agents associated with water droplets and which can be dispersed through the air and affect human health. These bioaerosols can contain bacteria, fungi, actinomycetes, arthropods, endotoxins, microbial enzymes, glucans and mycotoxins (Millner,1994). The level and type of bioaerosol depends on the kind of feedstock used in composting operations and can also be a function of facility design and operations.

The most important bioaerosols are *Aspergillus fumigatus* and microbial endotoxins. Other potential biological agents are the thermophilic actinomycetes, glucans and mycotoxins although their significance found in composting operations is unknown (Epstein,1994). *Aspergillus fumigatus* is a member of the genus *Aspergillus* which has approximately 300 species that are common in the environment. It is a common fungus found in decaying organic matter and soil throughout the world (Rippon,1974). *Aspergillus* spores are airborne, heat tolerant and normally found in composting. *Aspergillus fumigatus* has been found to grow on numerous substrates and media like wood, wood chips, green leaves, grass, paper, fabric, leather, rubber and plastics, aviation fuel, sludge, fireproofing material, compost, potting soil, manure and mulches. This pathogenic fungus is universally present wherever decaying organic matter occurs and can cause Aspergillosis. This disease is an acute or chronic inflammatory, granulomatous infection primarily of the respiratory tract i.e., sinuses, bronchi, and lungs (Epstein,1994).

Endotoxins can be toxic to humans and animals, and the highest levels of endotoxins have been found in the screening area while the lowest levels occur near compost piles. A cell count of up to 1000 gram-negative bacteria/m<sup>3</sup> and 0.1µg/m<sup>3</sup> of endotoxins should be considered safe until additional information is available (Rylander *et al.*,1983).

Enclosing the screening area or providing a dust hood would greatly reduce bioaerosol dispersion. The screening of materials at >40% moisture content will also reduce the dust. For outdoor composting, water spraying during turning reduces the dust emissions. A

composting site should be selected which has adequate buffer zones and residences and commercial enterprises should be separated by such zones and barriers of planted shreds and trees (Epstein,1994).

## 2.8 FINAL PRODUCT STANDARD

A regulatory approach is very important for establishing a final compost product standard. The regulatory body should recognize that there is no such thing as risk free. Recovery of any resource involves some risk. The concept of acceptable risk rather than risk free must be embraced as the only realistic approach. The recommended density of fecal coliforms in the final product should be 1000/g solids, because salmonellae are considered to be absent when compost samples containing amounts of fecal coliform lower than that (Vuorinen & Saharinen,1997).The following standards shown in Table 2.4 are proposed by Haug,(1993) which are achievable with good management practices, with economically reasonable processes and involves low risk to the users from the final product.

Table 2.4 Final Product Standard of Compost.

Name of Pathogens	Standard Limit	Unit	Remarks
Virus	0.1 to 0.25 or less	PFU/g dry solids	
<i>Ascaris</i>	0.5 or less	Viable ova/g dry solids	
<i>Salmonella</i>	Median: < 1	MPN/g dry solids	Not more than 10% of samples to exceed 10 MPN/g dry solids. No sample to exceed 100 MPN/g dry solids.
Fecal Coliform	Median: < 10	MPN/g dry solids	Not more than 20% of samples to exceed 1000 MPN/g dry solids. No sample to exceed 10000 MPN/g dry solids.

Source: Haug (1993).

## 2.9 MATURITY AND STABILITY OF COMPOST

Stability is a condition of compost while maturity is a quality of this material. A compost product which decomposes slowly due to dryness or lack of key nutrients can be stable

without exhibiting maturity. Similarly, an immature compost which has stability due to dryness can start to decompose quickly if it becomes wet. Immature composts contain high levels of fulvic acids and low levels of humic acids. As decomposition proceeds, the fulvic acid fraction decreases or remains unchanged but humic acids are produced. Compost maturity can be evaluated by means of the humification index which is the ratio between humic acids and fulvic acids expressed as a percentage of the total organic carbon (Tuomela *et al.*, 2000).

According to Anon.(1999), a mature compost decomposes slowly under all conditions, and humic compounds content is high. Thus heat generation, carbon dioxide evolution and oxygen uptake can be used to judge maturity, as well as stability. The lack of phytotoxicity does not mean that the compost is mature. Similarly, the occurrence of phytotoxicity does not mean that the compost is immature. Thus, phytotoxicity is a clue, but not a measure of maturity or stability.

## **2.10 CHARACTERISTICS OF HIGH MOISTURE MANURE**

According to research undertaken in New Zealand, manure deposits in a farm dairy holding area at about 2.0kg/head/day and comprised 60% faeces and 40% urine and the composite waste (faeces + urine) contained 92.6%(w/w) moisture with a C:N ratio of 12:1 which should be pre-dewatered up to 18.5% solids for composting (Mason & Reijnen,1999).

Manure is a high protein substrate with low C:N ratio. During biodegradation much of the N will be lost to the vapor phase through  $\text{NH}_3$  volatilization, as the N content exceeds its requirement for biomass synthesis with respect to available C in the slurry (Witter & Lopez-Real,1987). For biomass synthesis, living microorganisms utilize about 30 parts of C for each part of N (Golueke,1992) whereas Seekins (1999) reported that organisms need about 1 part of N for every 12 to 15 parts of C used for protein synthesis. Nitrogen may undergo one or more of four possible processes. These are, remain in solution as ionic  $\text{NH}_4^+$ , be lost from the solution as  $\text{NH}_3$ , be incorporated into new cellular material as protein or being adsorbed from the fluid phase onto the surface of particles (Haug, 1993). Mahimairaja *et al.*(1994) reported that during composting of poultry manure with different amendments, the reduction in

nitrogen loss was mainly due to the immobilization of  $\text{NH}_4^+$  ions by the carbonaceous materials. In manure slurry, much of the organic N occurs in a form which is readily degradable through exothermic enzymatic activities called hydrolysis thus produce proteins, urea and uric acid from odourous compounds such as aliphatic amines, sulphides and  $\text{NH}_3$ , even under suboptimal conditions for microbial activity (Miner & Hazen, 1969, 1977; Elliott *et al.*, 1971)

The aerobic microbial activity that transforms the malodorous compounds of manure slurry into  $\text{NO}_3^-$ ,  $\text{SO}_4^{=}$ ,  $\text{CO}_2$  and  $\text{H}_2\text{O}$  is impaired by a lack of  $\text{O}_2$  supply and by low temperature. Under prevailing anaerobic condition, microbial activity produces  $\text{CH}_4$ , amines,  $\text{NH}_3$ ,  $\text{CO}_2$ , sulphides including  $\text{H}_2\text{S}$  and other toxic compounds from manure slurry (Vogtmann & Besson, 1978). Nitrite then nitrate, produced by the nitrification of  $\text{NH}_3$  under partly aerated conditions cause eutrophication of water bodies and the acidification of soil (Voorburg, 1980; Schroder, 1985) because when manure slurry dissolves in water, nitrous oxides and nitrate ion produce nitrous and nitric acids respectively. Even highly viscous and malodorous slurries lose  $\text{NH}_3$  and  $\text{CO}_2$  rapidly during handling and land application. On the other hand, dilute and less odorous slurries release less  $\text{NH}_3$  but these are costly to transport and apply to land (Mathur *et al.*, 1990). Whereas, manure slurry is a low grade waste which cannot be re-used directly (like paper waste & other MSW), it must be recycled or treated by the cheapest possible way which should be a compromise of technical, financial and environmental considerations. Because it is a slurry, land filling, incineration and dumping are not feasible treatment options. The traditional management systems for animal slurries do not eliminate all adverse environmental impacts because they cannot conserve N and odorous compounds at all stages (Mathur *et al.*, 1990). The disadvantages associated with the traditional systems have been discussed in Chapter 1.

### **2.10.1 THE NEED FOR AMENDMENTS**

For manure slurry composting, a dry and bulky absorptive organic amendment and/or bulking agent must be used for pile structure and substrate energy conditioning by obtaining a desirable moisture content, thus offering sufficient opening of the pile for aeration & an

appropriate C:N ratio. The effect of initial conditions in terms of mixture of manure slurry as given by moisture content, C:N ratio, bulk weight, air space, pH can influence the temperature development and CO<sub>2</sub> production in the pile ( Hong *et al.*,1983).

The ideal characteristics of an organic amendment for composting of high moisture manure or other substrates are given in Table 2.5.

Table 2.5 The ideal characteristics of an organic amendment

Ideal Characteristics of amendment	
1.	Organic amendment materials required to be highly absorptive, rich enough in exchangeable H <sup>+</sup> ions to neutralize NH <sub>3</sub> and then the cations released by decomposition.
2.	Capable of protecting NH <sub>3</sub> loss by keeping the compost mix slightly acidic.
3.	Capable of absorbing anions and able to retard the leaching of NO <sub>3</sub> <sup>-</sup> and PO <sub>4</sub> <sup>=</sup> in soil.
4.	Fluffy enough to provide thermal insulation.
5.	Porous and allow sufficient air to prevent anaerobic conditions.
6.	Possible to use as litter.
7.	Biodegradable but not capable of sustaining thermophilic microbial activity by itself.
8.	Free of pathogens and weed seeds.

Source: Mathur *et al.*(1990)

Although a single material cannot provide all the criteria mentioned above but some materials are quite useful. Horticultural sphagnum peat has been reported to be useful to meet the above requirements (Mathur *et al.*,1990) because of its low bulk density (0.06g/cm<sup>3</sup>), high cation exchange capacity (130meq/100g-1), low pH (3-4), high absorption capacity (20 times its weight), NH<sub>3</sub> absorption capacity (3% its weight) but its high price and separate horticultural use has been triggering the search of other substitutes such as sawdust, straw, paper, wood chips.

For example sawdust has high C:N ratio 442 (Rynk,1992) and low pH 4.5 (Hong *et al.*, 1983). The high C:N ratio is helpful to adjust the C:N ratio of the compost mix and the initial low pH of sawdust can reduce pH of compost mix and prolong acidic conditions to minimize NH<sub>3</sub> losses (Hong *et al.*,1983). But the low water absorption capacity of sawdust (Hong *et al.*,1983) may cause the composts to be poor in nutrients and wood based composts take a long time to mature due to differential decomposition rate of cellulose (highly degradable), hemicellulose and lignin (Martin,1991). Shredded mixed paper may be another option and is considered highly cellulosic and exhibits a favourable C:N ratio & pH of 227 and 5 respectively (Haug,1993).

### **2.10.2 IMPACT OF HIGH MOISTURE CONTENT**

The maximum recommended moisture content for manure composting is 55-65%(w/w) which depends on the structural strength of the materials with which composting will be performed. Composting of mixtures of vegetable wastes and straw with 85% MC was found successful, but 76% MC was found too high when paper was used instead of straw. Straw or wood chips are fibrous and bulky and can absorb and maintain a high moisture content while still maintaining their integrity, porosity and adequate FAS (Haug,1993).The impact of moisture content was demonstrated by Senn (1971) during composting of dairy manure. At 66% MC, the temperature did not rise above 55°C and at 61% MC, temperature rose rapidly to above 75°C. However at 60% MC, the temperature rose to above 75°C and remained at this temperature for several days. Dairy & pig manure slurries are not instantly ideal for efficient composting because they have higher moisture contents and lower C:N ratios than the levels desirable for composting. Secondly, composting of manure slurry can produce drainage or leachate which needs further treatment. Due to its hydraulic head, it has almost no void volume and thus it does not allow adequate permeation of air during aeration. Therefore, due to low oxygen transfer efficiency, power input is required depending on the aeration mechanisms. Richard & Choi (1996) mentioned that “one of the major constraints in composting high moisture materials is the need for considerable quantities of dry bulking amendments to increase the air filled porosity of the composting mixture”. Thus manure slurry needs to be opened out on an absorbent solid support matrix (to provide void volume and extra carbon) such as peat, straw, sawdust, waste paper and wood chips. Wood chips are



stiff, rigid particles and provide good structure to hold the shape of the pile but paper lose their stiffness, structure and collapse as they absorb water and decompose (Seekins,1999). Biddlestone & Gray (1985) reported that cereal straw can maintain an open matrix for many days even at moisture contents above 80% and can admit adequate air during the initial period of high oxygen demand by the slurry as most of the high rate O<sub>2</sub> demand is met within about 3 weeks, whereas paper collapses at MC > 60%. Because straw has 4 layers in its wall, the inner layers are attacked by microbes readily but outer layers are more resistant. Straw ultimately goes through to the final product but wood chips need to be screened out for reuse whereby they immediately impose a major constraint on the initial moisture content of the next mixture, because it normally contains 55-65% MC. Most of the bulking amendments are expensive and that is why several studies have been initiated to evaluate the potential of using the biological energy of decomposition to evaporate moisture and reduce bulking amendment requirements.

Haug (1993) reported that the presence of so much water tends to compact the materials and can reduce the porosity, void space & composting temperature. He also suggested that higher the moisture content, the greater is the need to provide a large void volume for adequate aeration. Studies of moisture content on reaction rates have shown that the reaction rate at below 20% moisture content is very small and the rate of biological heat release may be limited by lack of moisture, lack of FAS, low oxygen content. Increasing this level of moisture content leads to oxygen uptake increases in a more or less linear fashion to maximum values that begin at 50-70%MC. The reaction rates begin to decrease at high moisture content not due to excessive moisture but due to loss of FAS. It is really difficult to isolate the effect of moisture content alone as it is related to bulk weight and FAS. Therefore, MC must be high enough to assure adequate rates of biological stabilization, yet not so high that FAS is eliminated. Optimum moisture contents tend to fall in the range of FAS between 20 and 35. Another problem with wet substrates windrow composting under downflow forced draft aeration is that moisture has been found to migrate downward through the compost and developed a saturated zone like "hardpan" causing headloss, short circuiting around that zone and odour development. The mechanisms for moisture migration is that the water vapor will be carried downward and only a few degree of cooling would be necessary

to condense a significant amount of water. But significant water migration problems have not been reported where wet sludge cake was composted with wood chips under a static pile system. The main advantage is that induced draft aeration can be used with wet substrates that are bulked with large particles like wood chips to prevent accumulation of moisture saturated materials. High moisture content causes anaerobic degradation of organics and produced odourous compounds like  $H_2S$ , volatile organic acids, mercaptans and methyl sulfides. Composting usually tends to go towards drying and supplemental water addition may be necessary periodically particularly for dry substrate but that may also true for energy rich wet substrate.

### **2.10.3 ENERGY CONSIDERATIONS**

Haug (1993) reported that “ energy can be extracted efficiently by thermal processes (incineration, pyrolysis & gasification), but thermal processing becomes much less efficient as moisture content increases. For combustion to be self-supporting, the moisture content should be less than 60-70%. Composting can be effective in converting wet materials to a suitable material for reuse or easily disposed of through drying and stabilization.” For composting systems, estimates of heat evolution can be calculated on the basis of heat of combustion (usually an overestimate) or measured directly for a variety of materials (Richard & Choi,1996).

Richard & Choi (1996) mentioned that “ microbes use organic compounds as a carbon source and oxidize chemical compounds (often organic) for energy. These molecules are used in metabolic processes for energy production through catabolic reactions or for cell synthesis through anabolism. This energy is used both to drive the synthesis reactions and to perform mechanical work within the cell, and a certain amount is lost as heat”. According to (Richard,1998), “manure and amendments contain energy, 60% of that energy is consumed by aerobic microorganisms for their cell synthesis or metabolic work and remaining 40% energy is transformed to “waste” heat. Air moves through the compost pile by forced ventilation or passive convection and diffusion gets hot and subsequent heating evaporates water from the surfaces of particles and air movement reduces moisture content to 45% or less over a period of weeks or months”.

A recommended range of energy ratio (E) and water ratio (W) is 600 to 700 Cal/g H<sub>2</sub>O and 8-10 g H<sub>2</sub>O/g BVS respectively (Haug, 1993). Therefore, if the feedstock contain E less than 600 Cal/g H<sub>2</sub>O or W less than 8 g H<sub>2</sub>O/g BVS, then it could be energy poor because of excessive evaporative burden on the process and thus drying may have to be reduced to maintain process temperatures. Sensible heat and latent heat are concurrently used to evaporate water. During the evaporation process (starts above 0°C), sensible heat is used to increase the temperature of water and as the temperature increases the rate of evaporation increases exponentially. The latent heat is consumed at a rate of 540 calories per gram of water evaporation irrespective of the temperature levels above 0°C which means that at lower temperature the same amount (540 Cal) of energy will be used over a longer period of time to evaporate one gram water and at higher temperatures the same energy will be consumed over a shorter period of time for one gram water evaporation. Therefore, too wet substrates indicate lower energy with respect to the amount of water to be evaporated and poor energy feedstock will provide less FAS, which will cause limited aeration and thus limited oxidation of available biodegradable organics. As a result a lower temperature will be developed that may not evaporate the water sufficiently and ultimately may leave a soggy, unsuitable end product. These types of feed materials can be made suitable if a supplemental source of energy is added through addition of amendment materials which can fuel the process (Haug, 1997).

#### **2.10.4 MOISTURE REMOVAL BY EVAPORATIVE DRYING**

Traditional composting (manure blended with amendment and bulking materials) can achieve only a moderate level of drying. Jewell *et al.* (1984) examined a range of operational parameters for drying dairy manure, finding maximum degradation rates at 60°C and 40% moisture, and maximum moisture removal rates at 46°C and 14 litres air per gram water added. Richard (1996; 1998) has suggested the need for some sort of reconfiguration of traditional composting systems for high moisture manure slurry composting. First, the linkage between microbial heat generation and evaporation is to be explicitly recognized and optimized. Second, is a change in the materials handling system.

Drying potential of wet material composting is an optimization problem relating the heat generated by microbial decomposition with convective moisture removal, both of which are functions of temperature and airflow (Richard & Choi,1996). One method of drying manure slurry is by composting where heat liberated from the decomposition of organics drives the evaporation of water, which is removed in the exhaust gases (Patni & Kinsman,1997). Walker *et al.*(1999) reported that a static bed of composting often exhibit spatial gradients in temperature, moisture content, oxygen concentration and BVS which can be diminished by proper mixing as it opens the structure to enhance aeration and expose more surface area. Whereas, Biddlestone & Gray (1985) mentioned that simple method of mechanical mixing of manure slurry with amendment and building of pile with a low cost mechanical device is a real problem in practice. Richard (1998) has suggested a sequencing batch or semi continuous process (starts out as a batch with manure slurry and sawdust mixture then gets repeated sequential additions of more high moisture manure of 2% solids without sawdust). The procedure adopted utilized mixing, forced aeration and sequential batch mode to compost liquid hog manure with 2500 kg of broiler litter and wood shavings and evaporated over 4300 kg of water in a three months period under winter conditions. Other investigators evaporated 5182 kg of water with 2770 kg straw/swine slurry in a two months period under a passive aeration system.

The moisture removal of very wet materials through composting is closely interrelated with biological heat energy released from biodegradation, convective energy losses, air flow rates and temperature. According to Richard & Choi (1996), biodrying results from the interaction of physical and biological processes. The physical processes include air flow rate, vapor transfer rates from the substrate to the air stream, inlet and outlet conditions of temperature and relative humidity, and the reactor configuration as it effects the balance between conductive and convective energy losses. The biological processes include degradation rate which is a function of temperature as well as moisture and oxygen concentration.

Convective moisture removal at any given airflow rate increases with temperature and airflow, as do microbial decomposition rates until they reach an optimum, at which point the

decomposition rate decrease rather dramatically due to thermal death of the microorganisms (Richard & Choi,1996). The airflow demand for convective heat removal is greater than that for drying of wet materials and air demand for drying is also greater than the stoichiometric demand for organic decomposition (Haug,1993; Finstein *et al.*,1986). The prediction of moisture removal from a composting system requires apportion of heat losses between conductive and convective manner (Richard & Choi,1996), because moisture can only be removed in a convective manner. The microbial heat generation can be determined by the kinetic and stoichiometric relationships and the heat removal can be determined by the psychrometric relationships. In a well insulated or large composting systems, approximately 90% of heat loss is through convection (Finstein *et al.*, 1986), although Haug (1993) mentioned that the latent heat of evaporation represents about 70-80% of the total energy demand.

The high aeration requirement for cooling and the thermophilic temperature of 45-65°C associated with high-rate aerobic decomposition combine to create a large drying potential. The exhaust gases are considered to be saturated. i.e. making assumption of homogeneity, rate of water removal can be found out from the following equation (Walker *et al.*,1999).

$$r_{H_2O} = \frac{F_{air.amb}}{S_{V.amb}} (H_s.T_{eff} - H_s.T_{amb}) \text{ ----- 2.23}$$

Where,

$r_{H_2O}$  = Rate of water removal

$F_{air.amb}$  = Volume flow rate of air, l min<sup>-1</sup>

$H_s$  = Humidity ratio of saturated air, g g<sup>-1</sup>

$S_{V.amb}$  = Specific volume of dry air, l g<sup>-1</sup>

$T_{eff}$  = Temperature of exhaust air, °C

$T_{amb}$  = Temperature of ambient air, °C

Thus, drying increases linearly with aeration rate and exponentially with temperature because the humidity ratio of saturated air increases exponentially with temperature. Furthermore, there is a non-linear relationship between rates of O<sub>2</sub> uptake and moisture content developed by Haug (1986) as follows:

$$F_1 = \frac{1.0}{e^{-17.684(M_f) + 7.0622} + 1.0} \quad \text{Or } F_1 = \frac{1.0}{e^{-17.684(1.0TS_f) + 7.0622} + 1.0} \text{ ----- } 2.24$$

Where,

$F_1$  = Discount factor for adjusting first order degradation constant for moisture content.

$M_f$  = Fractional moisture content on a wet basis

$TS_f$  = Total solids on a dry basis.

$F_1$  is empirically estimated to be reduced 24% for MC range 45-55 and 60% for 35-45%MC.

An analytical comparison of four (4) degradation kinetic models developed by Haug (1993); Andrews and Kambhu (1973); Regan *et al.*(1973) for newsprint and Regan *et al.*(1973) for stabilized mixed refuse was carried out by Richard & Choi (1996). In that analysis it was demonstrated that the selection of a maximum decomposition rates of substrate did not change the optimum biodrying temperature, but the predicted airflow requirement and drying rate were significantly affected. In the analysis, each of the four degradation kinetic models was used to predict airflow rates and moisture removal as a function of temperature assuming a maximum degradation rate of 0.1kg-VS degraded/kg-VS available per day and on the basis of the relationships between temperature, moisture removal and decomposition rate the authors concluded that (1) To optimize the moisture removal, the process needs to look for the temperature at or above the peak where the change in moisture removal rate with temperature is zero (2) the optimum temperature for maximum moisture removal is close to the temperature at which peak degradation occurs. (3) lower peak temperature requires higher airflow to remove the same amount of heat due to small enthalpy difference between inlet and outlet air. (4) moisture removal decreases at lower peak temperature because a greater fraction of convective heat losses in the sensible form rather than the latent form (5) Higher decomposition rates maximize moisture removal.

### 2.10.5 APPLICATIONS

Some important investigations have been done on manure slurry composting over the last two decades and the results of those researches have indicated that composting could be a viable waste management alternative for animal manure slurries because it provides a

potential waste stabilization technology including pathogen and weed seed disinfection and the production of stable low nuisance material suitable for use as a soil conditioner (Mason & Reijnen,1999; Crawford,1983).

Biddlestone & Gray (1985) investigated the composting of 0.4m<sup>3</sup> pig slurry (3.94%TS) using two straw bale of each 15.9 kg under upward forced aeration. The temperature rose quickly to above 60°C and sustained at >60°C for some 3 weeks. One third of the input liquor was drained (1.75%TS) through the straw. The drainage was recycled at a rate of 15.6 kg slurry per kg straw slowly by spraying over the compost cubicle and obtained a temperature of approximately 60°C. The slurry removed about 65% by absorption and evaporation process. The initial moisture content was 85% (w/w) and the product compost over 19 runs was 81.9% (w/w) moisture on average. The final moisture content indicates that the process obviously produced a very wet final product. A possible reason could be the recycling of drainage material, because most of the produced biological heat energy was used for evaporating the recycled liquor, thus the final product could not be dried well.

Sartaj *et al.*(1997) studied composting of poultry manure (88% MC) with sphagnum peat (65.6% MC) in a 1:1 ratio by weight under passive aeration, forced aeration and natural aeration. The initial MC of compost mixture was 76%(w/w) and the final MC values were 70.2%,70.1%, and 70.8% for passive, forced and natural aeration respectively. The process had an average peak temperature of 56.6°C. The energy ratio and water ratio of the feed mixture were 688 Cal/g H<sub>2</sub>O and 6.81 g H<sub>2</sub>O/g BVS respectively which indicated that the feed materials had sufficient energy to run the heat generation and evaporation process to produce a fairly dry product. But the results did not comply with the anticipated expectation, because all the substrates did not have the same value of heat of combustion, varying significantly in heat content depending on their composition (Haug,1993). From the energy balance it has found that about 35% of produced heat was lost to the surroundings through output solids, water, dry gases and water vapor as a sensible heat. The remaining 65% of the produced heat was not sufficient to evaporate a large amount of water to produce a dry product. The above fact has confirmed the findings of Richard & Choi (1996) that any

decrease in water removal rates at lower temperatures results from a greater fraction of convective heat loss in the sensible rather than the latent form.

Hong *et al.* (1983) studied the effect of aeration rate, MC, pH value, C:N ratio, bulk weight, air space on changing in the temperature and CO<sub>2</sub> production during composting of dairy manure over 7 days with bulking agents (rice straw, rice hulls, laun bark and sawdust) in accordance with various aeration rates. Air was supplied at different rates ranging from 0.4 to 3.0 L/min kg VS from the bottom of the laboratory scale composter. The mixing ratio of manure and bulking agents was 2:1 by weight and the initial MC of admixture was maintained at 55-65%(w/w). The composting rate was estimated by CO<sub>2</sub> production. The MC of end products from most of the tests (under aeration range 0.04 to 1.07 L/min kg VS) remained slightly higher than their initial MC whereas the MC of end product was lower than the initial MC when the aeration range exceeded 1.88 to 3.0 L/min kg VS. The possible reasons for this can be predicted from an analysis of energy balance of the initial and final state. From the analysis of tests results of composting with sawdust (where peak temperature was 46.5°C & MC had increased), it has found that the total production of H<sub>2</sub>O during composting period was higher than the total water evaporated and a significant part (18%) of the produced heat was lost as sensible heat rather than latent heat (8%) which indicated that the low peak temperature (46.5°C) could not evaporate more water due to the decomposition rate associated with an aeration rate of 0.76 L/min kg VS. The water ratio (W) and energy ratio (E) were calculated 3.39 g H<sub>2</sub>O/g BVS and 1385 Cal/g H<sub>2</sub>O respectively which indicated that the feedstock had a very high energy content, although the process could not evaporate sufficient water due to the combined effect of aeration, decomposition, peak temperature, pH, moisture content and bulk density. Moreover, authors have mentioned that the initial low pH (4.5) of sawdust depresses the pH and prolongs acidic conditions. The MC in the bottom layer was lower than that of top layer because of lower aeration level in the top layer. The average bulk weight of different raw compost (310kg/m<sup>3</sup>) was always slightly lower than that of final compost (290kg/m<sup>3</sup>). Bulk weight of 490kg/m<sup>3</sup> (manure+bark) could not be composted due to its high bulk weight and optimum bulk weight should be 250-330kg/m<sup>3</sup>. Insufficient air supply could not reduce bulk weight but over aeration decreased it sharply. Results show that the FAS from 32-40% was optimal for the MC range 55-



65%(w/w) but for fine particle size and uniform distribution of bulking agent like rice hulls, MC should have been at a lower level of about 50%. Lower FAS and higher MC need higher aeration rate for successful composting. Higher reduction in weight and MC resulted from evaporation at higher temperature and higher microbial activity causing carbohydrates to give higher CO<sub>2</sub> and H<sub>2</sub>O and loss in weight should be related to level of aeration rate. Higher aeration rate (1.06 L/min kg VS) caused an earlier decrease of temperature than the lower aeration rate (0.87 L/min kg VS).

A 2 to 4% solids slurry was sprayed intermittently (or with presoaking to enhance early temperature rise ) via flexible hose on to bales of dry straw arranged in cubicles lined with polythene sheets and under forced aeration. On day 56 the straw pile was deconstructed and reconstructed to increase the volume absorbed and to avoid compaction. After 110 days, 10,650 litres (a ratio of 10.24 to the initial straw dry matter) or 10.65 tons of slurry had been utilized by using 1.39 tons of straw (1.02 tons dry matter). Both moisture and weight were reduced by > 76%. Dry matter and VS losses were 64.7% and 69.9% respectively. In a 3 months period, the process released 8.29 tons of water vapor ending with a wetter (83.3%MC) but easier and less hazardous material to manage than initial 10.65 tons of slurry Bujang & Lopez-Real (1993).

Patni & Kinsman (1997) investigated the water removal performance of swine manure slurry using the static pile passive aeration composting process followed by a periodic irrigation of diluted manure slurry. The initial mixing ratio of slurry (91%MC) to straw (10% MC) was 3:1 by weight to have a MC of 70-75% (w/w) which was 73% and C:N ratio was 29. Each pile was irrigated with an additional 1000L of dilute slurry (98% water) initially, followed by 1000L of tap water after the peak temperatures (65-70°C) were reached and discontinued for 8 days to prevent rapid cooling. Thus, 5m<sup>3</sup> piles received about 2m<sup>3</sup> of additional water. Two treatment piles together had initially 2019 kg of water, excluding the 4000 kg water added during irrigation, a final moisture content of 59.8% was noted and thus left 837 kg of water; i.e. 5182 kg of water were removed from two piles in 60 days which proved that the irrigated composting system was able to remove 343% more water than the

non-irrigated composting system. The temperature was maintained at approximately 55°C for three or more days in all irrigated piles which should promote pathogen inactivation.

Mason & Reijnen (1999) have proposed that a bed of sawdust, bark or other suitable amendments should be used where manure and sawdust is incorporated progressively into a layered pile to build up the compost pile as employed in the Indore composting system (Haug,1993). Filtrate would be collected from an under-drain system and either stored for use in future moisture control or to be returned to the wastewater system. Alternatively a straw bale based system as described by Bujang & Lopez-Real (1993) or the process described by Patni & Kinsman (1997) or biodrying process described by Richard (1998) may be considered. Mason & Reijnen (1999) also suggested that using a non-waterborne collection system for manure composting could reduce 70% nitrogen phosphorus and potassium in waste waters and 30% water consumption.

Therefore, although water use is essential in all dairy farms but a non-waterborne collection of manure slurry can reduce wastewater volume and the potential for contamination of rivers and streams. To some extent, the reducing the amount of water to be dealt with for washing and reducing the strength of produced wastewater during milking in a dairy farm will contribute to environmental protection. To ensure the non-waterborne collection system function correctly, a covered farm dairy yard and covered composting facility would be needed. Non-waterborne collection of manure slurry can be done by mechanical scrapers or a vacuum pump system (Mason & Reijnen,1999). But it is to be noted that after implementing non-waterborne collection system the dairy farm would still require some water for final washdown of the yard and milking area. The proposed composting processes would incorporate this wastewater by fitting together both waterborne and non-waterborne collected waste in the way either as described by Mason & Reijnen (1999), Richard (1998), Bujang & Lopez-Real (1993) or Patni & Kinsmen (1997).

## CHAPTER-3

### RATIONALE & OBJECTIVES

#### 3.1 RATIONALE

Composting is a simple and economically attractive alternative to conventional waste-treatment systems for treatment of farm dairy manure slurry. For efficient composting, operational parameters such as available nutrients, moisture, aeration, free air space, C:N ratio and temperature have to be optimized to provide an environment which will maximize aerobic thermophilic activity. To optimize processing economics, high degradation rates and high-quality end products must be achieved at low cost under low-level technology. High degradation rates are achieved under conditions of optimal aeration rates. However, the cost of energy expenditure during aeration is a significant factor in the overall economics of composting. Therefore, and to optimize economics, (that is low cost, quality product, short term) a simple aeration method called passive aeration was chosen from the available methods (natural aeration, passive aeration, forced aeration, aeration by turning and in-vessel aeration ). This method enhances the natural aeration inside the pile and uses perforated pipes at the bottom of compost piles to do so. Although passive aeration is a simple and low-cost technology, there is in the literature limited information regarding this configuration as applied to dairy shed wastes. Because the farming community shows a high degree of interest in the composting of manure, the technology has gained rapid acceptance as a method of recycling relatively dry organic materials. However, high moisture substrates like manure, need extra measures prior to commencing composting, such as dewatering, feed conditioning, energy conditioning, structural conditioning and so on. In particular, dewatering of wet substrates can impose an extra burden on the economics of the process. High moisture materials also present increased risks of anaerobic odour formation through reduced oxygen transport (Miller,1991).

Dewatering of municipal and industrial sludge is achieved using centrifuges, filter presses and vacuum filters prior to composting, but the costs involved in the use of these technologies in dairy manure dewatering may cause farmers to be less interested in

composting, and thus would not be feasible or viable for a dairy farm situation. Therefore, the present study was carried out to develop an easy and economical method of dewatering as well as concurrent thermophilic composting of manure slurry without the input of extra electrical and mechanical energy in order to eliminate the energy consuming mechanical process of dewatering. Dewatering by mechanical devices can remove only water, whereas a suitable amendment and bulking agent could be useful for not only dewatering, but also for energy and structural conditioning.

The free air space of wet substrates such as sludge cake and manure slurry can be assumed to be zero (Haug,1993). A suitable bulking agent can provide structural support for the wet substrate to provide FAS within the voids between particles, to increase the size of pore spaces, and to allow easier air movement through the mixture. There are many amendments available, such as straw, rice hulls, sawdust, waste paper which can be used for manure composting. Each of these amendments has advantages and disadvantages in terms of costs, availability, transportation, mixing, structural rigidity & flexibility, C:N ratio, biodegradability and energy content, and their response in composting should be different from each other. The present study was carried out to compare the behaviors of sawdust and mixed paper as amendments during composting.

During composting, temperature should rise to the thermophilic range due to energy transformation from decomposition by microbial activities. This heat output should remove significant quantities of water through evaporation. The influence of temperature on moisture content over the period of composting is an important aspect in process performance. Therefore, the present study was designed to evaluate performance in terms of the moisture removal capability of the process. The moisture removal process in composting is dependent upon the energy exchange in the system, measured as the latent heat of evaporation. The present study was also carried out to ascertain the thermodynamics of the process responsible for the moisture removal which has been achieved during composting.

One of the major objectives of composting is to produce a hygienically safe and agriculturally useful product. Composting of dairy manure may reduce the number of

pathogens by heat inactivation. The process may offer a sanitation process by which pathogens are destroyed and thus improve the safety of the final compost. A detailed investigation of the entire compost output for its total pathogen content would become an enormous task. Therefore, from the water quality point of view, only total coliform bacteria were considered as representative pathogens (which are likely to be present in most animal manure). The present study was carried out to investigate whether total coliform bacteria were eliminated during composting.

### **3.2 OBJECTIVES**

The objectives of this study were as follows:

- (I) To develop a process having a suitable thermophilic temperature for composting high moisture manure.
- (II) To evaluate the moisture removal capacity of the process.
- (III) To ascertain the thermodynamics of the process in terms of energy exchange.
- (IV) To compare sawdust and mixed paper as amendments.
- (V) To assess the utility of the process for coliform disinfection.



## CHAPTER-4

### MATERIALS AND METHODS

#### 4.1 EXPERIMENTAL SITE

A composting study of farm dairy manure slurry as a substrate with sawdust as an amendment and wood chips as a bulking agent was conducted under passive aeration for Experiment-I at Massey University, Palmerston North, New Zealand (Fig.4.1) for a period of 70 days (22<sup>nd</sup> May to 31<sup>st</sup> July 2001). Additionally, Experiment-II was conducted for a period of 73 days (14<sup>th</sup> September to 27<sup>th</sup> November 2001) using shredded mixed paper (75% office paper + 25% news print) as an amendment with wood chips as a bulking material.



Fig. 4.1 The composting study site behind the rugby field at Massey University.

#### 4.2 RAW MATERIALS

The raw material used in this study was farm dairy manure slurry from No.4 and No.1 Dairy Units at Massey University, located adjacent to the University campus. In Experiment-I, manure was collected from both the dairy units mentioned above, as No.4 dairy unit alone could not provide the daily manure in required amounts. However,

during Experiment-II, No.4 dairy unit alone was sufficient to provide the daily required amount. Sawdust was procured from a local market to use as an amendment in Experiment-I and shredded mixed paper (75% office paper + 25% newsprint) was used as an amendment for Experiment-II. Office paper waste was collected and shredded into 8mm wide strips from the Facilities Management department of Massey University, which is responsible for management of waste paper. Waste newsprint was collected from the Evening Standard daily newspaper in Palmerston North, New Zealand and shredded to the same size as that from the Facilities Management department of Massey University. Sawdust and shredded mixed paper were used as an amendment for adjusting the C:N ratio, moisture content and energy content. Sawdust was also used as a pile cover material for insulation purposes for both the experiments. Wood chips (16mm $\phi$  down graded) were used as the bulking materials for both experiments to provide suitable structure, porosity and sufficient (30-35%) free air space (FAS) to ensure passive aeration.

#### **4.3 PILE CONSTRUCTION AND SET-UP**

A small shed for composting was built on a concrete platform with wooden frames and pillars and corrugated plastic sheet for roofing, (Fig.4.1).

Two replicate compost piles were set up for each treatment and monitored for periods of 70 days and 73 days for Experiment-I and Experiment-II respectively. The compost piles were cubic in shape (1.2m $\times$ 1.2m $\times$ 1.2m). To ensure the piles were identical in shape and size, a case was built for each pile using 4 detachable welded galvanized wire (2.5mm dia.) sides for each case and having uniform mesh size (42mm  $\times$ 42mm) over the total area of each frame. A galvanized tray (1.2m $\times$ 1.2m $\times$ 130mm) was placed at base of each pile for the collection of leachate. Two plastic buckets of 20 litres capacity were used for leachate collection through outlet plastic pipes inserted into the bottom of the trays.

Under passive aeration, both the perforated pipes and the porous wood chip base contributed to the availability of oxygen. Therefore, a 130mm thick base of wood chips

covered the tray for passive aeration. In each pile, three PVC drainage pipes were placed horizontally on top of this layer and 300mm distant from the outer face of the pile, and spaced 300mm from center to center (Fig. 4.2). Each PVC pipe was 1.2m long and 100mm internal dia.



Fig. 4.2 The passive aeration pipes placed on a base material wood chips.

Two rows of 12.5mm holes at 200mm centres were drilled in each pipe as shown in Fig.4.3. The peripheral distance between the 2 rows was 60mm. Three passive aeration pipes were used in each pile with the rows of holes facing downwards to prevent their clogging. The free spaces between the pipes up to the top of the pipes were also filled by wood chips. The total height of base layer and pipes layer was  $(130\text{mm}+100\text{mm}) = 230\text{mm}$  from the base of the piles.

In Experiment-I, one bucket of sawdust in the 1<sup>st</sup> layer, one bucket of wood chips in the 2<sup>nd</sup> layer, one bucket of manure in the 3<sup>rd</sup> layer and finally one bucket of wood chips on the top were placed before mixing. The same procedure was followed in Experiment-II as shown in Fig.4.4. The mixture was built up on top of the wood chip porous base that covered the passive aeration pipes as follows:



- Day 0, Layer-1 : Sawdust, 20 litres, measured in a bucket and spread evenly across the 1.2m × 1.2m area of the case.
- Layer-2 : Wood chips, 20 litres, measured with a bucket and spread evenly across and on top of layer-1.
- Layer-3 : Fresh dairy shed manure slurry, 20 litres measured in a bucket and spread evenly over layer-2.
- Layer-4 : Wood chips, 20 litres, measured in a bucket and spread evenly over layer-3.



Fig. 4.3 Two rows of 12.5mm holes at 200mm centres and 60mm apart.



Fig. 4.4 Manure is placed in the pile before mixing.



Fig. 4.5 Placement of different materials in the pile before mixing.

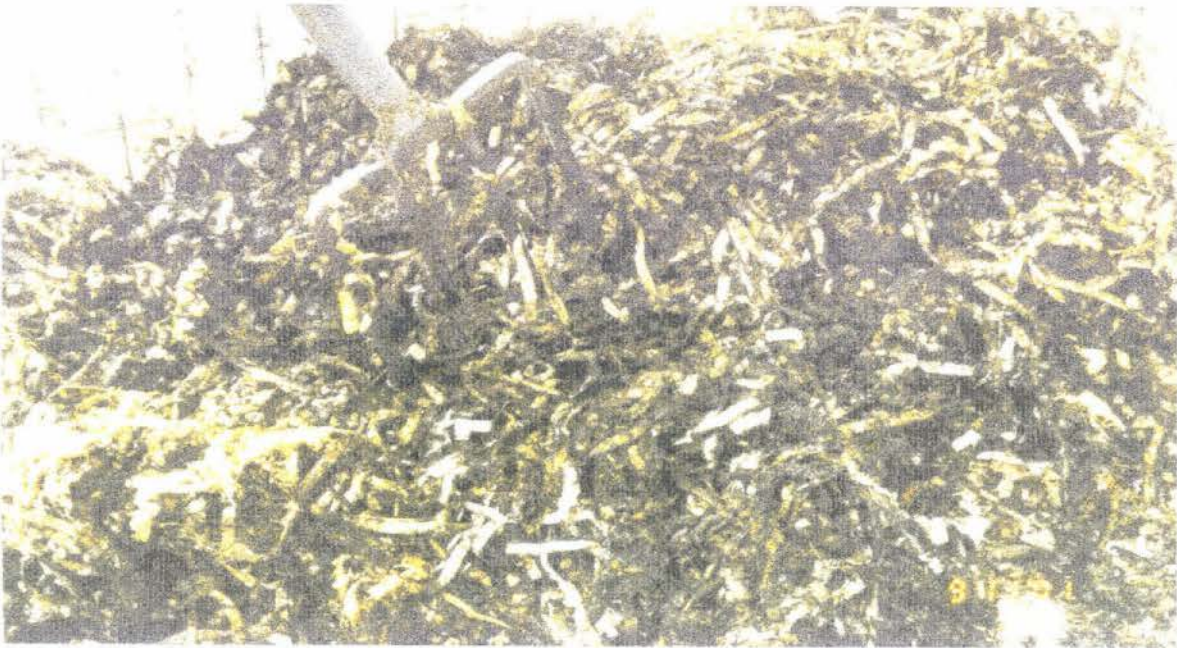


Fig. 4.6 Mixing of materials with the aid of a fork.

In Experiment-II, only the amount of shredded mixed paper required for one bucket (20 litres) of manure was used on a weight basis (Fig.4.5). However, manure and wood chips were mixed on a volume basis in Experiment-II. All layers were now intermixed thoroughly using a standard 25cm, 7 prong garden fork (Fig.4.6). The daily thickness increase of raw compost measured between 130mm-250mm.

The casting of piles in Experiment-I started on 8<sup>th</sup> May 2001 and finished on 22<sup>nd</sup> May 2001, and in Experiment-II started on 11<sup>th</sup> September 2001 and finished on 14<sup>th</sup> September 2001. The casting of piles of Experiment-I took a comparatively long time (15 days) to complete due to the scarcity of manure, transport failure and a week-end whereas Experiment-II took only 4 days for casting (improved resources).

#### **4.3.1 WIND PROTECTION**

The piles were located in the field and exposed to an open environment, away from any buildings or other obstructions which could block wind flow or sunshine. Wind runs are very common in the region. The piles were oriented along an East-West axis,

parallel to the prevailing East-West bound winds. Sometimes the winds were found to run from the South-East corner to North-West. Therefore, straw bales approximately 1180mm high were assembled as barriers on the south side of the piles in Experiment-I, to protect the piles from airflow. However, these barriers could not provide protection from prevailing winds, because there was no barrier on the East side.



Fig. 4.7 East view of straw bale wall wind barriers.

From this experience, approximately 910mm high wind barriers were further provided on the East side of the piles for Experiment-II (as shown in Fig.4.7) which helped to protect the compost pile from wind flow. However, the barriers on the East side were blown over twice by wind. The barriers were rebuilt 2 days after each event, but these events removed heat significantly from the interior of the piles.

#### 4.4 SAMPLING OF THE MATERIALS

Two major sampling operations of the composting materials were carried out, one at the beginning and one at the completion of each experiment. In both cases and before sampling, the material was mixed carefully in order to ensure samples were as

representative as possible. At the beginning of the experiments, a small volume (100ml) of a fresh manure sample was collected in a 1000ml beaker from each 20 litre manure bucket before weighing, and mixed properly in the beaker using a spoon. Then two 250ml representative manure samples were collected and stored in a refrigerator below 0°C for further laboratory analysis. Samples of other raw materials (sawdust, wood chips, shredded paper) were also preserved at sub-zero temperatures in 1000ml containers for subsequent analysis.

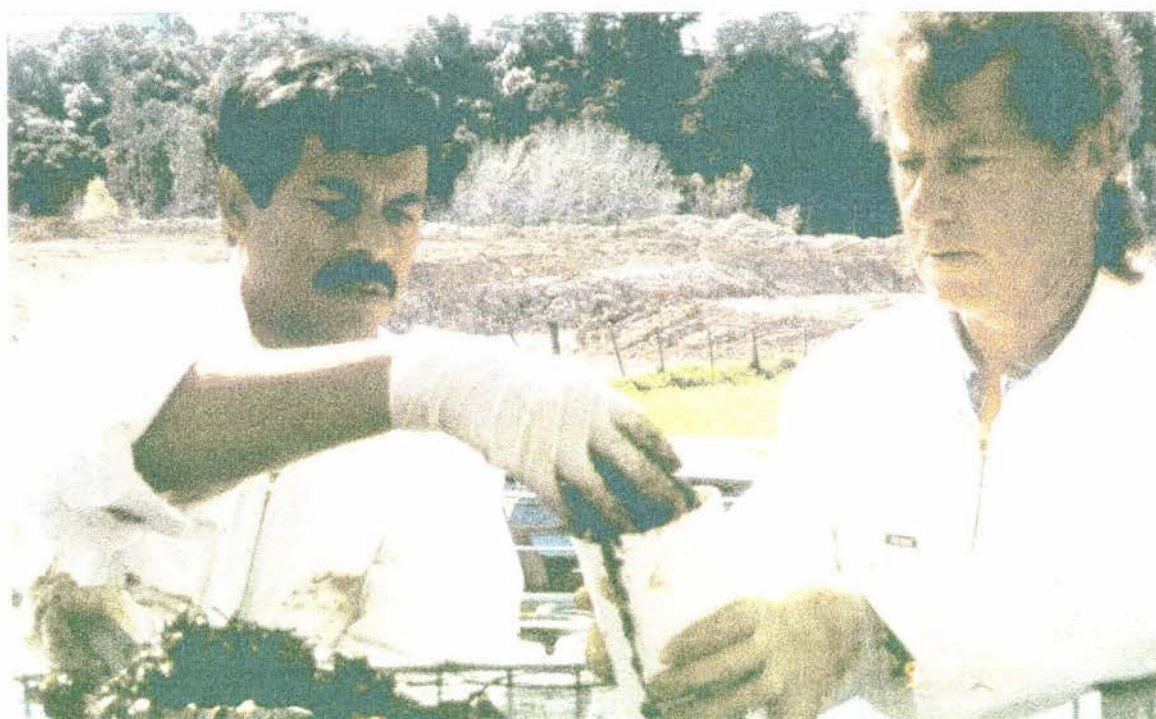


Fig. 4.8 Samples were loaded into a 1000ml plastic container.

Each day after completion of materials mixing in the piles, three samples of raw compost from distinct chosen positions in each pile were taken in 1000ml containers (as shown in Fig.4.8). One of these containers was transferred immediately to the laboratory for total coliform counting, and the other two containers were preserved for moisture content, volatile solids content, carbon, nitrogen, and energy content analysis (see section 4.8).

#### 4.5 BULK DENSITY MONITORING

Samples were taken from the raw compost and the final compost for analyzing bulk weight and bulk density during both experiments. On the day of pile casting completion, five samples were taken from the top layer at 1150mm level. Samples were taken from five position as shown in Fig. 4.9.

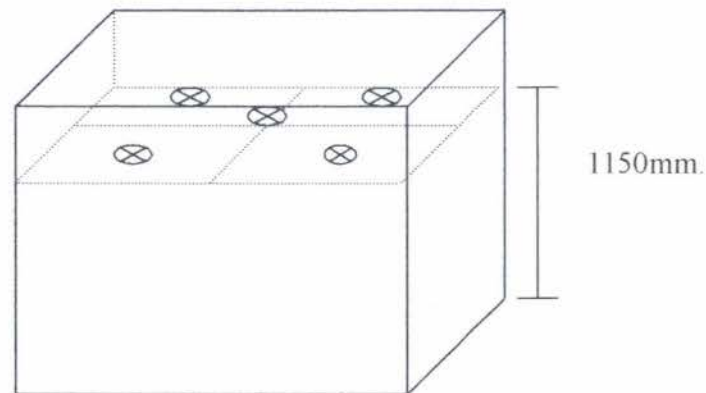


Fig. 4.9 The locations of the raw compost samples for bulk weight.



Fig. 4.10 The core cutter is hammered in to collect sample for bulk weight.

The samples were taken using a soil core cutter (Fig.4.11) usually used for soil sample collection. The core cutters were placed on the locations and hammered with a

carpenter's iron hammer on the wooden plate placed on it, to penetrate fully as shown in Fig.4.10.



Fig. 4.11 A knife was used to cut off unwanted materials.

Then the core cutter with sample was removed carefully from the piles to avoid displacement of materials. A knife was used to cut off the surplus materials as shown in Fig.4.11. These samples were then placed into labelled plastic bags and weighed. The samples were then dried in a freeze-drier for 4 days and reweighed. From this data and the volume of the core cutters, the wet bulk density and dry bulk density of raw compost was calculated. The following formula was used to calculate the wet bulk density and the dry bulk density.

$$\text{Bulk density} = \text{Weight of sample (Kg)} \div \text{Volume of sample (m}^3\text{)}. \text{-----} 4.1$$

The bulk weight was expressed as the wet weight of material per unit volume. The bulk density represented the dry weight of the material per unit volume of solids and voids occupied by the original material. The bulk weight and bulk density of the final compost were also determined for each pile in the four layers selected for MC and coliform sample collection. Three samples were collected from each layer using the same procedure followed for raw compost. The locations of samples in each layer were at the three points A, B & C of the triangular shape shown in Fig.4.12. Point A was 400mm

from the left and the front face and point B was at 400mm from the back face and 600mm from the left or right face. The point C is symmetrical to point A.

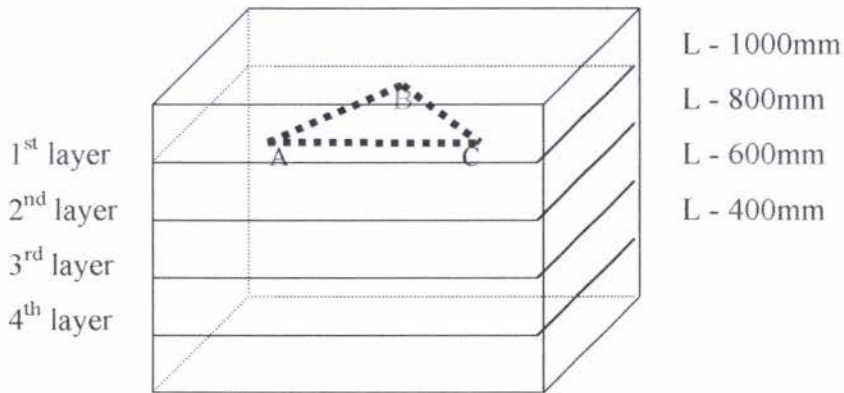


Fig. 4.12 The points A,B & C show locations for bulk weight sampling.

The specific gravity of the solids was defined as the dry weight of solid particles per unit volume of water displaced by them. The specific gravity of raw and final compost was determined by the formula given in Haug (1993) on the basis of the VS content fraction of dry matter. Porosity is the void volume occupied by both water and air. The porosity in this study was calculated by use of the formula by Hong *et al.*(1983).

$$\text{Porosity (\%)} = 100 \times ( 1 - \text{bulk density} / \text{sp. gravity} ). \text{-----} 4.2$$

The free air space (FAS) of porosity was calculated using the following formula:

$$\text{FAS (\%)} = \text{Porosity} ( 1 - \text{moisture content} / 100 ). \text{-----} 4.3$$

#### 4.6 PARTICLE SIZE DISTRIBUTION

A sieve analysis was carried out for sawdust and wood chips used in both the experiments. The samples of the materials were allowed to air dry at ambient temperature for 7 days and weighed and then passed through a set of British Standard (BS) sieves with mechanical shaking for 10 minutes each. The sieves' sizes were 16mm, 11.2mm, 8mm, 5.6mm, 2.8mm, 2mm, 1.68mm, 1.4mm, 850MIC, 710MIC, 500MIC, 250MIC and Pan. The materials retained on each sieve were weighed and converted to a percentage of total material sieved. This physical property was measured to show the progression of the particle size distribution and to help reveal the structure, texture and porosity of the materials.



#### 4.7 TEMPERATURE MONITORING

A total of eight (numbered 1 to 8) thermocouples were manufactured and used for temperature monitoring using type K thermocouple wire as shown in Fig.4.13. Six 10mm PVC pipes and 6mm plastic tubes were used to keep the thermocouple cables straight and insert them at an exact position inside the two replicated compost piles from the outer edge. Three thermocouple positions at three different horizontal locations (400mm, 600mm and 800mm above the base) were chosen for each compost pile and each of them were at 600mm inside from the outer edge of the pile as shown in Figs.4.13 and 4.14. One thermocouple was used to measure ambient temperature and the last thermocouple was placed at 100mm soil depth from the adjacent ground surface to measure the ground temperature. The thermocouples' positions were chosen for both experiments to collect the core temperatures at the above mentioned locations. The thermocouples were connected to a data logger and were calibrated using an ice bath. The data logger was programmed to register temperature at 5-minute time intervals. Monitoring was carried out for 70 days in Experiment-I and 73 days in Experiment-II.



Fig. 4.13 Cables of thermocouples and data logger.

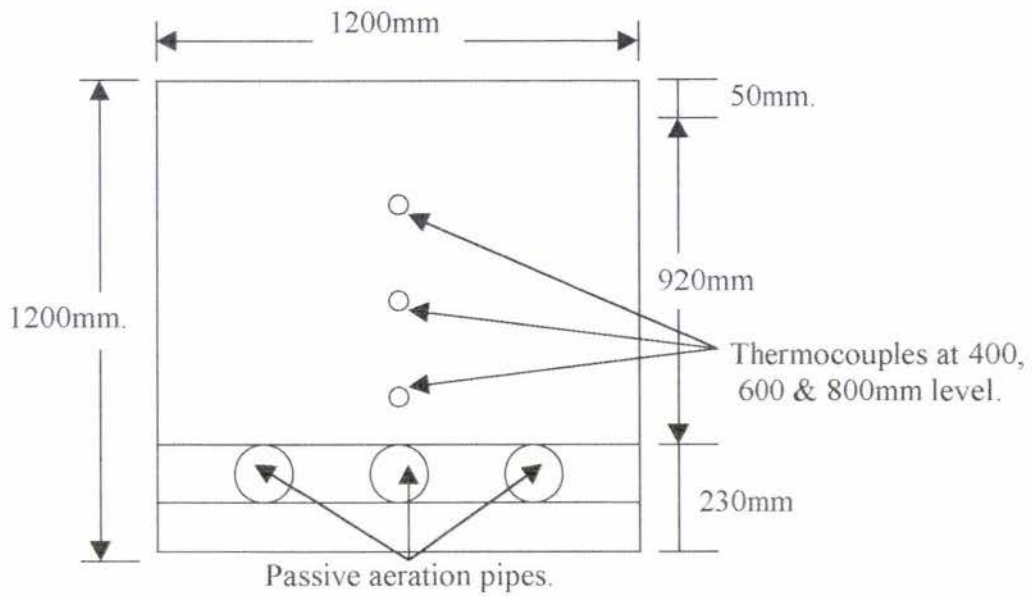


Fig. 4.14 The locations of thermocouples in pile.

A K type heavy duty single input thermometer (Model No.421305, made by Extech Instruments, Wellington, New Zealand, 1995) was also used to measure the daily temperature between 12:00 noon and 2:00 PM at different locations inside the piles, including the same locations used for the thermocouples inside the piles.



Fig. 4.15 Manual temperature probe was used to measure the compost temperature.

This manual temperature probe had a digital monitor and a rod shaped sensor which was pushed into each layer at 100mm, 300mm and 600mm from the front outer edge of the piles, and was held for 5-minute at every location to ensure a stable temperature reading, as shown in Fig.4.15.

This probe was used to monitor the temperature distribution of 4 layers (400mm, 600mm, 800mm and 1000mm from bottom of the piles) in each pile. Calibration of the temperature probe was conducted monthly by placing the probe into iced water and boiling water and calibrating it to 0°C and 100°C.

#### **4.8 ANALYTICAL PROCEDURES**

The following analytical procedures were performed in this study.

##### **4.8.1 MOISTURE CONTENT MONITORING**

The moisture content of compost material for Experiment-I was monitored once a week, commencing on the 10th day of composting and continuing until the last day of observations. It was difficult to collect the sample from the pile center with the usual soil sampler because of the wood chips, which precluded easy penetration of the tool. To overcome this problem, a sampler was designed and manufactured which had two parts; one was a 12mm inner diameter stainless steel cylinder and another was a 12mm outer diameter piston connected with a piston rod and handle. Two plastic piston rings were used to make the piston workable for suction of materials from inside the pile. The samples were collected (at 600mm inside from the outer edge of piles) for each pile from four layers (300mm, 500mm, 700mm and 900mm above the base ). On the day of the deconstruction of piles, samples were also collected from the same locations. The samples from Experiment-II could not be collected with the sampler used in Experiment-I because of the shredded paper. A different types of sampler was used to collect the samples once a week for Experiment-II, although this failed after three weeks. The replacement sampler for Experiment-II had an arrangement of four fingers (like an anchor) to grab the materials from inside the piles.

Samples were also collected in 1000ml containers from the core areas of four layers of each pile on the day of the deconstruction of pile for both the experiments. The samples were then preserved in a freezer for laboratory analysis.

#### **4.8.2 MOISTURE CONTENT DETERMINATION**

Moisture content measurement was carried out according to Standard Methods (1995) using a Contherm Digital Series Oven (Made by: Contherm, Lower Hutt, New Zealand, 1992). According to Standard Methods (1995) to determine moisture content a well-mixed sample is dried in an oven at 103-105°C overnight. Accordingly, sub-samples were taken from the preserved samples and then oven dried to constant weight ( two weight readings were taken to ensure constant dry weight for each sample) in duplicate at 105°C for 24 hours for moisture content determination. Dried samples were then stored in a desiccator to stabilize the temperature prior to the weighing of the samples.

#### **4.8.3 VOLATILE SOLIDS AND ASH CONTENT DETERMINATION**

Volatile solids measurements were performed according to the temperature and duration selected for volatile solids determination by Lopez-Real & Baptista (1996) during the composting of dairy manure with straw. However, the compost samples of this study contained heavier wood chips which took 3-4 hours at 550°C for complete ignition. Dried samples (from the moisture content determinations) in crucibles were weighed and placed in a 550°C oven (NEY M-525 Muffle Furnace made by: NEY, Bloomfield, USA, 1996) for approximately 4 hours. The samples were then cooled in a desiccator to stabilize the temperature prior to the weighing of the samples.

#### **4.8.4 CARBON, NITROGEN ANALYSIS**

The C and N were determined by a LECO FP 2000 automated analyzer (Manufacturer: LECO, Michigan, USA). The frozen samples of each raw material, raw compost and final compost were defrosted and freeze-dried for four days before measurement. The freeze-dried samples were then broken down into a fine particle size (<0.25mm) in a hammer mill. These fine particle samples were then combusted in a

resistance furnace heated to 1050°C in a stream of pure oxygen, which converted carbon and nitrogen to CO<sub>2</sub>, N<sub>2</sub> and NO<sub>x</sub>. The gases then passed through an Infrared cell to determine carbon and a Thermal Conductivity cell to determine nitrogen.

#### 4.8.5 ENERGY CONTENT ANALYSIS

A Bomb Calorimetry method was followed (The Calorimeter was manufactured by: GALLENKAMP AUTOBOMB, Agent: WATSON VICTOR LTD, 4 Adelaide Road, Wellington, New Zealand) to determine the gross energy content. The frozen samples of each raw materials, raw compost and final compost were defrosted and freeze-dried for four days before measurement. The freeze-dried samples were then broken down into a fine particle size (<0.25mm) in a hammer mill. The weighed sample was totally combusted in an insulated environment. The energy released in oxidative combustion causes a temperature increase in the insulated system, which is of known heat capacity. The following calculation procedures were used for determining the gross energy of samples.

Energy released by sample (KJ) = Temperature rise (°C) × Heat Capacity (KJ/°C). ---- 4.4

Gross energy of sample (KJ/g) = Energy released (KJ) ÷ Mass of sample (g). ----- 4.5

#### 4.9 WEIGHT

Mass values were measured using a four decimal places electronic scale, Mettler AE 2009 (Mettler, Teledo AG, Greifensee, Switzerland, 1995). The electronic scale was calibrated always before use with the help of “Mode” key and “calibration lever”.

#### 4.10 COLIFORM MONITORING

During the casting of piles and immediately after completion of casting on each working day for both the experiments, samples were collected from different locations in a pile layer to ensure a representative samples were taken for both piles. For Experiment-I, no intermediate samples were collected but for Experiment-II, four samples were collected from four layers of each pile for total coliform counts. For both the

experiments, on the final day of deconstruction of the piles, samples of the final product were collected from 4 core locations in each pile (The final location of the 400mm, 600mm, 800mm and 1000mm layers from the base after shrinkage and 600mm inside the pile from its outer edge). Immediately after the collection of the samples, they were homogenized by hand and transported to the laboratory for coliform analysis. Sub-samples were taken for analysis of moisture content and volatile solids content. The density of coliform populations were computed in terms of the Most Probable Number (MPN) 5 tube method. Fresh compost samples (50g) and peptone water (500ml) were homogenized using the Colworth stomacher for 2 minutes and allowed to settle well, after which additional dilutions were made up to  $10^{-6}$ . Using 1ml pipettes, one ml from the following dilutions  $10^{-2}$ ,  $10^{-3}$ ,  $10^{-4}$  and  $10^{-5}$  was inoculated in five replicates, single strength MacConkey broth, 5ml, with Durham tube, 4x5 array. Then twenty MPN tubes (5 tubes for each dilution) were incubated at 30°C for 24hrs. The tubes were further incubated for 24hrs at 30°C to ensure the same response. After observing the MPN tubes for colour change (yellow colour is positive due to acid formation) and Durham tubes for gas formation, the results were recorded as positive or negative using the “fractional” notation, e.g. 3/5 to signify 3 positives out of 5 replicates. The significant part of the results were identified from the 3-dilution tables. From MPN probability tables, the MPN/100ml for diluted sample was read and then adjusted for undiluted sample. The MPN values for diluted samples, were obtained at 95% confidence limits as MPN/100ml from Tables 9221: II, III and IV for MPN index given in the Standard Methods (1995). These values were adjusted for undiluted samples and finally converted to MPN/g dry solids of compost.

#### **4.11 CALCULATION OF AREA UNDER TIME-TEMPERATURE CURVE**

The time-temperature curves obtained from the data recorded by the manual temperature probe were used to calculate the areas under curves (see Appendix J). The area under curve at regions above 55°C was only considered. This is because, 55°C for 3 days is usually considered as the required magnitude and duration for coliform destruction. A digital planimeter (PLANIX 7, Manufacturer: TAMAYA TECHNICS INC. JAPAN) was used to calculate these areas. The graphs were leveled and pasted on a horizontally placed

drawing table. The roller axle and the tracer arm of the planimeter were placed at right angles to each other. The tracer arm was placed at a starting point (which is on approximately the centre line of the area to be measured) on the outline of the area to be measured. Then the tracer was moved clockwise along the outline of the area until it returned to the starting point. The same area was measured three times and values averaged to obtain the most reliable results.

#### 4.12 DATA ANALYSIS

Microsoft Excel 5.0 was employed for the analysis of the research data. Statistical tests (T-test, and ANOVA) were used to determine the standard error of differences in temperature, moisture content, volatile solids, bulk density, C & N content, energy content and coliform counts.

#### 4.13 DESIGN OF MATERIALS MIXTURES

For the mix design of compost, a mathematical model developed by Haug (1993) was followed for mass balance, energy balance, water ratio and energy ratio. Since the dairy manure was very wet (about 90% MC) as a substrate, it was conditioned by adding sawdust for Experiment-I and shredded mixed paper for Experiment-II as an amendment to get a combined moisture content of (manure+sawdust) or (manure+shredded paper) around 80%. From the mass balance, the mix proportion by weight for manure : sawdust was 1: 0.34 and for manure : mixed paper was 1:0.13. With this mixing ratio, free air space was calculated according to the formula given by Haug (1993) as follows:

$$FAS = 1 - (D_{sa} \cdot S_{sa} / G_{sa} \cdot D_w) - D_{sa}(1 - S_{sa}) / D_w, \text{ ----- } 4.6$$

Where,  $D_{sa}$  = Bulk density of (manure+sawdust).

$S_{sa}$  = Solid content of (manure+sawdust).

$G_{sa}$  = Specific gravity of (manure+sawdust).

$D_w$  = density of water.

The free air space values for (manure+sawdust) and (manure+mixed paper) were found to be only 14.35% and 11.35% respectively, which did not comply with the minimum recommended FAS of 30%. Since the design was considered under passive aeration, where there was no turning or tumbling, sufficient FAS was very important. To get the desirable level of FAS, wood chips as a bulking material were included in the design for both the experiments. Wood chips were chosen as a bulking agent because they have moisture absorbing characteristics expected to be 60% of their dry weight for structural conditioning. The wood chips were too dry and porous in Experiment-I before mixing and were expected to draw a significant amount of water from the (manure+sawdust) mixture and an equivalent void volume increase was also expected. However, the wood chips in Experiment-II were not as dry because they were made from wet & raw wood shavings.

A mass balance was done to find the ratio of bulking agent to (manure+sawdust) and (manure+mixed paper) under the following assumptions:

That-

- The mixture of (manure+sawdust) or (manure +mixed paper) is a semi-fluid and will occupy the interstices of the final mixture of (manure+sawdust+wood chips) or (manure+mixed paper+wood chips).
- Sufficient bulking agent will be added to provide structural support for the mixture and this condition will be satisfied only if the mixture remains porous.
- Moisture absorption will be limited by the bulking agent saturation.
- Moisture release from (manure+sawdust) or (manure+mixed paper) will be limited by a maximum solid content.
- Bulking particles will be solid with no internal FAS.

The mixing ratio was obtained from the following formula developed by Haug (1993),



$$1/M_{bs} = D_b/D_w \cdot (S_b/S_{bm(m)} - 1) + M_{mb}(1-F_m) - (1 - F_b). \text{-----} 4.7$$

Where,  $M_{bs}$  = volumetric mixing ratio of (manure+sawdust) or (manure+mixed paper) to wood chips.

$D_b$  = bulk density of bulking agent.

$D_w$  = density of water.

$S_b$  = solid content of bulking agent.

$S_{bm(m)}$  = minimum solid content of bulking agent achievable.

$M_{mb}$  = volume increase factor after mixing.

$F_m$  = FAS within the interstics of final mixture.

$F_b$  = FAS within the interstics of bulking agent.

A check was done with the another formula developed by Haug (1993) to find out whether the moisture absorption was limited by the bulking agent or by the substrates (manure+sawdust or manure+mixed paper), which indicated that it was limited by bulking agent absorption. The formula for checking was:

$$M_{bs} = (1 - D_s/D_w)[1 - S_s/S_{sm(m)}] / M_{mb}(1-F_m) - (1 - F_b). \text{-----} 4.8$$

Where,

$M_{bs}$  = volumetric mixing ratio of (manure+sawdust or manure+mixed paper) to wood chips.

$D_s$  = bulk density of (manure+sawdust or manure+mixed paper).

$D_w$  = density of water.

$S_s$  = solid content of (manure+sawdust or manure+mixed paper).

$S_{sm(m)}$  = maximum solid content of (manure+sawdust or manure+mixed paper) achievable.

$M_{mb}$  = volume increase factor after mixing.

$F_m$  = FAS within the interstics of final mixture.

$F_b$  = FAS within the interstics of bulking agent.

The mixing ratio by volume obtained from the above calculation was then transformed into the mixing ratio by weight. After obtaining the mixing ratio, the FAS obtained for the final compost mixtures was still less than 30%. Since firstly, the thermophilic temperature during composting process can evaporate some water from the mixture and secondly, the wood chips were considered to be absorptive to some extent, this FAS value was assumed to be effective.

The biodegradable fraction of only substrate (manure) and amendment (sawdust or mixed paper) was considered to be totally decomposed during composting. An analysis was done to establish various components of amendments and substrate such as biodegradable volatile solids (BVS), non biodegradable volatile solids (NBVS), water (WAT) and inert fraction (ASH). The chemical formula for manure could not be found in the literature<sup>1</sup>. The empirical formula for sewage sludge, namely  $C_{10}H_{19}O_3N$ , was used to determine the water that could be produced during composting for manure. The total solid and volatile solid contents of the final compost were expected to be 60% and 45% respectively. The amount of water to be evaporated per kg of sawdust or mixed paper is calculated by considering 60% total solids and 45% volatile solids of final compost.

As a considerable amount of water was expected to be removed with the exhaust gases during the thermophilic stage, specific humidity (moisture carrying capacity) of the inlet and outlet gases was determined from water vapour pressure, molecular weight of water (18.015g) and dry air (28.96g) using the following formula (Haug,1993).

$$W = 18.015/28.96 [ PV / ( PAIR - PV ) ]. \text{-----} 4.9$$

Where, W = specific humidity of inlet & outlet gases in g-water/g-dry air.

PAIR = atmospheric pressure, in mmHg.

PV = water vapour pressure.

---

<sup>1</sup> However, Haug (1993) has published an approximate empirical formula for sewage biosolids.

Saturation vapour pressure (PVS) and actual water vapour pressure (PV) can be determined by solving the following two equations:

$$\text{Log}_{10} \text{PVS} = a/Ta + b. \text{ ----- } 4.10$$

$$\text{PV} = \text{RHAIR}(\text{PVS}). \text{ ----- } 4.11$$

Where, a = constant equal to -2238 for water.

b = constant equal to 8.896 for water.

Ta = absolute temperature, K.

RHAIR = relative humidity, fraction of saturated vapour pressure.

The moisture carrying capacity of inlet and outlet gases was found to be 0.1146 and 0.1033g water/g dry air respectively. From the data obtained from the analysis, a mass balance for the different components and a mass balance for the water components was established.

An energy balance was done to find the input stored energy of feed materials and the required energy demands for the process, according to Haug (1993).

After calculating the energy balance for both the experiments (see Appendix 9), it was found that the total energy demands were more than the energy supplied by the feed materials. The difference could be adjusted by adding more amendment but that was not done so that performance of the process with energy poor feed materials could be established.

The other two energy factors, water ratio (W) and energy ratio (E), which are usually used to judge the thermodynamic characteristics of the composting process were calculated on the basis of the rule of thumb for water and energy ratio provided by Haug (1993).

## CHAPTER-5

### RESULTS

#### 5.1 COMPOST PILE CHARACTERIZATION

Important physical, chemical and biological properties of manure slurry, sawdust, office paper, newsprint, wood chips, raw compost and final compost are shown in Tables 5.1 and 5.2, obtained from Experiment-I and Experiment-II respectively. The C:N ratio and Moisture Content (MC) of raw dairy manure slurry were 16.16% and 90.1% for experiment-I and 89.7% and 10.57% for experiment-II. The dairy manure was not possible to compost directly without addition of a dry amendment because of very high moisture content and low C:N ratio. To adjust these parameters manure slurry was mixed with sawdust and wood chips (mixing ratio: 1:1:2 by volume) in experiment-I. Mixed paper (75% office paper + 25% newsprint) was used as an amendment in experiment-II. The mixed paper was mixed with manure on a weight basis (manure:mixed paper = 1:0.13) and the wood chips were mixed on a volume basis (manure:wood chips = 1:2).

Table 5.1.(Exp-I)Physical chemical and biological properties of initial and final materials. Standard errors are in brackets.

Properties	Manure	Sawdust	Wood chips	Raw Compost (pile-1)	Raw Compost (Pile-2)	Final Compost (Pile-1)	Final Compost (Pile-2)
Weight of materials in kg.	509.251* 516.80**	173.5	256.2	939.00	946.50	511	574.60
Bulk weight in kg/m <sup>3</sup> .	-	362	267	639 (100)	624 (122)	420 (21)	464 (41)
Dry matter (DM)(%)	9.9 (0.6)	38.4 (4.0)	79.4 (2.5)	33.1 (1.5)	33.7 (1.5)	41.6 (2.2)	43.2 (2.5)
Moisture content(MC)(%)	90.1 (0.6)	61.6 (4.0)	20.6 (2.5)	66.9 (1.5)	66.3 (1.5)	58.4(2.2)	56.8 (2.5)
Volatile solids(VS)(%DM)	66.4 (2.6)	99.0 (0.5)	98.2 (0.1)	93.1 (0.7)	91.3 (1.5)	90.9 (2.0)	90.5 (0.7)
Ash (%DM)	33.6 (2.6)	1.0 (0.5)	1.8 (0.1)	6.9 (0.7)	8.7 (1.5)	9.1 (2.0)	9.5 (0.7)
Total carbon(TC)(%DM)	37.5 (2.5)	50.2 (0.0)	49.5 (0.0)	46.86 (0.9)	45.7 (2.0)	44.3 (3.0)	44.9 (0.9)
Total nitrogen(TN)(%DM)	2.35 (0.3)	0.11 (0.0)	0.44 (0.0)	0.91 (0.25)	0.87 (0.1)	1.21 (0.5)	1.22 (0.2)
C/N ratio	16.16	456.36	112.5	53.10	53.00	37.70	36.71
Energy content (Cal/g-ds)	3990 (290)	4732 (0.0)	4692 (0.0)	4610 (110)	4515 (140)	4365 (190)	4365 (178)
Coliform (MPN/g-ds)	-	-	-	8.68*10 <sup>7</sup>	1.17*10 <sup>8</sup>	2.20*10 <sup>6</sup>	6.58*10 <sup>5</sup>

\* Pile-1; \*\* Pile-2. All % values expressed as weight in weight.

Table 5.2 (Exp-II) Physical chemical and biological properties of initial and final materials. Standard errors are in brackets.

Properties	Manure	Office paper	News print	Wood chips	Raw Compost (pile-1)	Raw Compost (Pile-2)	Final Compost (Pile-1)	Final Compost (Pile-2)
Weight of materials in kg.	574* 580.2**	56.16	18.63	568.81	1217.62	1223.81	355.9	398
Bulk weight in kg/m <sup>3</sup> .	-	-	-	526	593 (45)	623 (16)	307 (48)	333 (30)
Dry matter (DM)(%)	10.3 (0.3)	94.2 (0.2)	92.3 (0.4)	52.4 (0.8)	29.3 (0.6)	30.5 (0.7)	53.4 (5.0)	52.4 (6.0)
Moisture content(MC) (%)	89.7 (0.3)	5.8 (0.2)	7.7 (0.4)	47.6 (0.8)	70.7 (0.6)	69.5 (0.7)	46.6 (5.0)	47.6 (6.0)
Volatile solids(VS) (%DM)	63.5 (0.5)	78.9 (0.1)	99.0 (0.5)	98.3 (0.4)	85.1 (0.7)	85.8 (0.7)	80.8 (6.0)	82.7 (2.8)
Ash (%DM)	36.5 (0.5)	21.1 (0.1)	1.0 (0.5)	1.7 (0.4)	14.9 (0.7)	14.2 (0.7)	19.2 (6.0)	17.3 (2.8)
Total carbon(TC) (%DM)	31.5 (2.0)	38.0	49.0	48.8	43 (2.5)	42.8 (1.5)	42.5 (3.2)	41.6 (1.0)
Total nitrogen(TN) (%DM)	2.98 (0.1)	0.05	0.07	0.56	1.20 (0.3)	1.18 (0.3)	1.86 (0.7)	1.75 (0.6)
C/N ratio	10.57	760	700	87.14	35.84	36.88	23.36	24.14
Energy content (Cal/g-ds)	3480 (430)	3184	4585	4635	4189 (175)	4125 (245)	4015 (290)	3975 (95)
Coliform (MPN/g-ds)					1.92*10 <sup>8</sup>	1.54*10 <sup>8</sup>	4.36*10 <sup>6</sup>	2.01*10 <sup>6</sup>

\*Pile-1; \*\* Pile-2. All % values expressed as weight in weight.

The justification for using wood chips as bulking agent was investigated. For experiment-I, the mixing ratio of sawdust and manure slurry was 1:1 by volume. A question may arise as to why sawdust and manure in 1:1 ratio was not selected for composting without using a bulking agent? To answer this question, bulk densities, MC and VS of (sawdust + manure) mixture in 1:1 and 1.2:1 ratio by volume were determined in the laboratory and FAS were calculated as given in Table 5.3:

Table 5.3 Physical properties of (manure+sawdust) mixture used in the study.

Samples	Volumetric mixing ratio (Sawdust : Manure)	Moisture content (%)	VS content of manure (%)	VS content of sawdust (%)	Bulk weight in kg/m <sup>3</sup>	Bulk density in kg/m <sup>3</sup> .	FAS of mixture (%)
Sawdust +Manure	1:1	85.51	66.07	99.58	1009	146.9	0.77
Sawdust +Manure	1.2:1	84.76			989.8	150.76	3.27

From the above results, it is evident that the MC and bulk weights of both the mixtures (sawdust and manure) were too high for composting. The calculated FAS was close to zero. Using the above mixing ratio, the process would not have sufficient FAS for keeping the process aerobic and ultimately anaerobic conditions would prevail.

The FAS in the compost matrix is influenced by the moisture content and becomes limiting when the moisture is raised above 60% (Schulze,1961). However, the MC of these mixtures was around 85%. Optimum moisture contents should fall in the range of FAS between 30-35% and a minimum 30% FAS should be maintained especially where there is no provision for turning (Haug,1993). The bulk weight of the mixtures was close to 1000 kg/m<sup>3</sup>, thus making it difficult to aerate the material. Effective aeration requires that the bulk weight should be maintained between roughly 475-600 kg/m<sup>3</sup> (Seekins,1999). Material that is too dense would not compost adequately, no matter what system is provided.

The bulk weight of mixtures of sawdust and manure were found to be higher than the recommended level of bulk weight. Therefore, although the use of sawdust could meet the required C:N ratio for composting, it did not meet the required level of moisture content, bulk density and FAS. The mixture of manure and sawdust still needed to be adjusted for moisture content and its structure opened up to meet the recommended levels of bulk density and FAS. Although a range of 50-60% (w/w) moisture content is generally recommended for composting, Fernandes *et al.*(1994) found that composting with 80% (w/w) moisture content was feasible if proper aeration could be provided. However, the FAS values found in the present experimental

mixtures were low and did not comply with the recommended levels. Therefore, in the present study the amount of sawdust or mixed paper used was calculated to give a mixture (manure + sawdust and manure + mixed paper) of around 80% (w/w) moisture content. Therefore, in order to open up the matrix to the required bulk density and FAS for aeration, wood chips as a bulking agent were used because they have a porous structure, which facilitates air movement through passive and natural airflow circulation. They also offer a rigid structure to the matrix of compost to resist settling and compaction over time.

## 5.2 TEMPERATURE

The composting process involves the biological formation of heat energy from organic materials thus causing a temperature rise as the produced heat accumulates within the composting pile. Therefore, temperature can be used as an indicator of the process performance. The temperature curves of two replicate piles at different positions for Experiments-I and II at pile center (600mm inside from outer edge of pile) obtained from 3 thermocouples in each pile during composting are shown in Figs.5.1, 5.2, 5.3 and 5.4 respectively. The figures also show the corresponding ambient temperature profiles.

### 5.2.1 TEMPERATURE PROFILES

From the source data used in plotting Fig.5.1, it was found that the trend of temperature variation (due to the combined effect of aeration, decomposition, heat generation, heat accumulation and heat loss processes) at different levels in pile-1 of Experiment-I are very similar to the typical temperature profiles in composting, and followed a similar trend of variation over the 70 days of composting (22<sup>nd</sup> May to 31<sup>st</sup> July,2001).

Fig.5.1 shows that the temperature at Level-400mm did not reach 55°C, but that may not be true in practice because this level was formed on the first day of pile casting and the peak temperatures of this level possibly decreased before installation of thermocouples. These peak temperatures were recorded with the help of a manual temperature probe.

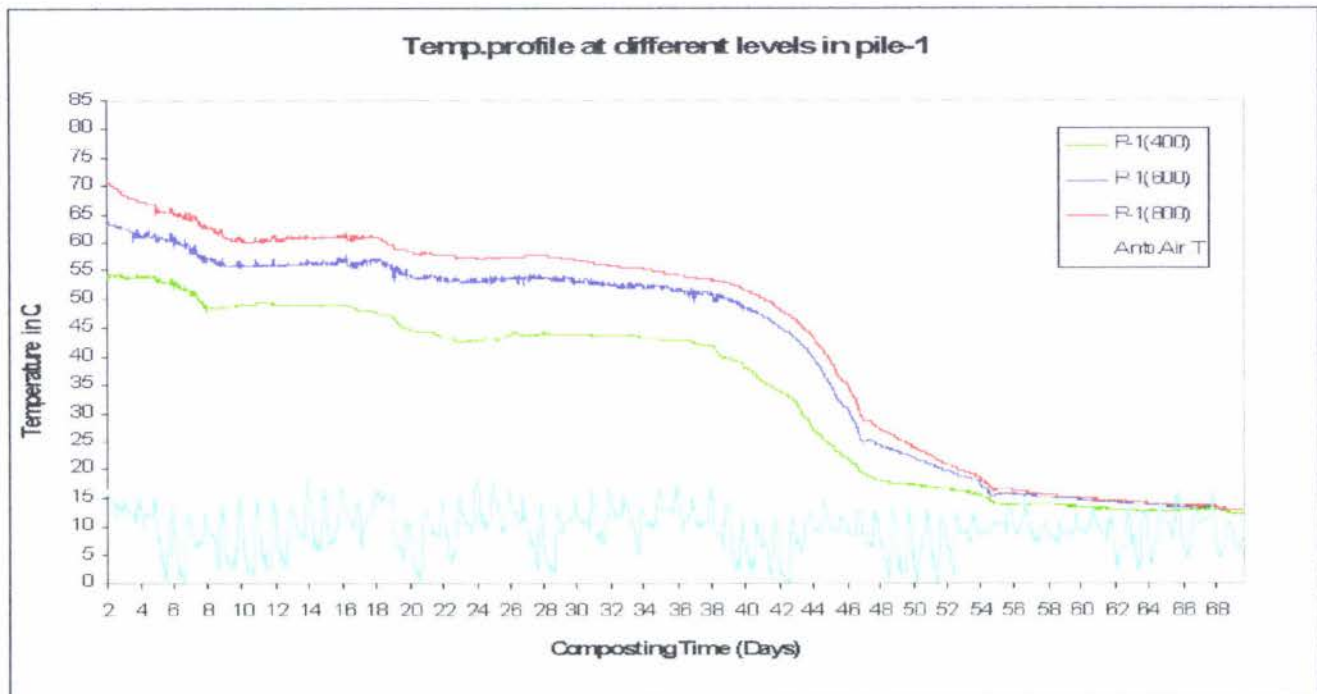


Fig. 5.1 Temperature profile at different levels in pile-1 under Experiment-I. P-1 (400) indicates the temperature profile of pile-1 at 400mm level.

Therefore, all temperatures in all piles at different levels were above 55°C for more than the desirable period of time (3 days). The variation of ambient temperature ranged from 0.06 to 18.4°C over the period and the minimum was recorded in 8 instances. These low ambient temperatures did not affect the internal pile temperatures remarkably at any level of pile-1. However, the temperature curves for the replicate (pile-2 shown in Fig.5.2) are quite different in trend from the typical composting time-temperature curve.

Although the temperatures in pile-2 at different levels had increased from ambient temperature and were between above 55°C to 65°C within 24 hours, they were not sustained for a long period, as did pile-1. The temperatures in pile-2, at all levels, suddenly started to drop from a range of 56 to 66°C during day 5 and had reached to a range of 35 to 39°C during day 8. This fall in temperature occurred due to the loss of large amount of accumulated heat through the loss of sensible heat within a short time and caused by the cold westerly winds. Because of its geographical position, pile-2 was especially affected by the cold prevailing winds in the absence of a wind barrier on the Eastern side (as shown in Fig.4.7).



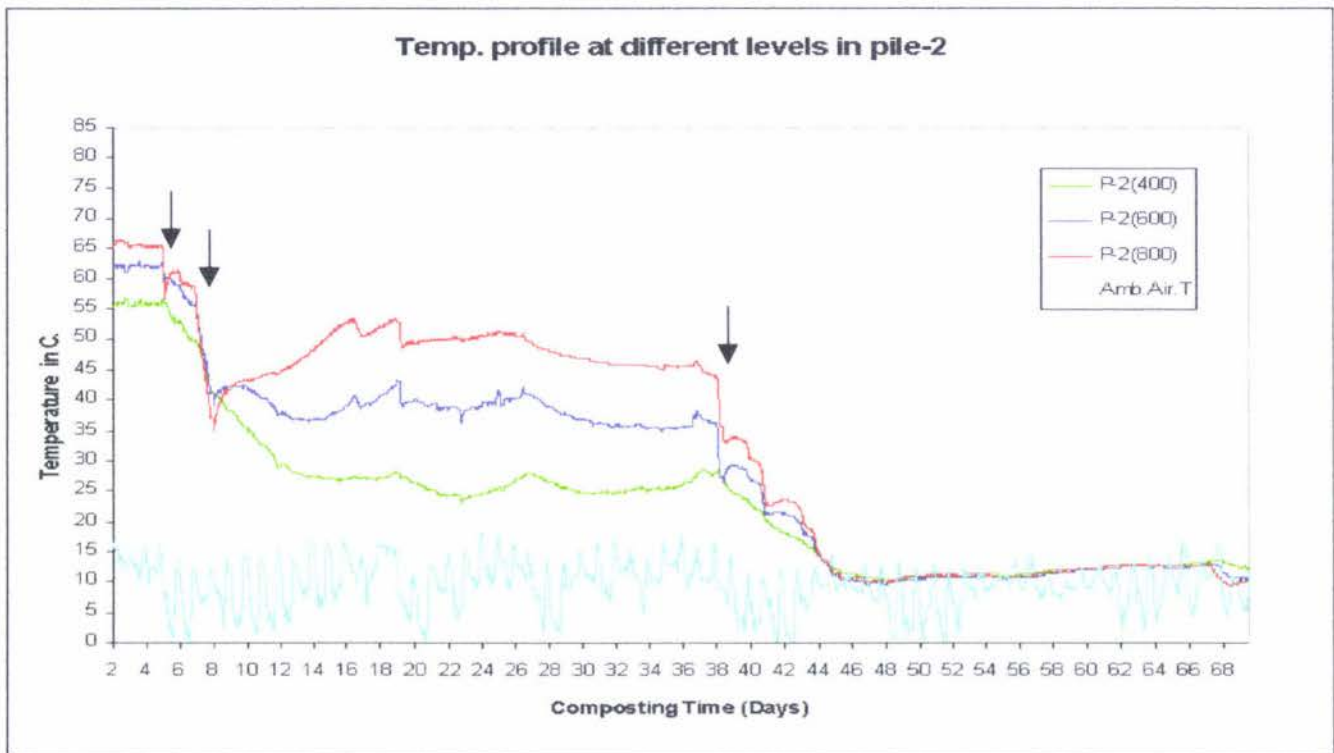


Fig. 5.2 Temperature profile at different levels in pile-2 under Experiment-I. P-2 (400) indicates the temperature profile of pile-2 at 400mm level. Arrow ( $\downarrow$ ) shows the wind action.

Pile-1 was protected on one side from the direct path of cold wind by pile-2, and on another side by a straw bale wall wind barrier and consequently temperatures were not affected by the cold wind. The top layer (L-800mm) of pile-2 started to cool first and gradually the subsequent layers were affected. However, with the passing of this cold and windy period, pile-2 started to regain temperatures and L-800mm had reached a second period of thermophilic temperature by day 12 and attained its second highest peak, 53.7°C on day 19, and thereafter exhibiting a rise and fall trend within the thermophilic range until day 37.

After the period of cold winds, temperatures at 600mm level (L-600) followed an undulating trend and regained thermophilic temperatures five times but the durations were very small, ranging from 0.3 to 3 days (a total time of 7.18 days). Temperatures at 400mm level (L-400) did not regain the thermophilic range again. Although, pile-2 was badly affected by wind

action, the temperatures at all levels monitored had attained a temperature above 55°C for more than the desirable period of time, i.e. 3 days.

Similarly, the source data of Figs.5.3 and 5.4, suggested that the trends in temperature variation at different positions in pile-1 and pile-2 of Experiment-II followed almost typical time-temperature profiles found in composting, although there were a few temperature undulations due to the cold wind. Temperatures maintained similar trends over the 73 days of composting (14<sup>th</sup> September to 27<sup>th</sup> November,2001). The affect of several cold wind storms on temperatures at different levels in pile-1 and pile-2 are given in Table 5.4 below, where the starting day and temperature, the day of the lowest temperature and the day when temperature was regained are included:

Table 5.4 (Exp-II) The affect of cold winds on temperature responses in two composting piles. Pile age (days) and pile temperatures are shown (The temperatures in °C are given in the brackets).

Pile No	1 <sup>st</sup> wind storm event			2 <sup>nd</sup> wind storm event			3 <sup>rd</sup> wind storm event			4 <sup>th</sup> wind storm event		
	Days (Temperature)			Days (Temperature)			Days (Temperature)			Days (temperature)		
	start	min	regain	start	min	regain	start	min	regain	start	min	regain
Pile-1 L-800	9.64 (71.4)	10.59 (63.68)	11.49 (71.4)	21.41 (65.68)	24.51 (52.98)	30.5 (65.52)	36.9 (59.28)	39.12 (49.54)	42.6 (56.04)	50.4 (52.01)	53.83 (21.07)	59.57 (30.63)
Pile-1 L-600	9.8 (69.0)	10.96 (66.9)	12.54 (69.53)	22.40 (64.45)	25.44 (53.25)	31.00 (63.14)	36.92 (58.01)	39.58 (48.45)	42.93 (55.93)	50.43 (50.01)	53.88 (20.20)	59.88 (28.96)
Pile-1 L-400	9.9 (65.21)	10.75 (64.28)	12.41 (67.02)	22.46 (57.23)	25.47 (47.29)	30.88 (57.79)	36.92 (53.4)	40.59 (43.81)	43.00 (48.44)	50.46 (39.06)	53.64 (16.98)	59.15 (26.89)
Pile-2 L-800	6.60 (72.70)	8.57 (55.53)	12.59 (72.00)	21.00 (65.04)	26.10 (46.30)	31.00 (66.56)	33.80 (64.61)	43.30 (41.55)	44.75 (43.47)	46.30 (41.89)	53.68 (13.91)	61.50 (24.34)
Pile-2 L-600	6.90 (67.30)	10.48 (52.50)	12.80 (64.37)	21.80 (55.15)	28.29 (36.69)	30.84 (54.11)	36.75 (51.48)	53.74 (13.71)	60.50 (21.45)			
Pile-2 L-400	8.12 (59.39)	9.93 (48.67)	13.50 (60.13)	23.80 (49.91)	28.46 (26.74)	31.95 (43.29)	36.90 (43.36)	53.53 (13.90)	60.70 (21.14)			

Legend: start = Age of pile at commencement of wind storm  
min = Pile age at time of minimum pile temperature.  
regain = Pile age when thermophilic temperatures were regained.

From the above data it can be ascertained that during all cold wind storms, pile-2 was affected first and pile-1 after few days or hours.

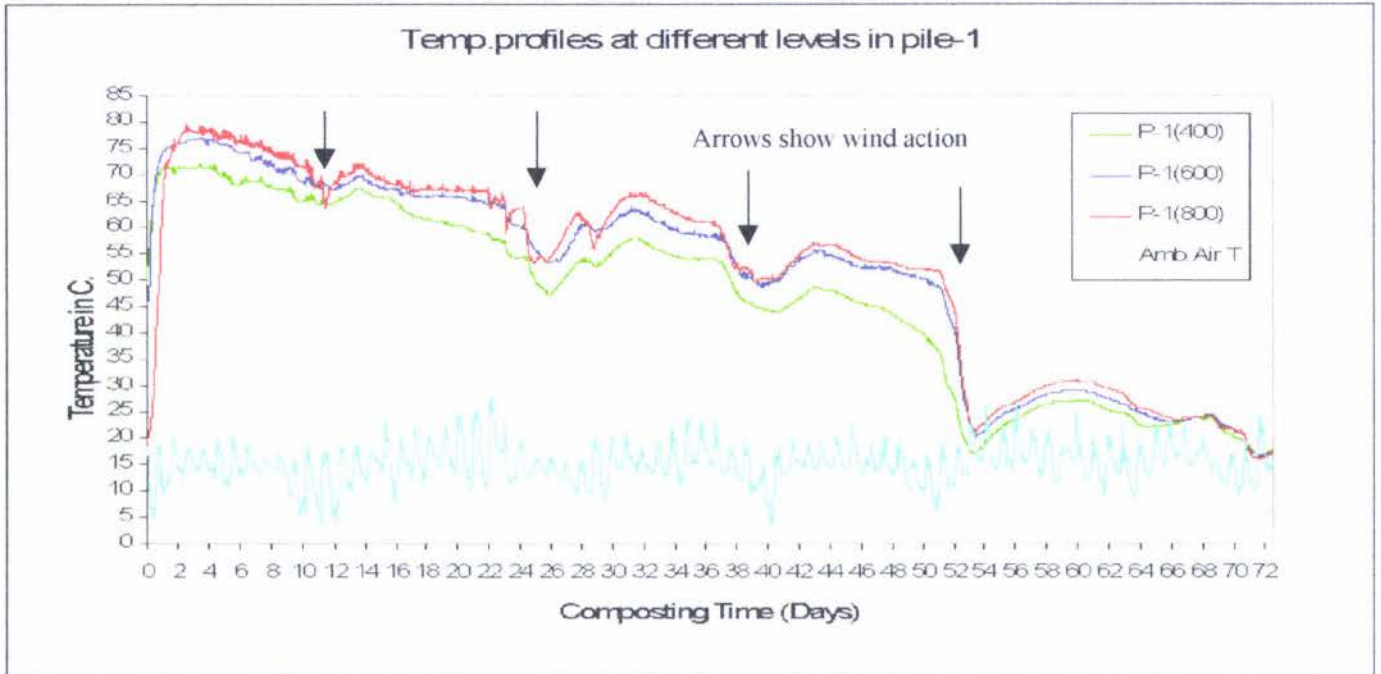


Fig. 5.3 Temperature profile at different levels in pile-1 under Experiment-II.

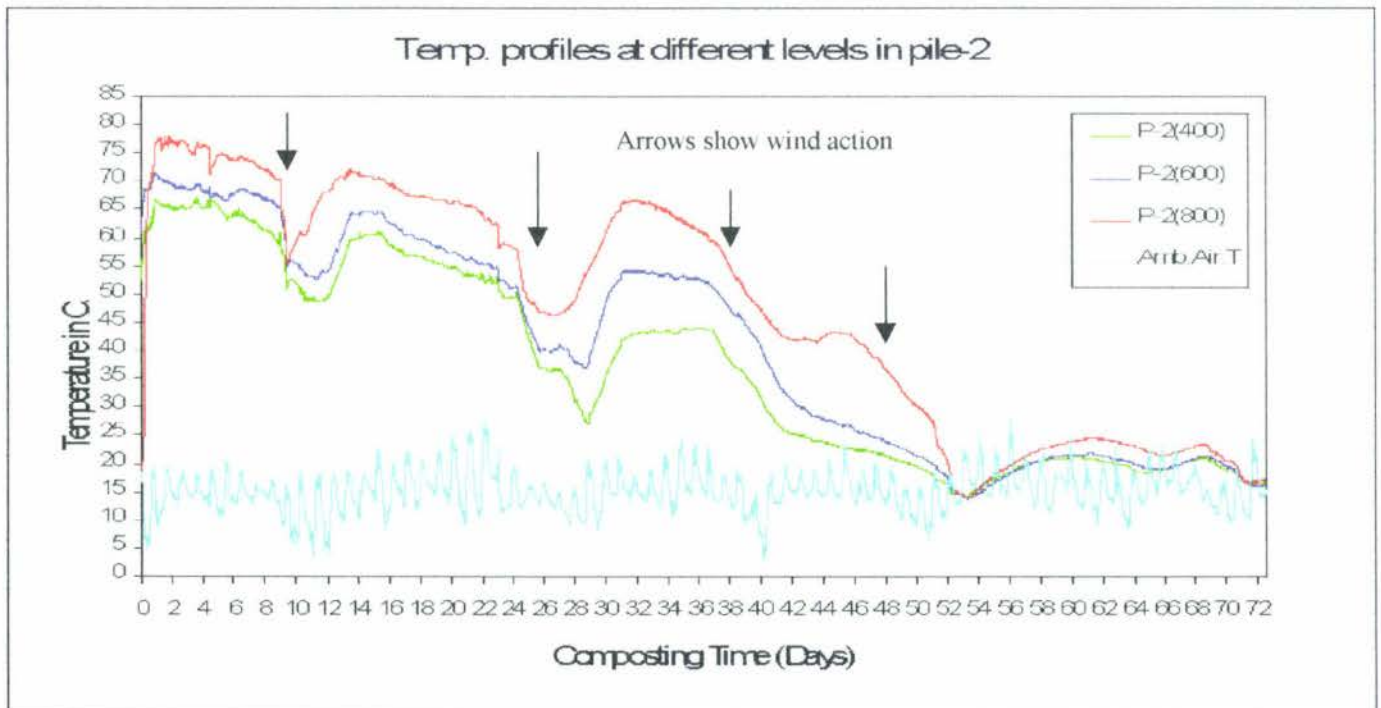


Fig. 5.4 Temperature profile at different levels in pile-2 under Experiment-II

Since pile-2 was always affected first by the wind action, with the third wind storm it started to lose its accumulated heat and it did not regain thermophilic temperatures before the fourth cold wind storm struck. Ultimately, the consecutive third and fourth wind events (all wind events are shown by arrows in Figs 5.3 and 5.4) prolonged temperature decreases. In comparison, from the curves of pile-1 (Fig. 5.3) it is evident that there were four cold wind storm events over the total period of composting. Each time, pile-1 was able to regain its thermophilic temperature at different levels. To some extent it was protected from the direct path of the wind storm by pile-2, although that protection could not safe-guard pile-1 entirely from the cooling effect.

Table 5.4 shows that first two events could not bring the temperature below 47°C. However, during the third and fourth event, temperatures reduced to 39°C and 17°C respectively. The effect of those wind events was more evident in pile-2 as it experienced the wind first. The wind barrier on its East side was partly successful in protecting pile-2 from sharp drops in temperature. Since pile-2 experienced the wind first, during second event, temperatures decreased to 26-29°C in different layers. During third event, temperatures decreased to about 14°C and did not increase, unlike pile-1, before the fourth event.

Another criterion of cooling effect due to windy conditions, can also be observed from Table 5.4. At every windy event, the materials of the top layers of pile-2 were affected first and this cooling effect had migrated gradually towards the bottom layers. The first windy event affected pile-2 at level-800mm on day 6.60 and this effect migrated into level-600mm and level-400mm on days 7 and 9 respectively. However, pile-1 was affected by the same windy event at level-800mm on day 9 and cooling effects noted at level-600mm and level-400mm on day 10.

Similar temperature responses were also noted during other individual windy events which indicated that the relatively dry and cold wind had directly contacted the hot materials of the upper layer of pile-2. The height of wind barriers on the East and South sides of pile-2 were 290mm and 20mm lower than the pile height. Pile-1 was protected by pile-2 from the direct action of the wind. Ultimately pile-1 experienced a dispersed wind action during each event. This cold air consumed the heat energy from the hot materials of the top layer (highest temperatures)

by sensible heat transfer due to temperature differences. As a result, the top layer of materials (air, vapor, water, solids) became less hot than the interior materials. It would seem that the sensible heat loss between the interior and exterior materials (air, vapor, water & solids) had proceeded gradually towards bottom levels of piles.

### 5.2.2 TEMPERATURE HOLDING TIMES

The temperature regimes inside the compost piles for Experiment-I and Experiment-II are presented in Tables 5.5 and 5.6 below:

Table 5.5 (Exp-I): Temperature characteristics at various levels recorded for piles 1 & 2 of Experiment-I. Periods of temperature regimes of interior of composts at pile center are shown in days.

Temperature regimes.	Pile-1				Pile-2			
	L-400mm	L-600mm	L-800mm	L-1000mm	L-400mm	L-600mm	L-800mm	L-1000mm
Highest peak temperature( $^{\circ}\text{C}$ ).	54.6	63.4	70.6	72.6	56.8	62.9	66.3	73.7
Peak temperature( $>55^{\circ}\text{C}$ ) duration(days)	11	18	33	19	4.9	6.5	6.6	7
Average peak temperature ( $^{\circ}\text{C}$ ).	57.62	57.74	60.08	62	55.83	60.56	63.11	65.38
Duration of thermophilic( $>40^{\circ}\text{C}$ ) temperature range (Days).	37	43	44	41	7	11	37	38
Duration of mesophilic temperature range (Days).	32	41	25	28	62	58	32	31
Time to return to ambient temperature (Days).	56	63	63	63	44	44	44	44

Table 5.6 (Exp-II): Temperature characteristics at various levels recorded for piles 1 & 2 of Experiment-II. Periods of temperature regimes of interior of composts at pile center are shown in days.

Temperature regimes.	Pile-1				Pile-2			
	L-400mm	L-600mm	L-800mm	L-1000mm	L-400mm	L-600mm	L-800mm	L-1000mm
Highest peak temperature( $^{\circ}\text{C}$ ).	72.3	77.1	79.5	78.5	67	71.5	77.9	78
Peak temperature( $>55^{\circ}\text{C}$ ) duration(days)	23+3 =26	25+11 =36	37+3 =40	20+5 =25	8+7 =15	9+11 =20	24+9 =33	22+5 =27
Average peak temperature ( $^{\circ}\text{C}$ ).	61.01	64.28	61.61	63.42	60.87	63.49	65.71	64.24
Duration of thermophilic ( $>40^{\circ}\text{C}$ ) temperature range (Days).	50	52	52.5	49	25+7 =32	25+11 =36	47	25+11 =36
Duration of mesophilic temperature range (Days).	23	21	20.5	24	41	37	26	37
Time to return to ambient temperature (Days).	72.3	72.3	72.3	72	51.5	52.4	52.6	52

Experiment-I: In pile-1, the materials at levels of 1000mm, 800mm, 600mm and 400mm reached thermophilic temperatures ( $>40^{\circ}\text{C}$ ) within a day of the completion of pile casting. These temperatures were sustained for 41, 44, 43 and 37 days respectively. The materials at level-400mm did not reach the desirable level of thermophilic temperature for pathogen killing ( $55^{\circ}\text{C}$  for 3 days) at all, but the materials at 1000mm, 800mm and 600mm reached temperatures of more than  $55^{\circ}\text{C}$  and thus was sustained for 19, 33 and 18 days respectively.

In pile-2, the materials at levels of 1000mm, 800mm, 600mm and 400mm reached thermophilic temperatures ( $>40^{\circ}\text{C}$ ) also within a day of the completion of pile casting. Temperatures were sustained for 38, 37, 11 and 7 days respectively. The materials at 1000mm, 800mm, 600mm and 400mm reached temperatures of more than  $55^{\circ}\text{C}$  and were sustained for 7,

6.6, 6.5 and 4.9 days respectively. The highest peak temperatures were 72.6°C and 73.7°C at top level in piles 1 & 2 respectively.

Experiment-II: In pile-1, the materials at levels of 1000mm, 800mm, 600mm and 400mm reached thermophilic temperatures (40°C) within a day of the completion of pile casting. These temperatures were sustained for 49, 52.5, 52 and 50 days respectively. The materials at levels of 1000mm, 800mm, 600mm and 400mm reached temperatures of more than 55°C, being sustained for 25, 40, 36 and 26 days respectively. In pile-2, the materials at levels of 1000mm, 800mm, 600mm and 400mm reached thermophilic temperatures (40°C) also within a day of the completion of pile casting. These temperatures were sustained for 36, 47, 36 and 32 days respectively. The materials at levels of 1000mm, 800mm, 600mm and 400mm reached temperatures of more than 55°C and were sustained for 27, 33, 20 and 15 days respectively. The highest peak temperatures were found 79.5°C at 800mm level in pile-1 and 78°C at 1000mm level in pile-2.

For both the Experiments, the bottom layer's average peak temperatures were found to be slightly lower than the average peak temperatures of the immediate next higher levels which indicate that the temperatures were higher at higher levels and lower at lower levels. The results also suggest that the composting process obtained very good support from various important related factors such as C:N ratio, MC, FAS, aeration and biodegradability to ensure better decomposition rate and desirable level of thermophilic temperatures and thus better end product.

Average peak temperatures shown in Tables 5.5 and 5.6 are the average of all temperatures  $\geq 55^\circ\text{C}$ , although these average peak temperatures do not give any specific indication about the performance of the process whereas the product of time and temperature (above 55°C) at different locations in the piles was used as a tool for evaluating the performance of the composting process. The time-temperature curves (based on temperature data of the manual temperature probe, see Appendix J) for both the experiments were used to calculate the areas. Tables 5.7 and 5.8 for Experiment-I and II respectively, show the calculated areas.

Table 5.7 (Exp.-I) The areas under time-temperature curves at regions above 55°C at different locations.

Locations (Height above pile base in mm)	Pile-1			Pile-2			Remarks
	Areas under curves in Sq.mm			Areas under curves in Sq.mm			
	100mm inside	300mm inside	600mm inside	100mm inside	300mm inside	600mm inside	
Level-400mm	0	0	20	0	0	40	Different levels indicating the height of locations from the base of pile. Temperatures were recorded at 100mm, 300mm and 600mm inside from the front edge of piles.
Level-600mm	0	30	430	0	10	130	
Level-800mm	0	110	890	0	90	240	
Level-1000mm	0	80	520	0	90	280	

Table 5.8 (Exp.-II) The areas under time-temperature curves at regions above 55°C at different locations.

Locations (Height above pile base in mm)	Pile-1			Pile-2			Remarks
	Areas under curves in Sq.mm			Areas under curves in Sq.mm			
	100mm inside	300mm inside	600mm inside	100mm inside	300mm inside	600mm inside	
Level-400mm	0	200	920	0	250	320	Different levels indicating the height of locations from the base of piles. Temperatures were recorded at 100mm, 300mm and 600mm inside from the front edge of piles.
Level-600mm	0	360	1360	50	380	880	
Level-800mm	0	360	1240	0	430	1150	
Level-1000mm	50	230	970	0	210	1040	

The calculated areas (product of time and temperature) under the time-temperature curves indicate (Table 5.7) that the materials at 100mm inside the piles did not get the recommended magnitude and duration of temperature (calculated area zero). The materials at 300mm inside the piles were moderately composted (because the calculated areas are comparatively small and



materials at 400mm level could not reach the desirable temperature). The larger areas under time-temperature curves indicate that the materials at 600mm inside the piles had achieved the highest decomposition. Table 5.7 also indicates that the materials of pile-1 may have composted better than the materials of pile-2.

The calculated areas (product of time and temperature) under time-temperature curves (above 55°C at different thermocouple locations) suggest that (Table 5.8) the materials at 100mm inside the piles did not get the recommended magnitude and duration of temperature, as the temperature at every level could not reach above 55°C for sufficient duration. The materials at 300mm inside the piles were moderately composted (because the calculated areas are relatively smaller). The materials at 300mm inside the piles were composted better than that of Experiment-I. The larger areas under time-temperature curves indicate that the materials at 600mm inside the piles had got the highest decomposition. The Table 5.8 also indicates that the materials of pile-1 composted better than the materials of pile-2.

### **5.3 MOISTURE CONTENT VARIATION**

Moisture content of the composting components, intermediates and products over time was a key concern of this study. The moisture content variation at different levels of the pile for two replicate piles in each of two experiments (Experiments-I & II) over time was monitored weekly. Collected data are presented in Figs.5.5, 5.6, 5.7 and 5.8. Figures 5.5 and 5.6 indicate that the composting process started to remove moisture at the very beginning of the process, and moisture removal was continuous.

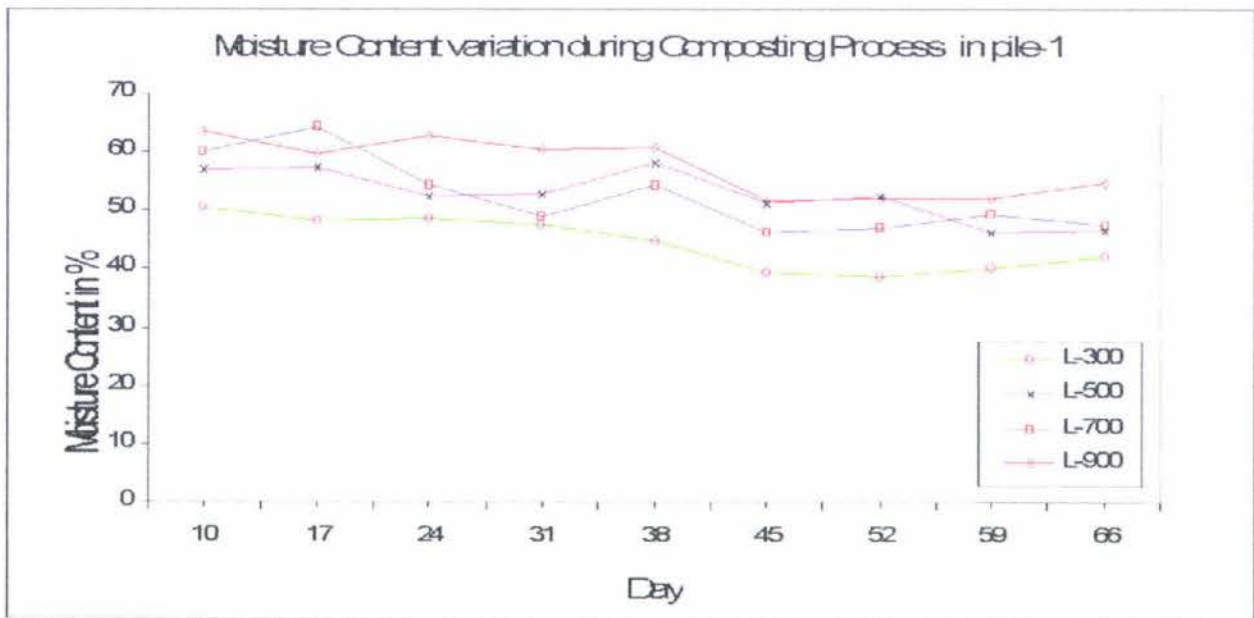


Fig. 5.5 Changes in moisture content (% w/w) in compost. Data for pile-1 of Experiment-I determined at 300, 500, 700 and 900mm distances from base of pile.

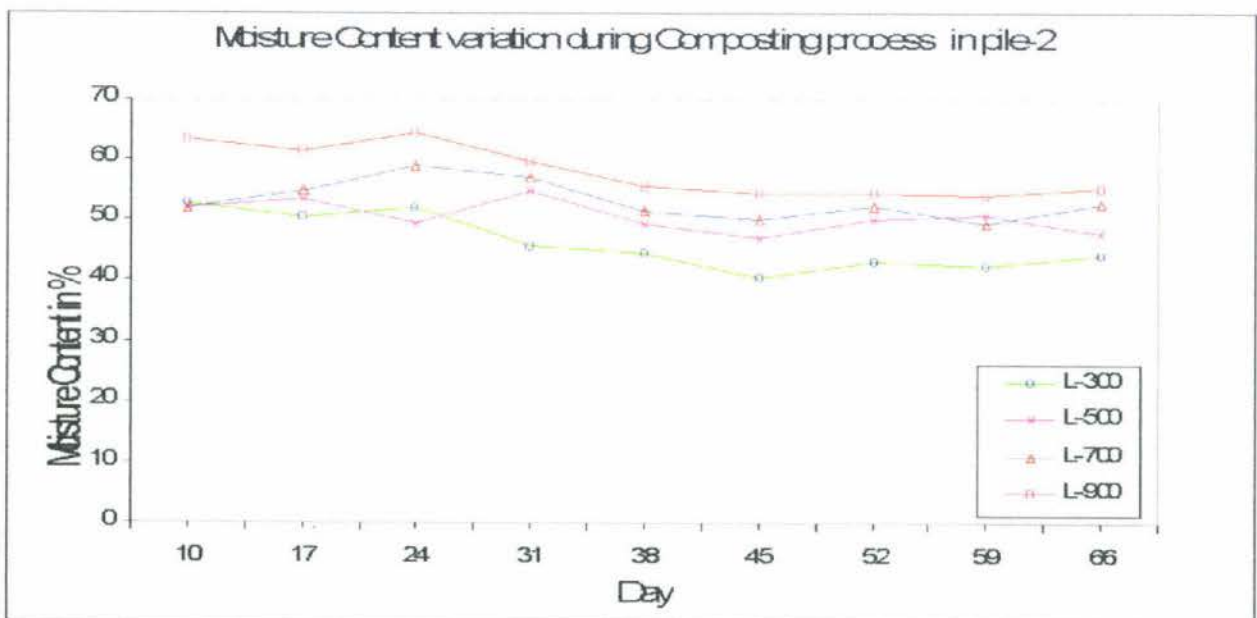


Fig. 5.6 Changes in moisture content (% w/w) in compost. Data for pile-2 of Experiment-I determined at 300, 500, 700 and 900mm distances from base of pile.

The moisture removal process was maximum during the active or thermophilic phase of composting, and it became minimum at the end of the mesophilic phase. The moisture removal monitoring for Experiment-II was discontinued at day 27.

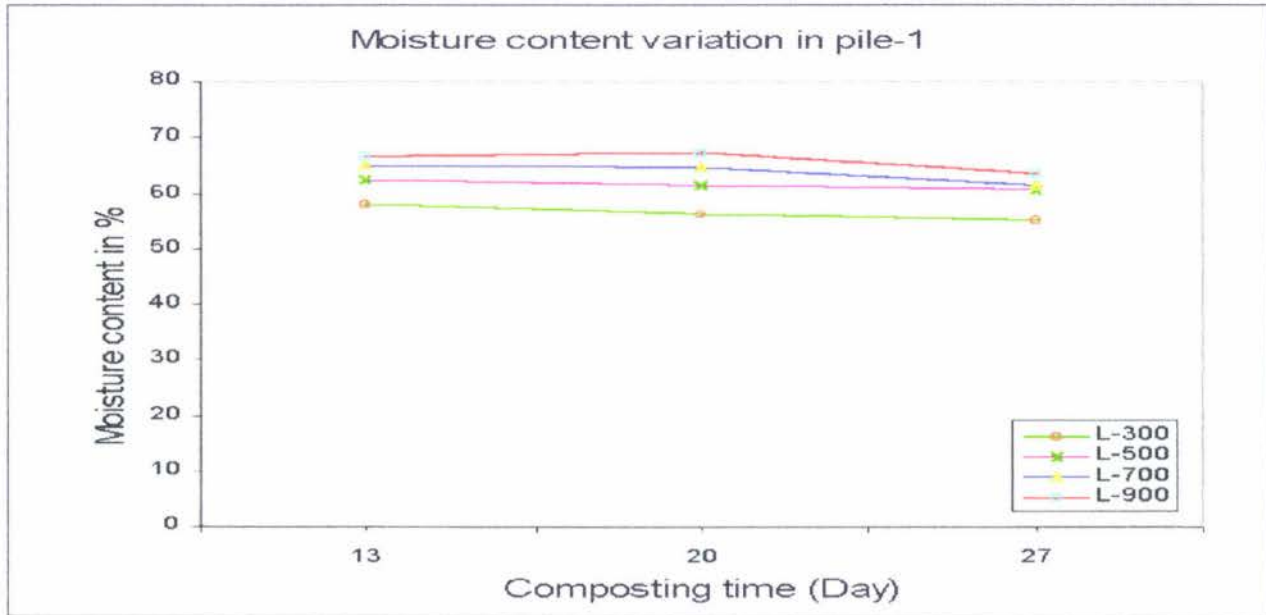


Fig. 5.7 Changes in moisture content (% w/w) in compost. Data for pile-1 of Experiment-II determined at 300, 500, 700 and 900mm distances from base of pile.

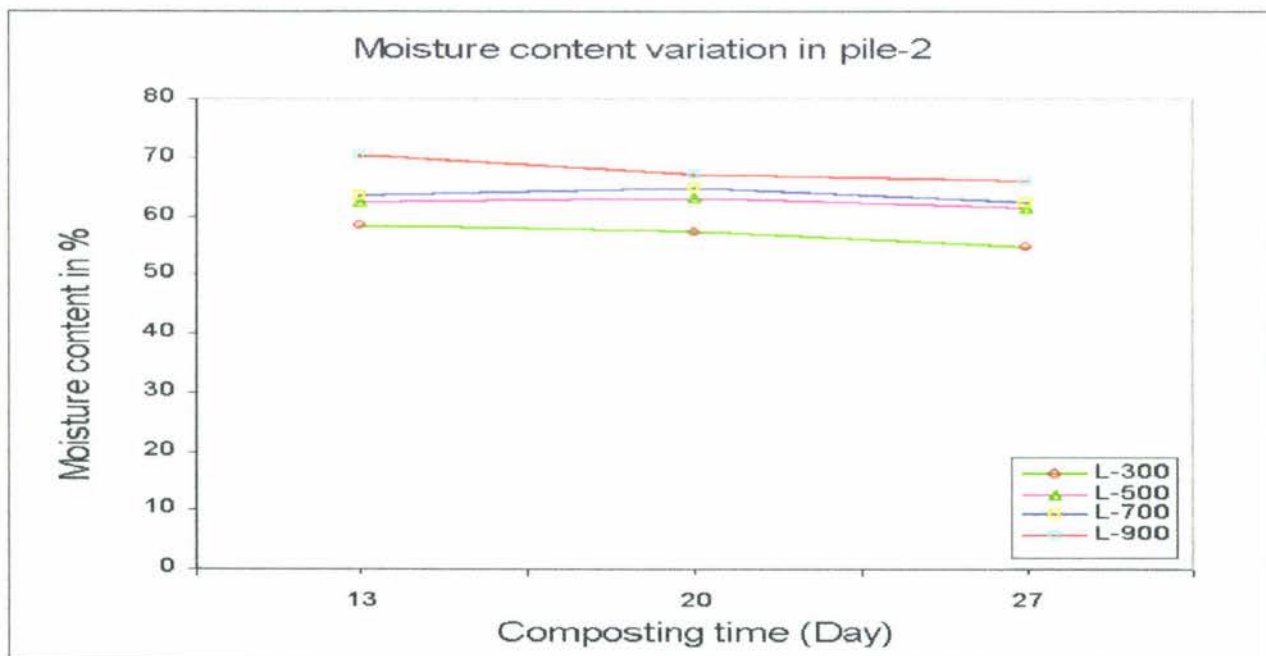


Fig. 5.8 Changes in moisture content (% w/w) in compost. Data for pile-2 of Experiment-II determined at 300, 500, 700 and 900mm distances from base of pile.

Figures 5.7 and 5.8 also show a similar trend of moisture removal during composting. From the above four figures, it is evident that the moisture content of samples taken from the bottom positions was lower than that of the top positions in the compost piles.

**5.3.1 FINAL MOISTURE CONTENT**

The moisture content distribution at time of pile deconstruction are shown in Figs. 5.9, 5.10, 5.11 and 5.12. Moisture content was lowest in the bottom locations and highest in the top locations, except for one bottom location in pile-1 of Experiment-I.

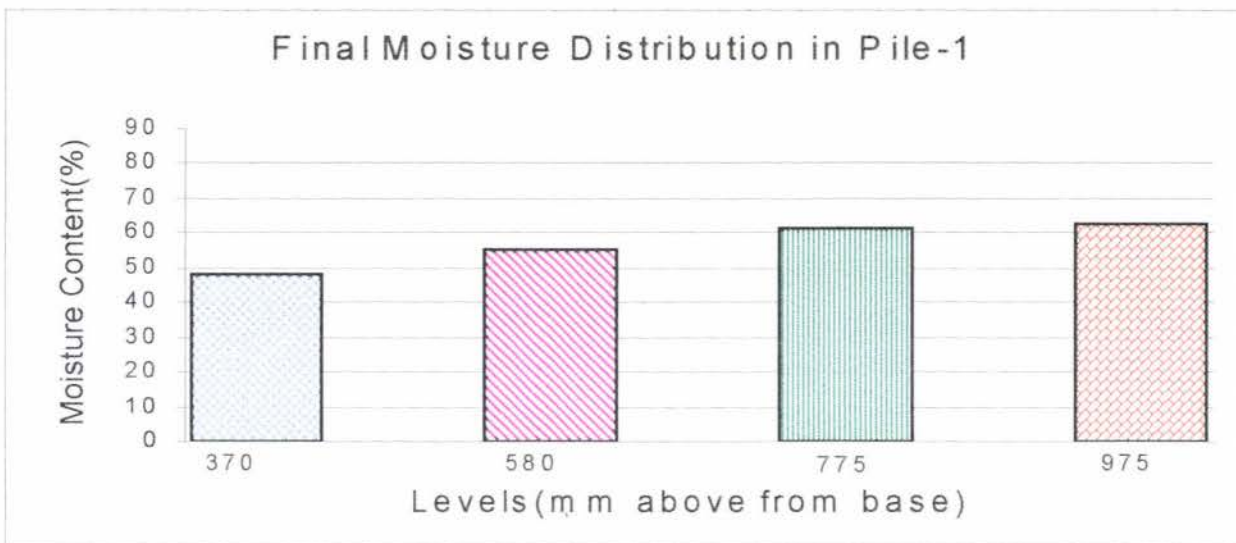


Fig. 5.9 Final moisture content distribution in pile-1 under Experiment-I.

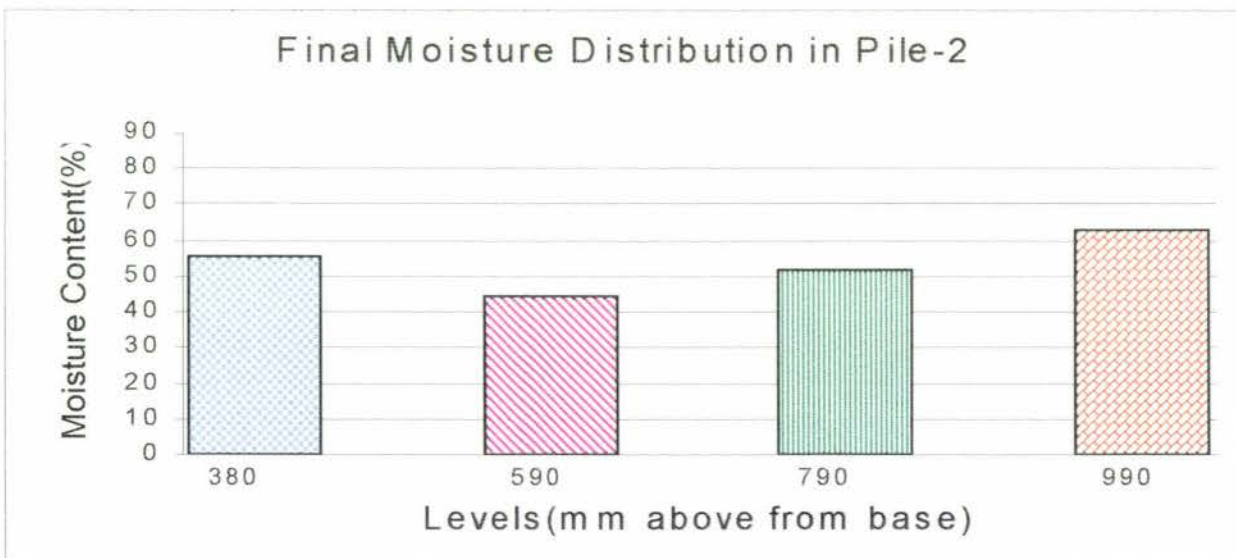


Fig. 5.10 Final moisture content distribution in pile-2 under Experiment-I

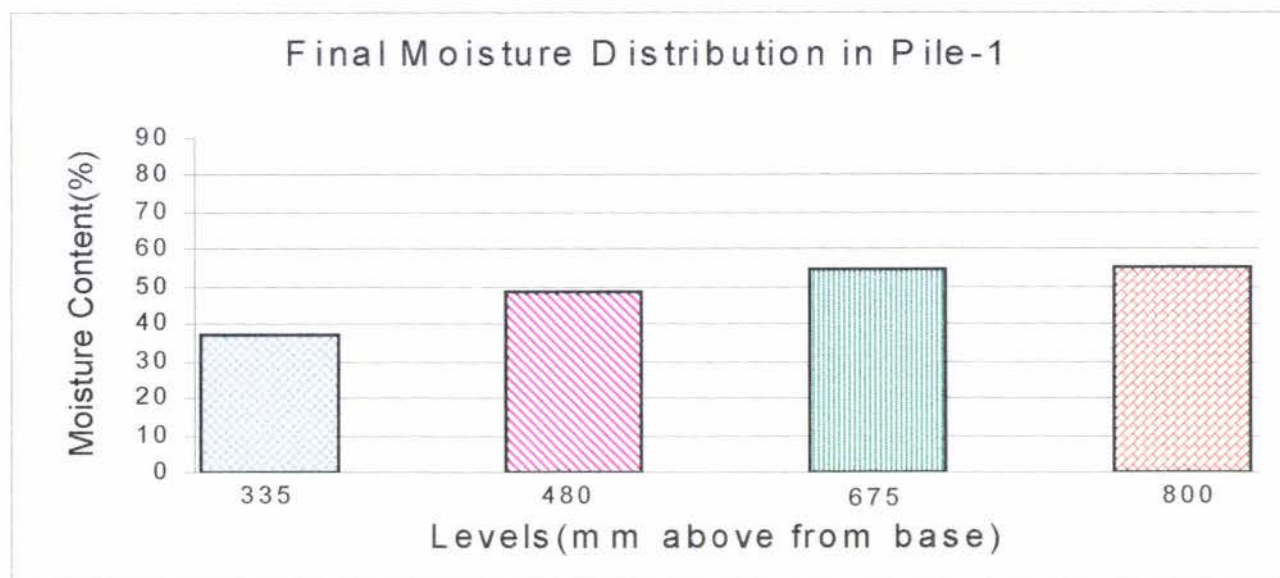


Fig. 5.11 Final moisture content distribution in pile-1 under Experiment-II

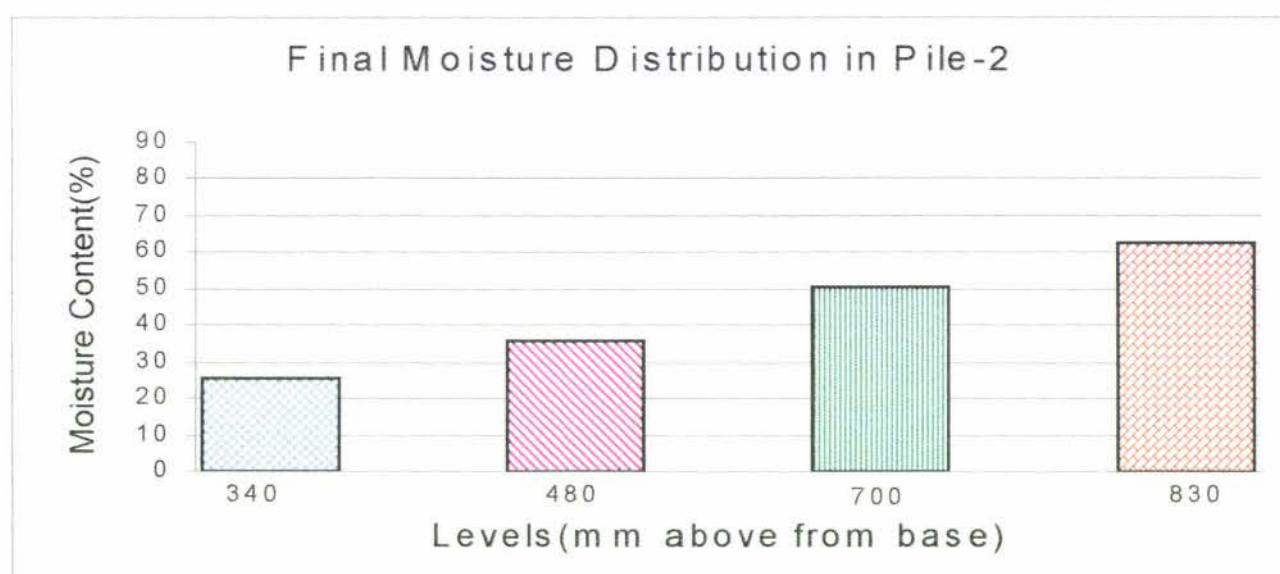


Fig. 5.12 Final moisture content distribution in pile-2 under Experiment-II

The initial moisture content of the manure slurry used in this study was around 90%. This moisture content came down to 67% and 70% (for raw compost) in Experiment-I and II respectively after addition of amendment and bulking material. Thereafter, composting process again brought down the moisture content of final compost to a range of 44%-62% and 25%-62% in Experiment-I and II respectively.

## 5.4 PARTICLE SIZE DISTRIBUTION

The particle size distribution of the amendment and bulking agent is an important factor for providing air filled porosity and FAS in a composting matrix. Sieve analysis for sawdust and wood chips used in Experiment-I and wood chips used in Experiment-II were done in the laboratory to ascertain the particle size distribution. The results of the sieve analysis is given in Table 5.9. The particles are divided into four categories: large, coarse, small and fine in terms of their size. The results indicate that the wood chips used in Experiment-I had a higher proportion (43%) of large particles than the wood chips used in Experiment-II (35%). This was because new blades were used in the hammer mill for making wood chips for Experiment-II. The distribution of different sizes of wood chips was: coarse = 50%, medium = 5.6% and fine = 1.67% in Experiment-I. Whereas in Experiment-II, it was: coarse = 60%, medium = 3.8% and fine = 1.11%. The large, coarse, medium and fine fractions of sawdust were found to be 0.30%, 13.5%, 69% and 17% respectively.

Therefore, the wood chips in experiment-I should have provided better porosity and FAS than those in Experiment-II because of the larger particle size (Table 5.9), but that did not happen, possibly due to the presence of sawdust as an amendment in experiment-I. Smaller particles may fill gaps between larger particles thus reducing the available porosity and thus free air space.

Table 5.9 Particle size distribution of sawdust and wood chips used in experiments.

Sample	Percentages Retained By Each Sieve												
	Large			Coarse			Medium				Fine		
	16mm	11.2mm	8mm	5.6mm	2.8mm	2mm	1.68mm	1.4mm	850MIC	710MIC	500MIC	250MIC	PAN
Wood chips*	16.08	12.87	13.95	16.71	27.23	6.09	2.41	1.42	1.44	0.32	0.24	0.36	0.87
Sawdust*	0	0	0.30	0.86	2.25	10.36	10.46	13	36.31	9.58	7.74	6.98	2.14
Wood chips**	8.49	9.67	17.06	28.34	27.07	4.47	1.67	0.85	0.71	0.53	0.47	0.42	0.22

\* Experiment-I; \*\* Experiment-II.

Although the wood chips in the study were considered to be non-biodegradable within this composting period, the fine particles of sawdust may be biodegradable. Consequently, FAS may increase over the composting period.

Table 5.10 shows the moisture distribution on day 70 at the different levels of two replicate piles in both the experiments. Due to the effect of long term consolidation, compaction and the loss of structure of amendment (especially mixed paper) as a result of water absorption and mass transport, the heights of the piles were reduced to some extent (data in brackets, Table 5.10).

Table 5.10 Moisture content changes in compost at center of piles at different levels and at day 70. True height above base is shown in brackets.

Experiment No	Pile No	Raw Compost MC (%)	MC% (wb) of final compost at 4 different initial levels				Final Compost MC (%)
			L-400mm	L-600mm	L-800mm	L-1000mm	
I	1	66.9	48.23 (370)	55.59 (580)	61.33 (775)	62.52 (975)	56.9
	2	66.3	55.28 (380)	44.37 (590)	51.86 (790)	62.66 (990)	53.5
II	1	70.7	36.94 (335)	48.78 (480)	54.86 (675)	55.51 (800)	46.6
	2	69.5	25.34 (340)	36.16 (480)	50.46 (700)	62.72 (830)	47.6

L-400mm = level measured at 400mm above pile base; MC = moisture content.

The changes in bulk weight, bulk density, sp.gravity, porosity and free air space due to the moisture, CO<sub>2</sub>, NH<sub>3</sub> removal and O<sub>2</sub> consumption from aeration over the period of composting are given in Table 5.11.

Table 5.11 Changes of physical properties of compost over the period of observation.

Exp. No	Pile No	Bulk weight kg/m <sup>3</sup>		Bulk density kg/m <sup>3</sup>		Sp. gravity g/cm <sup>3</sup>		Porosity %		Free air space %	
		Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
I	1	639	420	216	171.7	1.043	1.057	79.29	83.75	26.24	36.09
	2	624	464	215	192.9	1.055	1.060	79.62	81.80	26.83	37.95
II*	1	593	308	180	160	1.098	1.130	83.60	85.84	24.49	45.83
	2	623	333	186	165	1.093	1.115	82.98	85.20	25.30	44.64

\* Initial bulk weight, bulk density, Sp.gravity, Porosity and FAS were determined on day 2 (not on day 0).

Table 5.11 shows that the composting process had reduced the bulk weight and bulk density of the matrix suggesting the removal of water and VS from the materials. The initial porosity and free air space (FAS) increased over time as the water component and VS of

materials were removed through evaporative drying and decomposition of VS by microbes. Although the initial FAS was less than the recommended level ( $> 30\%$ ) for both the experiments, the conditions were not inhibitory to microbial degradative processes. Consequently, the process started to generate heat (see temperature Tables given in Appendix B) under the existing FAS and removed the water component gradually (see Table C2, C5, C8 and C11 in Appendix C), which also increased the FAS gradually towards its recommended level to ensure sufficient aeration for boosting the decomposition process (Table 5.11). In this way, the initially insufficient FAS gradually regained the recommended level and finally reached FAS which were more than the recommended level (Table 5.11).

## 5.5 CHARACTERISTICS OF THE PILE CORE

Characteristics of the pile core were investigated using temperature data obtained from each pile and accordingly mass and energy balance were done.

### 5.5.1 CORE TEMPERATURE

The temperature profiles at 100mm, 300mm and 600mm inside the piles have been taken into account to identify the horizontal core area of compost materials.

Table 5.12 The magnitude and duration of thermophilic temperatures at different locations. Duration (days) of thermophilic temperatures is given in the brackets.

Pile & Exp. No.	400mm above from base			600mm above from base			800mm above from base			1000mm above from base		
	100mm inside	300mm inside	600mm inside	100mm inside	300mm inside	600mm inside	100mm inside	300mm inside	600mm inside	100mm inside	300mm inside	600mm inside
P-1 E-I	40.35 (2)	42.88 (15)	49.83 (43)	42.51 (4)	48.20 (46)	57.27 (52)	44.92 (5)	49.92 (49)	59.79 (52)	46.3 (3)	48.37 (30)	55.20 (48)
P-2 E-I	-	46.44 (9)	54.24 (9)	44.3 (1)	51.77 (9)	49.27 (19)	44.81 (6)	47.48 (23)	52.23 (37)	45.70 (3)	47.17 (21)	52.86 (35)
P-1 E-II	44.72 (5)	50.78 (34)	58.03 (51)	47.53 (9)	53.53 (36)	61.79 (59)	48 (6)	53.95 (34)	60.06 (59)	52.10 (7)	50.95 (29)	56.91 (51)
P-2 E-II	46.15 (6)	53.60 (32)	55.09 (34)	48.16 (13)	55.58 (34)	59.95 (39)	42.93 (15)	57.23 (30)	61.54 (41)	46.13 (6)	52.29 (27)	60.96 (39)

Inside distances are measured from front edge of pile. Temperature values are means calculated over the duration shown in brackets.



From Table 5.12 it was noted that the average thermophilic temperature at 100mm inside the piles at different levels ranged from about 40 to 48°C and its duration ranged from 1 to 15 days. The average thermophilic temperature at 300mm inside the piles at different levels ranged from about 43 to 57°C and its duration ranged from 9 to 49 days and that at 600mm inside the piles at different levels ranged from about 49 to 62°C and its duration ranged from 9 to 59 days. Therefore, the magnitude and duration of thermophilic temperatures at 100mm inside the piles at all levels were very low in comparison to those of 300mm and 600mm inside the piles. The materials at more than 300mm horizontal distance from the central locations were considered to be poorly composted while those materials within 300mm horizontal distance from the center were considered as well composted (Fig. 5.13). Thus, temperature was used to define the core region.

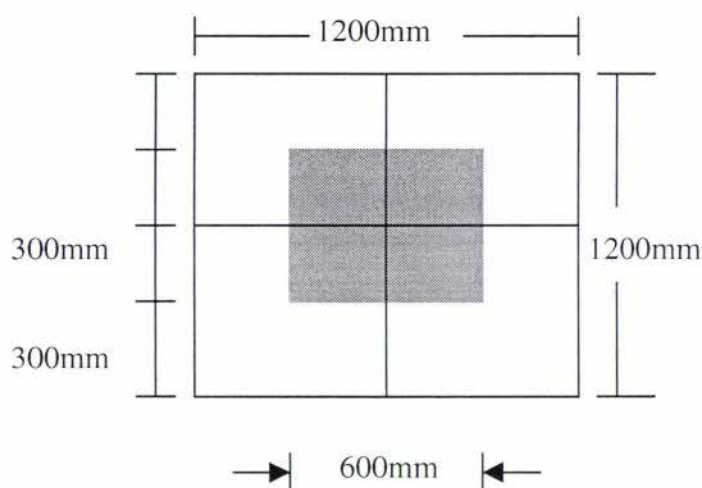


Fig. 5.13 Dimension of core area; Shaded region = core area; The area of the core regions is =  $600\text{mm} \times 600\text{mm} = 0.36 \text{ m}^2$ .

The initial positions of the temperature probe were 400mm, 600mm, 800mm and 1000mm above the base of each pile. However, these positions changed due to the shrinkage of piles with time.

### 5.5.2 VOLUME OF CORE

The size of compost piles ( $1.2\text{m} \times 1.2\text{m} \times 1.2\text{m}$ ) used in both the experiments was identical. The composting materials were placed on a base 230mm thick and which covered the aeration

pipes. The top 50mm of each pile was sawdust provided a cover material. Therefore, the total initial volume of raw compost in each pile was as follows:

$$\begin{aligned}\text{Volume of raw compost in each pile} &= (1200-230-50)\text{mm} \times 1200\text{mm} \times 1200\text{mm} \\ &= 1.33 \text{ m}^3.\end{aligned}$$

The above volume of materials did not appear to be composted uniformly, as shown in Fig.5.14. Figure 5.14 also shows that the colour of the materials near the periphery of the pile appeared unchanged and that in comparison, the materials near the central area had decomposed more. In addition, the samples for various laboratory analyses were collected only from the core area at different levels of the piles as shown in Fig. 5.13. For the above reasons, a volume of materials in the core of each pile was calculated and the value used in the analysis of results.



Fig. 5.14 The colour of the final compost is illustrated in this photograph. Note the central region of mature compost and the under processed material at the edges of the pile. (Photograph taken at deconstruction of pile).

### 5.5.3 PILE SHRINKAGE

Experiment-I: In pile-1, the 400mm probe position changed to 370mm and the top 1000mm probe position came down to 950mm as shown in Fig. 5.15. Similarly, in pile-2, the bottom 400mm probe position came down to 380mm and the top 1000mm probe position came down to 955mm. These changes occurred because of pile shrinkage.

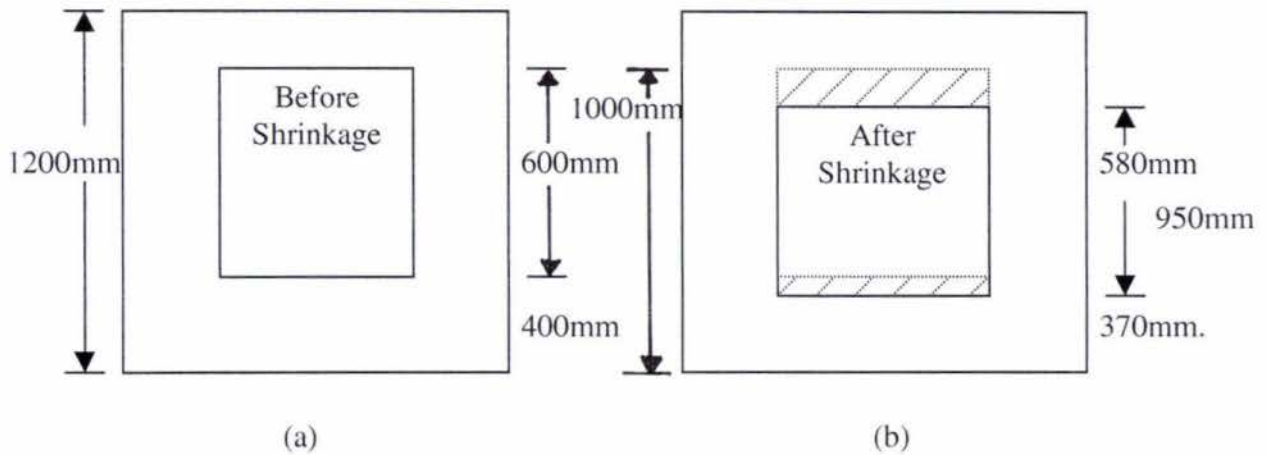


Fig. 5.15 Shrinkage of pile materials during composting (Pile-1, Experiment-I). Hatched zones signify shrinkage within the core zone.

Experiment-II: In pile-1, the bottom 400mm probe position decreased to 335mm and the top 1000mm probe position fell to 800mm (200mm shrinkage) as shown in Fig. 5.16. Similarly, In pile-2, the bottom 400mm probe position came down to 340mm after a 60mm shrinkage and the top 1000mm probe position came down to 830mm with 170mm shrinkage.

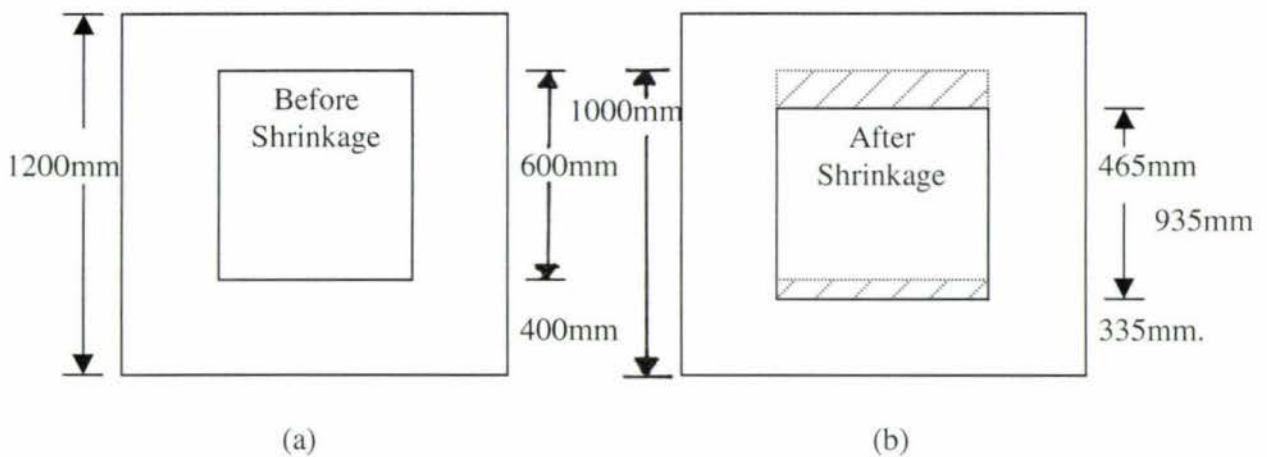


Fig. 5.16 Shrinkage of pile materials during composting (Pile-1, Experiment-II). Hatched zones signify shrinkage in core region. Initial volume of core region would be =  $0.36 \text{ m}^2 \times 0.6 \text{ m} = 0.22 \text{ m}^3$ .

The temperature profiles obtained at the 1000mm level indicate that the materials here in both piles were well composted. Thus, the magnitude and duration of thermophilic temperatures along the vertical plane (vertically 400mm above or below from center) of the compost piles were not as poor as they had been along horizontal plane (horizontally 300mm from center). Therefore, the initial thickness of core volume of raw compost materials would be 600mm (Level-400mm to Level-1000mm). The final thickness of core volume of compost materials can be selected as the vertical distance between the final positions of temperature monitoring locations at levels 400mm and 1000mm.

Final volume of core region would be =  $0.36 \text{ m}^2 \times$  Final height of core volume of compost, which will be only considered for the analysis of results.

Initial weight of raw compost for the core region in kg

$$= 0.22 \text{ m}^3 \times \text{bulk weight of raw compost in kg/m}^3.$$

The weight, water content, solid content, energy content, VS content and ash content of raw and final compost materials within the core volume of compost materials from both the experiments were obtained from laboratory experiments. The results of analysis of core material for both the experiments are shown in Tables 5.13 and 5.14 below.

Table-5.13 (Exp-I): Analysis of Core Material Recorded at Start and End of Composting.

Composition	Pile-1			Pile-2		
	Start	End	Removal (%)	Start	End	Removal (%)
Total volume in m <sup>3</sup>	0.216	0.208	3.33	0.216	0.207	4.16
Total weight in kg	138.02	87.36	36.70	134.78	96.05	28.73
Water in kg.	92.33	51.02	44.74	89.36	54.55	38.95
Energy in Kcal.	210,606	158,632	24.67	205,075	181,119	11.68
TS in kg.	45.68	36.34	20.44	45.42	41.49	8.65
VS in kg.	42.53	33.03	22.33	41.47	37.55	9.45
Ash in kg.	3.15	3.30	-	3.95	3.94	-

Table-5.14 (Exp-II): Analysis of Core Material Recorded at Start and End of Composting.

Composition	Pile-1			Pile-2		
	Start	End	Removal (%)	Start	End	Removal (%)
Total volume in m <sup>3</sup>	0.216	0.167	22.5	0.216	0.176	18.33
Total weight in kg.	128.09	51.39	59.88	134.57	58.74	56.35
Water in kg.	90.56	23.94	73.56	93.52	27.96	70.10
Energy in Kcal.	157214.72	110180.7	29.91	169305.88	122349.5	27.73
TS in kg.	37.53	27.44	26.88	41.04	30.78	25.00
VS in kg.	31.94	22.17	30.58	35.21	24.86	29.39
Ash in kg.	5.60	5.27	-	5.82	5.32	-

From the data it was found that piles 1 & 2 in Experiment-I had lost 36.7% and 28.73% respectively of their initial weights and that piles 1 & 2 in Experiment-II had lost 59.88% and 56.35% respectively of their initial weights. The removal of the water component in piles-1 & 2 in Experiment-I was 44.74% and 38.95% respectively and that in Experiment-II the removal was 73.56% and 70.10% respectively. The loss of gross energy content of materials in piles-1 & 2 in Experiment-I was 24.67% and 11.68% respectively and that for Experiment-II was 29.91% and 27.73% for piles-1 and 2 respectively. The loss of VS in piles-1 & 2 in Experiment-I was 22.33% and 9.45% respectively and that in Experiment-II was 30.58% and 29.39% respectively. The volume of materials within the selected core area was a heterogeneous mixture of different materials and it was difficult to mix them uniformly with the available facilities. Therefore, the ash values in raw and final composts in both the experiments were not as close as expected.

## 5.6 MASS AND ENERGY BALANCE

On the basis of data obtained from Experiment-I & II shown in Table 5.13 & 5.14, a mass balance and energy balance analysis was done for each pile according to the procedure outlined by Haug (1993). The details of the mass and energy balance analysis for each pile is given in the Appendix I. A summary of data analysis is presented in Table 5.15.

Table 5.15 (Experiments-I & II ) Data summary obtained from mass and energy analysis

Pile No	Water Ratio (W)	Energy Ratio (E)	Metabolic Activity During Composting (kg)				H <sub>2</sub> O evaporated Kg-H <sub>2</sub> O/kg-ds		Sensible heat (Kcal)		Energy released (Kcal)	Latent heat used (Kcal)	Energy balance (Kcal)	
			DVS	WATP	WATE	GASP	Prac	Theo.	Raw	Final			input	Output
1 (I)	7	702.84	8.03	5.75	48.38	2.27	1.05	1.02	3,065	12,503	39,774	27,370	42,838	39,873
2 (I)	6.95	710.70	3.92	2.81	37.61	1.11	0.82	0.763	2,686	11,090	19,421	21,279	22,107	32,370
1 (II)	10.2	480	10.08	7.22	73.84	2.86	1.96	1.73	3,803	16,205	49,657	41,771	53,461	57,976
2 (II)	9.56	503	10.26	7.35	72.92	2.91	1.77	1.60	3,832	16,588	49,346	41,250	53,178	57,839

W in g-H<sub>2</sub>O/g-BVS ; E in Cal/g-H<sub>2</sub>O ; DVS = degraded VS ; WATP = water produced; WATE = water evaporated; GASP = gas produced;

The mass balance diagrams obtained from the analysis (see Appendix I) are presented in Figs. 5.17, 5.18, 5.19 & 5.20. The terms BVS, NBVS, ASH, WAT, WATSO, WATVI, WATVO, DAIRI and DGASO are defined as follows:

BVS	= biodegradable volatile solids
NBVS	= non-biodegradable volatile solids
ASH	= ash component in the raw compost and in the final compost
WAT	= water component in the raw compost
WATSO	= water component in the final compost
WATVI	= water vapour associated with the air input
WATVO	= water vapour associated with the gas output
DAIRI	= dry air input to the process
DGASO	= dry gas output from the process

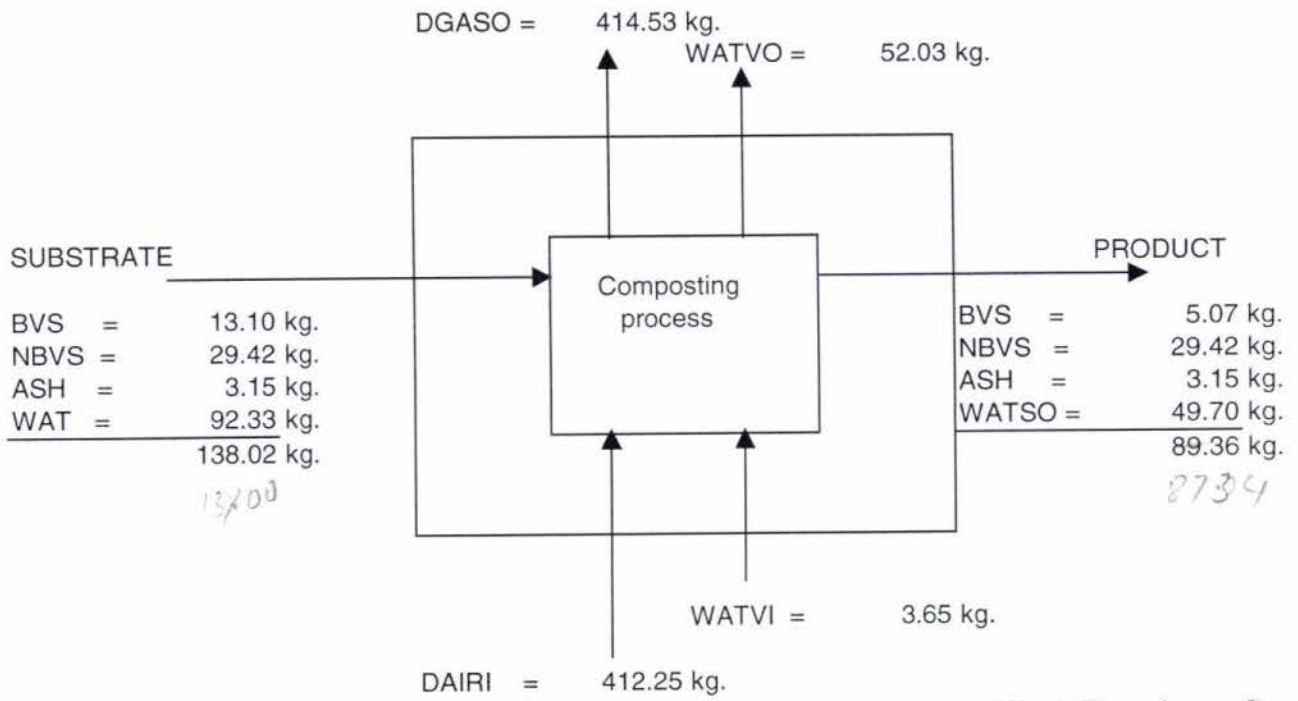


Fig. 5.17 Major material inputs and outputs to the composting process (Pile-1, Experiment-I)

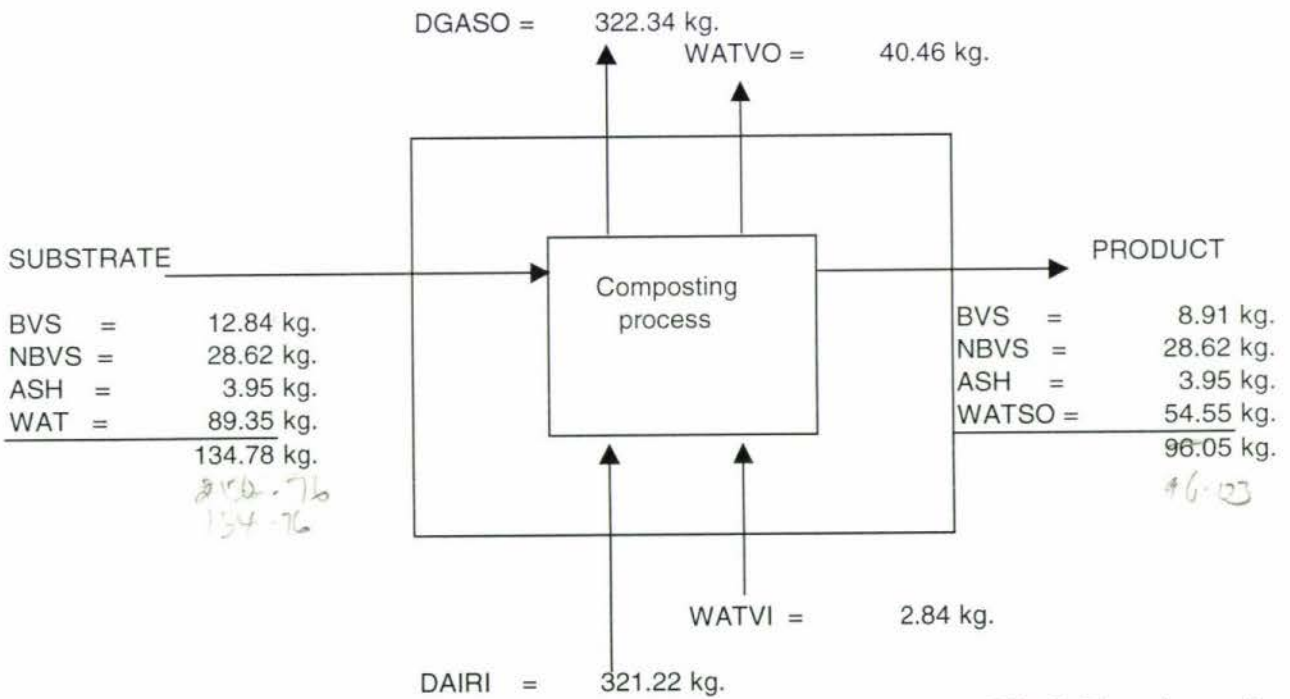


Fig. 5.18 Major material inputs and outputs to the composting process (Pile-2, Experiment-I)

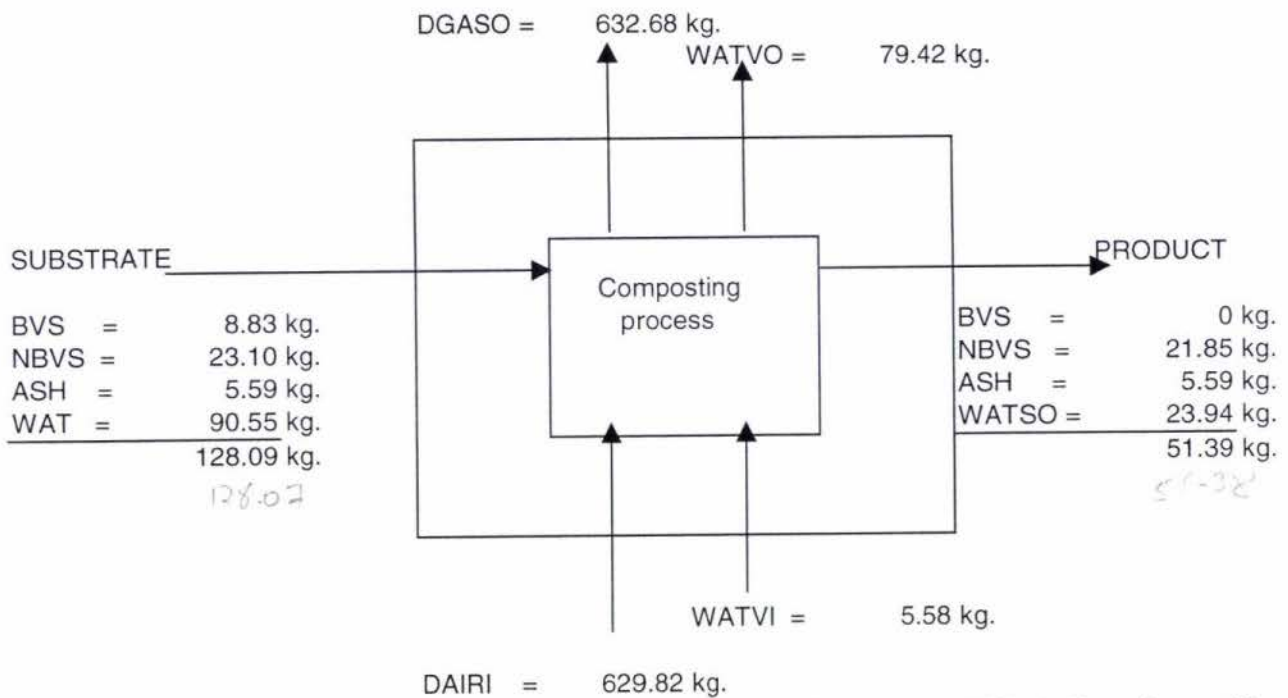


Fig. 5.19 Major material inputs and outputs to the composting process (Pile-1, Experiment-II)

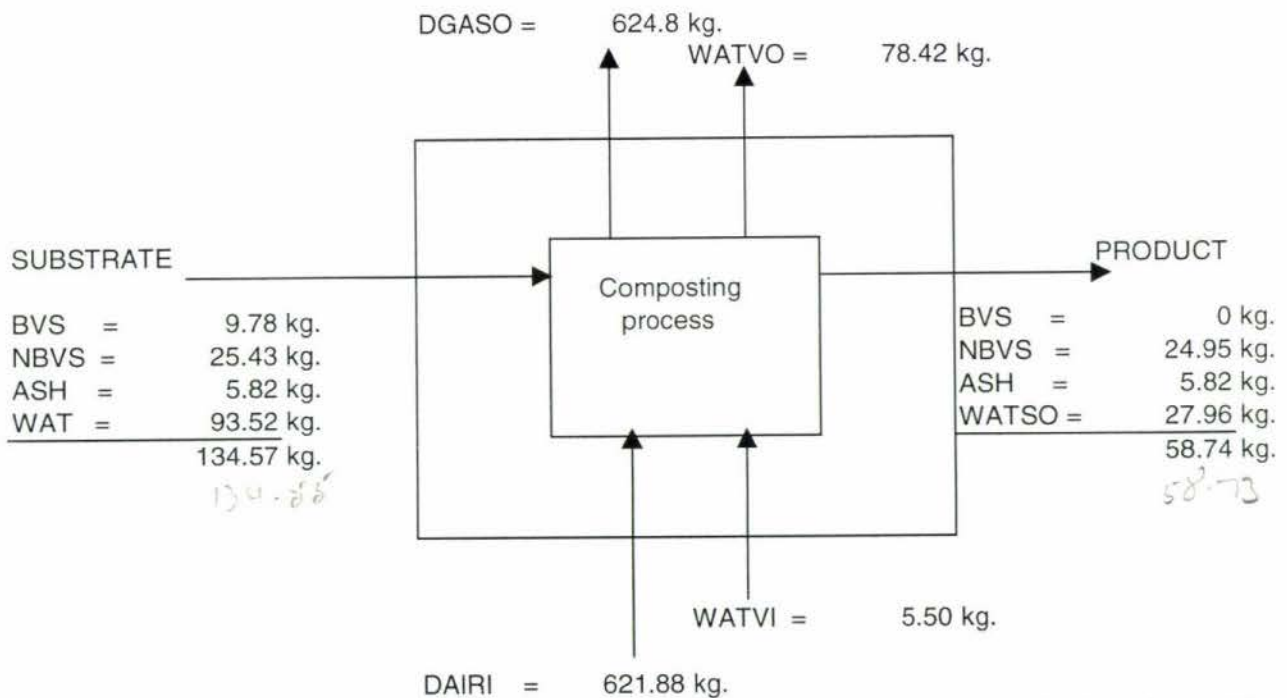


Fig. 5.20 Major material inputs and outputs to the composting process (Pile-2, Experiment-II)



Mass balance diagrams for Experiments-I and II indicate that the BVS in Experiment-II degraded more than the BVS in Experiment-I. The amount of BVS degraded in different piles was used as a tool for evaluating the process performance. Accordingly, pile-2 of Experiment-I shows that the decomposition of BVS was weak (due to cooling effect) as it could have been like pile-1 of Experiment-I, although 5 kg of BVS in pile-1 was residual. Whereas, the decomposition of BVS in both piles in Experiment-II exceeded expectations and there was no residual BVS at the end of composting. Thus, these piles degraded more BVS than anticipated.

### 5.6.1 ENERGY EXCHANGE

Experiment-I: The laboratory analysis of gross energy for initial and final compost indicates that the loss of gross energy (Table 5.1 & 5.2) in piles 1 & 2 was 24.67% (51,974 Kcal) and 11.68% (23,956 Kcal) and thus required 1258.14 and 688.2 Cal/g H<sub>2</sub>O evaporation. By considering 540 Cal/g H<sub>2</sub>O evaporation, about 47.22% of the produced heat was lost through latent heat of evaporation and the remaining as sensible heat (pile-1). Dryness of pile-2 indicated that about 65.56 kg of water was removed, although only 44.36 kg of the water could be removed (if 540 cal/g H<sub>2</sub>O evaporation is considered) by the full utilization of the total heat energy produced in the pile.

Experiment-II: The laboratory analysis of gross energy for initial and final compost indicates that the loss of gross energy (Table 5.1 & 5.2) in piles 1 & 2 was 29.91% (47,034 Kcal) and 27.73% (46,956.4 Kcal) and thus required 706 and 716.2 Kcal/kg H<sub>2</sub>O evaporation respectively. By considering 540 Cal/g-H<sub>2</sub>O evaporation, about 76.48% & 75.39% of the produced heat was lost through latent heat of evaporation and the remaining as sensible heat in piles 1 & 2 respectively.

## 5.7 TOTAL COLIFORMS

The total initial coliform counts for both raw and final compost (in each pile) for Experiments-I & II are presented in Tables 5.1 and 5.2. The total coliform data for Experiment-I & II was plotted in logMPN/g-dry solids (ds) and is shown in Figs. 5.21 and 5.22.

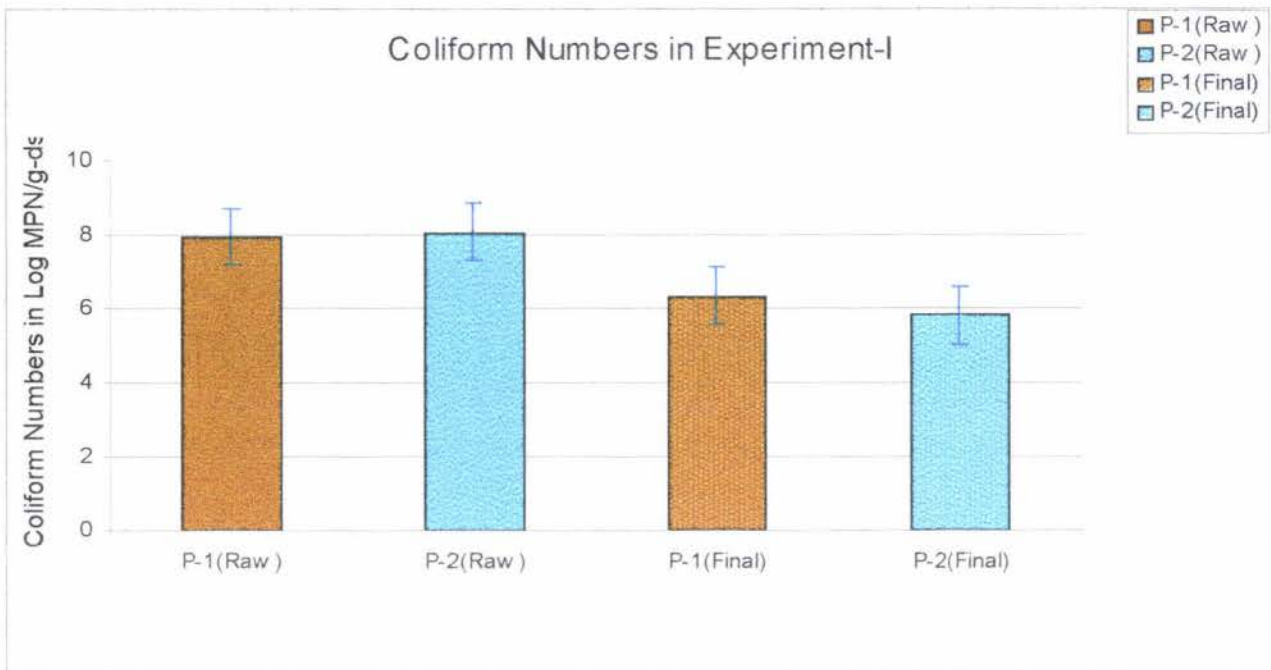


Fig. 5.21. Changes in the population of total coliforms during the composting process (Experiment-I); Coliform numbers are given in Log MPN/gm dry solids; P-1(Raw) = Raw compost of pile-1; P-1(Final) = Final compost of pile-1.

The number of total coliforms shown is for the average count at different locations in each pile. For both experiments, the coliforms were counted on every working day for the raw compost during the period of compost pile casting and for the final compost. Samples were also collected on the day of pile deconstruction. Under Experiment-II, an intermediate sample was taken for coliforms count on day 13. From the data of Figs. 5.21 & 5.22, it was found that the removal rate of coliforms in pile-1 and pile-2 under Experiment-I was 96.40% and 99.30% respectively and that for Experiment-II was 97.73% and 98.67% respectively.

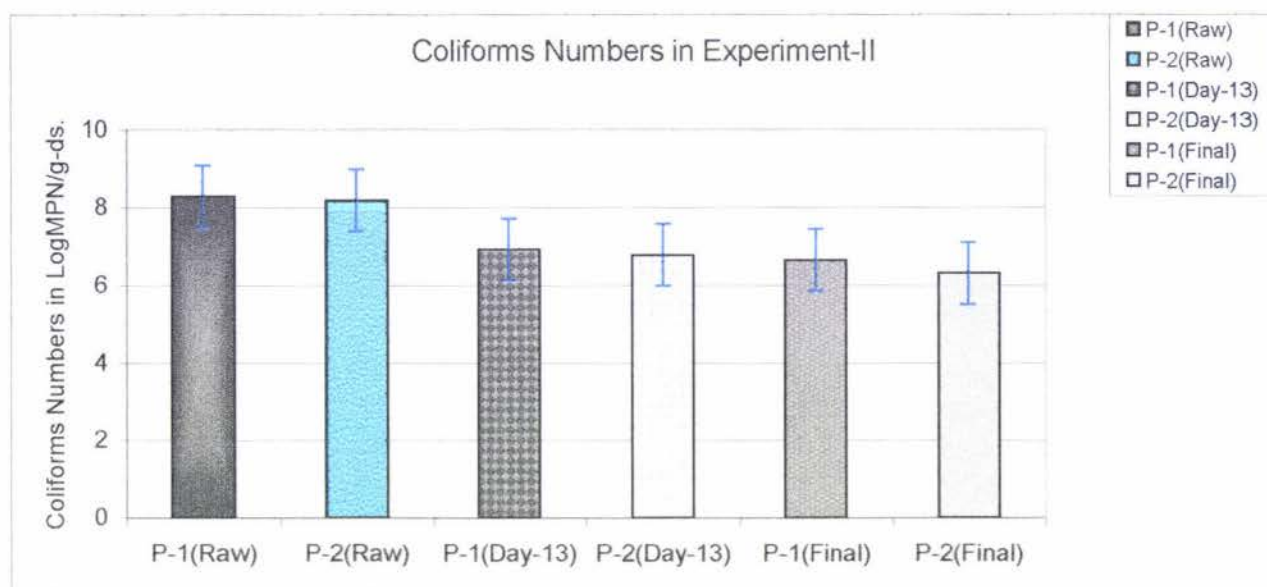


Fig. 5.22. Changes in the population of total coliforms during the composting process (Experiment-II); Coliform numbers are given in Log MPN/gm dry solids; P-1(Raw) = Raw compost of pile-1; P-1(Day-13) = Compost in pile-1 on day 13; P-1(Final) = Final compost of pile-1.

The results indicate that the thermophilic active composting under passive aeration was capable of destroying a small part of the coliform population and it could not achieve the recommended final coliform count within the observation period of this study. A final population of  $10^6$  MPN/g-dry solids is unacceptably high.

### 5.7.1 TIME-TEMPERATURE AND TOTAL COLIFORM DESTRUCTION

A relationship between time-temperature and total coliform destruction was developed (as shown in Fig.5.23) using the data for areas (product of time and temperature) from Tables 5.7 and 5.8 and coliform data in MPN/g-dry solids for the respective locations (see Tables G1 and G2 of Appendix G).

Figure 5.23 shows that the total coliform population fluctuated with increased area under curve above  $55^{\circ}\text{C}$  rather than showing a clear decrease. A greater area (product of time and temperature) in this study does not always ensure greater total coliform destruction. A linear regression analysis also confirmed that there was no correlation between area under time-

temperature curve above 55°C and total coliform destruction ( $R^2 = 0.12$ ). It is to be noted that the coliform count under conditions leading to the highest area under the curve was unexpectedly high (Fig.5.23).

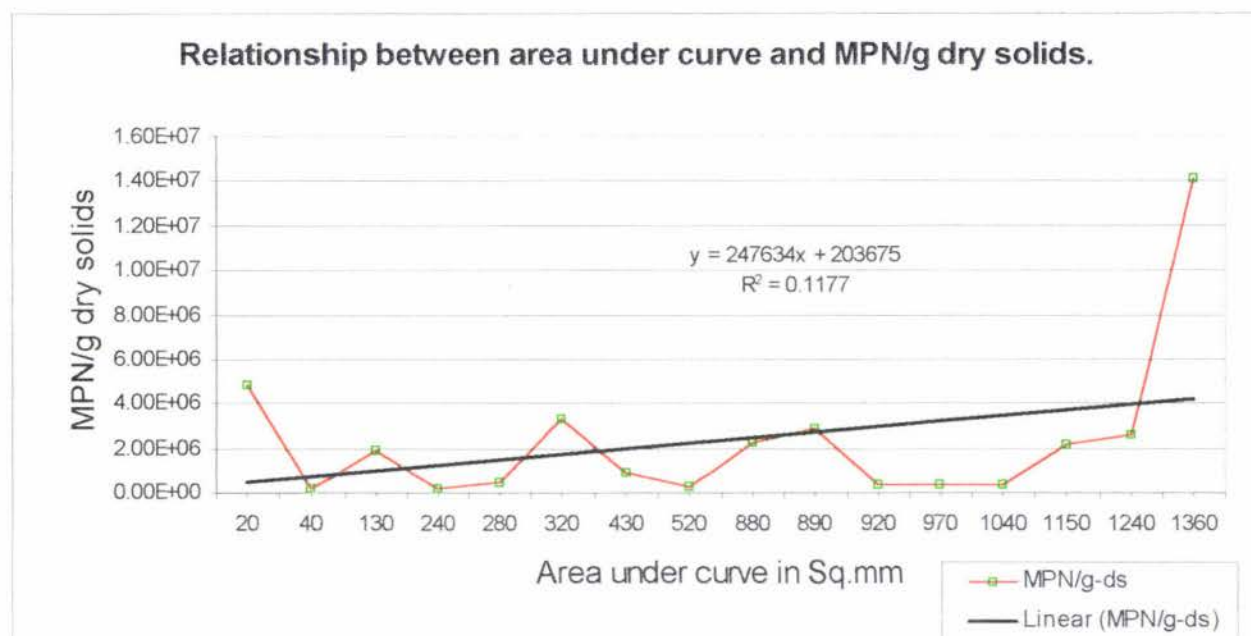


Fig. 5.23. Relationship between area under time-temperature curve above 55°C and total coliform destruction

If the coliform data for highest area is excluded from the analysis then the original inference still holds, there is no correlation between the variables ( $R^2 = 0.01$ ). Therefore, in this study, area under time-temperature curve above 55°C cannot be used as a tool for evaluating the process performance in terms of total coliform destruction. The results of this study do not comply with the hypothesis proposed by Haug (1993) that “high thermophilic temperature for shorter period and low thermophilic temperature for longer period can be equally effective in coliform disinfection”.

## 5.8 FINAL PRODUCT

Experiment-I: The physical appearance of the final product of pile-2 was not significantly different from pile-1. The physical appearance of the final product from both the piles was a moderately dry, dark brown compost (Fig.5.24). However, extensive white coloured fungal

mycelia were well developed on coarse and large size wood particles (Fig.5.25) which felt soft, like loam soil. An earthy smell was detectable.



Fig. 5.24 Showing the dark brown colour of final compost.

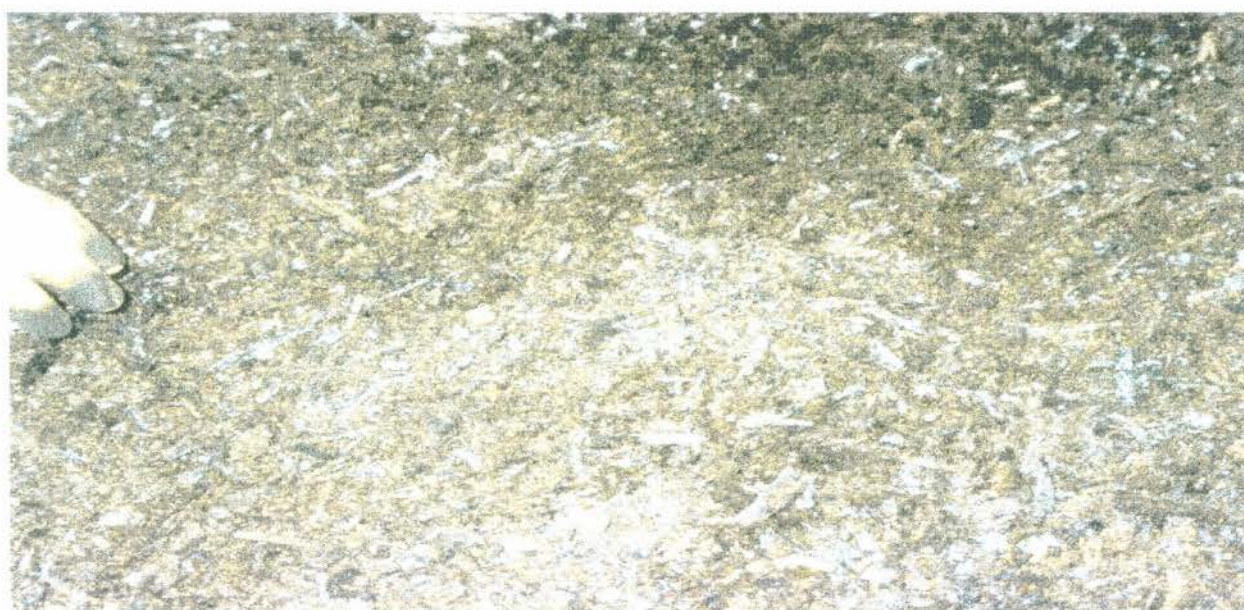


Fig. 5.25 Showing the dark brown final compost. White coloured fungi are obvious.



Fig. 5.26 Showing ash coloured final compost obtained from experiment-II.

Experiment-II: The physical appearance of final product of these piles was not significantly different from each other. The physical appearance of the final product from both the piles was quite different from that of Experiment-I. The colour of the final compost looked like white ash ( probably because of white office paper) with a lot of white coloured fungi well developed on the coarse and large size wood particles (Fig.5.26). The end product felt like burned paper ash and there was no smell. The structure of shredded papers was completely destroyed by microbial attack during composting which indicates the high degradability of mixed paper (specially office paper). The physical appearance and structure of newsprint in the final product indicated that it was not degraded as much as office paper.

## CHAPTER-6

### DISCUSSION

#### 6.1 COMPOSITION OF MATERIALS

In the research described in this thesis the composition of the raw materials, raw compost substrate (manure), raw compost and final compost was measured in terms of Moisture Content (MC), Free Air Space (FAS) and carbon to nitrogen ratios (C:N) and is summarized in Tables 5.1 & 5.2. The acceptable range of MC is 40-60% (Rynk,1992). The suggested highest MC limit (Haug,1993) for raw manure compost is 65% (w/w). Usually, an optimum MC of raw compost can be obtained when FAS values of raw compost fall in the range between 30-35% (Haug, 1993). Sartaj *et al.*(1997) composted poultry manure and peat at 76% MC under passive aeration and obtained a peak temperature of about 56°C and temperatures >55°C were sustained for 4 days. The calculated FAS value, based on the data of Sartaj *et al.*(1997) was approximately 37% (see Appendix I). Under this study, the moisture content of raw dairy manure compost approximated 67% and 71% in Experiments I and II respectively and FAS values were about 24% and 33% in Experiments I and II respectively. However, this higher MC did not affect the aeration mechanisms, as the process maintained the desired temperature (>55°C) for a relatively long period (from day 4.9 to day 33 in Experiment-I and from day 15 to day 40 in Experiment-II). Wilson (1971) obtained a thermophilic temperature range of 65-79°C from composting dairy manure with a MC 70-80% in an aerated bin-type reactor by adding small amounts of straw or dried compost. Temperatures in Experiment-I of this current study reached 54.6 to 73.7°C at different internal locations in the piles' levels whereas, Experiment-II reached 67 to 79.5°C at different points, although the piles of Experiment-II had the highest MC (70.7%). Therefore, composting at high MC is possible where sufficient FAS (Table 5.11) is provided, thus ensuring aeration under passive aeration conditions.

Usually 25:1 to 30:1 is an ideal range of C:N ratio for active composting, although for many applications 50:1 and higher are acceptable (Rynk,1992). The C:N ratio of raw compost in this study was within this range, being 53 in Experiment-I and 35 in Experiment II. (Tables 5.1 & 5.2). However, the results indicate that these high C:N ratios were not disadvantageous and

should be acceptable in manure composting. Higher C:N ratios did not seem to prolong the oxidation of carbon substrate. There was no detectable emission of ammonia gas around the compost piles during active phase and it seemed possible that N was not being lost as NH<sub>3</sub> during the process. It is possible that the C rich materials had a significant effect on both ammonification and possibly nitrification. There was a small decrease in C concentration during composting of both the experiments. The increase in N and ash at the end of composting presumably resulted from the loss of biodegradable volatile organic matters. Thus, the composting in both the experiments resulted in a N enriched product. The change in weight, C:N ratio, moisture content, VS content, energy content in both the experiments indicate the progress of the process from beginning to completion. The end materials can be considered sufficiently stabilized and this study reconfirming that the dairy manure can be composted with 67-71% MC after proper energy and structural conditioning by adding dry amendment (sawdust or mixed paper) and a suitable bulking agent like wood chips.

## 6.2 TEMPERATURE

Table 6.1 shows the comparison of temperature characteristics obtained from this current study with those of other researchers.

Table 6.1 Comparison of temperature characteristics in composting process.

Temperature characteristics	Experiment-I	Experiment-II	Sartaj <i>et al.</i> (1997)	Fernandes & Sartaj (1997)
Duration of initial mesophilic phase (Days)	< 1	<1	2*	3*
Time to reach peak (Days)	1.62-2.24	0.74-1.47	6.42	8
Average peak temperature (°C)	55.8-65.4	61-65.7	56.6	60.6
Duration of peak temperature (days)	4.9-33	15-40	3.83	8*
Duration of thermophilic temperature (days)	7-44	32-52	20*	19*
Duration of 2 <sup>nd</sup> mesophilic phase (days)	25-62	20-41	25*	26*
* Data recovered from the time-temperature curves provided in the Articles.				

The time-temperature profiles obtained (Figs.5.1 to 5.4) show a typical succession in change through mesophilic, thermophilic and second mesophilic phases (Crawford, 1983) except



for the pattern that developed in pile-2 of Experiment-I (Fig.5.2). The temperature profiles under passive aeration obtained by Fernandes & Sartaj (1997) and Sartaj *et al.*(1997) show a common configuration characterized by a sharp rise, a peak temperature of short duration followed by a relatively sharp drop to ambient temperature. The comparison of results indicate that the initial mesophilic phase was short in both the experiments as temperatures reached or exceeded 55°C in less than 48 hours. The rapid temperature rise is partly explained by the one day lapse between each 130mm-250mm pile height increase during casting.

However, in contrast to the observations of Fernandes & Sartaj (1997) and Sartaj *et al.*(1997), (See Figs. 5.1 to 5.4) duration of peak (thermophilic) temperatures were as mentioned, i.e., a range of 4.9-33 days (Exp I) and 15-49 days (Exp II). The possible reasons behind this could be (1) compost piles were built up in this current study over a period of 15 days (Exp I) and 4 days (Exp II). (2) high degradability of materials over a relatively longer period of time. (3) the loss of accumulated heat inside the piles through sensible and latent heat was less than the production of biological heat from the process due to relatively better insulation [the self-insulating qualities of the composting materials lead to an accumulation of heat (Rynk,1992)], and (4) the different configuration of materials, pile size and weather conditions. The second mesophilic phases of this current study show a slower declining trend that that found by Fernandes & Sartaj (1997) and Sartaj *et al.*(1997) which could be caused by better self-insulation qualities of the materials used and weather conditions. Therefore, the composting carried out under this current study was successful in terms of temperature development (>55°C) and duration (>3 days) of thermophilic temperatures.

The composting operations of the present study were found to be influenced by cold winds which prevailed during the Experiment (Figs. 5.2). Figure 5.2 shows the extent of cooling in pile-2 of Experiment-I. Here, and within a period of 3 days thermophilic temperatures (>55°C) decreased to the mesophilic range (<39°C). While loss of pile heat to the external environment can be expected where piles are not protected, Haug (1993), Rynk (1992) and Seekins (1999) have also presented other mechanisms through which heat can be lost. These mechanisms include (1) lack of readily biodegradable organics (2) microbial inhibitory conditions at lower moisture content (<40%) (3) development of anaerobic conditions and (4) inadequate heating in

the compost pile unless the volatile solids content is greater than 40% (w/w) on a dry weight basis. If the loss of accumulated heat exceeds the production of heat by exothermic microbial metabolism, then cooling occurs. It is most likely that this was the situation existing in the current experiments. The other mechanisms probably were not significant because thermophilic conditions were regained within 7 days suggesting that moisture content, volatile solids content and lack of degradable organics were not factors involved and furthermore anaerobic conditions were not detectable around the compost piles from emission of malodourous compounds during the period of temperature drop. Temperature development during composting and then the subsequent loss of heat during process are closely linked with some other factors which will be discussed in the subsequent sections.

### 6.3 MOISTURE REMOVAL

Table 6.2 also shows a comparison of results based on the mass balance calculations and the data of Tables 5.1, 5.2, 5.13 and 5.14.

Table 6.2 Comparison of Compost Drying results with other related published results.

Activities	Experiment-I	Experiment-II	Patni & Kinsman (1997)	Richard & Choi (1996)
Moisture content range of raw compost (%)	66.3 –66.9	69.5 –70.7	73	68.5
Moisture content range of final compost (%)	56.8 –58.4	46.6-47.6	41 -51	-
Moisture removal range (%)	38.9 - 44.7	70.1 –73.5	75 -79	45
Weight reduction range (%)	28.7 –36.7	56.3 –59.8	-	-
Mass reduction contributed by water removal (%)	81.5 –89.9	86.4 –86.8	-	-
Range of volatile solids degradation (%)	9.4 –22.3	29.4 –30.8	60	56
Water removal per kg TS (kg H <sub>2</sub> O/kg TS)	3.9 –8.2	5.7 –5.8	-	0.46 -0.78*

\*Richard & Choi (1996) published the data in kg H<sub>2</sub>O/kg TS per day; TS = total solids.

Optimal water contents for composting should lie between 40% and 65% (Rynk,1992). The initial moisture content of raw compost was about 67% and 71% in Experiment-I and II

respectively (Table 6.2). These final values of moisture in the finished product are similar to the values given by Patni & Kinsman (1997). As composting proceeded, the moisture contents of both the piles dropped continuously until the end (Figs.5.5 to 5.8) of the composting. Figs.5.5 to 5.8 show that the moisture removal process was higher during active phase than the maturation phase of composting. Patni & Kinsman (1997) investigated the moisture removal under passive aeration composting of swine manure and reported that there was no liquid at the base of the piles and thus concluded that water was removed only by evaporation. In this study, liquid did not appear in the leachate collection containers from any Experiment thus, suggesting that water in the piles was removed by evaporation and not by other mechanisms.

The comparison of MC data indicates that there was some variation in dryness of the finished product, that of Experiment-II being dryer than that of Experiment-I. The observations on moisture lost published by Richard & Choi (1996) were similar to those noted in Experiment-I and although the initial moisture content was lower than that of the pile in Experiment-II, or that of the material used by Patni & Kinsman (1997). A more successful removal of moisture (in terms of moisture content of final product and amount of moisture lost) was not achieved. Conversely, the initial higher moisture content in Experiment-II and reported by Patni & Kinsman (1997) did not produce a soggy and wet end product.

Both the Experiments in this study show relatively smaller VS degradation in comparison to the results of the authors mentioned above (Table 6.2). However, with these smaller percentages of VS degradation, Experiment-I attained a similar range of moisture removal as reported by Richard & Choi (1996). Similarly, Experiment-II also attained a similar range of moisture removal as reported by Patni & Kinsman (1997). Therefore, it would seem that higher VS degradation does not always ensure higher biodrying of compost materials during composting.

However, it is to be noted that the materials, method and configuration of composting adopted by Patni & Kinsman (1997) was different from that used in this study, although these authors also used passive aeration. Also, the materials, method and configuration described by Richard & Choi (1996) was different from those used in this study, because they used a

completely mixed aerobic reactor. In contrast, this present study was carried out in an open field environment where massive airflow movement prevailed.

Therefore, analysis of the drying characteristics of composting in this study implies that (1) microbial heat generation arises from the decomposition of VS and (2) convective moisture removal depends on air flow and temperature development in the pile. Both of these mechanisms have contributed to the formation of the final product.

#### 6.4 ENERGY EXCHANGE

During composting organic compounds energy is produced through catabolic reactions. This energy is used to drive the biosynthetic reactions within the cell and a certain amount is lost as heat (Richard & Choi,1996). This heat accumulates in the compost pile and thus raises the temperature. Haug (1993), Richard & Choi (1996) and Walker *et al.*(1999) attempted to measure both latent heat of evaporation and sensible heat loss during composting to maximize evaporative drying of wet organic wastes and to reduce the capital and bulking amendment costs associated with high moisture substrate composting.

From the laboratory analytical data given in Tables 5.1, 5.2, 5.13, 5.14 & 5.15, Table 6.3 was developed to explore further details concerning heat exchanges during composting.

Table 6.3 Comparison of Energy Exchange results with other related published results.

Studies	Loss of gross energy	Energy required in Cal/g-H <sub>2</sub> O evaporation	Heat lost through latent heat	Heat lost through sensible heat	Degraded VS in kg
Experiment-I	24.7% (51,974 Kcal)*	1258	47.2%	52.8%	8
	11.7% (23,956 Kcal)**	688			3.9
Experiment-II	29.9% (47,034 Kcal)*	706	76.5%	23.5%	10
	27.7% (46,956 Kcal)**	716	75.4%	24.6%	10.3
Walker <i>et al.</i> (1999)	-	-	90%	10%	-
Haug (1993)	-	-	65-74%	26-35%	-

\* Pile-1; \*\* Pile-2.

Experiment-I: By considering 540 Cal/g H<sub>2</sub>O evaporation (latent heat of evaporation<sup>1</sup>), in pile-1, 47.2% of the produced heat was lost through latent heat of evaporation and the remaining was lost as sensible heat. Pile-2 removed 65.56 kg (Table 5.13) of water, whereas a maximum of 44.36 kg of water can be removed by utilizing the total heat energy produced in the pile.

The heat energy produced can never be utilized fully for water removal because there must be some energy lost as sensible heat. The question which may now arise is, how has pile-2 achieved such a degree of dryness using only 688 Cal/g H<sub>2</sub>O without significant decomposition of VS and without the production of a large amount of heat energy? The possible explanations could be as follows:

- (1) Due to its geographical position, pile-2 experienced the cooling effect of wind flow which cooled the pile during the initial thermophilic stage. As a result, only a small amount of volatile solids were degraded and only a small amount of energy was released.
- (2) The total heat energy released from the decomposition of 3.92 kg of VS must be lost as both sensible heat and latent heat of evaporation.
- (3) The cooling effect suppressed the proliferation of thermophilic microbes and thus the small amount of VS metabolised generated a small amount of heat, water vapour and gas. From the decomposition of 3.92 kg VS, the process produced only 1.11 kg gas, 2.81 kg water vapour and 19,421 Kcal heat energy (Table 5.15). This small quantity of energy was not sufficient to evaporate 34.81 kg water, as it requires 18,797.4 Kcal (considering 540 cal/g H<sub>2</sub>O) of latent heat for its complete evaporation.
- (4) Mechanisms other than evaporative drying were responsible for drying the materials of pile-2. One possibility here could be air drying. The pile experienced the direct path of wind flow and physical convection of moisture may have dried the material.
- (5) Excessive aeration from wind badly affected the process by removing the accumulated heat from interior of the pile through conductive heat loss.
- (6) The peak temperatures (>55°C) in pile-2 was sustained only from 4.9 to 7 days in different layers.
- (7) Molecular diffusion could be the another mechanism by which water vapor molecules from the moist interior diffuse to less moist ambient air (Haug,1993).

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<sup>1</sup> Latent heat of evaporation is the amount of heat energy in Calories required to evaporate one gram of water.

Therefore, the heat produced in pile-2 was not entirely responsible for the evaporation of such a large amount of water. A massive airflow rate should be accounted for with higher sensible heat loss from pile-2 (Haug,1993) because excessive airflow can remove a lot of moisture by developing channels of air that occurs within the pile at high air flow rates (Seekins,1999). Although molecular diffusion transports a small amount of water vapor, over the period of more than 60 days, this amount could be considerable. Possibly, due to the contribution of airflow in drying, pile-2 may have used less energy than pile-1 to evaporate each gram of water (Table 6.3). Therefore, the evaporative heat loss could be maximized and air drying could be minimized in Experiment-I by providing a wind barrier to protect the piles from wind action.

Experiment-II: By considering 540 Cal/g-H<sub>2</sub>O evaporation, more than 75% of the produced heat was lost through latent heat of evaporation and the remaining was lost as sensible heat. Both the piles of Experiment-II show similar performance characteristics in terms of energy production, energy used per gram water evaporated and loss of energy as both latent and sensible heat.

Heat loss through evaporation can represent as much as 90% and the remaining 10% lost as sensible heat (Walker *et al.*,1999). Haug (1993) has reported 65-74% evaporative heat loss. Walker *et al.*(1999) in reporting results (Table 6.3) from composting of different materials in an agitated In-vessel system found it necessary to use insulation to minimize the sensible heat loss. Haug (1993) has reported that results from a simulation of a composting process of biosolids made assumptions which may not exist in actual practice under field conditions. This present study achieved around 47% and 76% evaporative heat loss from Experiment-I & II respectively. The evaporative heat loss of Experiment-I was lower than the values obtained by Walker *et al.*(1999) and Haug (1993). This is because, a large fraction of produced heat could not be used as latent heat due to both the shorter duration and lower range of thermophilic temperatures. Furthermore, the current study was carried out in an open field where the available insulation did not work well to minimize the sensible heat loss. However, the evaporative heat loss of experiment-II was very much similar (76.5%) to the upper limit of values (65-74%) reported by Haug (1993).

The results of these present studies, conducted under passive aeration in an open environment where there was no control, especially on aeration, may differ from the results of other authors, since a higher mass airflow rate accounts for higher sensible heat loss from the process (Haug,1993). Very high mass airflow occurred frequently during both the experiments of this study (pile-2 especially was highly affected in both cases). The results of these studies show that from 47.2% to 76.48% of produced heat was lost as latent heat of evaporation and the remaining as sensible heat. These losses represent considerable biodrying of materials for on-farm composting under passive aeration. Therefore, a considerable amount of VS in all the piles in both the experiments (except pile-2 of Experiment-I.) was decomposed through biological oxidation. Oxygen was available from passive ventilation into the piles in combination with forced aeration arising from wind action. Sufficient heat energy was produced to evaporate a considerable amount of water.

On the basis of the energy balance of both the experiments, it was noted from Table 5.15 that both the piles in Experiment-I had a similar initial volatile solids content and had an appropriate water and energy ratio. This suggested that both the piles should compost well, as they seemed to be energy rich initially (based on water and energy ratio). Pile-1 was not affected by wind action, as was pile-2. Pile-1 developed as being energy rich (because 8.03 kg of VS was decomposed) but pile-2 proved not to be energy rich (because only 3.92 kg of VS was decomposed). The cooling effect of the cold wind flow may have been responsible for the slowing of metabolic action in pile-2.

The water ratio and energy ratio of both the piles in Experiment-II were anticipated as being slightly energy poor, because of an energy ratio that was lower than the recommended energy ratio (600-700 Cal/g H<sub>2</sub>O to be evaporated) suggested by Haug (1993). However, both piles emerged as being nearly energy balanced. The input energy for both the piles was found to be closer to the output energy as shown in Table 5.15.

The anticipated biodegradability of materials in Experiment-II was expected to be 28% (see Appendix I) but in practice found to be approximately 30% (see Appendix I). It is possible that the biodegradability of mixed paper was higher than anticipated. The higher moisture

content did not diminish FAS values, this was due to the use of wood chips as a bulking agent. Therefore, this study suggests that the higher moisture content range from 67 to 71% was not harmful, rather it was helpful where sufficient FAS for aeration was provided using a suitable bulking agent. The initial recommended energy factors provided by Haug (1993) such as water ratio (W) and energy ratio (E) of feed materials do not guarantee the process to be successful unless proper FAS and aeration control mechanisms are provided.

## 6.5 AMENDMENTS

Table 6.4 summarises data from Tables 5.1 & 5.2, mass and energy balance information (see Appendix I) and the published data of other authors. The determination of individual biodegradability of sawdust, mixed paper and manure was beyond of scope of this study. However, the performance of sawdust and mixed paper can be compared and evaluated from the composition of materials, overall biodegradability of combined materials, and on the basis of information about biodegradability of the materials obtained from other researchers. This is because other materials except for the amendments used in both Experiments were the same.

Table 6.4 Comparison of Biodegradability results with other related published results.

Studies	C/N Ratio		VS content (%)		Biodegradability of combined materials		Biodegradability (%)		
	Sawdust	Mixed paper	Sawdust	Mixed paper	Anticipated	Practically obtained	Sawdust	Mixed paper	Manure
Experiment-I	456.4	-	99	-	31%	9.5-18.9%	-	-	-
Experiment-II	-	745	-	83.9	28%	31%	-	-	-
Haug (1993)	-	-	-	-	-	-	20	66.7	50
Atkinson <i>et al.</i> (1996)	-	-	-	-	-	-	29	-	-
Chandler <i>et al.</i> (1983)	-	-	-	-	-	-	-	28.1*	72-75

\* Chandler *et al.*(1983) reported that biodegradability of newsprint (not mixed paper) is 28.1%.



Sawdust and mixed paper<sup>2</sup> were used as amendments in Experiment-I & II respectively. The C/N ratio of mixed paper was greater than that of sawdust. Therefore, to obtain a desirable C/N ratio of raw compost, relatively small amounts of mixed paper were needed in comparison to sawdust. Due to a high C content of mixed paper and sawdust, both were suitable for adjustment of the C:N ratio of raw compost, although their high C content does not guarantee the availability of C for the microorganisms.

The anticipated combined biodegradability values of materials used in Experiments I & II were 31% and 28% of VS respectively. The individual biodegradability of manure and sawdust was considered as 50% and 20% of VS respectively (Haug,1993). The wood chips were assumed to remain unchanged during the shorter period of composting. According to the mass and energy balance (see Appendix I), the practical biodegradability of combined materials in Experiment-I was (9.5-18.9%) which is less than found in Experiment-II (31%). This indicated that VS of the sawdust in Experiment-I was not degraded as much as expected, whereas the VS of mixed paper degraded more than expectation.

Haug (1993) reported that the degradability of sawdust from softwood and hardwood was 11% and 50% respectively, whereas the degradability of mixed paper was 66.7%. Moreover, Experiment-II shows better results in terms of the temperature development, the amount of VS degraded, moisture removal and energy utilization. Therefore, the use of mixed paper (75% office paper + 25% newsprint) as an amendment in this study was found very successful in terms of C:N ratio adjustment, energy conditioning, water absorption capacity, biodegradability, temperature development and thus evaporative drying of very wet raw compost.

Therefore, sawdust should need more time for its VS decomposition. The degradability of sawdust depends on its source and particle size. The source of sawdust (whether it was from softwood or hardwood) used in this study was unknown. Most likely it was sourced from

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<sup>2</sup> Most office paper is made from a combination of softwood and hardwood fibers. For newsprint, mostly mechanically produced softwood long fibers used and lignin is not removed. In Kraft processing, chemically produced fibers from softwood and hardwood are combined to make office paper in which a major part of lignin is chemically dissolved and removed (Kline,1982). The mixed paper contained 25% newsprint and 75% office paper. Therefore, mixed paper should not have lignin content as much as in sawdust.

softwood, because it did not degraded<sup>3</sup> to an extent expected. To get a better result from sawdust, it should be sourced from hardwood. However, it would be very difficult to get sawdust always from hardwood because most sawmills in New Zealand are currently processing softwoods.

## 6.6 COLIFORMS

The presence of coliform bacteria is often used as an indicator of the overall sanitary quality of finished compost (Hassen *et al.*,2001). Use of an indicator such as coliforms, as opposed to the actual disease-causing organisms, is advantageous as the indicators generally occur at higher frequencies than the pathogen and are simpler and safer to detect (Hassen *et al.*,2001). The median of fecal coliform level in compost should to be < 10 MPN/g dry solids with not more than 20% of samples exceeding 1000 MPN/g dry solids and no sample to exceed 10,000 MPN/g dry solids (Haug,1993). Vuorinen & Saharinen (1997) recommended that an acceptable density of fecal coliforms for hygienization is 1000MPN/g dry solids.

Table 6.5 summarises coliform data from Tables 5.1 & 5.2 and published coliform data from Hassen *et al.*(2001).

Table 6.5 Comparison of Coliform Destruction results with other related published results.

Studies (Materials used)	Coliform Results in MPN/g dry solids (Log MPN/g dry solids)	
	Initial Raw Compost	Final Compost
Experiment-I (Manure, Sawdust and Wood chips)	8.68×10 <sup>7</sup> (7.93)* 1.17×10 <sup>8</sup> (8.06)**	2.20×10 <sup>6</sup> (6.34) 6.58×10 <sup>5</sup> (5.81)
Experiment-II (Manure, Mixed paper & Wood chips)	1.92×10 <sup>8</sup> (8.28)* 1.54×10 <sup>8</sup> (8.18)**	4.36×10 <sup>6</sup> (6.64) 2.01×10 <sup>6</sup> (6.30)
Hassen <i>et al.</i> (2001) (Municipal Solid Waste).	3.16×10 <sup>7</sup> (7.5)	1.25×10 <sup>5</sup> (5.10)

\* Pile-1; \*\* Pile-2. Coliform results are expressed in Log MPN/g dry solids and are given in the brackets.

<sup>3</sup> Sawdust (Exp I) and mixed paper (Exp II) are both plant derived materials. Sawdust comes from wood which composed of a mixture of cellulose (ca.40%), hemicellulose (ca.20-30%) and lignin (ca.20-30%) (Tuomela *et al.*, 2000). Cellulose is highly degradable (90%), hemicellulose and other sugars are moderately degradable (70%), lipids and proteins have low degradability (50%) and the lignin is difficult to break down in the typical time span of a composting process (Haug, 1993).

The observed decreases (Table 6.5) in coliforms were presumably the result of the high temperatures that each pile reached ( $>55^{\circ}\text{C}$ ) and unfavorable conditions established during the thermophilic phase. Although the removal of coliforms in pile-1 and pile-2 under Experiment-I was 96.40% and 99.30% respectively and that for Experiment-II was 97.73% and 98.67% respectively these final count values are far from a desirable level. The results of coliform data presented by Hassen *et al.*(2001) also indicate similar (99.6% removal) coliform destruction and also did not achieve the acceptable final value.

The piles in this study and in the study carried out by Hassen *et al.*(2001) reached well above  $55^{\circ}\text{C}$  (highest temperature in Experiment-I, II and Hassen *et al.*(2001) was 73,79.5 and  $62^{\circ}\text{C}$  respectively) and sustained those temperatures for more than the recommended duration (3-4 days). However, the final total coliform values did not reach an acceptable final value. Possible explanations are as follows:

- (1) The compost piles interior may have some micro-climate pockets where the peak temperature did not reach above  $55^{\circ}\text{C}$  or did not sustain  $>55^{\circ}\text{C}$  for a sufficient time to kill coliforms.
- (2) Mote *et al.*(1988) reported the similar results for total coliforms removal during the composting of dairy manure with sawdust. They reported that “ even though there may be an initial decline, or even disappearance of detectable total coliform bacteria in composting dairy waste, these bacteria can reestablish themselves in large numbers without any reinnoculation”. The secondary growth of faecal coliforms (possibly through recontamination from cooler regions or redistribution) has been observed also in composting by other authors. Hassen *et al.*(2001) reported that a phase of resurgent growth of faecal coliforms appeared from the ninth week (when peak temperature began to fall from  $65^{\circ}\text{C}$ ) in their study.

Therefore, this current study suggests that the required extent of total coliforms removal has not been achieved with this type of composting method, under traditional thermophilic temperature and time conditions. This current study did not support the conjecture that the area

under time-temperature curve for the thermophilic range (>55°C) provides an indication of coliform destruction. The non-agitated compost piles may provide micro-climates which shelter coliforms and or other bacteria including endspore forming bacteria, thus enabling their survival in the thermophilic composting environment. Therefore, a longer maturation or curing phase would seem necessary to achieve the recommended coliforms count. Sesay *et al.*(1997) reported that any increase in faecal coliforms at the end of thermophilic phase was reduced during the maturation period and neither faecal coliforms nor streptococci were detected after five months of maturation, although temperatures in the maturation pile were near ambient levels.

## **6.7 SIGNIFICANCE OF OBSERVATIONS TO THE DAIRY FARMER**

Composting of dairy shed manure would require the New Zealand dairy farmer to consider the following points:

1. Provision of a water/leachate impervious base (compost pad) upon which the compost windrow would be constructed. Provision of drainage lines around the compost pad is important.
2. A covered farm dairy yards and possibly a covered composted facility would be necessary.
3. Provision of passive aeration pipes (PVC).
4. Twice daily collection of manure from milking parlour holding yard's apron and from parlour itself.
5. Mechanical scrapers or a vacuum pump system for suitable collection of manure.
6. Twice daily mixing of manure, amendment and bulking agent.
7. Twice daily addition of raw compost mixture to the lengthening windrow.
8. Supplies on hand of amendment (sawdust or mixed paper) and bulking agent (wood chips) delivered to farm and paid for by dairy farmer.
9. Front end loader for transporting and mixing of materials.
10. Cold, prevailing winds may slow the composting process.

## CHAPTER-7

### CONCLUSIONS

#### 7.1 COMPOSTING PROCESS

Conditioning of high moisture dairy manure (in terms of both energy and structure) with suitable amendments (either sawdust or mixed paper) and a bulking agent (wood chips) was found to provide a satisfactory method for composting this substrate using passive aeration. In this study the compost piles reached the desirable thermophilic temperatures ( $>55^{\circ}\text{C}$ ) for at least 5 days. These temperatures caused moisture removal through latent heat of evaporation. The overall performance of piles in both experiments (except pile-2 of Experiment-I) were assessed in terms of temperature development, magnitude and duration of thermophilic temperatures, moisture removal, weight reduction, volume reduction and biodegradability of input volatile solids. However, comparison of the temperature profiles of composting piles of both the experiments revealed that those compost piles in an open environment needed protection (by providing a suitable wind barrier) from excessive natural heat loss to the surrounding environment. Thus the decomposition process of available biodegradable organics was hampered by cold winds which adversely affected the composting process in field scale experiments. Therefore, the provision for wind barriers on prevailing wind side should be provided. This study investigated the process with two amendments (sawdust and mixed paper) and a bulking agent under different configurations and conditions from studies carried out by other authors. The final results indicate that although the composting piles tested in this study were small, the results obtained suggested that the proposed composting system would be effective for dairy farm based windrows. The main advantage of this process is that the very wet dairy manure slurry can be composted without the need for costly pretreatment equipment (centrifuges or filter presses) for dewatering prior to its usage. The process should offer a product that can be used in landscaping, home gardening, nurseries and in greenhouse. Furthermore, the farmers themselves might be the major end users of the compost product.

## 7.2 MOISTURE REMOVAL

The results of this study indicate the following information:

1. High moisture content [90% (w/w)] dairy manure was reduced to 80% (w/w) moisture content by the addition of sawdust [ 61% (w/w), MC] or mixed paper [ 6.3% (w/w), MC].
2. Amended dairy shed manure exhibited FAS values of 14.4% (with sawdust) and 11.6% (with mixed paper).
3. Increases in FAS values were achieved using wood chips as bulking agent (27% FAS in case of sawdust and 25% FAS in case of mixed paper).
4. Amending agents plus a bulking agent produced final moisture contents of 67% (w/w) for sawdust/wood chips conditioning and 71% (w/w) for shredded mixed paper/wood chips conditioning.

The results of this study indicate the following conclusions about moisture removal:

1. Dairy manure slurry with an initial 70% MC can be composted successfully by using the materials and the procedures undertaken in this study.
2. Conditioning of high moisture dairy manure slurry with a suitable amendment and bulking agent were essential prior to composting.
3. Manure slurries, with their higher moisture content showed a greater sensitivity to changes in bulk weight and FAS due to pore space blocking. This sensitivity can be minimized by using a suitable amendment and bulking agent.
4. Water removal and weight reduction was maximized by using a highly degradable amendment (to supply nutrient and energy to the microorganisms) and a suitable bulking agent (to ensure an open structure of the compost matrix for sufficient aeration).
5. Static pile, passive aeration composting can be a feasible method to remove considerable quantities (Tables 5.13 & 5.14) of water (up to 70% of initial water of raw compost) from high moisture dairy manure slurry, if sawdust or mixed paper is used as an amendment and wood chips as a bulking agent. These methods allowed energy and structural conditioning of the feed materials to facilitate the composting process.

6. A deduction drawn from the results of this current study was that moisture removal can happen either by evaporation or air drying. Higher evaporative drying is an indicator of higher decomposition, whereas higher air drying indicates lower decomposition. Higher evaporative drying involves significant degradation of available volatile solids whereas, higher air drying may leave significant volatile solids undegraded.

### 7.3 ENERGY EXCHANGE

The results of this study indicate the following conclusions about energy:

1. The energy factors namely, water ratio (W) and energy ratio (E) can be used as preliminary tools for energy conditioning of substrate. However, they do not always ensure the ultimate successfulness of the process in terms energy produced during composting.
2. An anticipated energy rich feed material can be energy poor due to smaller VS degradation and an energy poor feed material can emerge as an energy rich due to greater VS degradation.
3. The more VS that are degraded then the greater amount of heat energy produced. The released and accumulated heat energy from decomposition of biodegradable volatile solids can be utilized to evaporate significant water from wet organic materials.
4. Accurate prediction of moisture removal from a composting system requires a partition of the generated heat into, losses through between convective (evaporation using latent heat) and conductive (losses to surroundings using sensible heat) processes.
5. The water removal can be maximized through achieving a greater fraction of convective heat losses in the latent mode rather than in the sensible heat manner.
6. The results of Experiment-I of this study indicated that pile-1 utilized approximately 47.2% of the produced heat as latent heat to remove water using 9.5 kg of VS and produced an end product of 58.4% MC whereas, due to excessive air drying from winds, pile-2 produced a drier end product although using only 3.92 kg of VS. On the other hand, both piles in Experiment-II utilized approximately 76% of produced heat as latent heat to remove water using approximately 10 kg of VS and thus produced a fairly dry end product of approximately 47% MC under conditions where wind barriers protected

the compost piles from excessive air drying. Therefore, an experiment based conclusion would be that “dryness of compost materials during composting is a result of multiple functions such as the amount of VS degradation, fraction of heat losses through latent heat and air-drying”.

7. Thus, process control guidelines for maximum moisture removal under passive aeration (using produced energy) should require operator: (1) to maximize decomposition of available volatile solids by providing highly degradable organics in the feed materials and sufficient FAS for aeration and oxidation. (2) to supply sufficient air to meet the stoichiometric oxygen demand for the oxidation of degradable organics. (3) to attain maximum temperature (water holding capacity of exhaust gases increases as temperature increases) and (4) to protect compost pile from cooling caused by excessive wind flow in an open environment (wind barriers can protect compost pile from excessive aeration).

#### **7.4 AMENDMENTS**

The results of this study indicate the following conclusions about amendments:

1. The dairy manure slurry is a nitrogen rich (C:N ratio = 10 to 16) substrate which needs extra readily available carbon for efficient degradation. The results of this study indicate that with suitable amendments by using any one of the two amendments (sawdust or mixed paper) the process is capable of achieving the recommended level and duration of thermophilic temperature.
2. Experiment-I shows lower biodegradability (9-18%) of materials than the anticipated value (31%) using sawdust as an amendment, while Experiment-II shows higher biodegradability (29-31%) of materials than the anticipated value (27%) using mixed paper as an amendment (this higher biodegradability was achieved due to the higher biodegradability of mixed paper). Thus mixed paper performed better as an amendment than sawdust in terms of magnitude and duration of thermophilic temperatures, amount of volatile solids degradation, energy production, utilization of energy for water removal, weight reduction and volume reduction.



3. Although sawdust has greatest VS content, only a small fraction of that VS is readily available for microorganisms. It biodegrades slowly and needs a longer time for the considerable degradation of coarse and large particles.
4. Sawdust may not be always available in the required quantity, at a reasonable price and every where in New Zealand to meet the composting requirements of the nation's farmers. However, mixed paper which is approximately the second largest fraction of municipal solid waste in New Zealand could be a regular and cheap source of an amendment for on-farm dairy manure composting using passive aeration.

### **7.5 TOTAL COLIFORMS**

The results of this study indicate the following conclusions about coliform destruction:

1. The required level of total coliforms destruction was not achieved within the time period of composting using the materials and methods undertaken.
2. The compost pile materials may have post-thermophilic stage coliform re-growth.
3. The compost pile materials may have provided micro-climates as shelters for coliforms during the thermophilic temperature range and duration. Therefore, a longer maturation (curing) phase could be helpful to achieve the recommended count of total coliforms in the finished product.

## CHAPTER-8

### BIBLIOGRAPHY

- Andrews, J. F. & Kambhu, K. (1973): Thermophilic Aerobic Digestion of Organic Solid Wastes. EPA-670/2-73-061, PB 222 396. NTIS, Springfield, VA. pp.76, cited by Richard, T. L. & Choi, H. L.(1996).
- Anonymous (1999): Reader's Q & A. *Biocycle* **40** (2): 18-19.
- Atkinson, C. F., Jones, D. D. & Gauthier, J. J. (1996): Biodegradability and microbial activities during composting of poultry litter. *Poultry Science* **75**: 608-617.
- Bell, R. G. & Pos, J. (1971): *Can. Ag. Eng.* **13** (2): 60, cited by Crawford, J. H. (1983).
- Biddlestone, A. J. & Gray, K. R. (1985): Practical experience with farm scale systems. In: Gasser, J.K.R. (Ed.) Composting of agricultural and other wastes. Elsevier Applied Science, London, England.
- Biddlestone, A. J. & Gray, K. R. (1973): *The Chemical Engineer*, **270**: 76, cited by Crawford, J. H. (1983).
- Bujang, K. B. & Lopez-Real, J. M. (1993): Composting for the treatment of cattle wastes. *Compost Science & Utilization* **1** (3): 38-40.
- Burt, T. P., Heathwaite, A. L., Trudgill, S. T. (eds.) 1993: *Nitrate: Processes, Patterns and Management*. John Wiley and Sons Ltd., London, England.
- Caruso, B. S. & Jensen, E. (2000): Effects of landslides on contaminant sources and transport in steep pastoral hill country. *Journal of Hydrology (NZ)* **39** (2): 127-154.
- Chandler, J. A., Jewel, W. J., Gossett, J. M., Van Soest, P. J. & Robertson, J. B. (1983): Predicting methane fermentation biodegradability. *Biotechnology & Bioengineering Symposium No 10*. John Wiley & Sons Inc, New York, USA.
- Choi, H. L., Richard, T. L. & Ahn, H. K.(2001): Composting High Moisture Materials: Biodrying Poultry Manure in a Sequentially Fed Reactor. *Compost Science & Utilization*. Vol. **9**, No. 4: 303-311.
- Cook, J. G. (1992): Phosphorus removal process in a wetland after a decade of receiving a sewage effluent. *Journal of Environmental Quality* **21** (4): 733-739.
- Cooper, A. B. & Cooke, J. (1984): Nitrate loss and transformation in two vegetated headwater streams. *New Zealand Journal of Marine and Freshwater Research* **18**: 441-450.
- Crawford, J. H. (1983): Composting of Agricultural Wastes-A Review. *Process Biochemistry* **18**: 14-18.

Crozier, M. J., Eyles, R. J., Marx, S. L., McConchie, J. A. & Owen, R. C. (1980): Distribution of landslips in the Wairarapa hill country. *New Zealand Journal of Geology and Geophysics* **23**: 575-586.

Dairy Facts and Figures (1999-2000): *New Zealand Dairy Board*, New Zealand.

Dairy Statistics (1999-2000): *Livestock Improvement Corporation Limited*. pp.5-44. Hamilton, New Zealand

Dakers, A. J. (1979): Management of livestock wastes in New Zealand- Problems and practice. *Prog. Wat. Tech.* **11** (6): 397-404.

Dakers, A. J. & Painter, D. J. (1983): Livestock waste management in New Zealand. *In*. McFarlane, P. N. (Ed) Waste stabilization ponds, *Proceedings of 15<sup>th</sup> Biotechnology Conference*, pp. 51-58. Massey University, Palmerston North, New Zealand.

Das, K. & Keener, H. M. (1997): Moisture Effect on Compaction and Permeability in Composts. *Journal of Environmental Engineering* **123** (3): 275-281.

Davis-Colley, R. J. (1996): Water quality criteria: an overview with regard to dairy shed and piggery wastewaters, edited by Mason, I. G. (1996): Tertiary treatment options for dairymshed and piggery wastewaters. *Proceedings of a seminar held at Massey University*, Palmerston North, New Zealand.

Dawn (1973): Disposal of Agricultural Wastes Newsletter. No.3. Ministry of Works and Development (NZ). Water and Soil Conservation Organisation cited by Dakers, A. J. (1979): Management of livestock wastes in New Zealand- Problems and practice. *Prog. Wat. Tech.* **11** (6): 397-404.

Di, H. J., Cameron, K. C., Moore, S. & Smith, N. P. (1998): Nitrate leaching from dairy shed effluent and ammonium fertiliser applied to a free draining pasture soil under spray or flood irrigation. *New Zealand Journal of Agricultural Research* **41**: 263-270, cited by Roygard, J. K. F. (1999).

Dickinson, D. (1974): The management of farm wastes. In: Practical waste treatment and disposal (ed) Denis Dickinson, Applied Science Publisher, London. pp.129-144.

Drysdale, A. B. (1977): Many a Muck'll Make a Muddle. *New Zealand Farmer*, Vol.98, No.23, December, New Zealand cited by Dakers, A. J. (1979).

Duncan, G. A. (1933): The New Zealand dairy Industry. The formation, administration, accounts, finance, costing and statistics of dairy factory companies and a review of the *New Zealand dairy industry*. H. L. Young Limited, Printers and publishers, Broadway and Kingsway, Palmerston North, New Zealand.

Economic Survey (1999-2000): Economic Survey of New Zealand Dairy Farmers, Dexcel Consulting Service, New Zealand Dairy Board.

- Elliott, L. F., Schuman, G. E. & Viets, F. G. Jr. (1971): Volatilization of nitrogen-containing compounds from beef cattle areas. *Soil Sci. Soc. Amer. Proc.* **35**: 752-755, cited by Mathur, S. P., Patni, N. K. & Levesque, M. P. (1990).
- Emerton, B. L., Mote, C. R., Dowlen, H. H., Allison, J. S. & Sanders, W. L. (1988): Comparison of forced and naturally aerated composting of dairy manure solids. *Applied Engineering in Agriculture* **4** (2): 159-164.
- Environment Waikato (1994): Changes to Transitional Regional Plan 1. Dairy shed effluent operative plan. *Waikato Regional Council*, Waikato. New Zealand.
- Epstein, E. (1994): Composting and bioaerosols. *Biocycle* **35**(1): 51-58.
- Faulkner, S. P. & Richardson, C. J. (1989): Physical and chemical characteristics of freshwater wetland soils. p. 41-72. In D. A. Hammer (ed.) *Constructed wetlands for wastewater treatment: Municipal, industrial, agricultural*. Lewis Publishers, Chelsea, MI, cited by Cooke, J. G. (1992).
- Fernandes, L. & Sartaj, M. (1997): Comparative study of static pile composting using natural, forced and passive aeration methods. *Compost Science & Utilization* **5** (4): 65-77.
- Fernandes, L., Zhan, W., Patni, N. K. & Jui, P. Y. (1994): Temperature distribution and variation in passively aerated static compost pile. *Bioresource Technology* **48**: 257-263.
- Finstein, M. S., Miller, F. C. & Strom, P. F. (1986): Waste treatment composting as a controlled system. pp. 363-398. In: *Biotechnology: a comprehensive treatise in 8 vol.*, H.-J. Rehm and G. Reed (eds.), *Vol. 8. Microbial degradations*, W. Schonborn (vol. Ed.). VCH Verlagsgesellschaft (German Chemical Society), Weinheim, FRG.
- Glenn, J. (1998): Dairy farm thrives with manure composting. *Biocycle* **39** (6): 40-42.
- Golueke, Clarence, G. (1992): Bacteriology of composting. *Biocycle* **33** (1): 55-59.
- Goulding, K. W. T., Matchett, L. S., Heckrath, G., Webster, C. P., Brookes, P. C. & Burt, T. P. (1996): Nitrogen and phosphorus flows from agricultural hillslopes. In M. G. Anderson and S. M. Brookes (eds.) *Advances in Hillslope Process*, Vol. **1**. Wiley, Chichester, pp. 213-227 cited by Caruso, B. S. & Jensen, E. (2000).
- Gray, K. R., Sherman, K. & Biddlestone, A. J. (1971): A review of composting-Part-1. *Process Biochemistry*. pp.32-36.
- Hansen, R. C., Keener, H. M. & Hoitink, H. A. J. (1989a): Poultry manure composting: An exploratory study. *Transactions of the ASAE* **32** (6): 2152-2157.
- Hassen, A., Belguith, K., Jedidi, N., Cherif, A., Cherif, M. & Boudabous, A. (2001): Microbial characterization during composting of municipal solid waste. *Bioresource Technology* **80**: 217-225.
- Haug, R.T. (1997): Feedstocks, conditioning and fire prevention. *Biocycle* **36** (4): 68-70.

- Haug, R.T.(1993): The practical handbook of compost engineering. Lewis publishers, Boca Raton, Florida, USA.
- Haug, R. T. (1986): Composting process design criteria: part III- aeration. *Biocycle* **27**: 53-71.
- Heatley, P. (1996): Managing farm dairy effluent. Dairying and the Environment Committee/ NZ Dairy Research Institute, Palmerston North, NZ.
- Hickey, C. W., Quinn, J. M. & Davis-Colley, R. J. (1989): Effluent characteristics of dairy shed oxidation ponds and their potential impacts on rivers. *New Zealand Journal of Marine and Freshwater Research*. **23**: 569-584.
- Hickey, C. W. & Quinn, J. M. (1992) edited by Mason, I. G. (1996): Tertiary treatment options for dairymshed and piggery wastewaters. *Proceedings of a seminar held at Massey University*, Palmerston North, New Zealand.
- Hills, D. J. (1975): Nutrient Budget in Management of Livestock Wastes. Proceedings, Ministry of Agriculture and Fisheries (NZ). Agricultural Engineering Conference, Lincoln College, November, New Zealand cited by Dakers, A. J. (1979).
- Hogan, J. A., Miller, F. C. & Finstein, M. S. (1989): Physical modeling of the composting ecosystem. *Applied and Environmental Microbiology* **55** (5): 1082-1092.
- Hong, J. H., Matsuda, J. & Ikeuchi, Y. (1983): High rapid composting of dairy cattle manure with crop and forest residues. *Transactions of the ASAE*, pp.533-545.
- Jackson, M. J. & Line, M. A. (1997): Composting pulp and paper mill sludge-Effect of temperature and nutrient addition methods. *Compost Science & Utilization* **5**(1): 74-81.
- Jewell, W. J., Dondero, N. C., Van Soest, P. J., Cummings, R. J., Vergara, W. W. & Linkenheil, R. (1984): *High Temperature Stabilization and Moisture Removal from Animal Wastes for By-Product Recovery*. Final report prepared for the Cooperative State Research Service, USDA, Washington, DC. Project number SEA/CR 616-15-168 cited by Richard, T. L. & Choi, H. L.(1996).
- Kayhanian, M. & Tchobanoglous, G. (1992): Computation of C/N Ratios for Various Organic Fractions. *Biocycle* **33** (5), cited by Haug, R.T.(1993).
- Kline, J. E. (1982): Paper and paperboard. Manufacturing and converting fundamentals. Miller freeman publications, inc. San Francisco, California, USA.
- Lau, A. K., Lo, K. V., Liao, P. H. & Yu, J. C. (1992): Aeration experiments for swine waste composting. *Bioresource Technology* **41**: 145-152.
- Lehninger, A. L. (1973): Bioenergetics- The Molecular Basis of Biological Energy Transformations. Second edition. W. A. Benjamin, Inc. California, USA.

- Lopez-Real, J & Baptista, M. (1996): A preliminary comparative study of three manure composting systems and their influence on process parameters and methane emissions. *Compost Science & Utilization* **4** (3): 71-82.
- Lufkin, C., Loudon, T., Kenny, M. & Scott, J. (1995): Practical applications of on-farm composting technology. *Biocycle* **36** (12): 76-78.
- Lynch, N. J. & Cherry, R. S. (1996): Design of passively aerated compost piles: Vertical air velocities between the pipes. *Biotechnol.Prog.* **12**: 624-629.
- MacGregor, S. T., Miller, F. C., Psarianos, K. M. & Finstein, M. S. (1981): Composting process control based on interaction between microbial heat output and temperature. *Applied Environmental Microbiology* **41**: 1321-30.
- Mahimairaja, S., Bolan, N. S., Hedley, M. J. & Macgregor, A. N. (1994): Losses and transformation of nitrogen during composting of poultry manure with different amendments: An incubation experiment. *Bioresource Technology* **47**: 265-273.
- Martin, A. M. (1991). (Ed.): Bioconversion of waste materials to industrial product. Elsevier Applied Science Publishers, London, UK.
- Mason, I. G. & Reijnen, B. P. A. (1999): Non-water borne collection and treatment of farm dairy yard waste. *Australasian Environmental Engineering Conference* (1999).
- Mason, I. G. (1996): Tertiary treatment options for dairymshed and piggery wastewaters. *Proceedings of a seminar held at Massey University, Palmerston North, New Zealand.*
- Mason, I. G. & Young, B. S. (1999): The influence of potassium on crop quality and animal health in land treatment system. Proceedings 1999 NZ Water & Wastes Conference, cited by Mason, I. G. & Reijnen, B. P. A. (1999).
- Mathur, S. P., Patni, N. K. & Levesque, M. P. (1990): Static pile, passive aeration composting of manure slurries using peat as a bulking agent. *Biological Wastes* **34**: 323-333.
- Merz, J. & Mosley, M. P. (1998): Hydrological behaviour of pastoral hill country modified by extensive landsliding, northern Hawke's Bay, New Zealand. *Journal of Hydrology New Zealand* **37** (2): 113-139
- Michel, F. (1999): Managing compost piles to maximize natural aeration. *Biocycle* **40** (3): 56-59.
- Miller, F. C. (1991): Biodegradation of solid wastes by composting. In: A. M. Martin (ed.) *Biological Degradation of Wastes*. Elsevier Applied Science, London. pp.1-30, cited by Choi, H. L., Richard, T. L. & Ahn, H. K.(2001).

Miller, F. C., MacGregor, S. T., Psarianos, K. M., Cirello, J. & Finstein, M. S. (1982): Direction of ventilation in composting wastewater sludge. *Journal of Water Pollution Control Federation* **54**: 111-113, cited by Emerton, B. L., Mote, C. R., Dowlen, H. H., Allison, J. S. & Sanders, W. L. (1988).

Millner, P. D. (ed.).1994: Bioaerosols Associated With Composting Facilities. The Composting Council, cited by Epstein, E. (1994).

Miner, J. R. & Hazen, T. E. (1969,1977): Ammonia and amines: Components of swine-building odor. *Trans. Amer. Soc. Agric. Engng* **12**: 772-774, cited by Mathur, S. P., Patni, N. K. & Levesque, M. P. (1990).

Ministry of Agriculture and Fisheries (1994): Dairy Shed Wastewater Treatment Ponds. *MAF Agriculture Policy Technical paper 94/17*. Policy Services, MAF, Wellington, New Zealand.

Mote, C. R., Emerton, B. L., Allison, J. S., Dowlen, H. H. & Oliver, S. P.(1988): Survival of coliform bacteria in static compost piles of dairy waste solids intended for freestall bedding. *Journal of Dairy Science*. Vol.**71**, No.6.

Muller, F. M. *Mushroom Science*. Vol. **6**: 213. (1967), cited by Crawford, J. H. (1983): Composting of Agricultural Wastes-A Review. *Process Biochemistry* **18**: 14-18.

Nakasaki, K., Sasaki, M., Shoda, M. & Kubota, H. (1985): Characteristic of mesophilic bacteria isolated during thermophilic composting of sewage sludge. *Appl. Environ. Microbiol.* **49**: 42-45, cited by Tuomela, M., Vikman, M., Hatakka, A & Itavaara, M. (2000).

Nguyen, M. L. & Tanner, C. C. (1998): Ammonium removal from wastewaters using natural New Zealand zeolites. *New Zealand Journal of Agricultural Research* 41.pp.427-446.

Nguyen (1996): Tertiary treatment options for dairymshed and piggery wastewaters. edited by Mason, I. G. (1996). *Proceedings of a seminar held at Massey University*, Palmerston North, New Zealand

Nishida, T., Shimizu, N., Ishida, M., Onoue, T. & Harashima, N.(1998): Effect of Cattle Digestion and of Composting Heat on Weed Seeds. *JARQ* **32**: 55-60.

Pare, T., Dinel, H., Schnitzer, M & Dumontet, S. (1997): Transformations of carbon and nitrogen during composting of animal manure and shredded paper. *Biology and fertility of soils* **26** (3): 173-178.

Patni, N. K. & Kinsman, R. G. (1997): Composting of dilute manure slurries to reduce bulk by water evaporation. *An ASAE Annual International Meeting Presentation.Paper No. 974115*.

Pelczar, M. J., Chan, E. C. S. & Krieg, N. R. (1993): Microbiology concepts and applications. McGraw-Hill, Inc. New York, USA.

- Rae, A. N., Wilson, W. A. & Schroder, W. R. (1985): Dairy development, trade and policy issues, within the pacific basin. *Agricultural policy paper No.11*. Centre for Agricultural Policy Studies, Massey University, New Zealand.
- Regan, R., Jeris, J. S., Gasser, R., McCann, K. & Hudek, J. (1973): Cellulose Degradation in Composting. USEPA Ecological Research Series- EPA-R3-73-029/NTIS PB-215 722. pp. 142, cited by Richard, T. L. & Choi, H. L.(1996).
- Richard, T. L. (1998): Composting strategies for high moisture manures. *Biocycle* **39** (6): 46.
- Richard, T. L. & Choi, H. L. (1997): Optimizing the composting process for moisture removal. *Korean Journal of Animal Science*. **39** (4): 446-456.
- Richard, T. L. & Choi, H. L.(1996): Optimizing the composting process for moisture removal: Theoretical analysis and experimental results. *An ASAE Annual International Meeting Presentation Paper No. 964014*.
- Rippon, J. W. (1974): Medical Mycology. The Pathogenic Fungi and The Pathogenic Actinomycetes, cited by Epstein, E. (1994): Composting and bioaerosols. *Biocycle* **35** (1): 51-58.
- Roygard, J. K. F. (1999): Land treatment of dairy-farm effluent using short rotation forestry. PhD Thesis. Massey University, Palmerston North, New Zealand.
- Rylander, R., Lundholm, M. & Clark, C. S. (1983): Exposure to aerosol of micro-organisms and toxin during handling of sewage sludge. In: Biological Health Risk of Sludge Disposal to Land in Cold Climates. Wallis, P. M. and Lehemann, D. L. (ed.). Calgary, Alberta. University of Calgary Press. pp. 69-78, cited by Epstein, E. (1994).
- Rynk, R. (1992): On- Farm Composting Handbook. *Northeast Regional Agricultural Engineering Services*. Ithaca, N.Y. USA.
- Sartaj, M., Fernandes, L.& Patni, N. K. (1997): Performance of forced, passive, and natural aeration methods for composting manure slurries. *Transactions of the American Society of Agricultural Engineers* **40** (2): 457-463.
- Schroder, H. (1985): Nitrogen Losses from Danish agriculture- trends and consequences. *Agric. Ecosyst. & Environ.* **14**: 279-289, cited by Mathur, S. P., Patni, N. K. & Levesque, M. P. (1990).
- Schulze, K. L. (1961): Relationship between moisture content and activity of finished compost. *Compost Sci.* **2** (2): 32-34, cited by Hong, J. H., Matsuda, J. & Ikeuchi, Y. (1983).
- Seekins, B. (1999): Troubleshooting the compost pile. *Biocycle* **40**(12): 58-59.
- Senn, C. L. (1971): Dairy Waste Management Project- Final Report. University of California Agricultural Extension Service, Public Health Foundation of Los Angeles County, cited by Haug, R.T.(1993).



- Sesay, A. A., Lasarid, K., Stentiford, E. & Budd, T. (1997): Controlled composting of paper pulp sludge using the aerated static pile method. *Compost Science & Utilization* **5** (1): 82-96.
- Silva, R. G., Cameron, K. C., Di, H. J. & Hendry, T. (1999): A Lysimeter study of the impact of cow urine, dairy shed effluent, and nitrogen fertiliser on leaching. *Australian Journal of Soil Research* **37**: 357-369, cited by Roygard, J. K. F. (1999).
- Spoehr, H. A. & Milner, H. W. (1949): The Chemical Composition of *Chlorella*; Effect of Environmental Conditions. *Plant Physiol.* **24**: 120, cited by Haug, R.T.(1993).
- Standard Methods for the Examination of Water and Wastewater, 19<sup>th</sup> Edition (1995), (Ed.) Lenore S. Clesceri, Arnold E. Greenberg and Andrew D. Eaton.
- Statistics New Zealand (1999-2000): Agricultural Production Survey for the year ended 30 June 1999, New Zealand.
- Stern, G. (1974): Pasteurization of Liquid Digested Sludge. In *Proceedings of the National Conference on Municipal Sludge Management*, cited by Haug, R.T.(1993).
- Stoecker, W. F. & Jones, J. W. (1982): Refrigeration and Air Conditioning. Second edition. McGraw-Hill, Inc. New York. USA.
- Strom, P. F. (1985): Effect of temperature on bacterial species diversity in thermophilic solid-waste composting. *Appl. Environ. Microbiol.* **50**: 899-905, cited by Tuomela, M., Vikman, M., Hatakka, A & Itavaara, M. (2000).
- Sukius, J. P. S., Davies-Colley, R. J. & Tanner, C. C. (1996): Pond upgrading options, NIWA, Hamilton, New Zealand edited by Mason, I.G. (1996): Tertiary treatment options for dairymed and piggery wastewaters. *Proceedings of a seminar held at Massey University*, Palmerston North, New Zealand.
- Tanner, C. C., Clayton, J. S. & Upsdell, M. P. (1995a): Effect of loading rate and planting on treatment of dairy farm wastewater in constructed wetlands-I. Removal of oxygen demand, suspended solids and faecal coliforms, *Water Research* **29** (1): 17-26
- Tanner, C. C., Clayton, J. S. & Upsdell, M. P. (1995b): Effect of loading rate and planting on treatment of dairy farm wastewater in constructed wetlands-II. Removal of nitrogen and phosphorus, *Water Research* **29** (1): 27-34
- Tanner, C. C., Sukias, J. P. S. & Upsdell, M. P. (1998): Relationships between loading rates and pollutant removal during maturation of gravel-bed constructed wetlands. *Journal of Environmental Quality* **27** (2): 448-458.
- Taranaki Regional Council (2000): Farm Dairy Discharges Standard Operating Procedures for Consent Processing and Compliance Monitoring. Taranaki Regional Council, New Zealand.
- Taranaki Regional Council (1995): Discharges to land and water strategy background report. Strategy for the management of dairymed effluent. *Taranaki Regional Council*, New Zealand.

- Tiquia, S. M., Wan Judy, H. C. & Tam Nora, F. Y. (2001): Extracellular enzyme profiles during co-composting of poultry manure and yard trimmings. *Process Biochemistry* **36**: 813-820.
- Tuomela, M., Vikman, M., Hatakka, A & Itavaara, M. (2000): Biodegradation of lignin in a compost environment: a review. *Bioresource Technology* **72**: 169-183.
- USEPA (1989): Control of pathogens in Municipal Wastewater Sludge for Land Application. Center for Environmental Research Information. Cincinnati, OH 45268. Environmental regulations and technology. EPA/625/10-89/006.pp.71, cited by Lau, A.K., Lo, K.V., Liao, P.H. & Yu, J.C. (1992).
- Vanderholm, D. H. (1984): Agricultural waste manual. NZAEI, Lincoln, New Zealand.
- Van Horn, H. H., Wilkie, A. C., Powers, W. J. & Nordstedt, R. A. (1994): Components of Dairy Manure Management Systems. *Journal of Dairy Science* **77** (7): 2009-2028.
- Vogtmann, H. & Besson, J. M. (1978): European composting methods: treatment and use of farm yard manure and slurry. *Compost Sci.* Jan.-Feb: 15-19, cited by Mathur, S. P., Patni, N. K. & Levesque, M. P. (1990).
- Voorburg, J. H. (1980): Pig production and environment. Institute of Agricultural Engineering, Wageningen, The Netherlands, Xnr 11890, pp. 14, cited by Mathur, S.P., Patni, N.K. & Levesque, M.P. (1990).
- Vuorinen, A. H. & Saharinen, M. H. (1997): Evolution of microbiological and chemical parameters during manure and straw co-composting in a drum composting system. *Agriculture, Ecosystems and Environment* **66**: 19-29.
- Walker, L. P., Nock, T. D., Gossett, J. M. & VanderGheynst, J. S. (1999): The role of periodic agitation and water addition in managing moisture limitations during high-solids aerobic decomposition. *Process Biochemistry* **34**: 601-612.
- Willson, G. B. & Hummel, J. W. (1972): Aeration rates for rapid composting dairy manure. Proceedings of the 1972 Cornell Agricultural Waste Management Conference. Cornell University, Ithaca, New York, USA. pp. 145-158 cited by Emerton, B. L., Mote, C. R., Dowlen, H. H., Allison, J. S. & Sanders, W. L. (1988).
- Wilson, G. B. (1971): Composting dairy cow wastes. In Livestock Waste Management & Pollution Abatement. *Proceedings of an International Symposium on Livestock wastes*. ASAE Publication PROC-271. ASAE, St Joseph, Michigan, USA, cited by Mason, I. G. & Reijnen, B. P. A. (1999).
- Witter, E. & Lopez-Real, J. M. (1987): The potential of sewage sludge and composting in a nitrogen recycling strategy for agriculture. *Biol. Agric. & Hort.* **5**: 1-23, cited by Mathur,S.P., Patni,N.K. & Levesque,M.P.(1990).

## APPENDICES

All the raw data obtained from Experiments I and II are presented in the subsequent sections as follows:

- (A) Amount of materials
- (B) Temperature data obtained from manual thermometer and data logger<sup>1</sup>.
- (C) Moisture content & Volatile solids content
- (D) Bulk density
- (E) Carbon & Nitrogen analysis
- (F) Gross energy content analysis
- (G) Total Coliform counts
- (H) Particle size distribution
- (I) Mass & Energy balance analysis<sup>2</sup> and
- (J) Graphs used for calculation of the areas under time-temperature curves (obtained from manual temperature probe) at regions above 55°C.

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<sup>1</sup> The temperature data at five minutes interval for both the experiments obtained from data logger are given in the floppy disks provided at the end of appendices.

<sup>2</sup> The detail calculations for mass and energy balance analysis for each pile in both the experiments were done in Microsoft Excel spread sheet which can be seen in the floppy disk provided at the end of appendices.

## APPENDIX A

### AMOUNT OF MATERIALS

Table A1(Exp.-I) Amount of different raw materials used in Experiment-I.

<b>Experiment- I</b>											
<b>Pile-1</b>						<b>Pile-2</b>					
Materials	Weight	Unit	Date	Buckets	Volume	Materials	Weight	Unit	Date	Buckets	Volume
Manure =	104.0048	kg.	8/5/01	5	100 L	Manure =	65.378	kg.	9/5/01	3	60 L
Manure =	65.245	kg.	10/5/01	3	60 L	Manure =	108.484	kg.	11/5/01	5	100 L
Manure =	105.137	kg.	15/5/01	5	100 L	Manure =	192.708	kg.	16/5/01	9	180 L
Manure =	128.341	kg.	18/5/01	6	120 L	Manure =	42.873	kg.	18/5/01	2	40 L
Manure =	106.53	kg.	22/5/01	5	100 L	Manure =	107.359	kg.	22/5/01	5	100 L
Total =	509.2578	kg.		24	480 L	Total =	516.802	kg.		24	480 L
Sawdust=	36.15845	kg.	8/5/01	5	100 L	sawdust=	21.69507	kg.	9/5/01	3	60 L
Sawdust=	21.69507	kg.	10/5/01	3	60 L	sawdust=	36.15845	kg.	11/5/01	5	100 L
Sawdust=	36.15845	kg.	15/5/01	5	100 L	sawdust=	65.08521	kg.	16/5/01	9	180 L
Sawdust=	43.39014	kg.	18/5/01	6	120 L	sawdust=	14.46338	kg.	18/5/01	2	40 L
Sawdust=	36.15845	kg.	22/5/01	5	100 L	sawdust=	36.15845	kg.	22/5/01	5	100 L
Total =	173.5606	kg.		24	480 L	Total =	173.5606	kg.		24	480 L
Woodchip	53.37238	kg.	8/5/01	10	200 L	Woodchip	32.02343	kg.	9/5/01	6	120 L
Woodchip	32.02343	kg.	10/5/01	6	120 L	Woodchip	53.37238	kg.	11/5/01	10	200 L
Woodchip	53.37238	kg.	15/5/01	10	200 L	Woodchip	96.07028	kg.	16/5/01	18	360 L
Woodchip	64.04686	kg.	18/5/01	12	240 L	Woodchip	21.34895	kg.	18/5/01	4	80 L
Woodchip	53.37238	kg.	22/5/01	10	200 L	Woodchip	53.37238	kg.	22/5/01	10	200 L
Total =	256.1874	kg.		48	960 L	Total =	256.1874	kg.		48	960 L

Table A2 (Exp.-II) Amount of different raw materials used in Experiment-II.

Experiment- II											
Pile-1						Pile-2					
Materials	Weight	Unit	Date	Buckets	Volume	Materials	Weight	Unit	Date	Buckets	Volume
Manure =	153.64	kg.	11/9/01	7	140 L	Manure =	153.06	kg.	11/9/01	7	140 L
Manure =	140.32	kg.	12/9/01	7	140 L	Manure =	147.2	kg.	12/9/01	7	140 L
Manure =	149.88	kg.	13/09/01	7	140 L	Manure =	150	kg.	13/09/01	7	140 L
Manure =	130.18	kg.	14/09/01	6	120 L	Manure =	129.95	kg.	14/09/01	6	120 L
Total =	574.02	kg.		27	540 L	Total =	580.21	kg.		27	540 L
Off.paper=	14.56	kg.	11/9/01			Off.paper=	14.56	kg.	11/9/01		
Off.paper=	14.56	kg.	12/9/01			Off.paper=	14.56	kg.	12/9/01		
Off.paper=	14.56	kg.	13/09/01			Off.paper=	14.56	kg.	13/09/01		
Off.paper=	12.48	kg.	14/09/01			Off.paper=	12.48	kg.	14/09/01		
Total =	56.16	kg.				Total =	56.16	kg.			
N.paper=	4.83	kg.	11/9/01			N.paper=	4.83	kg.	11/9/01		
N.paper=	4.83	kg.	12/9/01			N.paper=	4.83	kg.	12/9/01		
N.paper=	4.83	kg.	13/09/01			N.paper=	4.83	kg.	13/09/01		
N.paper=	4.14	kg.	14/09/01			N.paper=	4.14	kg.	14/09/01		
Total =	18.63	kg.				Total =	18.63	kg.			
Woodchip	53.372	kg.	11/9/01	14	280 L	Woodchip	32.0234	kg.	11/9/01	14	280 L
Woodchip	32.023	kg.	12/9/01	14	280 L	Woodchip	53.3724	kg.	12/9/01	14	280 L
Woodchip	53.372	kg.	13/09/01	14	280 L	Woodchip	96.0703	kg.	13/09/01	14	280 L
Woodchip	64.047	kg.	14/09/01	12	240 L	Woodchip	21.349	kg.	14/09/01	12	240 L
Total =	256.19	kg.		48	960 L	Total =	256.187	kg.		48	960 L

# APPENDIX B

## TEMPERATURE

Table B1: Temperature recorded by manual temperature probe at 100mm inside from front edge at different levels in pile-1 and 2 under Experiment-I

Experiment-I									
Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
22/05/01	0	40.2	43.5	43.7	22.2	38.8	44.3	48.4	22
23/05/01	1	37.6	43.4	44.9	44	31.7	33.6	41.5	44.8
24/05/01	2	40.5	47.6	51.3	54.4	38.1	39.2	47.1	51.2
25/05/01	3	32.2	33.9	34.5	31.8	27.5	29.1	34.6	36.4
26/05/01	4	32.5	34.5	36.1	36.5	33.6	35.5	38.2	38.4
27/05/01	5	32.6	37.9	32.7	26.8	37.8	43.1	49.8	41.1
28/05/01	6	32.6	33.5	32.7	29.1	34.2	35.1	42.1	37.3
29/05/01	7	28.6	30.4	31.7	26.5	30.3	34	40	30.4
30/05/01	8	19.1	25.5	27.7	22.5	32.7	38.7	38.2	25.3
31/05/01	9	24	31.4	29.6	25.3	26.5	29.2	31.5	28.8
1/6/01	10	25.2	31.1	29.6	24.8	24.2	24.5	26.6	23.4
2/6/01	11	27.2	32.5	32	30.1	23.4	23.6	26.3	24.4
3/6/01	12	25.4	32.3	32.2	28.6	22.3	22.3	25.5	24
4/6/01	13	26.1	31.2	34.3	30.8	20.2	19.8	24.4	23.6
5/6/01	14	27.2	34.7	39.8	38.3	22.3	22	27	27
6/6/01	15	28.2	35.3	38.4	36.5	21.4	23.2	27.2	27.4
7/6/01	16	25	38.2	40.9	39.5	19	20.1	27.4	27.4
8/6/01	17	26.4	34.4	35	31.1	21.7	27.3	34.5	32.9
9/6/01	18	31.2	40.2	43.8	40.5	17.6	21.3	29.4	27.7
10/6/01	19	28	35.1	35.3	23.8	21.3	31.6	43.9	25
11/6/01	20	25.7	31.4	33.6	31.6	22	25.6	35.1	30.2
12/6/01	21	21.2	28.6	30.4	28	17.1	19.7	27.8	27.6
13/6/01	22	20	27.3	27.9	22.5	17.1	19.4	22.4	21.1
14/6/01	23	16.8	23.9	26.1	22.9	16.7	17.4	20.2	20
15/6/01	24	19.3	26.6	28.6	25.1	18.5	20	24.2	24.4
16/6/01	25	20.5	25.9	28.3	24.5	18	21.9	26.7	26.6
17/6/01	26	20.7	28.3	29	25.8	18.9	22.1	27	26.8
18/6/01	27	24.2	31.3	33.8	31	24.7	30.9	37.5	36.4
19/6/01	28	22.3	31.7	34.3	31.8	22	26.2	33.4	34.2
20/6/01	29	23.9	31.3	33.1	30.4	18.8	22	29.7	31
21/6/01	30	27.3	33.6	37.6	31.9	18.2	21.7	26	29.6
22/6/01	31	29	35.8	39.5	36.1	21.3	23	27	27.6
23/6/01	32	23.3	27.8	31.2	24.1	15.8	20.2	23.1	25.4
24/6/01	33	29.6	35.2	38.8	34.4	19.1	23.7	25.5	28.4
25/6/01	34	28.4	33.5	36.6	33	21.4	26.5	31.1	32.1
26/6/01	35	25.5	34.3	35.9	31.1	19.1	23.4	26.8	28.2
27/6/01	36	30.7	36.1	39.5	34.7	21.8	25.1	30.1	31.7
28/6/01	37	24	29.7	32.5	26.5	23.6	28.8	36.5	30.3
29/6/01	38	22	31.1	34	28.2	20.5	27.3	31.8	29.9

**Table B1 Continued.**

Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
30/6/01	39	21.3	29.5	29.7	24.8	22.8	24.6	26.1	26.3
1/7/01	40	20.5	28.6	30.5	26.3	19.8	21.5	24.5	23.3
2/7/01	41	17.3	21.6	20.7	17.1	19.2	20.4	20.6	16.3
3/7/01	42	17.8	24.6	24.8	20.6	22.4	20.7	20	19.5
4/7/01	43								
5/7/01	44	13.8	14.7	12.1	11.2	12.2	12.4	12.1	10.6
6/7/01	45								
7/7/01	46	12.2	14.4	12.8	11.7	11.6	11.8	11.6	11.6
8/7/01	47								
9/7/01	48	13	14.9	13.9	12.5	13.5	12.7	12	11.9
10/7/01	49								
11/7/01	50	12.6	13.1	13.3	12.7	12.5	12.2	11.8	11.6
12/7/01	51								
13/7/01	52	13.8	14	14.2	13.2	13.1	13.5	13.7	12.2
14/7/01	53								
15/7/01	54	13.5	13.6	13.4	13.8	13.9	13.6	13	13
16/7/01	55								
17/7/01	56	12.5	12.8	12.7	12.2	12.3	12.2	12	11.8
18/7/01	57								
19/7/01	58	12.4	12.5	12.4	11.9	12.3	12.2	12.1	11.9
20/7/01	59								
21/7/01	60	12.4	12.5	12.4	12	12.5	12.2	12.1	11.9
22/7/01	61								
23/7/01	62	12.3	12.4	12.3	12	12.4	12.2	12	11.9
24/7/01	63								
25/7/01	64	12.3	12.3	12.1	12	12.3	12.2	12	12
26/7/01	65								
27/7/01	66	13.2	13.1	13	12.8	13.1	12.9	12.7	12.5
28/7/01	67								
29/7/01	68	12.1	12	11.9	11.8	12.1	12	11.8	11.7
30/7/01	69	11.8	11.7	11.7	11.4	11.9	11.8	11.6	11.2

After 03/07/01 temperatures were recorded at 48 hours interval.

Table B2: Temperature recorded by manual temperature probe at 300mm inside from front edge at different levels in pile-1 and 2 under Experiment-I

Experiment-I									
Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
22/05/01	0	53.6	58.4	60.6	23.1	51.6	57.2	58.3	23.2
23/05/01	1	52.1	59.2	63	64.5	47.1	51.9	59	64.7
24/05/01	2	52.7	59.4	65.1	69.1	48.3	54.4	60.9	67
25/05/01	3	49.4	53.9	55.8	56.3	44.1	48.9	54.2	55.2
26/05/01	4	48.8	54.1	55	55.7	48.1	52.5	57.4	56.1
27/05/01	5	49.1	55.1	53.4	52.5	52.4	58.7	62.1	57.2
28/05/01	6	46.9	50.7	48.3	45.1	44.3	50.9	55	52.8
29/05/01	7	44.4	49.7	46.8	43.7	40.9	48.8	52.1	45.5
30/05/01	8	39.8	44.8	40	33.5	41.2	42.7	41.5	38.2
31/05/01	9	38.1	45.2	40.6	33.3	32.5	38.7	38.8	33.5
1/6/01	10	38.5	46.1	43.8	37.3	27.8	31.2	34.8	30.5
2/6/01	11	40.1	47.8	48	45.9	25.7	30.9	34.2	29.7
3/6/01	12	38.4	47.7	47.6	45.5	23.1	27.4	33	30.5
4/6/01	13	40	47.5	51.4	50.5	21.7	27.4	34.5	33
5/6/01	14	39.8	49.7	55.6	54	23.1	26.8	36.5	36.7
6/6/01	15	41.5	49.8	54.8	52.3	22.3	28.4	39	38.9
7/6/01	16	41.2	50.5	57.1	55.3	22.2	28.9	41.7	41.4
8/6/01	17	41.9	49.3	52.9	49.7	25.1	33	43.6	44.3
9/6/01	18	42.1	52.2	57.3	55.5	22.3	30	43.1	39.9
10/6/01	19	42.4	49.5	51.7	46.9	25.6	36.8	48.6	43.8
11/6/01	20	37.5	47.8	51.5	47.2	24.7	32.9	43.2	41.5
12/6/01	21	35.1	44.3	48.7	45.2	19	28	41.1	38.6
13/6/01	22	34.3	44	46.6	41.6	19.5	26.5	37.6	35.6
14/6/01	23	34.4	41.7	45.5	40.5	18.6	25.1	37	35.7
15/6/01	24	33.4	43.5	44.6	40.4	19.9	27.1	38.5	36.8
16/6/01	25	33.7	42.2	44.8	40.7	21.7	30.9	41.9	39.7
17/6/01	26	33.6	42.7	45.3	39.5	22.2	30.6	40.2	39.5
18/6/01	27	36.7	45.3	48.4	41.9	27.2	35.3	44	45.1
19/6/01	28	37.2	45.1	49.7	45.1	25.7	32.6	42.2	42.5
20/6/01	29	36.7	45.7	49.1	42.4	21.8	28.3	39.6	40.6
21/6/01	30	39.2	48.7	53	45.5	21.6	28.1	38.5	40.8
22/6/01	31	39.5	48.7	52.9	47	24.1	29.8	39.5	40.4
23/6/01	32	36.5	44.9	47.7	39.9	19.6	26.6	38.5	39.8
24/6/01	33	38.3	46.9	49.4	42.3	22.4	29.4	38.7	39.4
25/6/01	34	38.5	47	49.3	40.4	23.9	30.7	40.3	44.2
26/6/01	35	37.4	46.3	47.3	39.7	22.4	29.8	38.7	41.9
27/6/01	36	38.2	46.6	49.3	41.5	24.8	31.8	40.1	41.1
28/6/01	37	37	45.2	47.5	38.1	27.8	35.3	41.5	42.7
29/6/01	38	34	42.7	45.5	38.1	24.2	33.7	40.1	41.7
30/6/01	39	31.8	39.6	41.4	33	23.9	27.1	29.8	30.1
1/7/01	40	30.1	39.2	40.5	33.2	22.2	25.2	27.6	27.1
2/7/01	41	28.1	38.7	39.2	27.9	20.9	23.3	24.4	23.3
3/7/01	42	24.6	33.5	33.2	25.6	20.8	22	21.9	20.3



**Table B2 Continued**

Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
4/7/01	43								
5/7/01	44	19.5	23.3	20.1	14.5	12.8	13.9	13.1	12.1
6/7/01	45								
7/7/01	46	15.3	17.5	16.6	13.8	11.3	11.3	10.7	11.3
8/7/01	47								
9/7/01	48	14	15.3	14.8	13.3	13.4	12.7	12.4	11.8
10/7/01	49								
11/7/01	50	13.3	15.2	15	13.2	13	12.5	12.2	11.6
12/7/01	51								
13/7/01	52	15.6	16.1	16.6	14.8	13.2	12.6	12	11.6
14/7/01	53								
15/7/01	54	16.8	17	16.6	15.9	15	14.8	14.5	13.7
16/7/01	55								
17/7/01	56	12.1	11.9	11.3	11	11.7	11.3	10.8	10.6
18/7/01	57								
19/7/01	58	12.2	12.1	12	11.9	12	12.1	11.9	11.7
20/7/01	59								
21/7/01	60	12.6	12.9	12.6	12	12.3	12.2	11.8	11.5
22/7/01	61								
23/7/01	62	12.5	12.8	12.5	12	12.2	12.2	11.8	11.6
24/7/01	63								
25/7/01	64	12.4	12.7	12.3	11.9	12.2	12.1	11.8	11.7
26/7/01	65								
27/7/01	66	12.5	12.8	12.5	12.1	12.5	12.3	12	12
28/7/01	67								
29/7/01	68	12.3	12.4	12.1	12	12.6	12.4	11.9	11.8
30/7/01	69	12.3	12.5	12.2	12	12.4	12.2	11.3	11.2

After 03/07/01 temperatures were recorded at 48 hours interval.

Table B3: Temperature recorded by manual temperature probe at 600mm inside from front edge at different levels in pile-1 and 2 under Experiment-I.

Experiment-I									
Date	Day	Pile-2				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
22/05/01	0	58.2	66.3	67.9	25	57.1	62.1	64.1	24.8
23/05/01	1	56.5	64.8	71.3	69	55.9	59.8	65.7	62.4
24/05/01	2	54.8	64.1	71.3	72.6	56.4	61.9	66.8	73.7
25/05/01	3	54.7	62.4	68.6	68.4	56.8	61.2	65.5	71.9
26/05/01	4	54.7	63	67.9	68.8	57.5	61.9	65.6	68.7
27/05/01	5	54.4	63.8	67.1	65.3	58.1	61.8	64.6	67.9
28/05/01	6	54.1	63.5	65	63.9	53.6	56.5	58.6	57.5
29/05/01	7	53.8	61.6	64	63.7	50.1	52.7	55.6	55.6
30/05/01	8	50.5	59.7	62.1	60.2	42.7	38.8	39.1	48
31/05/01	9	50.4	56.2	59.5	57.6	38.2	39.4	40	38.3
1/6/01	10	51.1	57.5	60.1	57.3	35.1	38.1	38.9	36.7
2/6/01	11	51.1	57.2	61.2	58.2	32.7	37.1	41	37.8
3/6/01	12	50.3	57.7	61.3	59.2	29.5	35.4	42.6	42.1
4/6/01	13	50.4	57.5	61.6	59.4	28	35.2	45.3	47.5
5/6/01	14	48.7	57.9	63	59.7	27.9	35.6	49.4	51.8
6/6/01	15	50.4	58.4	62.5	58.5	27.2	38.1	52.5	54.7
7/6/01	16	51.8	59.6	62.7	59.5	26.4	40.5	54.3	55.3
8/6/01	17	50.6	58.2	62.1	57.9	26.3	39.7	50.7	53.4
9/6/01	18	49.6	57.7	60.8	58.3	28.1	41.9	52.3	50.2
10/6/01	19	49.5	56.5	58.6	54.2	29.1	43.7	53.4	53.1
11/6/01	20	47.4	57.2	59.5	54.4	28.6	40.3	48.6	48.6
12/6/01	21	46.3	55	58	53.4	25.8	39.7	49.6	47.5
13/6/01	22	45.6	55	57.3	54.5	25.2	39.1	51	50.2
14/6/01	23	47	53.6	56.7	52.7	25.2	38.2	50.3	50.6
15/6/01	24	45.7	55	56.9	51.2	26.9	39.8	51.1	51
16/6/01	25	46.5	53.5	56.4	51.7	27.9	42.6	51.5	52.2
17/6/01	26	48.4	54.6	56.7	51	28.7	41.4	51.2	50.8
18/6/01	27	50.2	56.7	58.7	51.9	30.8	41.4	49	49
19/6/01	28	54.3	60.4	61.5	56.1	32.2	42.1	51.5	49.2
20/6/01	29	50	57	58.1	51.6	28.5	38.8	48.3	47
21/6/01	30	51.1	56.2	57.3	52.8	29	39.5	50	48
22/6/01	31	53.1	58.3	59.9	54.1	29.4	40	50	49
23/6/01	32	48	54.7	56.2	49.3	34.3	44	48.2	48.5
24/6/01	33	50.8	57	55.5	47.3	29.9	39.5	49.8	49
25/6/01	34	50.2	55.9	56.7	47.8	31.9	40.5	51	50.8
26/6/01	35	48.1	53.7	56.3	46.6	29.4	39.2	49.3	48.9
27/6/01	36	47	54	53.5	45.5	30.2	38.7	49	49.5
28/6/01	37	48.3	53.8	53.9	44.9	32.2	38.8	48.1	49.6
29/6/01	38	46.3	54	55.1	46.6	31.3	37.8	47.1	47
30/6/01	39	44.9	52.7	53	43.7	25.9	27.9	32.2	34.1
1/7/01	40	44.7	51.9	53.1	42.7	25	25.8	30.5	30.2
2/7/01	41	43.2	50.6	51.1	41.5	23.2	21.5	27.2	28.6
3/7/01	42	40	48.2	49.2	39.9	20.9	21.2	22	23.5
4/7/01	43								
5/7/01	44	31.6	40	41.8	32.6	14.5	13.3	14.6	16.8

**Table B3 Continued**

Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
6/7/01	45								
7/7/01	46	25.4	30.6	33	26.5	11.2	10.3	11.2	12.2
8/7/01	47								
9/7/01	48	22.1	24.5	26.3	21.9	12.5	11.7	11.2	11.5
10/7/01	49								
11/7/01	50	18.4	22.3	23.2	17.3	12.4	11.8	11.2	11.4
12/7/01	51								
13/7/01	52	20.7	22.5	22.4	18.7	11.8	11.4	11.1	10.5
14/7/01	53								
15/7/01	54	20.6	20.6	20.4	18.2	12	11.8	12	12.6
16/7/01	55								
17/7/01	56	14.3	15.3	15.1	13.4	11.2	10.5	10.3	10.3
18/7/01	57								
19/7/01	58	14.5	15.1	14.1	13.1	11.7	11.8	11.4	11.3
20/7/01	59								
21/7/01	60	14.8	14.8	14.3	12.9	12.2	12.1	11.5	11.2
22/7/01	61								
23/7/01	62	13.1	14.3	14.5	13.7	12.6	12.3	12.7	11.3
24/7/01	63								
25/7/01	64	12.7	13.9	14.1	13.9	12.5	12.4	12.7	12.2
26/7/01	65								
27/7/01	66	12.9	13.5	13.7	13	12.7	12.4	12.5	11.6
28/7/01	67								
29/7/01	68	13.3	13.6	13.8	13.7	13.5	12.7	10.8	10.6
30/7/01	69	12.5	13	13.1	12.8	12.6	10.6	9.7	9.6

After 03/07/01 temperatures were recorded at 48 hours interval

Table B4: Temperature recorded by manual temperature probe at 100mm inside from front edge at different levels in pile-1 and 2 under Experiment-II.

Experiment-II									
Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
15/9/01	0	47.3	55	53	47.1	47.1	55.3	45.3	32.1
16/9/01	1	47.7	52.7	47	59.5	48	57.2	46.4	44.7
17/9/01	2	45.2	53.1	47.5	61.2	48.9	57.2	46.7	45.7
18/9/01	3	42.7	46	40.7	33.2	50.2	62.6	53.6	48.3
19/9/01	4	38.2	41.6	36.7	30.2	36.5	40.1	35.1	29.4
20/9/01	5	36.1	43.1	39.8	44.2	37.9	46.4	39	30.4
21/9/01	6	40.7	49.5	51.5	59.5	39.7	49.3	41.3	46.1
22/9/01	7	39.2	46.6	48.3	52.9	41.7	49.8	46.7	51.5
23/9/01	8	35.9	40.2	39.7	38.9	36.9	43.1	40.9	40.5
24/9/01	9	30.2	30.4	28.8	25.4	32.1	34.8	33.5	27.4
25/9/01	10	28.3	28.5	25.6	24.7	32	34.6	31.8	27.5
26/9/01	11	25.3	25.6	23.7	23.9	31.8	34.5	27.7	27.3
27/9/01	12	33.2	34.5	28.1	34.9	33.5	38.1	33.9	32.8
28/9/01	13	37.9	38	29.8	38.3	36.8	42.1	35.8	34.1
29/9/01	14	37.7	38.2	34.9	39	36.1	40.6	40.9	34
30/9/01	15	37.9	38.5	38.3	40.3	35.5	38.4	41.7	34.2
1/10/01	16	35.8	36.2	36.4	35.4	35.2	38.5	40.8	33.1
2/10/01	17	34.9	35	35.3	35	35	38.9	40.4	32.7
3/10/01	18	35.8	36.2	35.4	34.1	37.8	40.1	41.6	33.1
4/10/01	19	36.5	37.5	35.6	33.6	41	42.3	43.6	33.6
5/10/01	20	35.5	36.3	34	30.8	38.7	39.9	38.1	30.1
6/10/01	21	34.4	34.9	32.2	27.7	35.9	37.4	31.7	26.2
7/10/01	22	31.9	33	31.1	26.6	33.9	35.4	32	26.1
8/10/01	23	29.1	31.2	29.7	25.5	31.5	33.4	32.5	25.9
9/10/01	24	27.3	28.5	27.9	24.5	29.2	31.3	31.9	24.1
10/10/01	25	26.1	27.2	25.8	23.1	26.9	28.3	28.9	22.5
11/10/01	26	23.1	24.9	24.8	19.1	23.9	26.7	28.5	20.3
12/10/01	27	23.2	24.2	23.9	19	23.4	24.8	23.9	20.1
13/10/01	28	23.4	23.9	22.2	18.9	22.4	22.5	21.3	19.3
14/10/01	29	26.1	28.9	26.9	32.7	26.3	28.9	29.3	31.5
15/10/01	30	27.4	32.9	29.7	39.8	26.9	33.6	33.9	36.8
16/10/01	31	27.2	31.5	29.8	36.1	28.5	35.8	36.1	37.1
17/10/01	32	27.1	31.1	30	33.4	29.9	37.5	36.6	37.3
18/10/01	33	27	30.9	30.5	31.3	31.9	39.7	37.5	37.3
19/10/01	34	29.3	32.7	31.3	31.9	32.2	37.4	36	35.1
20/10/01	35	31.1	34.7	32.5	32.4	32.5	36.5	35.7	35.5
21/10/01	36	27.3	29.1	27.4	27.3	28.3	30.4	29.5	29.2
22/10/01	37	23.3	23.3	22.2	22	23.7	24.1	23.2	22.7
23/10/01	38	21.8	21.9	21.6	21.4	21.9	22.4	22.5	21.6
24/10/01	39	20.1	20.6	20.2	18.5	20.1	20.5	21.7	20.2
25/10/01	40	19.3	19.7	19.5	18.2	19.5	19.8	19.9	19.5
26/10/01	41	18.1	19.2	18.2	17.8	18.4	18.5	18.4	17.8
27/10/01	42	19.5	19.8	19.7	19.3	19.7	20.2	20.4	19.3
28/10/01	43	20.9	22.1	20.7	21.1	21	21.1	20.4	20
29/10/01	44	23.3	26	26.4	24.5	20.8	21.7	21.9	21

**Table B4 Continued**

Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
30/10/01	45	26	30.2	32.3	27.7	20.7	22.1	23	22.1
31/10/01	46	25.8	29.2	29.5	27.2	21.8	22.7	23.1	22.1
1/11/01	47	25.5	28.6	32.4	26.1	23.1	22.9	23.2	22
2/11/01	48	23.1	23.8	24.4	23.5	22.2	22.7	23	21.1
3/11/01	49	18	20.3	21.1	19.5	18.8	18.8	18.6	18
4/11/01	50	18.2	20.1	20.5	20	18.7	19.1	18.9	18.5
5/11/01	51	18.9	19.3	19.7	18.6	18.8	19.2	19.7	19.2
6/11/01	52	18.8	19.2	19.6	18.4	18.5	18.8	19.2	19
7/11/01	53	18.7	19.1	19.4	18.3	18.1	18.2	18.9	19
8/11/01	54	23	23.1	23.2	22.8	21.6	21.4	21.5	21.3
9/11/01	55	23.2	23.3	23.4	22.5	21.8	21.6	21.6	21.4
10/11/01	56	23.9	23.7	23.8	22.4	21.8	21.5	21.7	21.4
11/11/01	57	24.7	24.1	24	21.9	21.8	21.7	21.9	20.4
12/11/01	58	24.6	23.8	23.6	22	22.2	22.1	22	21.8
13/11/01	59	21.8	21.6	21.5	21.1	21.2	21.3	21.3	21.6
14/11/01	60	22.1	22.4	22.8	22.6	23.6	23.7	23.8	23.7
15/11/01	61	22	22.1	22.3	22.1	22.2	22.4	22.5	22.3
16/11/01	62	20.8	21	21	20.8	20.9	21.1	21.2	20.8
17/11/01	63	19.3	19.4	19.4	19.5	19.4	19.5	19.5	19.6
18/11/01	64	19.5	19.7	19.8	20.5	19.3	19.6	19.7	19.8
19/11/01	65	20.1	20.3	20.4	20.7	19.9	20.3	20.4	20.5
20/11/01	66	20.9	20.4	20.4	20	20.2	20.1	20.3	20
21/11/01	67	19.5	19.4	19.3	20.2	19.2	19.4	19.4	19.8
22/11/01	68	20.6	20.6	20.4	20.5	20.3	20.1	20.2	20.4
23/11/01	69	21.1	21.3	21.4	21.5	20.9	21.1	21.3	21.4
24/11/01	70	21.3	21.5	21.6	21.4	20.8	21.1	21.3	21.4
25/11/01	71	22.1	21.9	21.8	21.6	22	21.8	21.7	21.5
26/11/01	72	20.5	20.4	20.5	20.2	20.4	20.3	20.1	19.9

Table B5: Temperature recorded by manual temperature probe at 300mm inside from front edge at different levels in pile-1 and 2 under Experiment-II.

Experiment-II									
Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
15/9/01	0	67.3	72.6	72.4	69.7	66.3	73.6	72.1	63.4
16/9/01	1	68.3	71.7	73.2	73.2	67	72.6	74.2	69.2
17/9/01	2	69.4	71.5	72.6	72.7	67.5	71.9	73.9	67.1
18/9/01	3	60.1	62.9	61.9	56.3	62.2	68.2	71.4	67.7
19/9/01	4	57.9	59.1	58.1	52.6	57.5	58.2	55.5	39.9
20/9/01	5	58.5	63.3	65.2	63.9	60.1	63.4	64.6	53.7
21/9/01	6	61.6	67.6	69.3	62.9	63.4	67.2	69	64.3
22/9/01	7	62.6	66.1	66.3	62.6	64.3	67.8	68.9	65.5
23/9/01	8	53.6	56.3	56.1	52.7	57.2	59.5	58.8	53.2
24/9/01	9	42.6	46.1	45.2	37.5	48.2	49.8	46.1	38.4
25/9/01	10	44.8	47.3	48.1	44.2	50.8	53	52.4	44.5
26/9/01	11	45.8	48.1	50.3	48.8	51.8	55.8	56.3	49.3
27/9/01	12	49.2	56.1	54.8	54	55.2	57.6	59.9	54.7
28/9/01	13	56.3	60.5	59	58.1	58.7	59.9	57.5	56.9
29/9/01	14	55.8	59.7	59.3	56.2	55.9	56.7	55.6	53.8
30/9/01	15	55.2	59.4	60.9	54.3	54.4	53.4	54.6	49.7
1/10/01	16	53.1	54.3	58.1	52.9	53.8	53.1	53.5	48.9
2/10/01	17	50.1	53.9	54.8	49.4	53.2	52.6	52.3	47.5
3/10/01	18	49.6	51.9	52.3	47.5	53	52.6	52.3	46.3
4/10/01	19	49.1	49.8	50.8	45.1	52.9	52.5	52.3	45.2
5/10/01	20	45.9	46.7	46	40.9	50.3	48.4	44.9	40.7
6/10/01	21	42.6	43.3	40.9	36.1	47.2	44.6	38.3	35.9
7/10/01	22	42.7	43.8	42.2	34.9	45	44.7	39.7	35.1
8/10/01	23	43	44.7	43.9	33.8	44.4	44.6	41.8	34.3
9/10/01	24	42.2	45.1	42.9	30.1	40.1	40.3	37.8	30.5
10/10/01	25	41.5	45.9	41	27.9	34.6	36.8	34.3	27.8
11/10/01	26	40.5	47.4	40.5	23.5	31.5	34.5	33.9	23.9
12/10/01	27	35.9	42.8	32.8	23	25.9	26.5	27.2	21.8
13/10/01	28	31.9	38.2	26.6	22.1	23.3	30.2	28.4	20.9
14/10/01	29	41.1	45.3	45.5	43.9	38.2	47.6	49.3	42.8
15/10/01	30	47.3	52.1	52.6	51.9	45.7	54.7	56	49.2
16/10/01	31	46.4	51	51.2	48.1	47.2	55.2	56.4	49.4
17/10/01	32	45.9	50.8	50.6	45.8	48.8	55.9	57	49.6
18/10/01	33	45.6	50.4	49.2	44.5	50.3	56.7	57.2	49.8
19/10/01	34	45.6	49.7	49.4	44.1	49.8	54.9	55.2	46.8
20/10/01	35	45.6	49.1	49.9	43.8	49.2	53.8	52.8	44.4
21/10/01	36	38.9	41.1	39.3	35.2	44.1	48.2	45.1	38.3
22/10/01	37	31.9	32.8	27.7	23.5	37.7	40.8	36.8	31.5
23/10/01	38	31.7	32.6	38.2	23.3	35.9	38.2	34.9	28.8
24/10/01	39	30.9	32.4	28.7	23.2	34.1	35.4	32.8	26
25/10/01	40	30.4	32.4	28.6	24.9	28.9	30.5	28.6	24.5
26/10/01	41	29.8	32.5	28.3	26.4	23.5	25.4	24.3	22.1
27/10/01	42	31.4	34.5	30.2	28.2	22.3	23.7	22.8	22.1
28/10/01	43	32.4	36.3	31.7	29.8	21.2	22.2	21.4	21.2
29/10/01	44	35.2	39.4	36.1	32	22.4	24.4	24.8	22.9

**Table B5 Continued**

		Pile-1				Pile-2			
Date	Day	Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
30/10/01	45	37.9	42.2	40.7	33.7	23.4	26.2	27.8	24.7
31/10/01	46	36.8	40.8	39.2	32.4	22.9	25.5	27.6	25.2
1/11/01	47	36	39.7	37.6	31.3	22.4	25	27.5	25.8
2/11/01	48	32.3	36.3	35.1	30.1	21.6	23.6	25.4	24.4
3/11/01	49	28.9	33.1	32.3	28.6	20.8	22.3	23.2	23
4/11/01	50	25.1	27.2	26.8	23.9	18.9	20.2	20.8	20.1
5/11/01	51	20.3	19.6	18.2	18.9	17.2	17.9	18.2	18.7
6/11/01	52	19.4	19.3	18.7	19.1	17.1	17.4	17.9	18.2
7/11/01	53	18.5	18.7	19.4	19.5	17.2	17.5	17.8	17.9
8/11/01	54	21.2	21.3	21.3	21.5	18.8	19.1	19.2	19.5
9/11/01	55	21.4	21.5	21.4	21.7	19	19.2	19.8	20.8
10/11/01	56	22.2	22.4	22.3	22.1	19.6	19.8	20.2	20.8
11/11/01	57	22.9	23.2	23.1	22.5	20.4	20.6	20.6	20.9
12/11/01	58	22.8	23	22.9	22.8	20.6	20.9	20.9	21.3
13/11/01	59	22.7	22.8	22.6	22.4	20.8	20.9	21.2	21.6
14/11/01	60	22.9	23	22.7	22.3	21.1	21.4	21.8	22.5
15/11/01	61	22.4	22.8	22.5	22.1	21.2	21.5	21.6	22.2
16/11/01	62	21.1	21.3	21.4	20.6	20.8	21.2	21.4	21.6
17/11/01	63	20.5	19.9	19.2	19.5	20.5	20.4	19.4	19.9
18/11/01	64	20.3	20.4	20.5	20.1	20.3	20.1	19.8	20
19/11/01	65	20.1	19.8	19.9	19.8	19.9	20.1	19.9	19.8
20/11/01	66	19.4	19.3	19.1	19.1	19	19.3	19.4	19.5
21/11/01	67	19.6	19.5	19.6	18.9	19.4	19.3	19.2	19.3
22/11/01	68	19.5	19.7	19.6	18.7	19.5	19.6	19.5	19.3
23/11/01	69	19.6	19.4	19.5	18.2	19.5	19.4	19.5	19.1
24/11/01	70	19.7	18.7	18.2	17.5	19.1	19.4	19.2	18.7
25/11/01	71	19.5	18.3	17.1	16.9	18.6	18.7	18.5	18.2
26/11/01	72	19.4	18.3	17.2	17.1	18.7	18.9	18.6	18.1

Table B6: Temperature recorded by manual temperature probe at 600mm inside from front edge at different levels in pile-1 and 2 under Experiment-II.

Experiment-II									
Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
15/9/01	0	74.2	76.5	75.5	71.2	67.7	74.5	78.4	77.2
16/9/01	1	74.8	79	79.7	78.5	66.9	73.5	77.2	77.7
17/9/01	2	76.2	79.9	78.6	77.2	68.2	73.2	76.5	78
18/9/01	3	72	75.2	78.4	77.5	62	67.5	71.5	67.1
19/9/01	4	73.3	77.2	76.3	71.9	65.5	70.4	74.7	74.1
20/9/01	5	72.1	76.9	77	75	66.1	70.9	74.7	75.8
21/9/01	6	71.5	75.8	74.4	70.3	65.7	70.8	73.2	75
22/9/01	7	69.8	74.3	74.8	70.6	65.2	70.1	72.6	73.4
23/9/01	8	67.8	71.9	70.8	67.5	57.9	63.4	64.2	64
24/9/01	9	66.4	69.9	68.9	63.7	49.2	55.9	54.5	54.4
25/9/01	10	66.9	70	68.5	66.8	50.6	61	62.3	65.2
26/9/01	11	67.2	70.2	67.9	68.9	51.7	65.5	71.5	73.1
27/9/01	12	67	69.9	68.1	68.9	56.3	67.1	70.7	71.1
28/9/01	13	66.7	69.5	68.6	69.2	61	68.5	70.1	70.4
29/9/01	14	66.3	68.7	67.4	66.1	60.1	66.2	68.9	68.7
30/9/01	15	64.9	67.1	65.9	61.5	58.7	65.4	67.4	66.5
1/10/01	16	64.2	67	65.9	62.7	57.4	63.6	67.2	66
2/10/01	17	63.9	67.1	66.1	64.4	56.8	62.1	66.5	65.1
3/10/01	18	63	66.8	64.7	63.9	56.1	61.3	65.9	64.2
4/10/01	19	61.9	66.1	62.9	63.4	55.1	60.9	64.8	63.4
5/10/01	20	59.9	64.4	59.5	58.7	53.4	58.7	61.6	60.6
6/10/01	21	57.8	62.3	55.4	54.5	51.4	56.8	58.3	58.1
7/10/01	22	56.4	61.1	56.4	54.8	49.5	53.9	56.6	55.4
8/10/01	23	54.8	59.8	58.2	55	47.3	51.4	54.7	52.5
9/10/01	24	54.1	58.2	57.9	52.3	42.6	43.8	47.1	45.8
10/10/01	25	53.7	57.4	59.8	50.2	37.3	40.6	43.2	41.3
11/10/01	26	53.3	56.8	56.2	48	35.3	38.7	41.3	39.1
12/10/01	27	53.8	56.9	52.3	45.2	32.9	41.7	44.6	43.1
13/10/01	28	54.2	57.1	48.2	41.3	30.1	45.3	47.9	44.9
14/10/01	29	56.6	60.6	59.2	58.1	39.1	54.3	56.1	54.1
15/10/01	30	58.8	63.3	62.5	60.9	47.4	59.8	63.7	60.6
16/10/01	31	57.6	62.1	61.8	58.9	48.9	60.4	64.8	60.9
17/10/01	32	56.4	60.9	60.7	57.3	49.6	60.9	65.1	61.1
18/10/01	33	55	59.6	58.9	56.7	50	61.4	65.6	61.3
19/10/01	34	54.6	58.4	58	54.8	49.7	59.3	62.7	58.4
20/10/01	35	54	57.8	57.1	52.9	49.3	57.8	59.9	54.6
21/10/01	36	50.1	53.9	49.8	47.6	48	55.5	55.7	49.6
22/10/01	37	45.2	49.7	42	41.5	46.3	52.9	51.3	44.3
23/10/01	38	44.8	49.2	45.3	41.3	41.6	48.4	47.2	41.5
24/10/01	39	44.7	48.6	47.9	41.1	36.6	43.7	42.9	38.5
25/10/01	40	45.9	49.5	48.7	41.9	31.9	39	40.4	35.5
26/10/01	41	46.8	50.3	49.2	42.7	26.3	33.9	38.6	32.2
27/10/01	42	48.2	52.3	50.6	44.5	24.8	32.1	38.2	35.3
28/10/01	43	49.5	54.5	52.2	46.4	23.4	30.4	37.9	38.1
29/10/01	44	48.8	53.5	51.8	45.7	26.7	30.3	39.3	38.7



**Table B6 Continued**

Date	Day	Pile-1				Pile-2			
		Level-400	Level-600	Level-800	Level-1000	Level-400	Level-600	Level-800	Level-1000
30/10/01	45	48.4	52.7	51.6	44.9	23.8	30.4	40.5	39.5
31/10/01	46	48.1	52.4	50.8	44	23.4	29.3	39.1	38.9
1/11/01	47	47.7	52.3	50.3	42.9	22.7	27.9	37.8	38.3
2/11/01	48	45.7	51.3	49.9	41.7	21.8	26.1	34.2	35.8
3/11/01	49	43.8	50.3	49.4	40.6	21	24.1	30.6	33.2
4/11/01	50	40.8	49.3	47.1	39.9	19.7	22.4	26.6	29.1
5/11/01	51	37.4	47.7	44.3	39.5	18.1	20.6	22.2	25.1
6/11/01	52	28.1	32.3	29.7	26.2	17.2	17.9	18.3	19.1
7/11/01	53	18.4	19.1	19	17.8	16.2	15.1	14.5	14
8/11/01	54	22.1	24	23.8	22.3	17.8	17.3	17.3	17.5
9/11/01	55	22.5	24.3	24.2	22.8	17.9	17.5	17.4	17.8
10/11/01	56	23.7	25.5	25.4	23.7	18.8	18.5	18.6	19.2
11/11/01	57	25.1	27.1	26.5	24.5	19.6	19.5	19.8	20.5
12/11/01	58	25.5	27.6	26.9	24.6	19.9	20.2	20.4	20.8
13/11/01	59	25.6	27.8	27.1	24.5	20.2	20.9	21.1	21.6
14/11/01	60	26	28.5	27.6	24.7	21	21.7	22	22.1
15/11/01	61	25.8	28.2	26.9	24.1	21.1	21.9	21.9	22.2
16/11/01	62	24.3	27.2	25.3	23.7	20.9	21.8	21.8	22
17/11/01	63	23.3	26	24.8	23.4	20.8	21.6	22.1	21.9
18/11/01	64	23	25.1	24.2	22.8	20.7	21.5	21.9	21.8
19/11/01	65	22.2	23.3	23.8	22.1	20.1	20.5	20.7	20.2
20/11/01	66	21.1	22.1	21.9	21	18.6	18.8	19.6	20
21/11/01	67	21	21.6	21.7	20.8	19.1	19.3	19.2	19.8
22/11/01	68	20.8	20.9	20.9	20.5	19.3	19.5	19.6	20
23/11/01	69	20.9	21.1	21	20.1	18.2	18.8	18.6	19.2
24/11/01	70	20.6	20.8	20.2	19.5	18.8	18.9	18.9	18.4
25/11/01	71	20.8	20.1	18.1	18.4	19	18.5	18	18.2
26/11/01	72	20.4	19.8	19.5	19.8	18.8	18.6	18.5	18.1

## APPENDIX C

### MOISTURE CONTENT & VOLATILE SOLIDS CONTENT

Table C1: Moisture content (MC) and Volatile solids content (VS) of raw materials & raw compost (Pile-1, Experiment-I). Both MC and VS are in (w/w).

Experiment-I								
Pile-1								
Date	Materials	MC (%)	MC (%)	VS (%)	VS (%)	Average	Average	Remarks
		Sample-1	Sample-2	Sample-1	Sample-2	MC (%)	VS (%)	
8/5/01	Manure	88.47	-	74.98	-	88.47	74.98	
	Compost	61.12	64.94	95.54	92.94	63.03	94.24	
10/5/01	Manure	88.62	-	64.06	-	88.62	64.06	
	Compost	68.07	67.44	92.96	92.94	67.755	92.95	
15/5/01	Manure	91.52	91.18	62.76	62.5	91.35	62.63	
	Compost	69.22	66.62	91.61	92.41	67.92	92.01	
18/5/01	Manure	91.87	91.88	69.65	69.35	91.875	69.5	
	Compost	67.29	68.92	93.98	93.31	68.105	93.645	
	Compost	64.84	70.03	94.94	92.4	67.435	93.67	
22/5/01	Manure	89.43	89.54	69.05	69.29	89.485	69.17	
	Compost	68.02	66.45	92.51	92.4	67.235	92.455	
8/5/01	Sawdust	61.98	61.26	99.55	99.62	61.62	99.585	
8/5/01	woodchip	20.4	20.8	98.01	98.42	20.6	98.215	

Table C2: Moisture content (w/w) distribution of materials during the period of composting. Samples were taken from the 600mm inside from front edge of pile at 300, 500, 700 and 900mm levels (Pile-1, Experiment-I).

Experiment-I									
Pile-1									
Dated	Day	Level-300	Level-300	Level-500	Level-500	Level-700	Level-700	Level-900	Level-900
1/6/01	10	50.36	0	56.84	0	60.02	0	63.6	0
8/6/01	17	48.22	0	57.36	0	64.27	0	59.5	0
15/6/01	24	48.56	48.64	52.81	51.82	54.79	53.68	62.01	63.41
22/6/01	31	47.24	47.35	52.55	53.38	50.86	47.21	60.74	59.95
29/6/01	38	42.81	46.53	59.31	57.29	54.43	54.46	60.59	60.68
6/7/01	45	37.8	41.31	51.56	50.66	46.33	46.52	51.34	51.73
13/7/01	52	36.95	40.22	52.59	52.33	46.53	47.24	53.29	50.48
20/7/01	59	41.87	38.27	46.98	45.72	49.64	48.67	52.09	51.8
27/7/01	66	43.64	40.25	46.91	46.1	48.14	46.74	54.98	54.54

Table C3: Moisture content (MC) and Volatile solids content (VS) of final compost (Pile-1, Experiment-I). Both MC and VS are in (w/w).

Experiment-I							
Pile-1							
Level*	Location	Test No	MC (%)	MC(av) (%)	VS (%)	VS(av) (%)	Sample No
370mm	600mm from front edge	1	48.3	48.23	92.76	92.97	4
		2	48.16		93.18		4
580mm	600mm from front edge	1	56.54	55.595	91.73	91.56	3
		2	54.65		91.39		3
775mm	600mm from front edge	1	60.81	61.335	91.96	92.035	2
		2	61.86		92.11		2
975mm	600mm from front edge	1	61.97	62.525	87.7	87.025	1
		2	63.08		86.35		1

\* The levels of thermocouple positions on the day of pile deconstruction.

Table C4: Moisture content (MC) and Volatile solids content (VS) of raw materials & raw compost (Pile-2, Experiment-I). Both MC and VS are in (w/w).

Experiment-I								
Pile-2								
Date	Material	MC (%)	MC (%)	VS (%)	VS (%)	Average	Average	Remarks
		Sample-1	Sample-2	Sample-1	Sample-2	MC (%)	VS (%)	
9/5/01	Manure	89.53	0	71.52	0	89.53	71.52	
	Compost	60.91	66.06	93.93	92.7	63.485	93.315	
11/5/01	Manure	89.32	89.16	62.38	61.86	89.24	62.12	
	Compost	67.73	66.65	90.02	91.82	67.19	90.92	
16/5/01	Manure	89.02	89.39	56.14	59.08	89.205	57.61	
	Compost	67.85	66.09	86.74	90.81	66.97	88.775	
18/5/01	Manure	91.87	91.88	69.65	69.35	91.875	69.5	
	Compost	67	67.88	92.77	92.53	67.44	92.65	
22/5/01	Manure	89.43	89.54	69.05	69.29	89.485	69.17	
	Compost	66.04	67.27	91.58	90.8	66.655	91.19	
8/5/01	sawdust	61.98	61.26	99.55	99.62	61.62	99.585	
8/5/01	Wood chip	20.4	20.8	98.01	98.42	20.6	98.215	

Table C5: Moisture content (w/w) distribution of materials during the period of composting. Samples were taken from the 600mm inside from front edge of pile at 300, 500, 700 and 900mm levels (Pile-2, Experiment-I).

Experiment-I									
Pile-2									
Dated	Day	Level-300	Level-300	Level-500	Level-500	Level-700	Level-700	Level-900	Level-900
1/6/01	10	52.63	0	51.94	0	51.8	0	63.22	0
8/6/01	17	50.48	0	53.25	0	54.97	0	61.46	0
15/6/01	24	51.18	52.57	49.23	49.37	56.91	60.83	63.25	65.54
22/6/01	31	45.75	45.9	55.03	55.09	57.44	56.58	60.19	58.87
29/6/01	38	44.27	44.6	49.01	49.97	52.58	50.39	55.98	55.1
6/7/01	45	38.56	42.13	47.85	46.75	50.39	49.54	54.34	54.45
13/7/01	52	41.8	44.72	50.8	49.77	50.33	53.96	54.33	55
20/7/01	59	43.74	40.92	51.82	49.85	49.55	49.48	55.3	53.15
27/7/01	66	43.43	44.65	47.45	48.26	54.29	51.17	54.67	55.66

Table C6: Moisture content (MC) and Volatile solids content (VS) of final compost (Pile-2, Experiment-I). Both MC and VS are in (w/w).

Experiment-I							
Pile-2							
Level*	Location	Test No	MC (%)	MC(av) (%)	VS (%)	VS(av) (%)	Sample No
380mm	600mm from front edge	1	55.3	55.28	91.52	90.77	8
		2	55.27		90.02		8
590mm	600mm from front edge	1	46.26	44.375	90.27	90.42	7
		2	42.49		90.57		7
790mm	600mm from front edge	1	51.49	51.865	91.59	90.56	6
		2	52.24		89.53		6
990mm	600mm from front edge	1	62.96	62.665	91.2	90.71	5
		2	62.37		90.22		5

\* The levels of thermocouple positions on the day of pile deconstruction.

Table C7: Moisture content (MC) and Volatile solids content (VS) of raw materials & raw compost (Pile-1, Experiment-II). Both MC and VS are in (w/w).

Experiment- II								
Pile-1								
Date	Name	MC (%)	MC (%)	VS (%)	VS (%)	Average	Average	Remarks
		Sample-1	Sample-2	Sample-1	Sample-2	MC (%)	VS (%)	
11/9/01	Manure	90.17	90.18	54.91	53.99	90.17	54.45	
12/9/01	Manure	88.59	88.49	53.34	52.73	88.54	53.03	
13/9/01	Manure	89.89	89.94	62.47	63.99	89.91	63.23	
14/9/01	Manure	90.52	90.49	64.4	65.28	90.5	64.84	
11/9/01	Compost	69.66	68.99	81.71	83.52	69.32	82.61	
12/9/01	Compost	69.47	68.59	84.48	84.31	69.03	84.39	
13/9/01	Compost	73.62	71.17	87.15	87.8	72.39	87.47	
14/9/01	Compost	73.14	71.31	85.5	86.75	72.22	86.12	
14/9/01	News.print	7.74	-	99.58	-	7.74	99.58	
14/9/01	Off. Paper	5.42	5.26	78.95	78.97	5.34	78.96	
14/9/01	Woodchip	47.31	47.96	98.39	98.29	47.63	98.34	

Table C8: Moisture content (w/w) distribution of materials during the period of composting. Samples were taken from the 100mm and 300mm inside from front edge of pile at 300, 500, 700 and 900mm levels (Pile-1, Experiment-II).

Experiment- II									
Pile-1									
Dated	Day	L-300(1)	L-300(3)	L-500(1)	L-500(3)	L-700(1)	L-700(3)	L-900(1)	L-900(3)
27/09/01	13	37.91	45.01	53.77	56.23	59.62	60.69	61.98	62.35
	20	40.27	44.36	49.33	58.12	50.88	61.28	56.25	63.38
	27	36.08	42.51	46.67	52.98	47.38	58.51	52.1	59.22

L-300(1) = 100mm inside from front edge at 300mm level; L-300(3) = 300mm inside from front edge at 300mm level.

Table C9: Moisture content (MC) and Volatile solids content (VS) of final compost (Pile-1, Experiment-II). Both MC and VS are in (w/w).

Experiment- II							
Pile-1							
Level*	Location	Test No	MC (%)	MC(av) (%)	VS (%)	VS(av) (%)	Sample No.
335mm	600mm from front edge	1	37.43	36.945	80.98	79.825	4
		2	36.46		78.67		4
480mm	600mm from front edge	1	49.12	48.785	89.34	88.865	3
		2	48.45		88.39		3
675mm	600mm from front edge	1	53.82	54.86	69.02	72.64	2
		2	55.9		76.26		2
800mm	600mm from front edge	1	54.65	55.515	85.59	81.88	1
		2	56.38		78.18		1

\*The levels of thermocouple positions on the day of pile deconstruction.

Table C10: Moisture content (MC) and Volatile solids content (VS) of raw materials & raw compost (Pile-2, Experiment-II). Both MC and VS are in (w/w).

Experiment- II								
Pile-2								
Date	Name	MC (%)	MC (%)	VS (%)	VS (%)	Average	Average	Remarks
		Sample-1	Sample-2	Sample-1	Sample-2	MC (%)	VS (%)	
11/9/01	Manure	90.17	90.18	54.91	53.99	90.17	54.45	
12/9/01	Manure	88.59	88.49	53.34	52.73	88.54	53.03	
13/9/01	Manure	89.89	89.94	62.47	63.99	89.91	63.23	
14/9/01	Manure	90.52	90.49	64.4	65.28	90.5	64.84	
11/9/01	Compost	66.05	67.28	88.04	88.65	66.66	88.34	
12/9/01	Compost	70.58	69.87	84.83	84.83	70.22	84.83	
13/9/01	Compost	70.72	67.41	85.54	83.5	69.06	84.52	
14/9/01	Compost	71.97	71.62	83.32	87.85	71.79	85.58	
14/9/01	News.print	7.74		99.58		7.74	99.58	
14/9/01	Off. Paper	5.42	5.26	78.95	78.97	5.34	78.96	
14/9/01	Woodchip	47.31	47.96	98.39	98.29	47.63	98.34	

Table C11: Moisture content (w/w) distribution of materials during the period of composting. Samples were taken from the 100mm and 300mm inside from front edge of pile at 300, 500, 700 and 900mm levels (Pile-2, Experiment-II).

<b>Experiment- II</b>									
<b>Pile-2</b>									
Dated	Day	L-300(1)	L-300(3)	L-500(1)	L-500(3)	L-700(1)	L-700(3)	L-900(1)	L-900(3)
27/9/01	13	47.38	51.8	58.44	63.09	60.46	61.58	54.72	68.29
	20	47.94	50.56	50.72	62.19	58.23	60.25	52.98	66.55
	27	44.61	48.55	47.33	61.01	49.02	57.31	51.86	65.4

L-300(1) = 100mm inside from front edge at 300mm level; L-300(3) = 300mm inside from front edge at 300mm level.

Table C12: Moisture content (MC) and Volatile solids content (VS) of final compost (Pile-2, Experiment-II). Both MC and VS are in (w/w).

<b>Experiment- II</b>							
<b>Pile-2</b>							
Level*	Location	Test No	MC (%)	MC(av) (%)	VS (%)	VS(av) %	Sample No.
340mm	600mm from front edge	1	25.5	25.34	80.23	81.165	8
		2	25.18		82.1		8
480mm	600mm from front edge	1	37	36.16	85.11	83.345	7
		2	35.32		81.58		7
700mm	600mm from front edge	1	50.03	50.465	87.06	86.835	6
		2	50.9		86.61		6
830mm	600mm from front edge	1	63.67	62.725	79.99	79.18	5
		2	61.78		78.37		5

\* The levels of thermocouple positions on the day of pile deconstruction.

## APPENDIX D

### BULK DENSITY

Table D1: Bulk Density of Raw Compost. Samples were taken from 1150mm level. (Pile-1, Experiment-I).

Experiment-I									
Pile-1									
Sample	Sample's Level	Wet weight in gm	Dry weight in gm	Cont. weight in gm	Dry bulk density in Mg/m <sup>3</sup>	Moisture Content in %	Wet bulk density in Mg/m <sup>3</sup>	Dry bulk density (av) in Mg/m <sup>3</sup>	Wet bulk density (av) in Mg/m <sup>3</sup>
1	1150mm	517.59	252.95	109.66	0.246	64.8738	0.7	0.216	0.638
2	1150mm	439.27	204.54	81.72	0.211	65.6495	0.614		
3	1150mm	389.55	195.03	80.18	0.197	62.8761	0.53		
4	1150mm	452.99	195.29	71.67	0.212	67.581	0.654		
5	1150mm	481.52	200.74	76.23	0.214	69.2787	0.696		

Table D2: Bulk Density of Raw Compost. Samples were taken from 1150mm level.(Pile-2, Experiment-I).

Experiment-I									
Pile-2									
Sample	Sample's Level	Wet weight in gm	Dry weight in gm	Cont. weight in gm	Dry bulk density in Mg/m <sup>3</sup>	Moisture Content in %	Wet bulk density in Mg/m <sup>3</sup>	Dry bulk density (av) in Mg/m <sup>3</sup>	Wet bulk density (av) in Mg/m <sup>3</sup>
1	1150mm	470.14	216.07	80.37	0.233	65.1845	0.669	0.215	0.624
2	1150mm	444.6	228.1	112.72	0.198	65.2344	0.569		
3	1150mm	435.36	235.03	112.98	0.209	62.1409	0.551		
4	1150mm	451.23	227.09	113.13	0.195	66.2939	0.578		
5	1150mm	554.22	255.23	115.51	0.24	68.152	0.753		

Table D3: Bulk Density of Final Compost. Samples were taken at different levels on the day of pile deconstruction. (Pile-1, Experiment-I).

Experiment-I									
Pile-1									
Sample	Sample's Level	Wet weight in gm	Dry weight in gm	Cont. weight in gm	Dry bulk density in Mg/m <sup>3</sup>	Moisture Content in %	Wet bulk density in Mg/m <sup>3</sup>	Dry bulk density (av) in Mg/m <sup>3</sup>	Wet bulk density (av) in Mg/m <sup>3</sup>
1	975mm	336.83	177.58	78.88	0.169	61.7367	0.4416	0.17175	0.420433
2	975mm	375.73	224.85	115.81	0.187	58.0486	0.4457		
3	975mm	315.87	184.56	81.91	0.176	56.1249	0.4011		
4	775mm	343.12	179.21	80.39	0.17	62.3872	0.4519		
5	775mm	373.72	210.39	113.17	0.167	62.6866	0.4475		
6	775mm	333.49	175.46	75.68	0.171	61.297	0.4418		
7	580mm	315.61	180.93	79.95	0.173	57.1501	0.4037		
8	580mm	313.6	180.4	80.61	0.171	57.1698	0.3992		
9	580mm	295.14	178.95	76.4	0.176	53.1178	0.3754		
10	370mm	295.71	172.71	81.63	0.156	57.4551	0.3666		
11	370mm	364.7	179.03	80.52	0.169	65.3353	0.4875		
12	370mm	336.57	215.63	112.91	0.176	54.0731	0.3832		

Table D4: Bulk Density of Final Compost. Samples were taken at different levels on the day of pile deconstruction. (Pile-2, Experiment-I).

Experiment-I									
Pile-2									
Sample	Sample's Level	Wet weight in gm	Dry weight in gm	Cont. weight in gm	Dry bulk density in Mg/m <sup>3</sup>	Moisture Content in %	Wet bulk density in Mg/m <sup>3</sup>	Dry bulk density (av) in Mg/m <sup>3</sup>	Wet bulk density (av) in Mg/m <sup>3</sup>
1	990mm	370.78	187.01	71.85	0.198	61.4759	0.5139	0.192916	0.464416
2	990mm	421.36	226.82	113.15	0.195	63.1193	0.5287		
3	990mm	430.54	226.82	113.31	0.195	64.2183	0.5449		
4	790mm	363.16	225.48	114.23	0.191	55.3087	0.4273		
5	790mm	353.88	222.29	115.7	0.183	55.2481	0.4089		
6	790mm	340.11	192.01	78.06	0.195	56.5159	0.4484		
7	590mm	387.39	224.76	109.87	0.197	58.6011	0.4758		
8	590mm	340.21	191.07	80.53	0.19	57.4322	0.4463		
9	590mm	326.14	190.81	78.93	0.192	54.7429	0.4242		
10	380mm	315.4	201.18	95.7	0.181	51.989	0.3769		
11	380mm	655.02	429.88	302.13	0.219	63.7989	0.6049		
12	380mm	488.28	375.28	270.94	0.179	51.9922	0.3728		



Table D5: Bulk Density of Raw Compost. Samples were taken from 1150mm level.(Pile-1, Experiment-II).

<b>Experiment- II</b>									
<b>Pile-1</b>									
Sample	Sample's Level	Wet weight in gm	Dry weight in gm	Cont. weight in gm	Dry bulk density in Mg/m <sup>3</sup>	Moisture Content in %	Wet bulk density in Mg/m <sup>3</sup>	Dry bulk density (av) in Mg/m <sup>3</sup>	Wet bulk density (av) in Mg/m <sup>3</sup>
1	1150mm	436.98	183.22	78.92	0.179	70.87	0.614	0.180	0.593
2	1150mm	446.40	215.73	115.79	0.171	69.77	0.567		
3	1150mm	468.23	196.38	81.96	0.196	70.37	0.663		
4	1150mm	407.57	183.11	80.41	0.176	68.6	0.561		
5	1150mm	439.91	217.50	113.17	0.179	68.06	0.56		

Table D6: Bulk Density of Raw Compost. Samples were taken from 1150mm level.(Pile-2, Experiment-II).

<b>Experiment- II</b>									
<b>Pile-2</b>									
Sample	Sample's Level	Wet weight in gm	Dry weight in gm	Cont. weight in gm	Dry bulk density in Mg/m <sup>3</sup>	Moisture Content in %	Wet bulk density in Mg/m <sup>3</sup>	Dry bulk density (av) in Mg/m <sup>3</sup>	Wet bulk density (av) in Mg/m <sup>3</sup>
1	1150mm	430.67	185.11	76.40	0.186	69.31	0.608	0.186	0.623
2	1150mm	447.09	187.50	80.56	0.183	70.82	0.629		
3	1150mm	441.49	181.15	71.88	0.187	70.43	0.634		
4	1150mm	480.32	223.96	113.33	0.190	69.85	0.629		
5	1150mm	474.58	223.40	115.72	0.185	69.99	0.615		

Table D7: Bulk Density of Final Compost. Samples were taken at different levels on the day of pile deconstruction. (Pile-1, Experiment-II).

<b>Experiment- II</b>									
<b>Pile-1</b>									
Sample	Sample's Level	Wet weight in gm	Dry weight in gm	Cont. weight in gm	Dry bulk density in Mg/m <sup>3</sup>	Moisture Content in %	Wet bulk density in Mg/m <sup>3</sup>	Dry bulk density (av) in Mg/m <sup>3</sup>	Wet bulk density (av) in Mg/m <sup>3</sup>
1	875mm	273.31	191.21	112.17	0.136	50.95	0.276	0.160	0.307917
2	875mm	301.90	154.23	77.12	0.132	65.69	0.386		
3	875mm	209.40	154.04	74.45	0.137	41.02	0.231		
4	675mm	285.37	203.69	111.73	0.158	47.03	0.298		
5	675mm	253.22	168.63	77.36	0.157	48.1	0.301		
6	675mm	247.53	172.13	74.89	0.167	43.67	0.296		
7	480mm	228.94	180.09	81.70	0.169	33.17	0.252		
8	480mm	267.44	210.77	110.16	0.173	36.03	0.27		
9	480mm	213.39	163.72	73.52	0.155	35.51	0.24		
10	335mm	287.11	217.50	113.75	0.178	40.15	0.297		
11	335mm	392.38	188.94	79.10	0.188	64.93	0.537		
12	335mm	259.76	179.78	78.45	0.174	44.11	0.311		

Table D8: Bulk Density of Final Compost. Samples were taken at different levels on the day of pile deconstruction. (Pile-2, Experiment-II).

<b>Experiment- II</b>									
<b>Pile-2</b>									
Sample	Sample's Level	Wet weight in gm	Dry weight in gm	Cont. weight in gm	Dry bulk density in Mg/m <sup>3</sup>	Moisture Content in %	Wet bulk density in Mg/m <sup>3</sup>	Dry bulk density (av) in Mg/m <sup>3</sup>	Wet bulk density (av) in Mg/m <sup>3</sup>
1	875mm	327.63	163.95	78.86	0.146	65.79	0.426	0.165	0.333167
2	875mm	364.79	199.32	115.71	0.143	66.43	0.427		
3	875mm	272.20	154.40	80.36	0.127	61.4	0.329		
4	700mm	283.07	210.79	113.14	0.167	42.53	0.291		
5	700mm	280.65	179.78	79.91	0.171	50.24	0.344		
6	700mm	268.04	177.24	80.58	0.166	48.43	0.321		
7	480mm	284.29	186.80	81.61	0.180	48.1	0.347		
8	480mm	260.65	216.57	112.93	0.178	29.84	0.253		
9	480mm	290.46	216.50	113.12	0.177	41.7	0.304		
10	340mm	287.40	216.66	114.21	0.176	40.84	0.297		
11	340mm	283.38	179.53	78.05	0.174	50.57	0.352		
12	340mm	288.82	213.82	109.85	0.178	41.9	0.307		

## APPENDIX E

### CARBON & NITROGEN ANALYSIS

Table E1: Carbon and Nitrogen Analysis for the raw materials, raw compost and final compost (Experiment-I).

<b>Experiment-I</b>							
Date	Sample	C (%)	N (%)	C/N ratio	C/N (Aver)	C (Aver) (%)	N (Aver) (%)
8/5/01	Manure-1(Pile-1)	40.2	2.05	19.60976	16.16616	37.5625	2.355
9/5/01	Manure-2 (Pile-2)	40.2	2.43	16.54321			
10/5/01	Manure-3 (Pile-1)	34	1.92	17.70833			
11/5/01	Manure-4 (Pile-2)	36.3	2.05	17.70732			
15/5/01	Manure-5 (Pile-1)	36.5	2.65	13.77358			
16/5/01	Manure-6 (Pile-2)	34	2.32	14.65517			
18/5/01	Manure-7 (Pile-1& 2)	41.3	2.91	14.19244			
22/5/01	Manure-8 (Pile-1& 2)	38	2.51	15.13944			
8/5/01	Sawdust	50.2	0.11	456.3636	456.3636	50.2	0.11
8/5/01	Wood chips	49.5	0.44	112.5		49.5	0.44
8/5/01	Raw compost (Pile-1)	46.9	0.72	65.13889	53.10869	46.86	0.912
9/5/01	Raw compost (Pile-1)	47.3	0.78	60.64103			
10/5/01	Raw compost (Pile-1)	46.5	1.08	43.05556			
11/5/01	Raw compost (Pile-1)	47.6	0.85	56			
15/5/01	Raw compost (Pile-1)	46	1.13	40.70796			
16/5/01	Raw compost (Pile-2)	45.8	0.83	55.18072	53.00837	45.74	0.87
18/5/01	Raw compost (Pile-2)	46.5	0.76	61.18421			
18/5/01	Raw compost (Pile-2)	44.4	0.98	45.30612			
22/5/01	Raw compost (pile-2)	47.6	0.89	53.48315			
22/5/01	Raw compost (Pile-2)	44.4	0.89	49.88764			
<b>All the samples of final compost were collected from the different levels of each pile</b>							
Levels	Samples	C (%)	N (%)	C/N Ratio	C/N (Aver)	C (Aver) (%)	N (Aver) (%)
L-975mm	Final compost (Pile-1)	42.6	1.52	28.02632	37.70374	44.3	1.2175
L-775mm	Final compost (Pile-1)	44	1.2	36.66667			
L-580mm	Final compost (Pile-1)	44.2	1.22	36.22951			
L-370mm	Final compost (Pile-1)	46.4	0.93	49.89247			
L-990mm	Final compost (Pile-2)	45.5	1.28	35.54688	36.71506	44.9	1.2275
L-790mm	Final compost (Pile-2)	44.8	1.31	34.19847			
L-590mm	Final compost (Pile-2)	44.8	1.21	37.02479			
L-380mm	Final compost (Pile-2)	44.5	1.11	40.09009			

Table E2: Carbon and Nitrogen Analysis for the raw materials, raw compost and final compost (Experiment-II).

<b>Experiment- II</b>							
Date	Sample	C (%)	N (%)	C/N ratio	C/N (Aver)	C (Aver) (%)	N (Aver) (%)
11/9/01	Manure (Pile-1 & 2)	30.8	2.97	10.37037	10.57633	31.6	2.9875
12/9/01	Manure (Pile-1 & 2)	31.1	2.97	10.47138			
13/9/01	Manure (Pile-1 & 2)	31.7	2.96	10.70946			
14/9/01	Manure (Pile-1 & 2)	32.8	3.05	10.7541			
14/9/01	News print	49	0.07	700	700	49	0.07
14/9/01	Office Paper	38	0.05	760	760	38	0.05
14/9/01	Wood chips	48.8	0.56	87.14286	87.14286	48.8	0.56
11/9/01	Raw compost (Pile-1)	42.7	1.1	38.81818	35.84323	43	1.2125
12/9/01	Raw compost (Pile-1)	42.7	1.23	34.71545			
13/9/01	Raw compost (Pile-1)	44.7	1.12	39.91071			
14/9/01	Raw compost (Pile-1)	41.9	1.4	29.92857			
11/9/01	Raw compost (Pile-2)	43.4	0.99	43.83838	36.88257	42.85	1.18
12/9/01	Raw compost (Pile-2)	43.3	1.12	38.66071			
13/9/01	Raw compost (Pile-2)	42.8	1.37	31.24088			
14/9/01	Raw compost (Pile-2)	41.9	1.24	33.79032			
<b>All the samples of final compost were collected from the different levels of each pile</b>							
Levels	Samples	C (%)	N (%)	C/N Ratio	C/N (Aver)	C (Aver) (%)	N (Aver) (%)
L-875mm	Final compost (Pile-1)	41.9	2.34	17.90598	23.3658		
L-675mm	Final compost (Pile-1)	44.1	1.75	25.2			
L-480mm	Final compost (Pile-1)	43.3	1.54	28.11688			
L-335mm	Final compost (Pile-1)	40.7	1.83	22.24044			
L-875mm	Final compost (Pile-2)	41.3	2.17	19.03226	24.1424		
L-700mm	Final compost (Pile-2)	42.4	1.62	26.17284			
L-480mm	Final compost (Pile-2)	41.4	1.52	27.23684			
L-340mm	Final compost (Pile-2)	41.5	1.72	24.12791			

## APPENDIX F

### ENERGY CONTENT ANALYSIS

Table F1: Gross Energy Analysis for the raw materials, raw compost and final compost.

<b>Experiment- I</b>							
Date	Samples	Dry Matter (%)	KJ/g (FD)	KJ/g (DM)	Cal/g-ds	Cal/g-ds (Av)	Pile No
8/5/01	Manure	90.67	15.71	17.33	4141.87	3993.39125	Pile-1
9/5/01	Manure	92.22	15.73	17.06	4077.34		Pile-2
10/5/01	Manure	93.05	14.12	15.17	3625.63		Pile-1
11/5/01	Manure	90.77	13.68	15.08	3604.12		Pile-2
15/5/01	Manure	91.46	15.84	17.32	4139.48		Pile-1
16/5/01	Manure	93.68	14.33	15.3	3656.7		Pile-2
18/5/01	Manure	87.76	16.5	18.8	4493.2		Pile-1 & 2
22/5/01	Manure	92.01	16.2	17.61	4208.79		Pile-1 & 2
22/5/01	Sawdust	95.32	18.88	19.8	4732.2	4732.2	Pile-1 & 2
22/5/01	Wood chips	96.42	18.93	19.63	4691.57	4691.57	Pile-1 & 2
8/5/01	Raw Compost	96.73	18.3833	19.0051	4542.2248	4609.308674	Pile-1
10/5/01	Raw Compost	95.82	18.8811	19.7045	4709.3666		
15/5/01	Raw Compost	95.82	18.7369	19.5549	4673.6220		
18/5/01	Raw Compost	96.26	18.4573	19.1750	4582.8157		
22/5/01	Raw Compost	95.81	18.1943	18.9896	4538.5141		
9/5/01	Raw Compost	95.65	18.3535	19.1877	4585.8644	4515.328321	Pile-2
11/5/01	Raw Compost	96.12	18.3518	19.0923	4563.0493		
16/5/01	Raw Compost	97.17	17.9176	18.4397	4407.0878		
18/5/01	Raw Compost	97.11	18.7381	19.2953	4611.5874		
22/5/01	Raw Compost	96.89	17.8742	18.4479	4409.0525		
<b>All the samples of final compost were collected from the different levels of each pile</b>							
Levels	Samples	Dry Matter (%)	KJ/g (FD)	KJ/g (DM)	Cal/g-ds	Cal/g-ds (Av)	Pile No
L-975mm	Final Compost	97.22	17.6870	18.1932	4348.1849	4367.893825	Pile-1
L-775mm	Final Compost	97.73	18.0682	18.4884	4418.7184		
L-580mm	Final Compost	97.68	17.3886	17.8016	4254.5835		
L-370mm	Final Compost	97.61	18.1741	18.6196	4450.0883		
L-990mm	Final Compost	97.72	17.7608	18.1747	4343.7437	4366.699877	Pile-2
L-790mm	Final Compost	97.97	17.5221	17.8848	4274.4696		
L-590mm	Final Compost	97.83	17.9120	18.3095	4375.9674		
L-380mm	Final Compost	98.11	18.3598	18.7139	4472.6186		

FD = Fixed dry matter basis; DM = Dry matter basis; Cal/g-ds = Calories/ gram dry solids.

Table F2: Gross Energy Analysis for the raw materials, raw compost and final compost.

<b>Experiment- II</b>							
Date	Samples	Dry Matter (%)	KJ/g (FD)	KJ/g (DM)	Cal/g-ds	Cal/g-ds (Av)	Pile No
11/9/01	Manure	95.61	13.64	14.27	3409.4784	3486.2870	Pile-1 & 2
12/9/01	Manure	95.45	13.09	13.71	3277.2875		Pile-1 & 2
13/9/01	Manure	95.39	14.01	14.69	3510.0496		Pile-1 & 2
14/9/01	Manure	94.83	14.87	15.68	3748.3326		Pile-1 & 2
14/9/01	Office Paper	97.8	13.0274	13.3208	3183.6712	3183.6712	Pile-2
14/9/01	News Print	98.05	18.81	19.18	4584.6653	4584.6653	Pile-1 & 2
14/9/01	Wood chips	97.68	18.94	19.39	4634.688	4634.688	Pile-1 & 2
11/9/01	Raw Compost	95.80	16.83	17.56	4197.8677	4189.0187	Pile-1
12/9/01	Raw Compost	95.72	16.93	17.69	4228.2446		
13/9/01	Raw Compost	94.26	16.7993	17.822	4259.458		
14/9/01	Raw Compost	94.88	16.1586	17.0314	4070.5046		
11/9/01	Raw Compost	95.53	16.89	17.68	4225.3288	4126.6098	Pile-2
12/9/01	Raw Compost	92.65	16.0839	17.3592	4148.8488		
13/9/01	Raw Compost	95	16.5686	17.4412	4168.4468		
14/9/01	Raw Compost	95.9300	15.9105	16.5850	3963.815		
<b>All the samples of final compost were collected from the different levels of each pile</b>							
Levels	Samples	Dry Matter (%)	KJ/g (FD)	KJ/g (DM)	Cal/g-ds	Cal/g-ds (Av)	Pile No
L-875mm	Final Compost	99.02	16.65	16.82	4019.98	4015.20	Pile-1
L-675mm	Final Compost	99.33	17.49	17.61	4208.79		
L-480mm	Final Compost	99.46	16.42	16.51	3924.38		
L-335mm	Final Compost	99.33	16.24	16.35	3907.65		
L-875mm	Final Compost	99.09	16.57	16.73	3998.47	3977.5575	Pile-2
L-700mm	Final Compost	99.57	16.78	16.85	4027.15		
L-480mm	Final Compost	99.39	16.42	16.53	3950.67		
L-340mm	Final Compost	99.75	16.42	16.46	3933.94		

## APPENDIX G

### TOTAL COLIFORM ANALYSIS

Table G1: Total Coliform Analysis of raw compost and final compost (Experiment-I).

<b>Experiment- I</b>								
<b>Samples were taken from the top layer of each pile on every working day</b>								
Dated	Sample No.	Results	Unit	Pile No	Converted Results	Unit	Average	Remarks
8/5/01	1	<10 <sup>7</sup>	MPN/100ml.	1	2.93E+06	MPN/g-ds	8.68E+07	
8/5/01	2	<10 <sup>7</sup>	MPN/100ml.		2.93E+06	MPN/g-ds		
10/5/01	1	5.4×10 <sup>8</sup>	MPN/100ml.		1.58E+08	MPN/g-ds		
10/5/01	2	1.6×10 <sup>9</sup>	MPN/100ml.		4.69E+08	MPN/g-ds		
15/5/01	1	3.3×10 <sup>7</sup>	MPN/100ml.		9.68E+06	MPN/g-ds		
15/5/01	2	2.6×10 <sup>7</sup>	MPN/100ml.		7.62E+06	MPN/g-ds		
18/5/01	1	3.5×10 <sup>8</sup>	MPN/100ml.		1.02E+08	MPN/g-ds		
18/5/01	2	3.5×10 <sup>8</sup>	MPN/100ml.		1.02E+08	MPN/g-ds		
18/5/01	1	3.5×10 <sup>8</sup>	MPN/100ml.		1.02E+08	MPN/g-ds		
18/5/01	2	2.4×10 <sup>8</sup>	MPN/100ml.		7.04E+07	MPN/g-ds		
22/5/01	1	3.3×10 <sup>7</sup>	MPN/100ml.		9.68E+06	MPN/g-ds		
22/5/01	2	2.1×10 <sup>7</sup>	MPN/100ml.		6.16E+06	MPN/g-ds		
9/5/01	1	2.4×10 <sup>7</sup>	MPN/100ml.	2	7.00E+06	MPN/g-ds	1.17E+08	
9/5/01	2	1.6×10 <sup>8</sup>	MPN/100ml.		4.67E+07	MPN/g-ds		
11/5/01	1	3.5×10 <sup>8</sup>	MPN/100ml.		1.02E+08	MPN/g-ds		
11/5/01	2	2.4×10 <sup>8</sup>	MPN/100ml.		7.00E+07	MPN/g-ds		
16/5/01	1	3.5×10 <sup>8</sup>	MPN/100ml.		1.02E+08	MPN/g-ds		
16/5/01	2	7.0×10 <sup>8</sup>	MPN/100ml.		2.04E+08	MPN/g-ds		
18/5/01	1	5.4×10 <sup>8</sup>	MPN/100ml.		1.57E+08	MPN/g-ds		
18/5/01	2	1.6×10 <sup>9</sup>	MPN/100ml.		4.67E+08	MPN/g-ds		
22/5/01	1	1.3×10 <sup>7</sup>	MPN/100ml.		3.79E+06	MPN/g-ds		
22/5/01	2	3.3×10 <sup>7</sup>	MPN/100ml.		9.63E+06	MPN/g-ds		
<b>Samples were collected from the Final Compost on 31-07-01</b>								
31/7/01	1	1.80E+07	MPN/100ml.	1	4.80E+06	MPN/g-ds	2.20E+06	
	1	1.80E+07	MPN/100ml.	1	4.80E+06	MPN/g-ds		
31/7/01	2	3.50E+06	MPN/100ml.	1	9.05E+05	MPN/g-ds		
	2	3.50E+06	MPN/100ml.	1	9.05E+05	MPN/g-ds		
31/7/01	3	1.60E+07	MPN/100ml.	1	3.60E+06	MPN/g-ds		
	3	9.20E+06	MPN/100ml.	1	2.07E+06	MPN/g-ds		
31/7/01	4	4.90E+05	MPN/100ml.	1	9.46E+04	MPN/g-ds		
	4	2.40E+06	MPN/100ml.	1	4.63E+05	MPN/g-ds		
31/7/01	5	7.90E+05	MPN/100ml.	2	2.11E+05	MPN/g-ds	6.58E+05	
	5	4.90E+05	MPN/100ml.	2	1.31E+05	MPN/g-ds		
31/7/01	6	9.20E+06	MPN/100ml.	2	1.91E+06	MPN/g-ds		
	6	9.20E+06	MPN/100ml.	2	1.91E+06	MPN/g-ds		
31/7/01	7	1.10E+06	MPN/100ml.	2	1.97E+05	MPN/g-ds		
	7	4.90E+05	MPN/100ml.	2	8.79E+04	MPN/g-ds		
31/7/01	8	1.30E+06	MPN/100ml.	2	2.90E+05	MPN/g-ds		
	8	2.40E+06	MPN/100ml.	2	5.30E+05	MPN/g-ds		

Table G2: Total Coliform Analysis of raw compost, compost on day 13 and final compost (Experiment-II).

<b>Experiment- II</b>								
<b>Samples were taken from the top layer of each pile on every working day</b>								
Dated	Sample No.	Results	Unit	Pile No	Converted Results	Unit	Average	Remarks
11/9/01	1	2.2×10 <sup>9</sup>	MPN/100ml.	1	7.17E+08	MPN/g-ds	1.92E+08	
"	2	1.3×10 <sup>9</sup>	MPN/100ml.	1	4.23E+08	MPN/g-ds		
12/9/01	1	1.3×10 <sup>8</sup>	MPN/100ml.	1	4.19E+07	MPN/g-ds		
	2	2.4×10 <sup>8</sup>	MPN/100ml.	1	7.74E+07	MPN/g-ds		
13/9/01	1	1.7×10 <sup>8</sup>	MPN/100ml.	1	6.15E+07	MPN/g-ds		
	2	1.1×10 <sup>8</sup>	MPN/100ml.	1	3.98E+07	MPN/g-ds		
14/9/01	1	3.5×10 <sup>8</sup>	MPN/100ml.	1	1.25E+08	MPN/g-ds		
	2	1.3×10 <sup>8</sup>	MPN/100ml.	1	4.67E+07	MPN/g-ds		
11/9/01	1	7.9×10 <sup>8</sup>	MPN/100ml.	2	2.36E+08	MPN/g-ds	1.52E+08	
	2	7.9×10 <sup>8</sup>	MPN/100ml.	2	2.36E+08	MPN/g-ds		
12/9/01	1	5.4×10 <sup>8</sup>	MPN/100ml.	2	1.81E+08	MPN/g-ds		
	2	1.7×10 <sup>8</sup>	MPN/100ml.	2	5.70E+07	MPN/g-ds		
13/9/01	1	2.4×10 <sup>8</sup>	MPN/100ml.	2	7.75E+07	MPN/g-ds		
	2	3.5×10 <sup>8</sup>	MPN/100ml.	2	1.13E+08	MPN/g-ds		
14/9/01	1	3.5×10 <sup>8</sup>	MPN/100ml.	2	1.24E+08	MPN/g-ds		
	2	5.4×10 <sup>8</sup>	MPN/100ml.	2	1.91E+08	MPN/g-ds		
<b>Samples were taken on 27-09-02 during the period of composting</b>								
27/09/01	4	4×10 <sup>6</sup>	MPN/100ml.	1	9.61E+05	MPN/g-ds	8.25E+06	L-400mm
27/09/01	3	<10 <sup>5</sup>	MPN/100ml.	1	2.64E+04	MPN/g-ds		L-600mm
27/09/01	2	1.1×10 <sup>8</sup>	MPN/100ml.	1	3.20E+07	MPN/g-ds		L-800mm
27/09/01	1	<10 <sup>5</sup>	MPN/100ml.	1	2.97E+04	MPN/g-ds		L-1000mm
27/09/01	8	<10 <sup>5</sup>	MPN/100ml.	2	2.56E+04	MPN/g-ds		L-400mm
27/09/01	7	<10 <sup>5</sup>	MPN/100ml.	2	2.69E+04	MPN/g-ds		L-600mm
27/09/01	6	<10 <sup>5</sup>	MPN/100ml.	2	2.97E+04	MPN/g-ds		L-800mm
27/09/01	5	7×10 <sup>7</sup>	MPN/100ml.	2	2.36E+07	MPN/g-ds		L-1000mm
<b>Samples were collected from the Final Compost on 27-11-01</b>								
27/11/01	1	>1.8×10 <sup>6</sup>	MPN/100ml.	1	3.85E+05	MPN/g-ds	4.36E+06	L-1000mm
		>1.8×10 <sup>6</sup>	MPN/100ml.	1	3.85E+05	MPN/g-ds		L-1000mm
27/11/01	3	1.3×10 <sup>7</sup>	MPN/100ml.	1	2.52E+06	MPN/g-ds		L-800mm
		1.4×10 <sup>7</sup>	MPN/100ml.	1	2.71E+06	MPN/g-ds		L-800mm
27/11/01	5	1.4×10 <sup>7</sup>	MPN/100ml.	1	2.27E+06	MPN/g-ds		L-600mm
		1.6×10 <sup>8</sup>	MPN/100ml.	1	2.59E+07	MPN/g-ds		L-600mm
27/11/01	7	1.8×10 <sup>6</sup>	MPN/100ml.	1	3.36E+05	MPN/g-ds		L-400mm
		1.8×10 <sup>6</sup>	MPN/100ml.	1	3.36E+05	MPN/g-ds		L-400mm
27/11/01	2	9.2×10 <sup>5</sup>	MPN/100ml.	2	2.56E+05	MPN/g-ds	2.01E+06	L-1000mm
		>1.8×10 <sup>6</sup>	MPN/100ml.	2	5.01E+05	MPN/g-ds		L-1000mm
27/11/01	4	1.1×10 <sup>7</sup>	MPN/100ml.	2	2.11E+06	MPN/g-ds		L-800mm
		1.1×10 <sup>7</sup>	MPN/100ml.	2	2.11E+06	MPN/g-ds		L-800mm
27/11/01	6	3.3×10 <sup>6</sup>	MPN/100ml.	2	5.40E+05	MPN/g-ds		L-600mm
		2.4×10 <sup>7</sup>	MPN/100ml.	2	3.93E+06	MPN/g-ds		L-600mm
27/11/01	8	4.9×10 <sup>6</sup>	MPN/100ml.	2	8.12E+05	MPN/g-ds		L-400mm
		3.5×10 <sup>7</sup>	MPN/100ml.	2	5.80E+06	MPN/g-ds		L-400mm



# APPENDIX H

## PARTICLE SIZE DISTRIBUTION

Table H1: Particle size analysis of Sawdust used in Experiment-I.

<b>Experiment- I</b>				
<b>Name of Sample : Sawdust</b>				
<b>Weight of sample: 321.44 gm</b>				
Seive size	Retained in gm	Passed in gm	% retained	% passing
16mm	0	321.44	0	100
11.2mm	0	321.44	0	100
8mm	0.96	320.48	0.3	99.698233
5.6mm	2.77	317.71	0.86	98.839597
2.8mm	7.23	310.48	2.25	96.590343
2mm	33.3	277.18	10.36	86.230712
1.68mm	33.62	243.56	10.46	75.771528
1.4mm	41.79	201.77	13	62.770657
850MIC	116.71	85.06	36.31	26.46217
710MIC	30.8	54.26	9.58	16.880289
500MIC	24.88	29.38	7.74	9.1401195
250MIC	22.43	6.95	6.98	2.1621453
Pan.	6.88	0	2.14	0
	321.37			

Table H2: Particle size analysis of Wood chips used in Experiment-I.

<b>Experiment- I</b>				
<b>Name of Sample : Wood Chips</b>				
<b>Weight of sample: 637.88 gm.</b>				
Seive size	Retained in gm	Passed in gm	% retained	% passing
16mm	102.57	535.31	16.079827	83.920173
11.2mm	82.1	453.21	12.870759	71.049414
8mm	88.98	364.23	13.949332	57.100082
5.6mm	106.59	257.64	16.71004	40.390042
2.8mm	173.7	83.94	27.230827	13.159215
2mm	38.84	45.1	6.0889195	7.0702953
1.68mm	15.37	29.73	2.4095441	4.6607551
1.4mm	9.05	20.68	1.4187621	3.241989
850MIC	9.18	11.5	1.4391421	1.8028469
710MIC	2.04	9.46	0.3198094	1.4830375
500MIC	1.53	7.93	0.239857	1.2431805
250MIC	2.29	5.64	0.3590017	0.8841788
Pan.	5.55	0	0.8700696	0
	637.79			

Table H3: Particle size analysis of Wood chips used in Experiment-II.

<b>Experiment- II</b>				
<b>Name of Sample : Wood Chips</b>				
<b>Weight of sample: 524.9 gm.</b>				
Seive size	Retained in gm	Passed in gm	% retained	% passing
16mm	44.56	480.34	8.49	91.51
11.2mm	50.76	429.58	9.67	81.84
8mm	89.55	340.03	17.06	64.78
5.6mm	148.75	191.28	28.34	36.44
2.8mm	142.10	49.18	27.07	9.37
2mm	23.46	25.72	4.47	4.89
1.68mm	8.78	16.94	1.67	3.22
1.4mm	4.48	12.46	0.85	2.37
850MIC	3.73	8.73	0.71	1.66
710MIC	2.79	5.94	0.53	1.13
500MIC	2.47	3.47	0.47	0.66
250MIC	2.21	1.26	0.42	0.24
Pan.	1.16	0	0.22	0
	524.8			

# APPENDIX I

## MASS AND ENERGY BALANCE

### Mass & Energy Balance of pile-1(Experiment-I)

	Manure	sawdust	Woodchip	Raw comp	Final com
Weight of materials in kg.	74.86	25.502	37.658	138.02	87.36
Dry solids (%)	0.099	0.384	0.794	0.331	0.431
Moisture content (%)	0.901	0.616	0.206	0.669	0.569
Volatile solids (%)	0.664	0.99	0.982	0.931	0.909
Biodegradability of VS (%) K	0.5	0.2	0	0.308147	0.188855
Dry solids in kg.				45.68462	37.65216
Water in kg.				92.33538	49.70784
Volatile solids in kg.				42.53238	34.22581
Biodegradable VS in kg.				13.10621	0
Ash content in kg.				3.152239	3.152239
Total BVS degraded in kg.	<b>8.03246</b>				
Water ratio (W) in g-H <sub>2</sub> O/g-BVS.	7.045162				
Energy ratio ( E) in Cal/g-H <sub>2</sub> O.	702.8468				
Initial temperature in C	15				
Final peak temperature in C.	59.94				
Heat of combustion in Cal/g-VS	4951.67				
Sp.heat of water in Cal/g-C.	1				
Sp.heat of solids in Cal/g-C.	0.25				
Sp.heat of dry gases in Cal/g-C.	0.24				
Sp.heat of water vapor in Cal/g-C.	0.44				
Latent heat of vaporization at peak T from steam table	565.7				
Actual vapor pressure of Inlet air, PV in mmHg.	10.672				
Actual vapor pressure of outlet air, PV in mmHg.	127.61				
Sp. humidity of inlet air, g-H <sub>2</sub> O/g-dry air.	0.00886				
Sp. humidity of outlet air, g-H <sub>2</sub> O/g-dry air.	0.125527				
Relative humidity at initial temperature from Chart,	0.8				

In		Out	
BVS	13.10621	BVSO	
NBVS	29.42617	NBVSO	34.49992
ASH	3.152239	ASHO	3.152239
WAT	92.33538	WATSO	49.70784
<b>Total</b>	<b>138.02</b>	<b>Total</b>	<b>87.36</b>

Now the water produced from degraded VS given in J16.  
 $8 \times 18 \times 70.6104$

WATP = ----- . Used formula for Sludges.  
 $201$   
 $= \mathbf{5.754598 \text{ kg}}$

Now, Water balance:

$$\text{Water in} + \text{Water produced} = \text{Water out.}$$

$$\text{Or, } (WAT + WATVI) + WATP = (WATSO + WATVO).$$

$$\text{Or, Total water evaporated } (WATVO - WATVI) = WAT + WATP - WATSO.$$

$$(WATVO - WATVI) = 48.38214 \text{ kg}$$

$$\text{Saturated vapor pressure, Log}_{10}(\text{PVS}) = \frac{-2238}{(273 + T)} + 8.896.$$

$$= 1.125167$$

$$\text{Saturated vapor pressure, PVS} = 13.34$$

$$\text{Actual vapor pressure, PV} = \text{Relative humidity} * \text{PVS}$$

$$= 10.672 \text{ mmHg.}$$

Sp. humidity of inlet air,

$$= 18.015/28.96 [ 10.672/(760-10.672)]$$

$$= 0.00886 \text{ g-H}_2\text{O/g-dry air.}$$

$$WATVI = \text{Sp.humidity of inlet air} * (\text{DAIRI}).$$

$$WATVO = \text{Sp.humidity of exhaust air} * (\text{DGASO}).$$

The exhaust gases are usually saturated with vapor, So relative humidity =

$$1$$

$$\text{Sp. humidity of outlet air, Log}_{10}(\text{PVS}) = \frac{-2238}{(273 + T)} + 8.896.$$

$$= 2.174068$$

$$\text{Saturated vapor pressure, PVS} = 127.61$$

$$\text{Actual vapor pressure, PV} = \text{Relative humidity} * \text{PVS}$$

$$= 127.61 \text{ mmHg.}$$

Sp. humidity of inlet air,

$$= 18.015/28.96 [ 127.61/(760-127.61)]$$

$$= 0.125527 \text{ g-H}_2\text{O/g-dry air.}$$

$$\text{Net moisture removing rate} = \frac{J54 - J45}{\dots}$$

$$= 0.116667 \text{ g-H}_2\text{O/g-ai}$$

Now, the theoretical rate of H<sub>2</sub>O evaporated in this experiment would be,

$$W = [ (1 - S_s) / S_s ] - [ (1 - V_s) / (1 - V_p) ] [ (1 - S_p) / S_p ]$$

$$= 1.020128 \text{ g-H}_2\text{O/g-dry solids.}$$

$$\text{On biodegradability} = 0.884591 \text{ g-H}_2\text{O/g-dry solids.}$$

But, the practical rate of H<sub>2</sub>O evaporation,

Total amount of water evaporated

$$W = \frac{\dots}{\dots}$$

Total amount of dry solids.

$$= 1.059047 \text{ kg-H}_2\text{O/kg-dry solids.}$$

**Input energy terms:**

$$\begin{aligned} \text{Sensible heat associated with solids, HS.I} &= m.Cp.T \quad (\text{dry solids} * \text{Sp.heat of solids} * \text{Temperature difference}). \\ &= \mathbf{171.3173} \text{ kcal.} \end{aligned}$$

$$\text{Sensible heat associated with water, HW.I} = \mathbf{1385.031} \text{ kcal.}$$

$$\begin{aligned} \text{Sensible heat with inlet air, HDAIRI} &= m.Cp.T = \text{DAIRI.Cp.T} = 4990.809 * 0.24 * 15 &= \mathbf{1484.107} \text{ kcal} \\ \text{Mass of DGASO} &= \text{DAIRI} + \text{CO}_2 + \text{NH}_3 - \text{O}_2 \\ &= \text{DAIRI} + \frac{70.6104 * 10 * 44}{201} + \frac{70.6104 * 17}{201} - \frac{70.6104 * 12.5 * 32}{201} \\ \mathbf{DGASO} &= \mathbf{DAIRI} + \mathbf{2.277862} \end{aligned}$$

We know that,

$$\text{Total water lost} = \text{DGASO (Sp.humidity of exhaust air)} - \text{DAIRI (Sp.humidity of inlet air)}.$$

$$\text{Or, } 584.77 = \text{DGASO (0.1255)} - \text{DAIRI (0.0088)}$$

$$\text{Or, } 584.77 = [\text{DAIRI} * 0.1255 + 20.02384 * 0.1255] - \text{DAIRI} * (0.0088)$$

$$\mathbf{DAIRI} = \mathbf{412.252} \text{ kg.}$$

$$\mathbf{DGASO} = \mathbf{414.5299} \text{ kg.}$$

$$\mathbf{WATVI} = \text{Sp.humidity of inlet air (DAIRI)} = \mathbf{3.65235} \text{ kg}$$

$$\mathbf{WATVO} = \text{Sp.humidity of exhaust air (DGASO)} = \mathbf{52.03449} \text{ kg}$$

$$\text{Total water evaporated} = \mathbf{48.38214} \text{ kg}$$

$$\begin{aligned} \text{Sensible heat with water vapor, HSWVI} &= m.Cp.T = \text{WATVI.Cp.T} \\ &= \mathbf{24.10551} \text{ kcal} \end{aligned}$$

Heat energy released by the used BVS,

$$\begin{aligned} \mathbf{HORG} &= \text{Heat of combustion of substrates in cal/g-vs} * (\text{Used BVS}). \\ &= \mathbf{39774.09} \text{ kcal} \end{aligned}$$

**Output energy terms:**

Sensible heat with solids,  $HSO = m.Cp.T$   
 $= 564.2176$  kcal.

Sensible heat with water,  $HWO = 2979.488$  kcal.

Sensible heat with dry gases,  $HDGASO = m.Cp.T = DGASO.Cp.T$   
 $= 5963.261$  kcal.

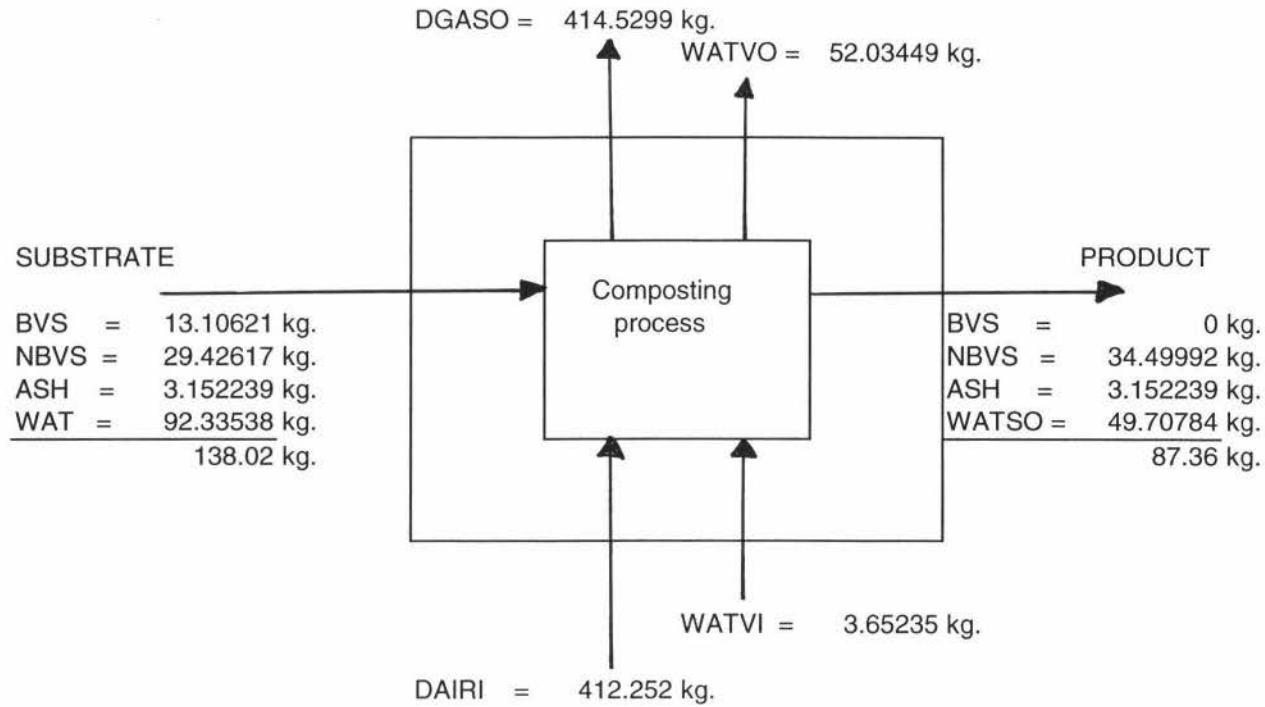
Sensible heat with water vapor,  $HSWVO =$  sensible heat with inlet water vapor + sensible heat used to raise the water temperature to exit temperature.  
 $= WATVI.Cp.T + (WATVO - WATVI).Cp.T$   
 $= 2996.351$  kcal.

Latent heat used to evaporate water,  
 $HLWVO =$  Amount of water evaporated\*( Latent heat of evaporation at temperature T from steam table)  
 $HLWVO = (WATVO - WATVI) * ( Latent heat )$   
 $= 27369.78$  kcal.

**Mass balance:**

Incoming	
BVS =	13.10621
NBVS =	29.42617
ASH =	3.152239
WAT =	92.33538
WATVI =	3.65235
DAIRI =	412.252
Total =	<b>553.9244</b>

Outgoing	
BVS =	0
NBVS =	34.49992
ASH =	3.152239
WATSO =	49.70784
WATVO =	52.03449
DGASO =	414.5299
Total =	<b>553.9244</b>



**Energy balance:**

Incoming			Outgoing		
Solids,	HS.I	= 171.3173 kcal	Solids,	HS.I	= 564.2176 kcal
Water,	HWI	= 1385.031 kcal	Water,	HWO	= 2979.488 kcal
Dry air,	HDAIRI	= 1484.107 kcal	Dry gas,	HDGASO	= 5963.261 kcal
H2O vapor,	HSWVI	= 24.10551 kcal	Sensible,	HSWVO	= 2996.351 kcal
Total Sensible Heat =		<b>3064.561 kcal</b>	Total Sensible Heat =		<b>12503.32 kcal</b>
Total Heat Released,	HORG	= 39774.09 kcal	Latent Heat Used,	HLWVO	= 27369.78 kcal
Total =		<b>42838.65 kcal.</b>	Total =		<b>39873.09 kcal</b>



### Mass & Energy Balance of pile-2 (Experiment-I)

	Manure	sawdust	Woodchip	Raw comp	Final com
Weight of materials in kg.	73.6	24.7	36.48	134.78	96.05
Dry solids (%)	0.099	0.384	0.794	0.337	0.432
Moisture content (%)	0.901	0.616	0.206	0.663	0.568
Volatile solids (%)	0.664	0.99	0.982	0.913	0.905
Biodegradability of VS (%) K	0.5	0.2	0	0.30969	0.094703
Dry solids in kg.				45.42086	41.4936
Water in kg.				89.35914	54.5564
Volatile solids in kg.				41.46925	37.55171
Biodegradable VS in kg.				12.8426	8.915345
Ash content in kg.				3.951615	3.951615
Total BVS degraded in kg.					<b>3.92726</b>

Water ratio (W) in g-H <sub>2</sub> O/g-BVS.	6.958023
Energy ratio ( E) in Cal/g-H <sub>2</sub> O.	710.7234
Initial temperature in C	15
Final peak temperature in C.	61.22
Heat of combustion in Cal/g-VS	4945.23
Sp.heat of water in Cal/g-C.	1
Sp.heat of solids in Cal/g-C.	0.25
Sp.heat of dry gases in Cal/g-C.	0.24
Sp.heat of water vapor in Cal/g-C.	0.44
Latent heat of vaporization at peak T from steam table	565.7
Actual vapor pressure of Inlet air, PV in mmHg.	10.672
Actual vapor pressure of outlet air, PV in mmHg.	127.61
Sp. humidity of inlet air, g-H <sub>2</sub> O/g-dry air.	0.00886
Sp. humidity of outlet air, g-H <sub>2</sub> O/g-dry air.	0.125527
Relative humidity at initial temperature from Chart,	0.8

In	
BVS	12.8426
NBVS	28.62664
ASH	3.951615
WAT	89.35914
<b>Total</b>	<b>134.78</b>

Out	
BVSO	8.915345
NBVSO	28.62664
ASHO	3.951615
WATSO	54.5564
<b>Total</b>	<b>96.05</b>

Now the water produced from degraded VS given in J16.

$$8 \times 18 \times 70.6104$$

WATP = -----, Used formula for Sludges.

$$= \frac{201}{8} = \mathbf{2.813559 \text{ kg}}$$

Now, Water balance:

$$\text{Water in} + \text{Water produced} = \text{Water out.}$$

$$\text{Or, } (WAT + WATVI) + WATP = (WATSO + WATVO).$$

$$\text{Or, Total water evaporated } (WATVO - WATVI) = WAT + WATP - WATSO.$$

$$(WATVO - WATVI) = 37.6163 \text{ kg}$$

$$\text{Saturated vapor pressure, Log10 (PVS)} = \frac{-2238}{(273 + T)} + 8.896.$$

$$= 1.125167$$

$$\text{Saturated vapor pressure, PVS} = 13.34$$

$$\text{Actual vapor pressure, PV} = \text{Relative humidity} * \text{PVS}$$

$$= 10.672 \text{ mmHg.}$$

Sp. humidity of inlet air,

$$= 18.015/28.96 [ 10.672/(760-10.672)]$$

$$= 0.00886 \text{ g-H}_2\text{O/g-dry air.}$$

$$WATVI = \text{Sp.humidity of inlet air} * (\text{DAIRI}).$$

$$WATVO = \text{Sp.humidity of exhaust air} * (\text{DGASO}).$$

The exhaust gases are usually saturated with vapor, So relative humidity =

$$-2238$$

$$\text{Sp. humidity of outlet air, Log10 (PVS)} = \frac{-2238}{(273 + T)} + 8.896.$$

$$= 2.199812$$

$$\text{Saturated vapor pressure, PVS} = 127.61$$

$$\text{Actual vapor pressure, PV} = \text{Relative humidity} * \text{PVS}$$

$$= 127.61 \text{ mmHg.}$$

1

Sp. humidity of inlet air,

$$= 18.015/28.96 [ 127.61/(760-127.61)]$$

$$= 0.125527 \text{ g-H}_2\text{O/g-dry air.}$$

$$\text{Net moisture removing rate} = \frac{J54-J45}{\dots}$$

$$= 0.116667 \text{ g-H}_2\text{O/g-ai}$$

Now, the theoretical rate of H<sub>2</sub>O evaporated in this experiment would be,

$$W = [ (1-Ss)/Ss ] - [ (1-Vs)/(1-Vp) ] [ (1-Sp)/Sp ]$$

$$= 0.763265 \text{ g-H}_2\text{O/g-dry solids.}$$

$$\text{On biodegradability} = 0.935902 \text{ g-H}_2\text{O/g-dry solids.}$$

But, the practical rate of H<sub>2</sub>O evaporation,

Total amount of water evaporated

$$W = \frac{\dots}{\dots}$$

Total amount of dry solids.

$$= 0.828172 \text{ kg-H}_2\text{O/kg-dry solids.}$$

**Input energy terms:**

$$\begin{aligned} \text{Sensible heat associated with solids, HS.I} &= m.Cp.T \quad (\text{dry solids} * \text{Sp.heat of solids} * \text{Temperature difference}). \\ &= \mathbf{170.3282} \text{ kcal.} \end{aligned}$$

$$\text{Sensible heat associated with water, HW.I} = \mathbf{1340.387} \text{ kcal.}$$

$$\begin{aligned} \text{Sensible heat with inlet air, HDAIRI} &= m.Cp.T = \text{DAIRI.Cp.T} = 4990.809 * 0.24 * 15 &= \mathbf{1156.414} \text{ kcal} \\ \text{Mass of DGASO} &= \text{DAIRI} + \text{CO}_2 + \text{NH}_3 - \text{O}_2 \\ &= \text{DAIRI} + \frac{70.6104 * 10 * 44}{201} + \frac{70.6104 * 17}{201} - \frac{70.6104 * 12.5 * 32}{201} \\ \mathbf{DGASO} &= \mathbf{DAIRI} + \mathbf{1.113701} \end{aligned}$$

We know that,

$$\text{Total water lost} = \text{DGASO (Sp.humidity of exhaust air)} - \text{DAIRI (Sp.humidity of inlet air)}.$$

$$\text{Or, } 584.77 = \text{DGASO (0.1255)} - \text{DAIRI (0.0088)}$$

$$\text{Or, } 584.77 = [\text{DAIRI} * 0.1255 + 20.02384 * 0.1255] - \text{DAIRI} * (0.0088)$$

$$\mathbf{DAIRI} = \mathbf{321.2262} \text{ kg.}$$

$$\mathbf{DGASO} = \mathbf{322.3399} \text{ kg.}$$

$$\mathbf{WATVI} = \text{Sp.humidity of inlet air} * (\text{DAIRI}). = \mathbf{2.845906} \text{ kg}$$

$$\mathbf{WATVO} = \text{Sp.humidity of exhaust air} * (\text{DGASO}). = \mathbf{40.46221} \text{ kg}$$

$$\text{Total water evaporated} = \mathbf{37.6163} \text{ kg}$$

$$\begin{aligned} \text{Sensible heat with water vapor, HSWVI} &= m.Cp.T = \text{WATVI.Cp.T} \\ &= \mathbf{18.78298} \text{ kcal} \end{aligned}$$

Heat energy released by the used BVS,

$$\begin{aligned} \mathbf{HORG} &= \text{Heat of combustion of substrates in cal/g-vs} * (\text{Used BVS}). \\ &= \mathbf{19421.2} \text{ kcal} \end{aligned}$$

**Output energy terms:**

Sensible heat with solids,  $HSO = m.Cp.T$   
 $= 635.0595 \text{ kcal.}$

Sensible heat with water,  $HWO = 3339.943 \text{ kcal.}$

Sensible heat with dry gases,  $HDGASO = m.Cp.T = DGASO.Cp.T$   
 $= 4736.076 \text{ kcal.}$

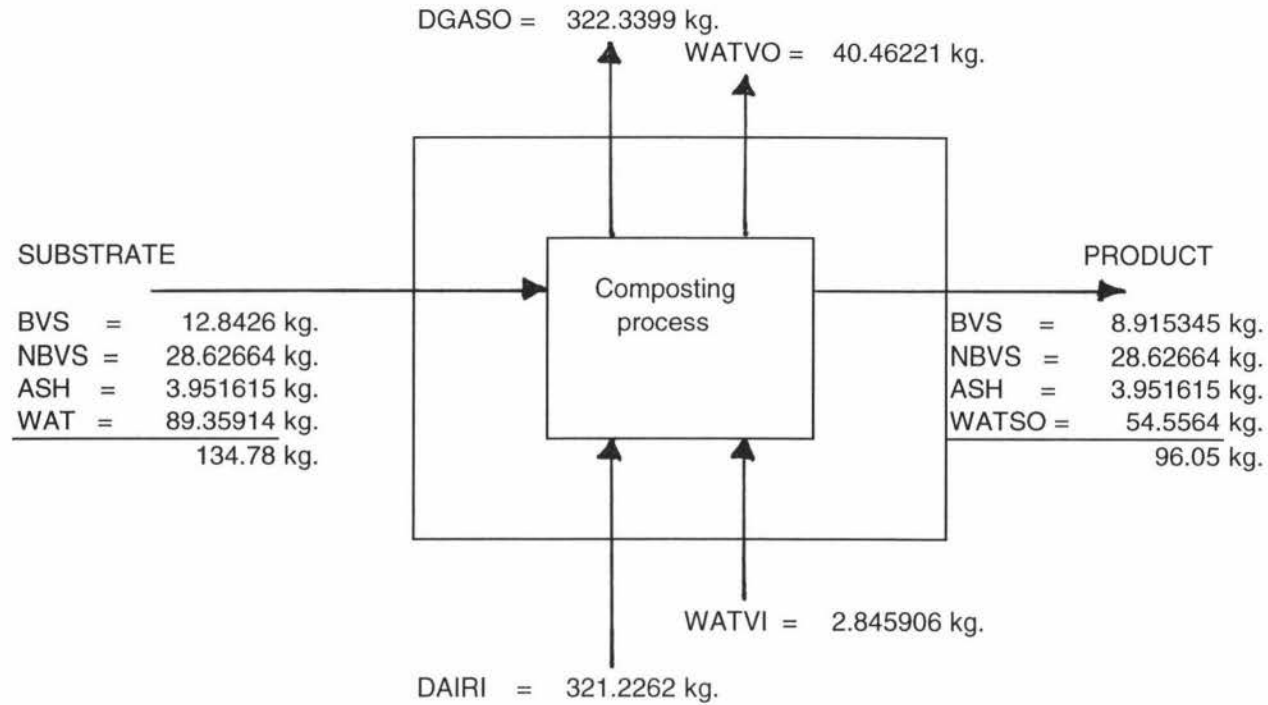
Sensible heat with water vapor,  $HSWVO =$  sensible heat with inlet water vapor + sensible heat used to raise the water temperature to exit temperature.  
 $= WATVI.Cp.T + (WATVO - WATVI).Cp.T$   
 $= 2379.529 \text{ kcal.}$

Latent heat used to evaporate water,  
 $HLWVO =$  Amount of water evaporated\*( Latent heat of evaporation at temperature T from steam table)  
 $HLWVO = (WATVO - WATVI) * ( \text{Latent heat} )$   
 $= 21279.54 \text{ kcal.}$

**Mass balance:**

Incoming	
BVS =	12.8426
NBVS =	28.62664
ASH =	3.951615
WAT =	89.35914
WATVI =	2.845906
DAIRI =	321.2262
<b>Total =</b>	<b>458.8522</b>

Outgoing	
BVS =	8.915345
NBVS =	28.62664
ASH =	3.951615
WATSO =	54.5564
WATVO =	40.46221
DGASO =	322.3399
<b>Total =</b>	<b>458.8522</b>



**Energy balance:**

Incoming			Outgoing		
Solids,	HS.I	= 170.3282 kcal	Solids,	HS.I	= 635.0595 kcal
Water,	HWI	= 1340.387 kcal	Water,	HWO	= 3339.943 kcal
Dry air,	HDAIRI	= 1156.414 kcal	Dry gas,	H DGASO	= 4736.076 kcal
H2O vapor,	HSWVI	= 18.78298 kcal	Sensible,	HSWVO	= 2379.529 kcal
Total Sensible Heat =		<b>2685.913 kcal</b>	Total Sensible Heat =		<b>11090.61 kcal</b>
Total Heat Released,	HORG	= 19421.2 kcal	Latent Heat Used,	HLWVO	= 21279.54 kcal
Total =		<b>22107.12 kcal.</b>	Total =		<b>32370.15 kcal</b>

### Mass & Energy Balance of pile-1 (Experiment-II)

	Manure	Sawdust	Mix.paper	Raw comp	Final com	
Weight of materials in kg.	60.38	7.87	59.84	128.09	51.39	
Dry solids (%)	0.103	0.937	0.524	0.293	0.534	
Moisture content (%)	0.897	0.063	0.476	0.707	0.466	
Volatile solids (%)	0.635	0.839	0.983	0.851	0.808	
Biodegradability of VS (%) K	0.5	0.667	0	0.276675	0.315862	
Dry solids in kg.				37.53037	27.44226	
Water in kg.				90.55963	23.94774	
Volatile solids in kg.				31.93834	22.17335	
Biodegradable VS in kg.				8.836539	0	
Ash content in kg.				5.592025	5.592025	
Total BVS degraded in kg.						<b>10.08811</b>

Water ratio (W) in g-H <sub>2</sub> O/g-BVS.	10.24831
Energy ratio ( E) in Cal/g-H <sub>2</sub> O.	480.3131
Initial temperature in C	15
Final peak temperature in C.	62.58
Heat of combustion in Cal/g-VS	4922.4
Sp.heat of water in Cal/g-C.	1
Sp.heat of solids in Cal/g-C.	0.25
Sp.heat of dry gases in Cal/g-C.	0.24
Sp.heat of water vapor in Cal/g-C.	0.44
Latent heat of vaporization at peak T from steam table	565.7
Actual vapor pressure of Inlet air, PV in mmHg.	10.672
Actual vapor pressure of outlet air, PV in mmHg.	127.61
Sp. humidity of inlet air, g-H <sub>2</sub> O/g-dry air.	0.00886
Sp. humidity of outlet air, g-H <sub>2</sub> O/g-dry air.	0.125527
Relative humidity at initial temperature from Chart,	0.8

In	
BVS	8.836539
NBVS	23.10181
ASH	5.592025
WAT	90.55963
Total	<b>128.09</b>

Out	
BVSO	
NBVSO	21.85023
ASHO	5.592025
WATSO	23.94774
Total	<b>51.39</b>

Now the water produced from degraded VS given in J16.

$$8 \times 18 \times 70.6104$$

WATP = -----, Used formula for Sludges.

$$= \frac{201}{20} = 7.227303 \text{ kg}$$

Now, Water balance:

Water in + Water produced = Water out.

Or, (WAT + WATVI) + WATP = (WATSO + WATVO).

Or, Total water evaporated (WATVO - WATVI) = WAT + WATP - WATSO.

$$(WATVO - WATVI) = 73.83919 \text{ kg}$$

$$\begin{aligned} \text{Saturated vapor pressure, Log}_{10}(\text{PVS}) &= \frac{-2238}{(273 + T)} + 8.896. \\ &= 1.125167 \end{aligned}$$

$$\begin{aligned} \text{Saturated vapor pressure, PVS} &= 13.34 \\ \text{Actual vapor pressure, PV} &= \text{Relative humidity} * \text{PVS} \\ &= 10.672 \text{ mmHg.} \end{aligned}$$

$$\begin{aligned} \text{Sp. humidity of inlet air,} \\ &= 18.015/28.96 [ 10.672/(760-10.672)] \\ &= 0.00886 \text{ g-H}_2\text{O/g-dry air.} \end{aligned}$$

**WATVI = Sp.humidity of inlet air \*( DAIRI).**

**WATVO = Sp.humidity of exhaust air \*( DGASO).**

The exhaust gases are usually saturated with vapor, So relative humidity =

-2238

$$\begin{aligned} \text{Sp. humidity of outlet air, Log}_{10}(\text{PVS}) &= \frac{-2238}{(273 + T)} + 8.896. \\ &= 2.226949 \end{aligned}$$

$$\begin{aligned} \text{Saturated vapor pressure, PVS} &= 127.61 \\ \text{Actual vapor pressure, PV} &= \text{Relative humidity} * \text{PVS} \\ &= 127.61 \text{ mmHg.} \end{aligned}$$

1

$$\begin{aligned} \text{Sp. humidity of inlet air,} \\ &= 18.015/28.96 [ 127.61/(760-127.61)] \\ &= 0.125527 \text{ g-H}_2\text{O/g-dry air.} \end{aligned}$$

$$\begin{aligned} \text{Net moisture removing rate} &= \frac{J54-J45}{J54-J45} \\ &= 0.116667 \text{ g-H}_2\text{O/g-ai} \end{aligned}$$

Now, the theoretical rate of H<sub>2</sub>O evaporated in this experiment would be,

$$\begin{aligned} W &= [ (1-Ss)/Ss ] - [ (1-Vs)/(1-Vp) ] [ (1-Sp)/Sp ] \\ &= 1.735749 \text{ g-H}_2\text{O/g-dry solids.} \end{aligned}$$

On biodegradability = 1.51715 g-H<sub>2</sub>O/g-dry solids.

But, the practical rate of H<sub>2</sub>O evaporation,

Total amount of water evaporated

$$W = \frac{\text{Total amount of water evaporated}}{\text{Total amount of dry solids.}}$$

$$= 1.967452 \text{ kg-H}_2\text{O/kg-dry solids.}$$

**Input energy terms:**

$$\begin{aligned} \text{Sensible heat associated with solids, HS.I} &= m.Cp.T \quad (\text{dry solids} \times \text{Sp.heat of solids} \times \text{Temperature difference}). \\ &= \mathbf{140.7389} \text{ kcal.} \end{aligned}$$

$$\text{Sensible heat associated with water, HW.I} = \mathbf{1358.394} \text{ kcal.}$$

$$\begin{aligned} \text{Sensible heat with inlet air, HDAIRI} &= m.Cp.T = \text{DAIRI.Cp.T} = 4990.809 \times 0.24 \times 15 &= \mathbf{2267.379} \text{ kcal} \\ \text{Mass of DGASO} &= \text{DAIRI} + \text{CO}_2 + \text{NH}_3 - \text{O}_2 \\ &= \text{DAIRI} + \frac{70.6104 \times 10 \times 44}{201} + \frac{70.6104 \times 17}{201} - \frac{70.6104 \times 12.5 \times 32}{201} \\ \mathbf{DGASO} &= \mathbf{DAIRI} + \mathbf{2.860807} \end{aligned}$$

We know that,

$$\text{Total water lost} = \text{DGASO (Sp.humidity of exhaust air)} - \text{DAIRI (Sp.humidity of inlet air)}.$$

$$\text{Or, } 584.77 = \text{DGASO (0.1255)} - \text{DAIRI (0.0088)}$$

$$\text{Or, } 584.77 = [\text{DAIRI} \times 0.1255 + 20.02384 \times 0.1255] - \text{DAIRI} \times (0.0088)$$

$$\mathbf{DAIRI} = \mathbf{629.8275} \text{ kg.}$$

$$\mathbf{DGASO} = \mathbf{632.6883} \text{ kg.}$$

$$\mathbf{WATVI} = \text{Sp.humidity of inlet air} \times (\text{DAIRI}). = \mathbf{5.579962} \text{ kg}$$

$$\mathbf{WATVO} = \text{Sp.humidity of exhaust air} \times (\text{DGASO}). = \mathbf{79.41915} \text{ kg}$$

$$\text{Total water evaporated} = \mathbf{73.83919} \text{ kg}$$

$$\begin{aligned} \text{Sensible heat with water vapor, HSWVI} &= m.Cp.T = \text{WATVI.Cp.T} \\ &= \mathbf{36.82775} \text{ kcal} \end{aligned}$$

Heat energy released by the used BVS,

$$\begin{aligned} \mathbf{HORG} &= \text{Heat of combustion of substrates in cal/g-vs} \times (\text{Used BVS}). \\ &= \mathbf{49657.71} \text{ kcal} \end{aligned}$$



**Output energy terms:**

Sensible heat with solids,  $HSO = m.Cp.T$   
 $= 429.3342 \text{ kcal.}$

Sensible heat with water,  $HWO = 1498.65 \text{ kcal.}$

Sensible heat with dry gases,  $HDGASO = m.Cp.T = DGASO.Cp.T$   
 $= 9502.473 \text{ kcal.}$

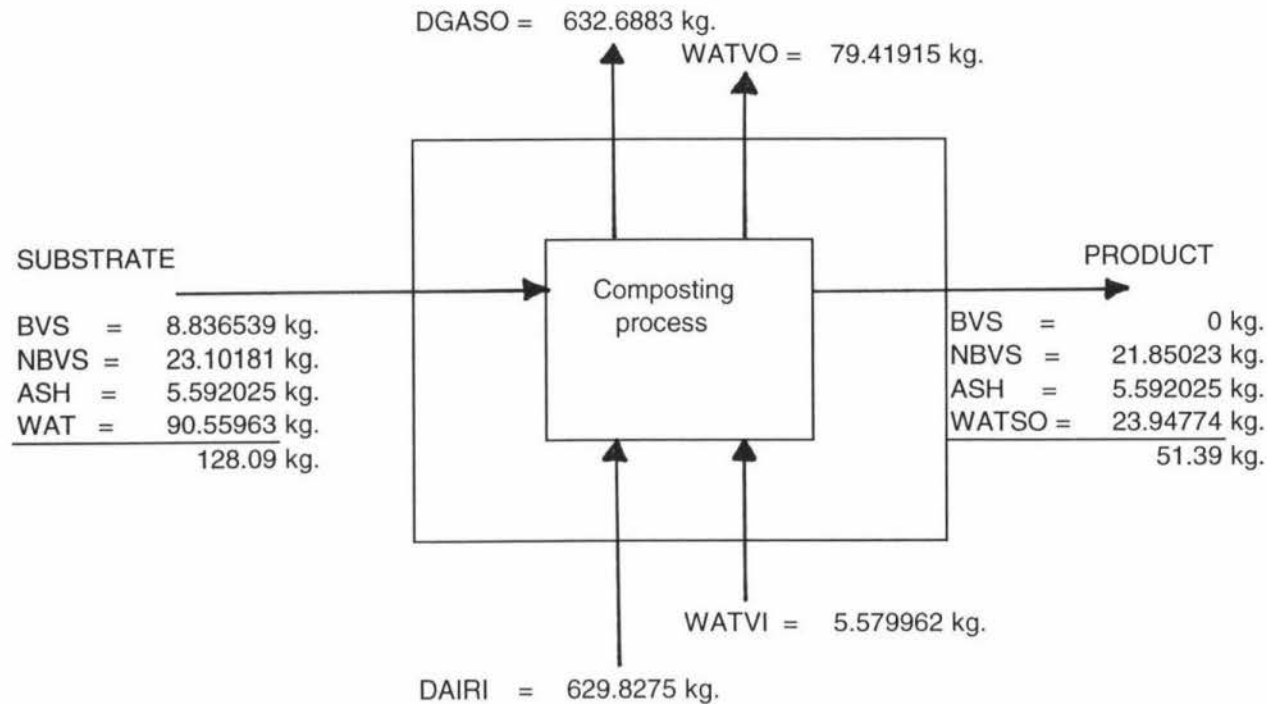
Sensible heat with water vapor,  $HSWVO =$  sensible heat with inlet water vapor + sensible heat used to raise the water temperature to exit temperature.  
 $= WATVI.Cp.T + (WATVO - WATVI).Cp.T$   
 $= 4774.502 \text{ kcal.}$

Latent heat used to evaporate water,  
 $HLWVO =$  Amount of water evaporated\*( Latent heat of evaporation at temperature T from steam table)  
 $HLWVO = (WATVO - WATVI) * ( \text{Latent heat} )$   
 $= 41770.83 \text{ kcal.}$

**Mass balance:**

Incoming	
BVS =	8.836539
NBVS =	23.10181
ASH =	5.592025
WAT =	90.55963
WATVI =	5.579962
DAIRI =	629.8275
Total =	<b>763.4975</b>

Outgoing	
BVS =	0
NBVS =	21.85023
ASH =	5.592025
WATSO =	23.94774
WATVO =	79.41915
DGASO =	632.6883
Total =	<b>763.4975</b>



**Energy balance:**

Incoming			Outgoing		
Solids, HS.I	=	140.7389 kcal	Solids, HS.O	=	429.3342 kcal
Water, HWI	=	1358.394 kcal	Water, HWO	=	1498.65 kcal
Dry air, HDAIRI	=	2267.379 kcal	Dry gas, HDGASO	=	9502.473 kcal
H2O vapor, HSWVI	=	36.82775 kcal	Sensible, HSWVO	=	4774.502 kcal
Total Sensible Heat	=	<b>3803.34 kcal</b>	Total Sensible Heat	=	<b>16204.96 kcal</b>
Total Heat Released, HORG = 49657.71 kcal			Latent Heat Used, HLWVO = 41770.83 kcal		
Total = <b>53461.05 kcal.</b>			Total = <b>57975.79 kcal</b>		

### Mass & Energy Balance of pile-2 (Experiment-II)

	Manure	Sawdust	Mix.paper	Raw comp	Final com
Weight of materials in kg.	63.79	8.23	62.55	134.57	58.74
Dry solids (%)	0.103	0.937	0.524	0.305	0.524
Moisture content (%)	0.897	0.063	0.476	0.695	0.476
Volatile solids (%)	0.635	0.839	0.983	0.858	0.808
Biodegradability of VS (%) K	0.5	0.667	0	0.277806	0.291464
Dry solids in kg.				41.04385	30.77976
Water in kg.				93.52615	27.96024
Volatile solids in kg.				35.21562	24.87005
Biodegradable VS in kg.				9.783126	0
Ash content in kg.				5.828227	5.828227
Total BVS degraded in kg.	<b>10.26409</b>				

Water ratio (W) in g-H <sub>2</sub> O/g-BVS.	9.559945
Energy ratio ( E) in Cal/g-H <sub>2</sub> O.	502.9004
Initial temperature in C	15
Final peak temperature in C.	63.57
Heat of combustion in Cal/g-VS	4807.7
Sp.heat of water in Cal/g-C.	1
Sp.heat of solids in Cal/g-C.	0.25
Sp.heat of dry gases in Cal/g-C.	0.24
Sp.heat of water vapor in Cal/g-C.	0.44
Latent heat of vaporization at peak T from steam table	565.7
Actual vapor pressure of Inlet air, PV in mmHg.	10.672
Actual vapor pressure of outlet air, PV in mmHg.	127.61
Sp. humidity of inlet air, g-H <sub>2</sub> O/g-dry air.	0.00886
Sp. humidity of outlet air, g-H <sub>2</sub> O/g-dry air.	0.125527
Relative humidity at initial temperature from Chart,	0.8

In	
BVS	9.783126
NBVS	25.4325
ASH	5.828227
WAT	93.52615
<b>Total</b>	<b>134.57</b>

Out	
BVSO	0
NBVSO	24.95153
ASHO	5.828227
WATSO	27.96024
<b>Total</b>	<b>58.74</b>

Now the water produced from degraded VS given in J16.  
 $8 \times 18 \times 70.6104$

WATP = ----- . Used formula for Sludges.  
 $= \frac{201}{7.353378} \text{ kg}$

Now, Water balance:

$$\text{Water in} + \text{Water produced} = \text{Water out.}$$

$$\text{Or, } (WAT + WATVI) + WATP = (WATSO + WATVO).$$

$$\text{Or, Total water evaporated } (WATVO - WATVI) = WAT + WATP - WATSO.$$

$$(WATVO - WATVI) = 72.91929 \text{ kg}$$

$$\text{Saturated vapor pressure, Log}_{10}(\text{PVS}) = \frac{-2238}{(273 + T)} + 8.896.$$

$$= 1.125167$$

Saturated vapor pressure, PVS = 13.34

Actual vapor pressure, PV = Relative humidity \* PVS

$$= 10.672 \text{ mmHg.}$$

Sp. humidity of inlet air,

$$= 18.015/28.96 [10.672/(760-10.672)]$$

$$= 0.00886 \text{ g-H}_2\text{O/g-dry air.}$$

$$WATVI = \text{Sp. humidity of inlet air} * (\text{DAIRI}).$$

$$WATVO = \text{Sp. humidity of exhaust air} * (\text{DGASO}).$$

The exhaust gases are usually saturated with vapor, So relative humidity =

$$\text{Sp. humidity of outlet air, Log}_{10}(\text{PVS}) = \frac{-2238}{(273 + T)} + 8.896.$$

$$= 2.246566$$

Saturated vapor pressure, PVS = 127.61

Actual vapor pressure, PV = Relative humidity \* PVS

$$= 127.61 \text{ mmHg.}$$

1

Sp. humidity of inlet air,

$$= 18.015/28.96 [127.61/(760-127.61)]$$

$$= 0.125527 \text{ g-H}_2\text{O/g-dry air.}$$

---

Net moisture removing rate = J54-J45

$$= 0.116667 \text{ g-H}_2\text{O/g-ai}$$

Now, the theoretical rate of H<sub>2</sub>O evaporated in this experiment would be,

$$W = [(1-Ss)/Ss] - [(1-Vs)/(1-Vp)] [(1-Sp)/Sp]$$

$$= 1.606853 \text{ g-H}_2\text{O/g-dry solids.}$$

On biodegradability = 1.373684 g-H<sub>2</sub>O/g-dry solids.

But, the practical rate of H<sub>2</sub>O evaporation,

Total amount of water evaporated

$$W = \frac{\text{Total amount of water evaporated}}{\text{Total amount of dry solids.}}$$

$$= 1.776619 \text{ kg-H}_2\text{O/kg-dry solids.}$$

**Input energy terms:**

$$\begin{aligned} \text{Sensible heat associated with solids, HS.I} &= m.Cp.T \quad (\text{dry solids} \times \text{Sp.heat of solids} \times \text{Temperature difference}). \\ &= \mathbf{153.9144} \text{ kcal.} \end{aligned}$$

$$\text{Sensible heat associated with water, HW.I} = \mathbf{1402.892} \text{ kcal.}$$

$$\begin{aligned} \text{Sensible heat with inlet air, HDAIRI} &= m.Cp.T = \text{DAIRI.Cp.T} = 4990.809 \times 0.24 \times 15 &= \mathbf{2238.8} \text{ kcal} \\ \text{Mass of DGASO} &= \text{DAIRI} + \text{CO}_2 + \text{NH}_3 - \text{O}_2 \\ &= \text{DAIRI} + \frac{70.6104 \times 10 \times 44}{201} + \frac{70.6104 \times 17}{201} - \frac{70.6104 \times 12.5 \times 32}{201} \\ \mathbf{DGASO} &= \mathbf{DAIRI} + \mathbf{2.910712} \end{aligned}$$

We know that,

$$\text{Total water lost} = \text{DGASO (Sp.humidity of exhaust air)} - \text{DAIRI (Sp.humidity of inlet air)}.$$

$$\text{Or, } 584.77 = \text{DGASO (0.1255)} - \text{DAIRI (0.0088)}$$

$$\text{Or, } 584.77 = [\text{DAIRI} \times 0.1255 + 20.02384 \times 0.1255] - \text{DAIRI} \times (0.0088)$$

$$\mathbf{DAIRI} = \mathbf{621.889} \text{ kg.}$$

$$\mathbf{DGASO} = \mathbf{624.7997} \text{ kg.}$$

$$\mathbf{WATVI} = \text{Sp.humidity of inlet air} \times (\text{DAIRI}). \quad = \mathbf{5.50963} \text{ kg}$$

$$\mathbf{WATVO} = \text{Sp.humidity of exhaust air} \times (\text{DGASO}). \quad = \mathbf{78.42892} \text{ kg}$$

$$\text{Total water evaporated} = \mathbf{72.91929} \text{ kg}$$

$$\begin{aligned} \text{Sensible heat with water vapor, HSWVI} &= m.Cp.T = \text{WATVI.Cp.T} \\ &= \mathbf{36.36356} \text{ kcal} \end{aligned}$$

Heat energy released by the used BVS,

$$\begin{aligned} \mathbf{HORG} &= \text{Heat of combustion of substrates in cal/g-vs} \times (\text{Used BVS}). \\ &= \mathbf{49346.67} \text{ kcal} \end{aligned}$$

**Output energy terms:**

Sensible heat with solids,  $HSO = m.Cp.T$   
 $= 489.1673$  kcal.

Sensible heat with water,  $HWO = 1777.432$  kcal.

Sensible heat with dry gases,  $HDGASO = m.Cp.T = DGASO.Cp.T$   
 $= 9532.444$  kcal.

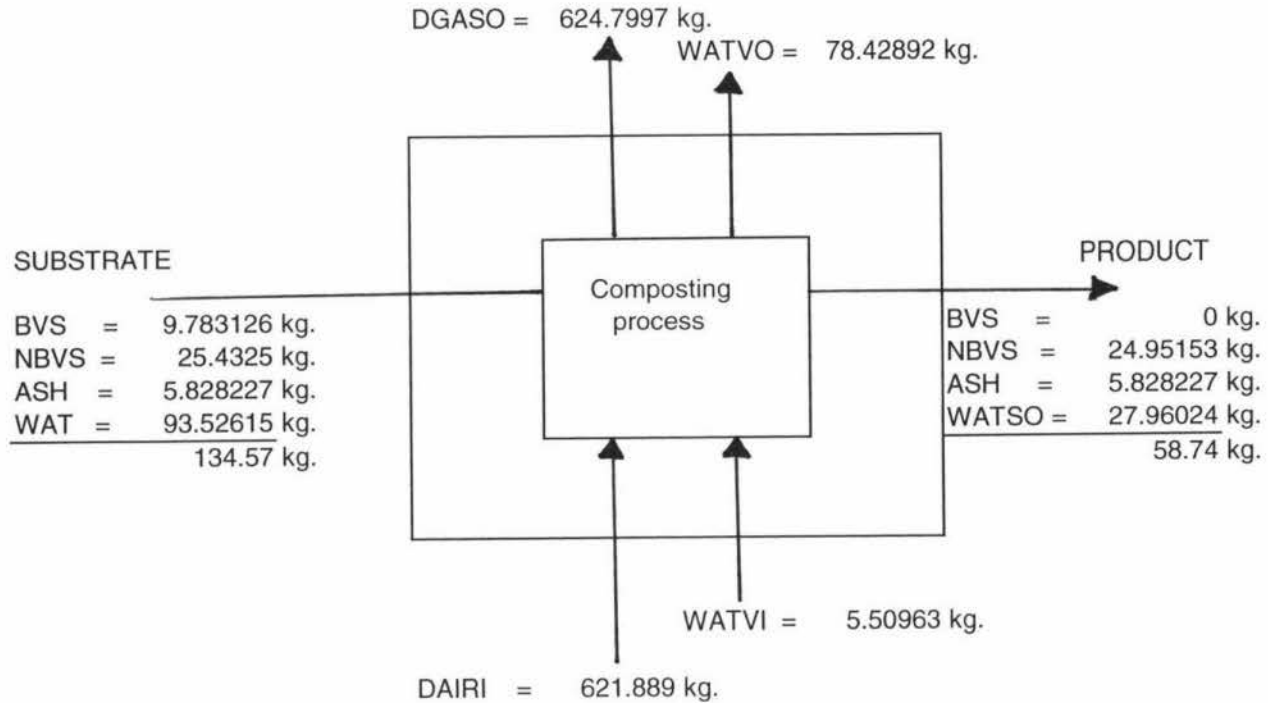
Sensible heat with water vapor,  $HSWVO =$  sensible heat with inlet water vapor + sensible heat used to raise the water temperature to exit temperature.  
 $= WATVI.Cp.T + (WATVO - WATVI).Cp.T$   
 $= 4789.588$  kcal.

Latent heat used to evaporate water,  
 $HLWVO =$  Amount of water evaporated\*( Latent heat of evaporation at temperature T from steam table)  
 $HLWVO = (WATVO - WATVI) * ( Latent heat )$   
 $= 41250.44$  kcal.

**Mass balance:**

Incoming	
BVS =	9.783126
NBVS =	25.4325
ASH =	5.828227
WAT =	93.52615
WATVI =	5.50963
DAIRI =	621.889
<b>Total =</b>	<b>761.9686</b>

Outgoing	
BVS =	0
NBVS =	24.95153
ASH =	5.828227
WATSO =	27.96024
WATVO =	78.42892
DGASO =	624.7997
<b>Total =</b>	<b>761.9686</b>



**Energy balance:**

Incoming			Outgoing		
Solids,	HS.I =	153.9144 kcal	Solids,	HS.I =	489.1673 kcal
Water,	HWI =	1402.892 kcal	Water,	HWO =	1777.432 kcal
Dry air,	HDAIRI =	2238.8 kcal	Dry gas, HDGASO =		9532.444 kcal
H2O vapor,	HSWVI =	36.36356 kcal	Sensible, HSWVO =		4789.588 kcal
Total Sensible Heat =		<b>3831.971 kcal</b>	Total Sensible Heat =		<b>16588.63 kcal</b>
Total Heat Released, HORG = 49346.67 kcal			Latent Heat Used, HLWVO = 41250.44 kcal		
Total = <b>53178.64 kcal.</b>			Total = <b>57839.07 kcal</b>		

**MASS & ENERGY BALANCE ANALYSIS USING THE DATA GIVEN BY Sartaj *et al.*(1997)**

**DATA TABLE  
ACCORDING TO Sartaj *et al.*(1997).**

Design Parameters symbol	Manure	Peat	Man+Peat
1.Xs/Xa/Xsa/Xb/Xm = Wet weight of material.	1	1	2
2.Ms/Ma/Msa/Mb/Mm = Moisture content	0.88	0.656	0.768
3.Ss/Sa/Ssa/Sb/Sm = Solid Content	0.12	0.344	0.232
4.Cs/Ca/Csa/Cb/Cm = Carbon Content.	0.334	0.492	
5.Ns/Na/Nsa/Nb/Nm = Nitrogen Content.	0.029	0.01	
6.(C/N)s/(C/N)a/(C/N)sa/(C/N)b/(C/N)m = C/N ratio.	11.5	51.8	29.43075
7.Ds/Da/Dsa/Db/Dm = Bulk density.	1016.839	60	538.4194
8.Gs/Ga/Gsa/Gb/Gm = Specific Gravity.	1.160093	1.037	1.098546
9.Vs/Va/Vsa/Vb/Vm = Volatile solid content.	0.77	0.94	
10.Ks/Ka/Ksa/Kb/Km = Degradability.	0.6	0.55	
11.Fsa/Fb/Fm = Free air space.			0.472786
12.Ssam = S cont.of substrate in mix. after absorption.			0.3
13.(Ssam)m = Max.S cont.of Substrate achievable.			0.4
14.Sbm = S cont. of bulking agent in mix. after absorption.			
15.(Sbm)m = Min. S cont. of bulking agent achievable by absorption.			
16.Mbs = Volumetric mixing ratio.			

We like to achieve the solid content of (Manure+Peat) up to 20%.Then the amount of Sawdust would be,

$$\begin{aligned}
 S_m &= (X_s.S_s + X_a.S_a)/(X_s + X_a) \\
 &= 0.232 \text{ kg.}
 \end{aligned}$$



Now the C/N ratio of ( Manure+Peat), considering all organic C & N are biodegradable,

$$\begin{aligned} \text{(C/N)}_{sa} &= \frac{(Xs.Ss.Cs + Xa.Sa.Ca)}{(Xs.Ss.Ns + Xa.Sa.Na)} \\ &= 30.24971 \end{aligned}$$

If we consider the biodegradability of Manure & Sawdust then,

$$\begin{aligned} \text{(C/N)}_{sa} &= \frac{(Ks. Xs.Ss.Cs +Ka. Xa.Sa.Ca)}{(Ks. Xs.Ss.Ns +Ka. Xa.Sa.Na)} \\ \text{(C/N)}_{sa} &= 29.43075 \end{aligned}$$

Now Sp.Gravity of Manure, We know.

$$1/Gs = Vs/Gv + (1 - Vs )/Gf. \quad \text{Where } Gv=1 \text{ and } Gf = 2.5$$

$$\begin{aligned} 1/Gs &= 0.862 \\ Gs &= 1.160093 \end{aligned}$$

Bulk density of Manure.

$$\begin{aligned} Ds &= 1/[(Ss/Gs)+1-Ss] , ( Vg = 0 ) \\ Ds &= 1.016839 \text{ g/cm}^3 \\ &= 1016.839 \text{ kg/m}^3. \end{aligned}$$

As we know the bulk density of woodchips & Peat, from above equation we find out Sp.Gravities.

$$\begin{aligned} 1/Gs &= Vs/Gv + (1 - Vs )/Gf. \\ &= 1.037 \end{aligned}$$

$$\begin{aligned} Gb &= Sb/(Dwat./Db + Sb - 1 ) \\ Gb &= 0 \end{aligned}$$

Bulk density of (Manure+Peat),

$$\begin{aligned} Dsa &= \frac{(Xs.Ds + Xa.Da)}{(Xs + Xa)} \\ &= 538.4194 \text{ kg/m}^3. \end{aligned}$$

Sp. Gravity of ( Manure+Peat),

$$\begin{aligned} Gsa &= \frac{(Xs.Gs + Xa.Ga)}{(Xs + Xa)} \\ &= 1.098546 \end{aligned}$$

Now the free air Space of (Manure+Peat),

$$\begin{aligned} F_{sa} &= 1 - (D_{sa}.S_{sa}/G_{sa}.D_{wat.}) - D_{sa}(1 - S_{sa})/D_{wat.} \\ &= \mathbf{0.472786} \end{aligned}$$

**Conditioning with Amendments:**

$$\text{For 1 kg Peat we need} = \text{1 kg-manure}$$

**For 1 kg Peat: ( Xa = 1 )**

$$\begin{aligned} \text{BVS (Biodegradable VS) of Peat} &= K_a.V_a.S_a.X_a = 0.177848 \text{ kg.} \\ \text{NBVS(Non-biodegradable VS) of Peat} &= (1-K_a).V_a.S_a.X_a = 0.145512 \text{ kg.} \\ \text{WAT(Water component) of Peat} &= (X_a - S_a.X_a) = 0.656 \text{ kg.} \\ \text{ASH(Inert component) of Peat} &= (1-V_a).S_a.X_a = 0.02064 \text{ kg.} \end{aligned}$$

**For 1kg Manure: ( X = 1 )**

$$\begin{aligned} \text{BVS ( Biodegradable VS ) of Manure} &= K_s.V_s.S_s.X_s = 0.05544 \text{ kg.} \\ \text{NBVS(Non-biodegradable VS) of Manure} &= (1-K_s).V_s.S_s.X_s = 0.03696 \text{ kg.} \\ \text{WAT(Water component) of Manure} &= (X_s - S_s.X_s ) = 0.88 \text{ kg.} \\ \text{ASH(Inert component) of Manure} &= (1 - V_s ).S_s.X_s = 0.0276 \text{ kg.} \end{aligned}$$

All BVS will be lost during composting and NBVS & ASH will be conservative.

$$\begin{aligned} \text{NBVSO} = \text{NBVS} &= 0.182472 \text{ kg.} \\ \text{ASHO} = \text{ASH} &= 0.04824 \text{ kg.} \\ \text{Total} &= 0.230712 \text{ kg.} \end{aligned}$$

Let, We need 60% TS in final compost product.

$$\text{WATSO(Water component)} = 0.153808 \text{ kg.}$$

Assume Chemical formula of Manure is  $C_{10}H_{19}O_3N + 12.5O_2 = 10CO_2 + 8H_2O + NH_3$ .

$$\text{WATP(Water produced)} = 0.167132 \text{ kg.}$$

**Mass balance of Water.**

$$\begin{aligned} \text{Water in} + \text{Water produce} &= \text{Water out.} \\ (\text{WAT} + \text{WATVI}) + \text{WATP} &= (\text{WATVO} + \text{WATSO}). \\ \text{or' } (\text{WATVO} - \text{WATVI}) &= \text{WAT} + \text{WATP} - \text{WATSO}. \\ \text{or' } \text{WATVO} - \text{WATVI} &= 1.549324 \text{ kg.} \end{aligned}$$

**Moisture carrying capacity of Inlet gas:**

$$\begin{aligned} W &= (18.015/28.96)[P_V/(P_{AIR}-P_V)]. \\ &= 0.11468 \text{ g-water/g-dry air.} \end{aligned}$$

**Moisture carrying capacity of outlet gas:**

$$\begin{aligned} W &= [(1-S_{sa})/S_{sa}] - [(1-V_{sa})/(1-V_p)][(1-S_p)/S_p]. \\ &= 0.011335 \text{ g-water/g-dry air.} \end{aligned}$$

**Net moisture removed with exit gases,**

$$= 0.103346 \text{ g-water/g-dry inlet air.}$$

**Water Balance:**

$$\begin{aligned} \text{WATVO} &= \text{DGASO} \times 0.1147 = 1.717811 \\ \text{WATVI} &= \text{DAIRI} \times 0.0113 = 0.168488 \\ \text{Or' } \text{WATVO} - \text{WATVI} &= \text{DGASO} \times 0.1147 - \text{DAIRI} \times 0.0113. \\ \text{Or' } 0.1147 \times \text{DGASO} - 0.0113 \times \text{DAIRI} &= 1.549324 \text{ ----(1).} \end{aligned}$$

But DGASO = DAIRI - Oxygen consumed + (CO<sub>2</sub> + NH<sub>3</sub>) formed.

$$\text{DGASO} = \text{DAIRI} + 0.066156 \text{ ---- (2) \quad Oxygen} = 0.464255$$

$$\text{CO}_2 = 0.51068$$

$$\text{NH}_3 = 0.019731$$

$$\text{From Eqn 1 \& 2, \quad DAIRI} = 14.9104$$

$$\text{DGASO} = 14.97656$$

**Water Vapour Input and Output:**

$$\text{WATVI} = 0.168488 \text{ kg.}$$

$$\text{WATVO} = 1.717811 \text{ kg.}$$

**Check Mass  
balance:**

<b>In =</b> BVS = 0.233288	<b>Out =</b> NBVS = 0.182472
NBVS = 0.182472	ASHO = 0.04824
ASH = 0.04824	WATSO = 0.153808
WAT = 1.536	WATVO = 1.717811
WATVI = 0.168488	DGASO = 14.97656
DAIRI = 14.9104	
<b>Total = 17.07889 kg</b>	<b>Total = 17.07889 kg</b>

**Check water  
balance:**

<b>In =</b> WAT = 1.536	<b>Out =</b> WATSO = 0.153808
WATVI = 0.168488	WATVO = 1.717811
WATP = 0.167132	
<b>Total = 1.871619 kg</b>	<b>Total = 1.871619 kg</b>

**Energy Balance:**

<b>Input:</b> HSI (sensible heat in substrate solids)	=	$m.C_p.(T_1-T_2)$ .	$m = S_s.(X_s + X_a) =$	0.464
	=	2.32 Kcal.		
HWI(sensible heat in water component)	=	30.72 Kcal.		
HDAIRI(sensible heat in input dry air)	=	71.56993 Kcal.		
HSWVI(sensible heat in water vapour)	=	1.48269 Kcal.		
HORG(heat released)	=	1294.748 Kcal.		(Assuming all BVS decomposed with a unit heat release, $H_s = 5550 \text{ cal/g-BVS.}$ )
<b>Total</b>	=	<b>1400.841 Kcal.</b>		

<b>Output:</b> HSO(sensible heat in output product)	=	3.17229 Kcal.
HWO(sensible heat in output water)	=	8.45944 Kcal.
HDGASO(sensible heat in output gas)	=	197.6906 Kcal.
HSWVO(sensible heat in water vapour)	=	89.2902 Kcal.
HLWVO(latent heat of vapourization)	=	876.4524 Kcal.
<b>Total</b>	=	<b>1175.065 Kcal.</b>

Considering latent heat of vaporization at 55 degreeC from steam table = 565.7cal/g.

**So the input materials are energy rich.**

$$\begin{aligned}
 \text{Water Ratio} &= (\text{Weight of water})/(\text{Weight of degradable organics}). \\
 &= (X_s - S_s.X_s) + (X_a - S_a.X_a) / (K_s.V_s.S_s.X_s + K_a.V_a.S_a.X_a). \\
 &= 6.584136 \text{ g-H}_2\text{O/g-BVS}.
 \end{aligned}$$

$$\begin{aligned}
 \text{Energy Ratio} &= (\text{Heat released/Weight of water}). \\
 &= (K_s.V_s.S_s.X_s)H_s + (K_a.V_a.S_a.X_a)H_a / (X_s - S_s.X_s) + (X_a - S_a.X_a) \\
 &= 721.3594 \text{ cal/g-H}_2\text{O}.
 \end{aligned}$$

**Advantages:**

1. C/N ratio is good enough for composting.
2. The moisture content would be 76.8%, which is reasonable for wet substrate composting.
3. The C/N ratio is 29.43% which is good for composting process.
4. FAS is 47.2%, which is more than enough for composting process.
5. The input materials are rich in energy content.
6. Water ratio,  $W = 6.58 \text{ g-H}_2\text{O/g-BVS}$  which is  $< 8 \text{ g-H}_2\text{O/g-BVS}$ . So the input materials are sufficient to provide energy for evaporation.
7. Energy ratio,  $E = 721 \text{ cal/g-H}_2\text{O}$  which is more than  $700 \text{ cal/g-H}_2\text{O}$ , So sufficient energy is available for composting and drying.

## APPENDIX J

GRAPHS USED FOR CALCULATION OF THE AREAS UNDER TIME-TEMPERATURE CURVES (OBTAINED FROM MANUAL TEMPERATURE PROBE) AT REGIONS ABOVE 55°C.

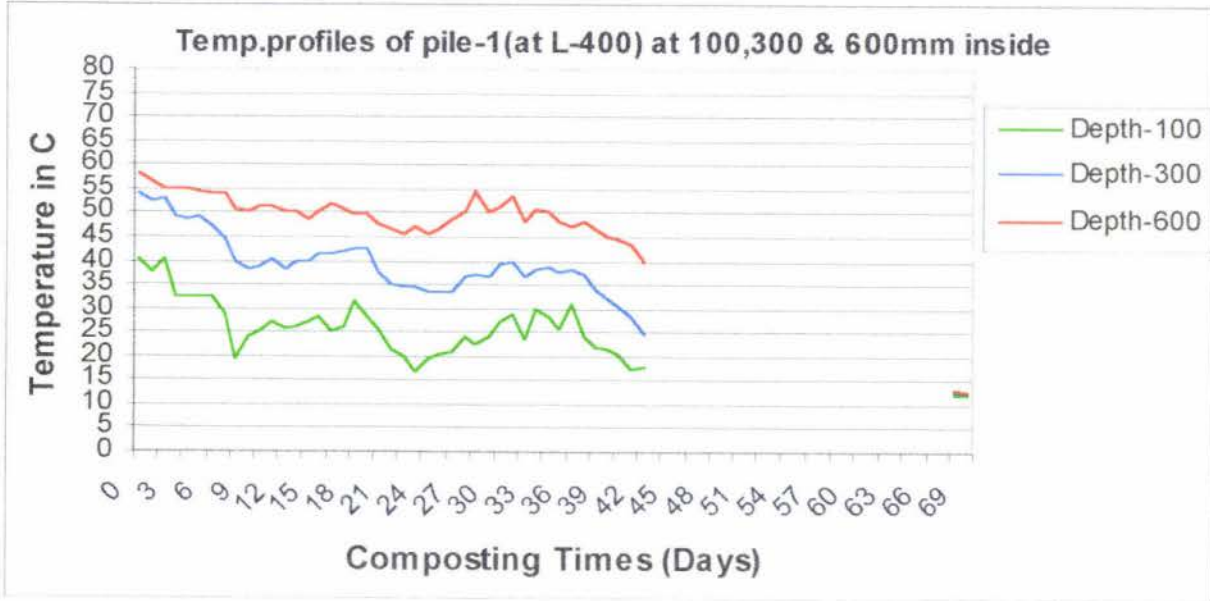


Fig.J.1 Temperature profiles (pile-1 of Experiment-I) at 100, 300 & 600mm inside from front edge of pile (at Level-400mm above pile base).

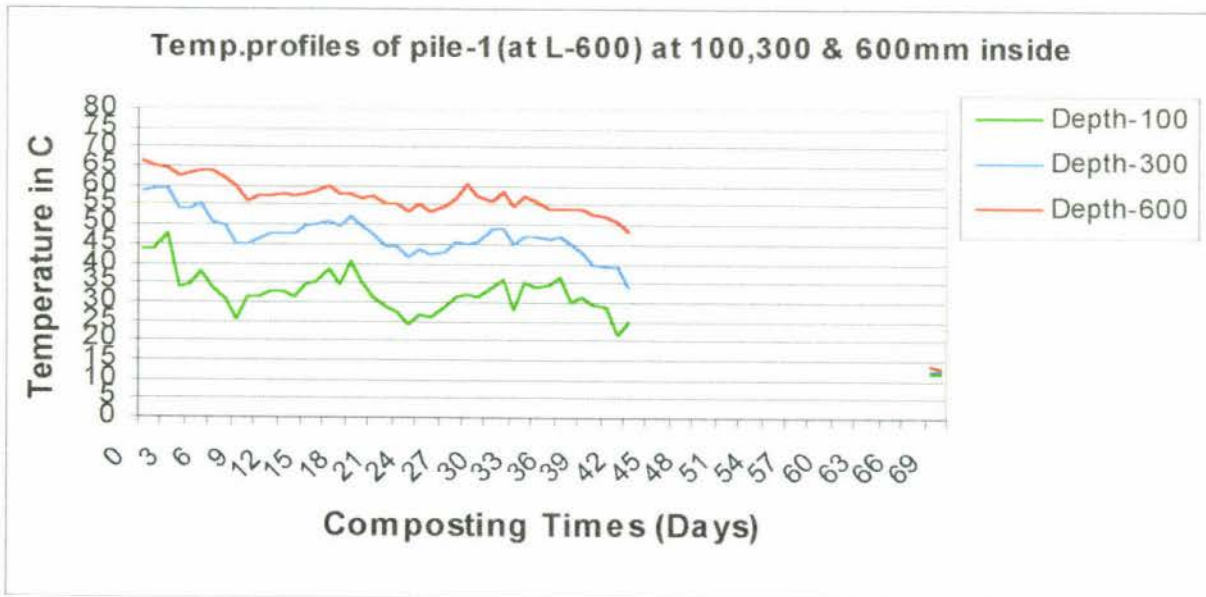


Fig.J.2 Temperature profiles (pile-1 of Experiment-I) at 100, 300 & 600mm inside from front edge of pile (at Level-600mm above pile base).

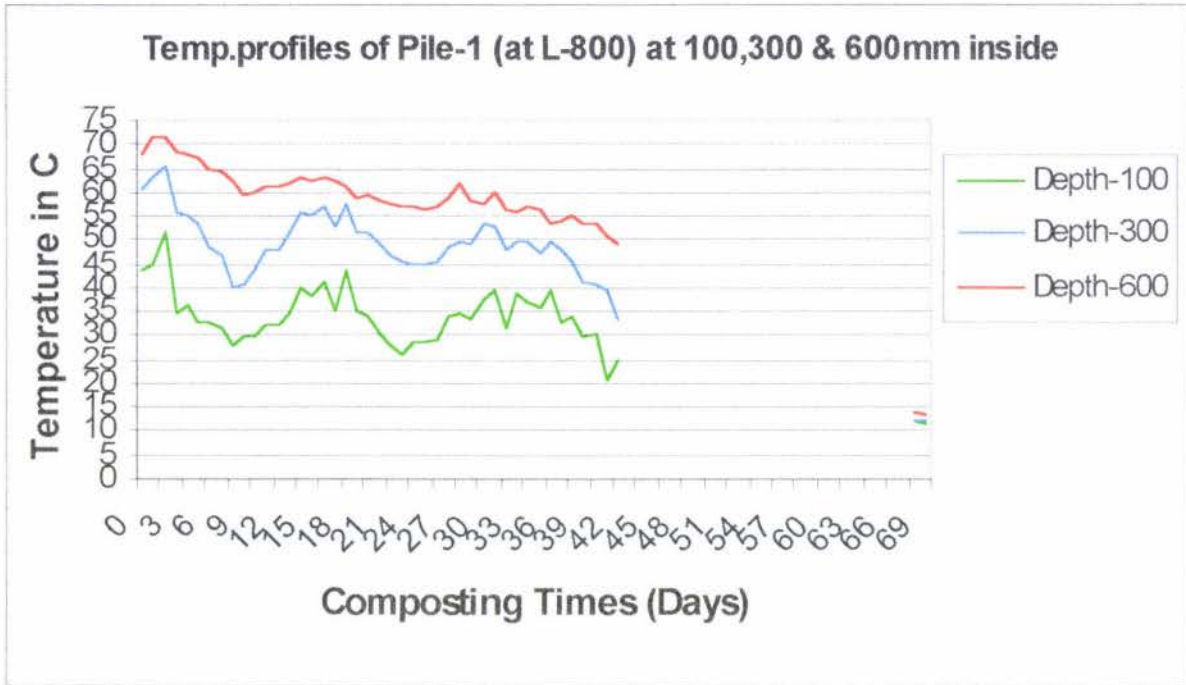


Fig.J.3 Temperature profiles (pile-1 of Experiment-I) at 100, 300 & 600mm inside from front edge of pile (at Level-800mm above pile base).



Fig.J.4 Temperature profiles (pile-1 of Experiment-I) at 100, 300 & 600mm inside from front edge of pile (at Level-1000mm above pile base).

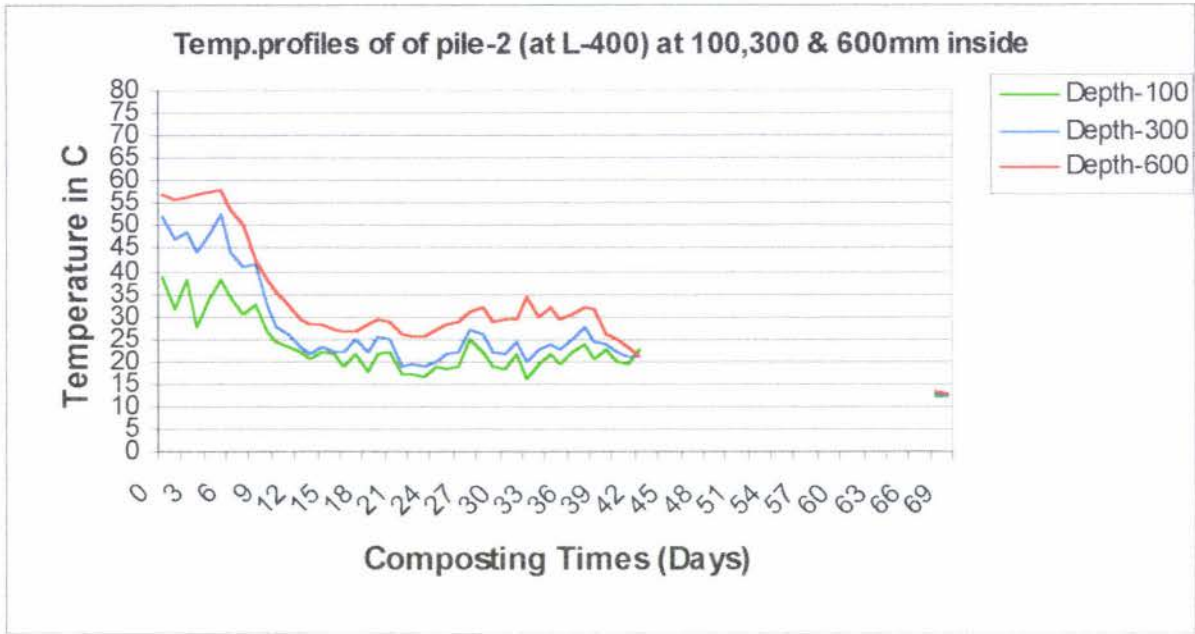


Fig.J.5 Temperature profiles (pile-2 of Experiment-I) at 100, 300 & 600mm inside from front edge of pile (at Level-400mm above pile base).

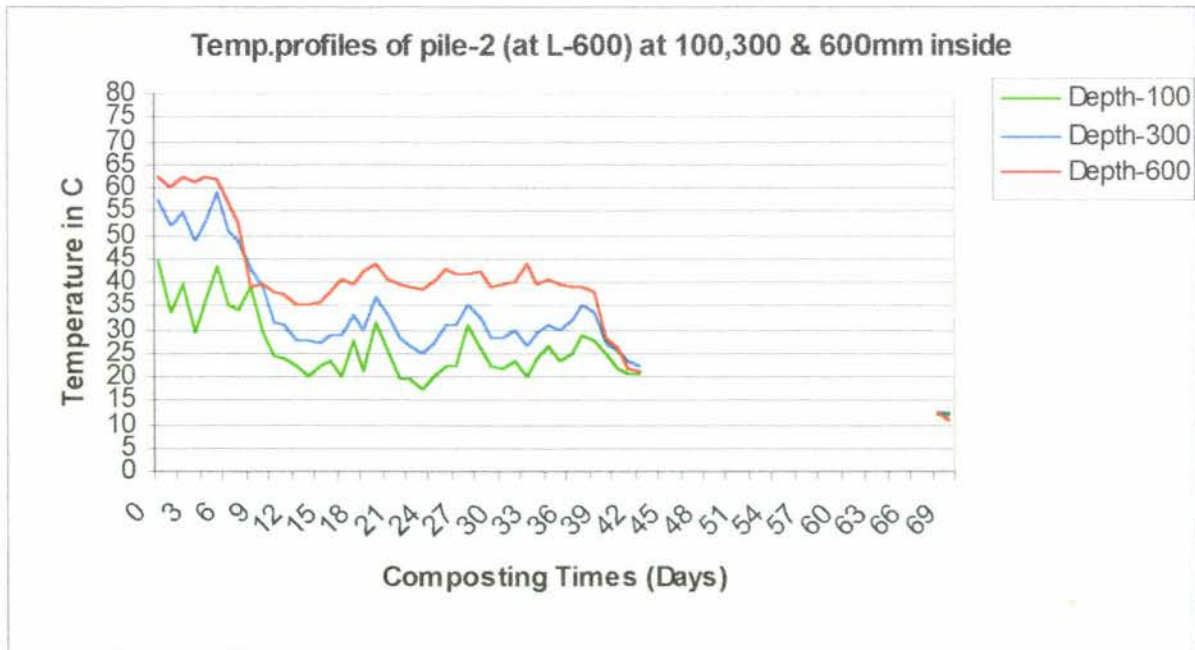


Fig.J.6 Temperature profiles (pile-2 of Experiment-I) at 100, 300 & 600mm inside from front edge of pile (at Level-600mm above pile base).



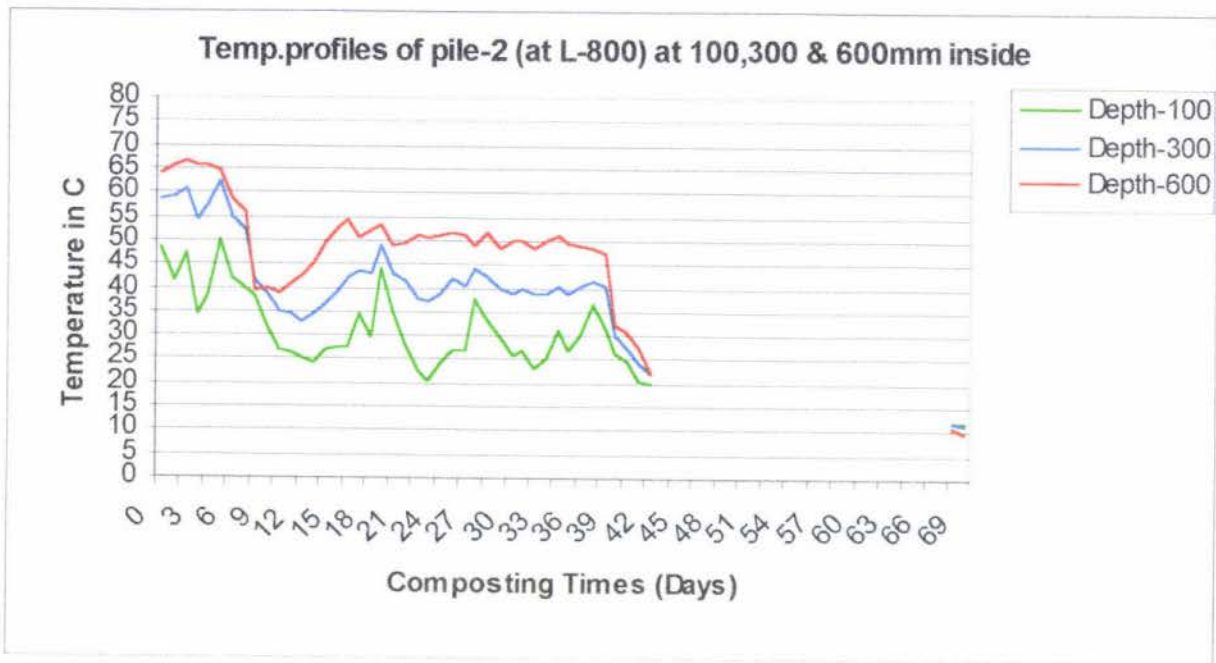


Fig.J.7 Temperature profiles (pile-2 of Experiment-I) at 100, 300 & 600mm inside from front edge of pile (at Level-800mm above pile base).

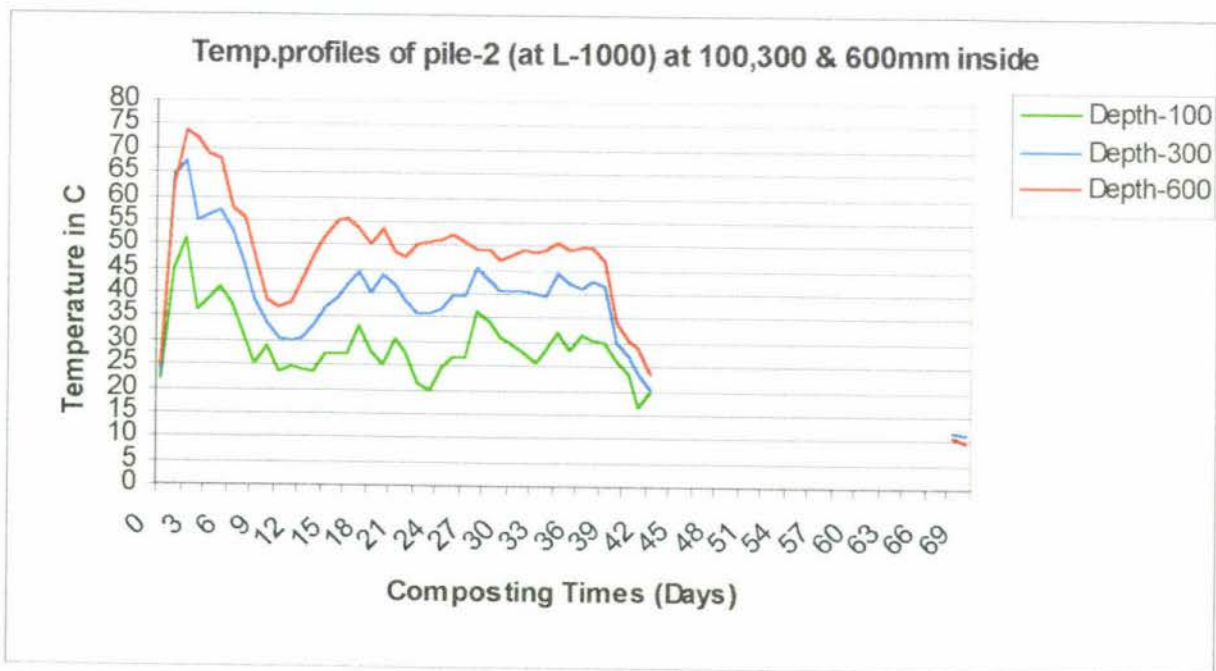


Fig.J.8 Temperature profiles (pile-2 of Experiment-I) at 100, 300 & 600mm inside from front edge of pile (at Level-1000mm above pile base).

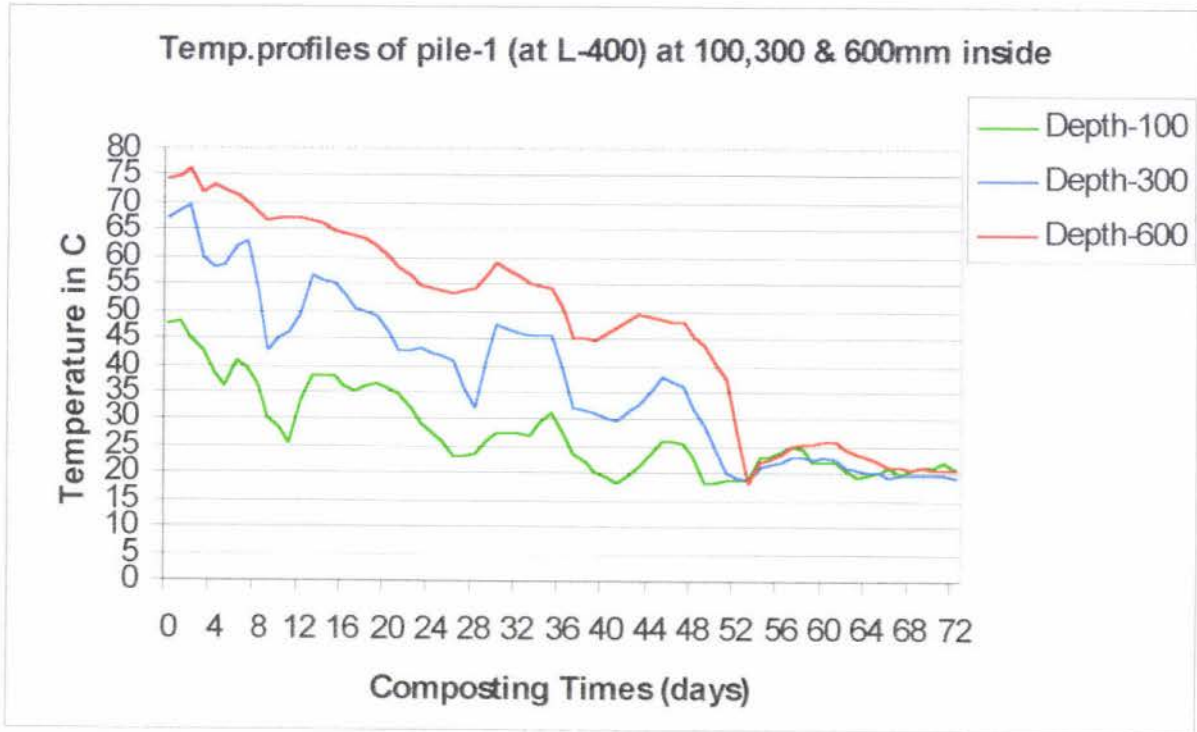


Fig.J.9 Temperature profiles (pile-1 of Experiment-II) at 100, 300 & 600mm inside from front edge of pile (at Level-400mm above pile base).

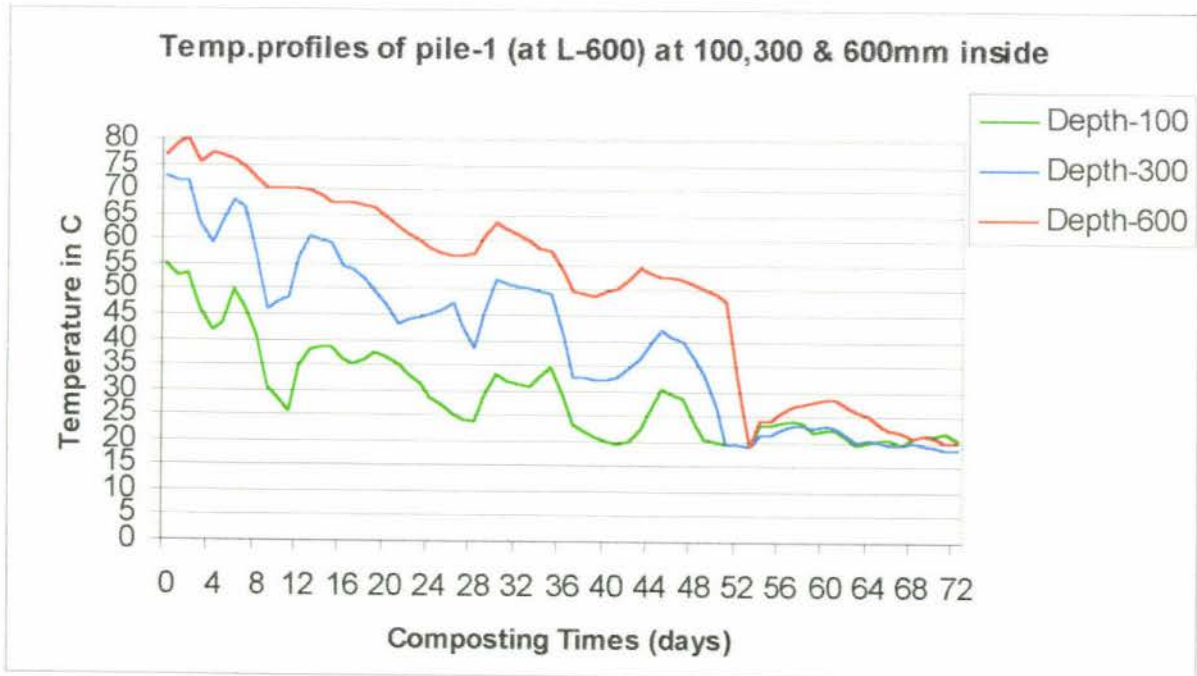


Fig.J.10 Temperature profiles (pile-1 of Experiment-II) at 100, 300 & 600mm inside from front edge of pile (at Level-600mm above pile base).

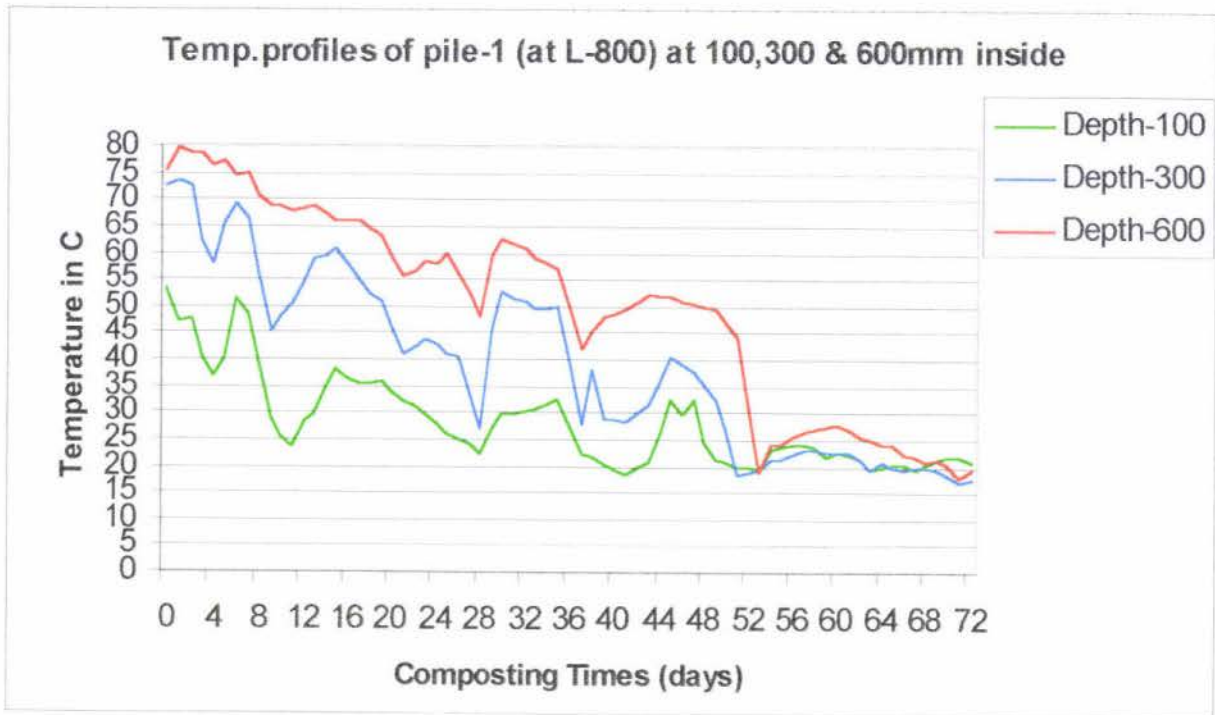


Fig.J.11 Temperature profiles (pile-1 of Experiment-II) at 100, 300 & 600mm inside from front edge of pile (at Level-800mm above pile base).

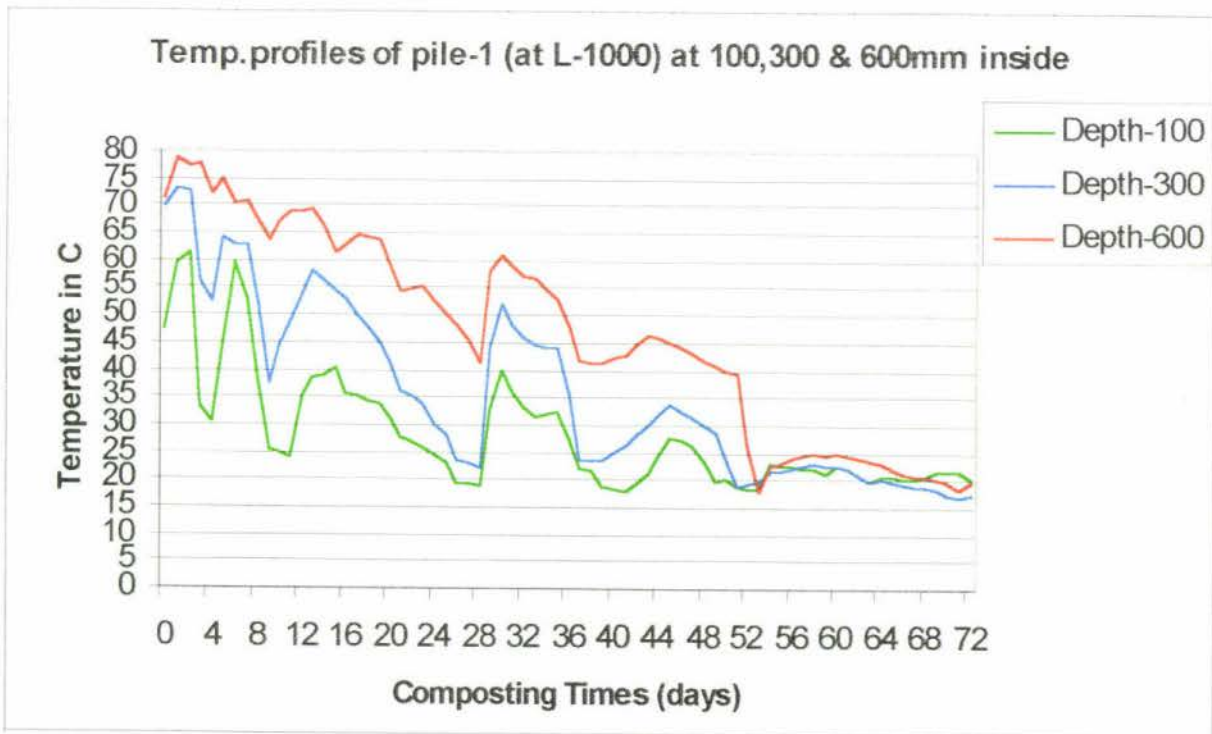


Fig.J.12 Temperature profiles (pile-1 of Experiment-II) at 100, 300 & 600mm inside from front edge of pile (at Level-1000mm above pile base).

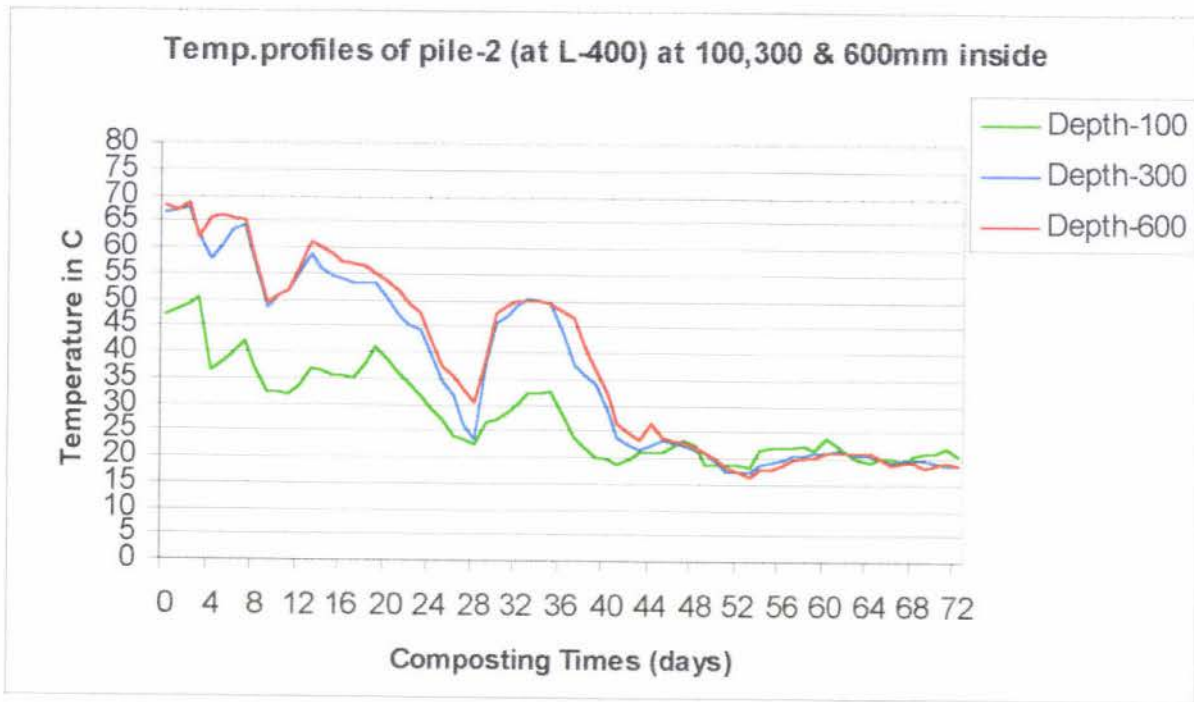


Fig.J.13 Temperature profiles (pile-2 of Experiment-II) at 100, 300 & 600mm inside from front edge of pile (at Level-400mm above pile base).

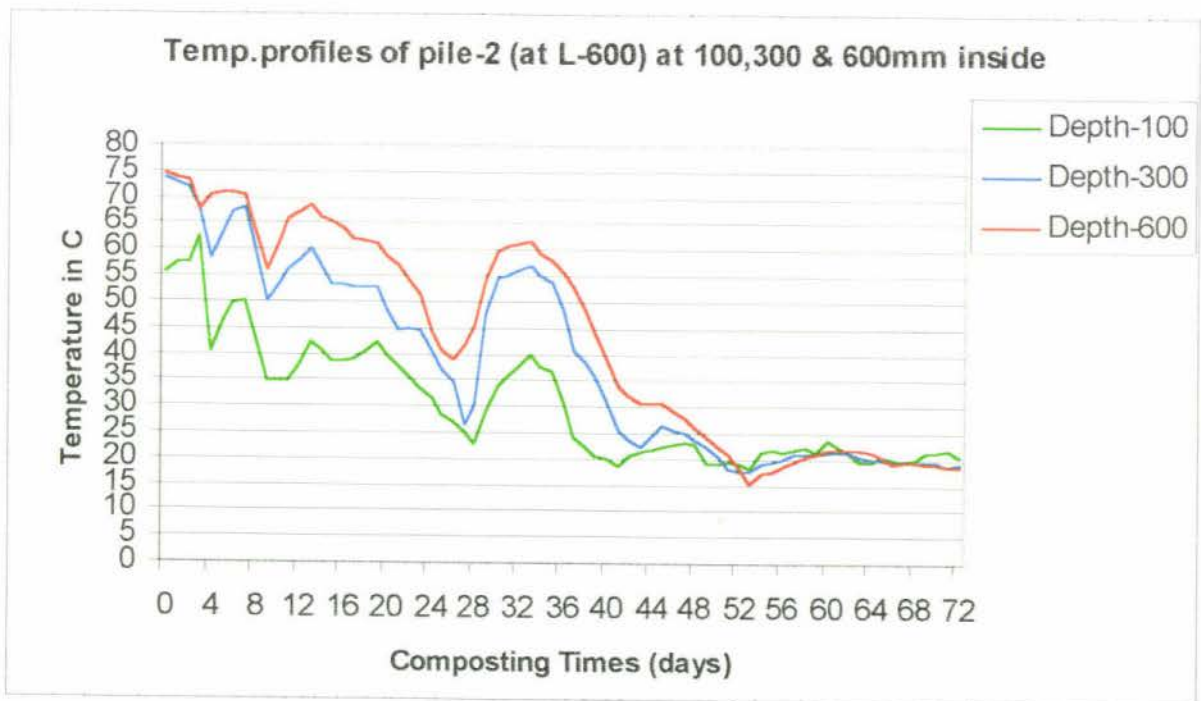


Fig.J.14 Temperature profiles (pile-2 of Experiment-II) at 100, 300 & 600mm inside from front edge of pile (at Level-600mm above pile base).

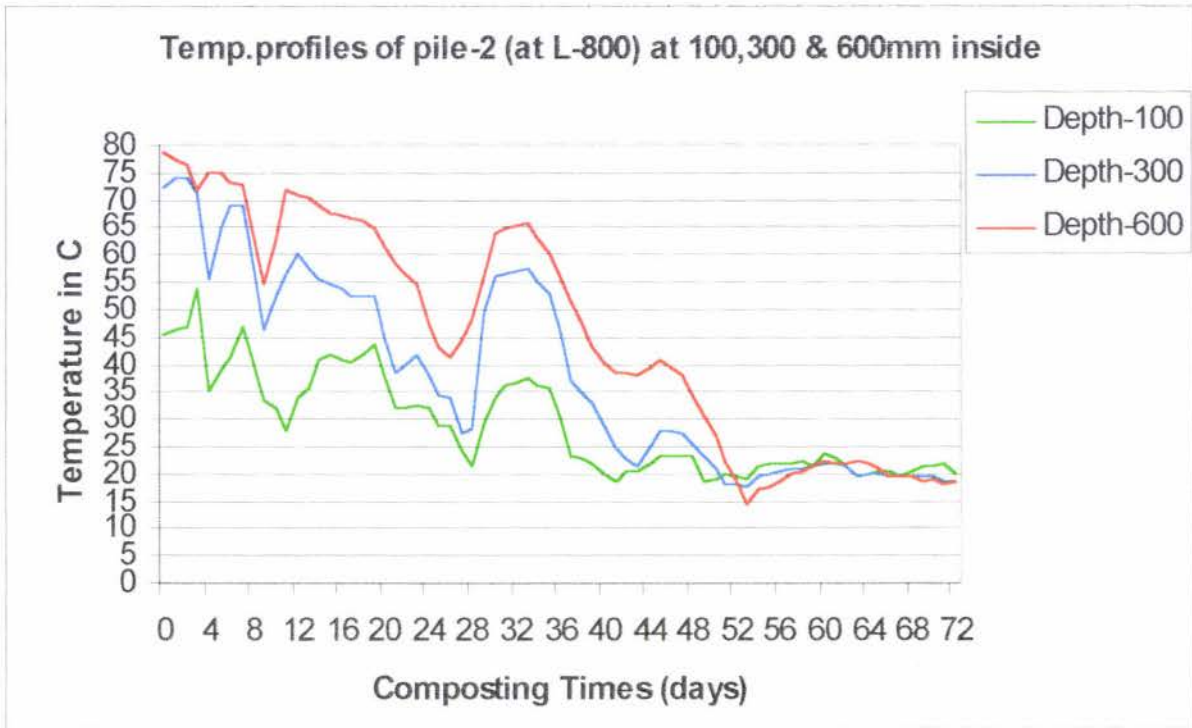


Fig.J.15 Temperature profiles (pile-2 of Experiment-II) at 100, 300 & 600mm inside from front edge of pile (at Level-800mm above pile base).

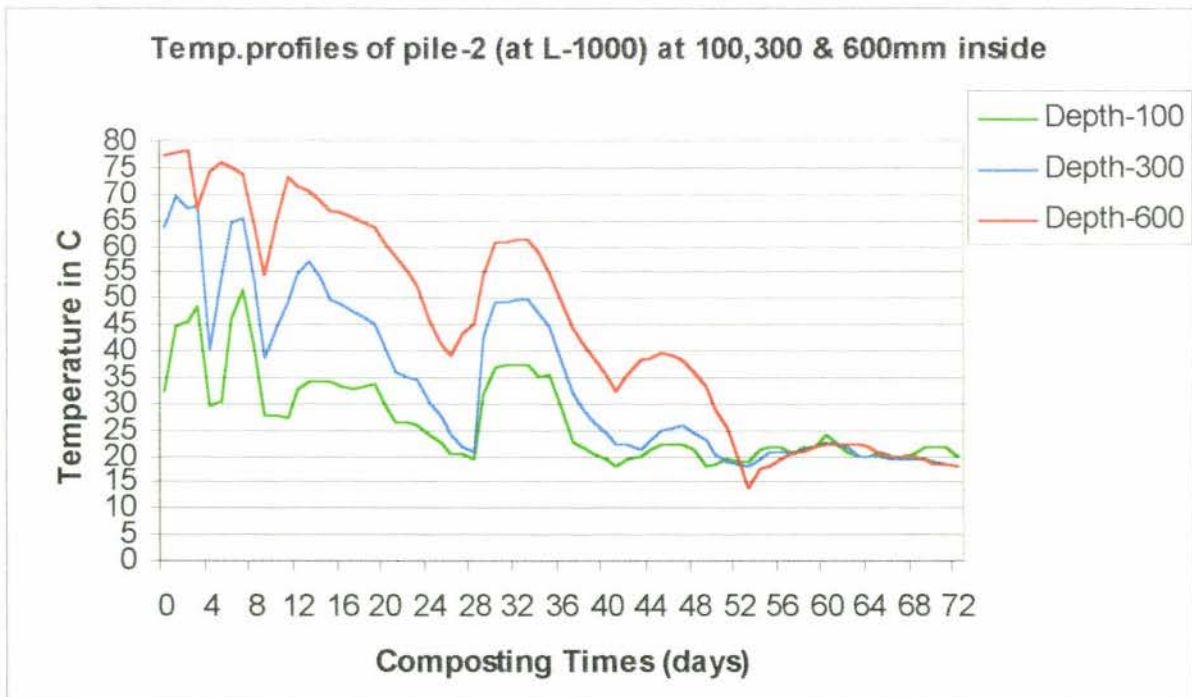


Fig.J.16 Temperature profiles (pile-2 of Experiment-II) at 100, 300 & 600mm inside from front edge of pile (at Level-1000mm above pile base).