SIMULATION OF THE SEWAGE SLUDGE COMPOSTING PROCESS

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ABSTRACT

Sanitary sludge composting is a biological degradation in the presence of air and at high temperatures (above 45°C) of the organic substrates present in the solid residues obtained during wastewater treatment. This process requires the use of a bulking agent to give structural stability and increase the porosity of the resulting mixture, contributing also to the nutrients balance. In this work, the effect of different types of bulking agents, locally available in Puerto Rico, on the performance of the process was studied. Woodchips from local, fast-growing tree (African tuliptree) and shredded spent rubber tires were used as bulking agents. The effect of temperature control of the process was also studied. In some experimental runs the temperature was allowed to spontaneously reach high levels (above 75°C), while in others it was maintained under 60°C by increasing the rate of aeration.

Four experimental trials were carried out. The one using woodchips as bulking agent and temperature control showed the best performance based on the percent reduction of the volatile solids accomplished. From a statistical analysis of the results obtained, the most significant variable, of the two considered, was temperature control. The type of bulking agent used did not prove to be a significant variable, as long as it satisfies the requirements of humidity and porosity inherent to the process.

Even though the characteristics of the sludge used were highly variable, the heavy metal content of the finished compost was always low enough to render it a product useful for agricultural applications.

It was found that approximately 75% by weight of the finished compost could be separated from the final product and recycled as bulking agent. Further studies should be undertaken to investigate the effect of using recycled compost as bulking agent on the process performance.

COMPENDIO

El proceso de composta es una descomposición biológica, aerobea, de los substratos orgánicos presentes en los lodos, resultantes de las plantas de tratamiento de aguas servidas, a temperaturas termofílicas (>45°C). Este proceso utiliza un agente de volumen para aumentar la porosidad de la mezcla resultante, y ayudar al balance de nutrientes (nitrógeno, fósforo, potasio). En esta investigación se estudió el efecto del tipo de agente de volumen en el rendimiento del proceso de composta. Los agentes de volumen utilizados fueron madera triturada y goma de carro picada. La madera triturada era del árbol tulipán africano. También se estudió el efecto del control de temperatura en el proceso. El control de temperatura significa el no dejar que la temperatura de la mezcla del lodo y el agente de volumen pase de 60°C. Se hicieron pruebas con y sin este control de temperatura.

De las cuatro pruebas realizadas, la de madera triturada con control de temperatura obtuvo el mayor rendimiento basado en el porciento de cambio en los sólidos volátiles. Del análisis estadístico se desprende que el factor más importante , de los dos estudiados, era el control de temperatura. El agente de volumen utilizado demostró no ser un factor significativo, si éste cumple con las condiciones de contenido de humedad y porosidad necesarios para el proceso.

A pesar de la gran variabilidad en las características del lodo utilizado (Planta Regional de Aguas Servidas de Barceloneta), el contenido de metales pesados fue bajo y no fue impedimento para la utilización del producto final.

Un 75% por peso del producto final puede ser recirculado. Es necesario realizar estudios acerca del rendimiento del proceso utilizando recirculado.

Es recomendable realizar estudios acerca del coeficiente de degradabilidad del lodo y del agente de volumen, lo que haría posible el desarrollo de una simulación para el proceso a nivel de laboratorio.

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1. INTRODUCTION

Proper sewage sludge disposal in a manner that is environmentally acceptable, economically feasible and not hazardous to human health has been a problem in the United States and Puerto Rico. Some of the current disposal practices in which the wastewater treatment facilities are actually engaged include landfilling, incineration and ocean dumping, being landfilling and incineration the most utilized.

These disposal options present advantages and disadvantages which have to be carefully studied before selecting a sludge disposal alternative for a wastewater treatment facility. All disposal options must comply with the continuously changing state and federal regulations.

Landfilling is "a sludge disposal method in which sludge is deposited in a dedicated area, alone or with solid waste, and buried beneath a soil cover"[58]. A significant portion of the wastewater sludge generated in the United States and Puerto Rico is disposed by this method. During landfilling, anaerobic degradation may occur due to insufficient amount of oxygen available for the aerobic degradation of the putrescible matter of the sludge. This anaerobic degradation would create an odor problem, and also groundwater contamination could occur. This contamination could be too difficult to detect even long after the damage has occurred.

Another disposal option, incineration, is the burning of volatile materials in sludge solids in the presence of oxygen. This option reduces the sludge to a compact residue and eliminates some potential environmental problems by completely destroying pathogens and degrading many toxic organic chemicals. But being a highly mechanized process, it is subject to varying sludge specific gravity and quantity, equipment failure, and operator error. It can also be a large energy demanding process if the incinerated sludges have a high moisture content.

In ocean dumping, wastewater sludge is released into the ocean, either from vessels or through outfall pipes. When this disposal option is conducted in areas close to shore, it can degrade near shore and shoreline environments. On December 16 of 1987, the Merchant Marine and Fisheries Committee of the United States House of Representatives approved an amendment that would forbid the Environmental Protection Agency from issuing any permits for ocean dumping of sewage sludge after December 31 of 1991 [50].

The disadvantages of the above options, together with an increase in population and a reduction in the land space available, have contributed to the development of new, efficient, economic and environmentally sound methods of disposal.

One example of such methods is composting. Composting transforms raw sludge into an "aesthetically pleasant soil conditioner devoid of objectionable odors and containing insignificant levels of pathogenic organisms" [21]. Some of the advantages of composting over the above sludge treatment options are: lower energy requirements and capital investment than incineration, and a more productive beneficial use of the sludge than in landfilling or ocean dumping. Unlike incineration, landfilling, and ocean dumping, composting offers a means of recovering a resource and productively using the sludge [57].

Although composting is rapidly becoming an attractive option for stabilizing sewage sludge, the largest obstacle to widespread adoption of this process in Puerto Rico is the lack of information about the local availability of suitable materials to be used as bulking agents. Thus, one of the objectives of this investigation was to evaluate the performance of various potential bulking agents and combinations thereof.

Two different bulking agents were used; woodchips from the African tuliptree (Spathodea campanulata, a fast growing tree) and shredded rubber tires. In Puerto Rico, the African tuliptree is considered as a plague with no beneficial use . Also, due to the great number of cars, disposal or utilization of worn-out tires is a severe problem. Utilization of these bulking agents would help to solve part of the above problems.

Through the years, different types of composting processes have been developed. These processes try to improve the quality of the final product and to reduce the composting time. One of the most recent developments, the "Rutgers Strategy" [11], involves positive airflow to the composting mass, and temperature control which reduces the composting time to 3 weeks, obtaining a more completely degraded product. In this investigation, the composting process performance with and without temperature control is compared to determine optimum operating parameters for utilization of the process in Puerto Rico using locally available bulking materials.

The Puerto Rico Aqueduct and Sewer Authority is going through a difficult situation concerning the proper management and operation of the wastewater treatment plants including disposal of the sludges produced [50]. At this moment, two wastewater treatment plants, in Mayagüez and Arecibo [18], are in the design/bid process for implementation of the composting process. Little research has been carried in this area in Puerto Rico. The result of this research will help in the proper implementation of the composting process for sewage sludge in Puerto Rico.

2. LITERATURE REVIEW

2.1. DEFINITION OF COMPOSTING

There is not a unique definition for the term composting. One of the most complete definitions is the one presented by Roger T. Haug (1980), who defines composting as "the biological decomposition and stabilization of organic subtrates under conditions which allow the development of thermophilic temperatures as a result of biologically produced heat, with a final product sufficiently stable for storage and application to land without adverse environmentals effects" [21]. The final product, compost, is an ideal soil conditioner because of its nutrient content, porosity and water absorption capacity. Also, since most of the putrescible materials had been degraded in the biological decomposition, the remaining organic matter is available for decomposition at a lower rate by the soil organisms and plants. For wastewater sludge composting, dewatered sludge is mixed with a bulking agent, such as woodchips, shredded tires or previously composted sludge. The objective of the bulking agent is to lower the moisture content of the mixture, providing structural stability and porosity, and contributing to the nutrient balance.

2.2. HISTORY

Composting is one of the oldest waste treatment methods known to man. The oldest reference to composting related to the use of manure in agriculture was found in a set of clay tablets of the Akkadian Empire, who inhabited the Mesopotamian Valley a thousand years before Moses[41]. In the Bible, at Luke 13:8, there is a direct reference to the utilization of manure as a fertilizer : In answer, the man said, 'Sir, leave it another year, while I hoe around it and manure it ...'. In the 18th century, the first report of composting in the United States was made; an entry on April 14, 1760 in George Washington's diary mentions a compost of stable manure and soil [41]. By the 19th century, composting was known to most farmers. In the 1850's, Samuel Johnson, professor of Analytical and Agricultural Chemistry at Yale College and second director of the Connecticut Agricultural Experiment Station (1877 - 1900) wrote a book titled Essays on Peat, Muck, and Commercial Manures [32,41]. This book contained a chapter describing the different composting practices in Connecticut. By that time, most of the compost was prepared "by rotting 1 part stable manure with 2 or 3 parts of soil"[40]. The book also mentions that some compost was commercially available from the Liebig Manufacturing Company of East Hartford [40].

The first studies in composting were made by Sir Albert Howard, a British government agronomist. Howard was stationed in India from 1905 to 1934, were he developed the Indore method. In this method, refuse material, night soil and sewage sludge were alternated in layers, creating a pile not to exceed 5 feet in height [41]. The pile was turned over twice and composting was completed in 3 months [40].

Howard's studies mark the beginning of a new era in composting. New researches made modifications to the classical composting methods, trying to improve the process performance. By 1953, the Sanitary Engineering Department of the University of California at Berkeley published a booklet entitled Reclamation of Municipal Refuse by Composting [41]. This booklet established a method for aerobic composting of municipal refuse which helped the development of composting as a sewage sludge treatment method [40].

By the 1970's, the United States Department of Agriculture's Beltsville Agricultural Research Center developed a composting process known as the Beltsville Aerated Pile Composting Method. This method contributed to the acceptance of the composting process by regulatory agencies:

2.3. TYPES OF PROCESSES

Three different types of methods of composting have been developed in the United States. They are windrow composting, aerated pile composting and in-vessel composting.

Windrow composting is considered to be the oldest "sludge only" composting system, utilized since 1972 by the Los Angeles County Sanitation District to compost approximately 90 dry ton/day of digested, dewatered sludge cake [21]. In windrow composting, the sludge-bulking agent mixture is formed into long, open-air piles. The mixture is turned frequently to ensure an adequate supply of oxygen throughout the pile and to ensure that all parts of the pile are exposed to temperatures capable of killing all pathogens and parasites [58]. In general, windrow composting is low in cost, but can be a land-intensive operation.

In the aerated or static pile method (Figure 1), the sludge-bulking agent mixture is formed in rectangular piles that are supplied with air by blowers connected to perforated pipes located under the piles, assuring an even distribution of air throughout the pile [58]. This method had been studied extensively by the U.S. Department of Agriculture in Beltsville, Maryland; at Rutgers University, New Jersey; at Ohio State University and at the University of California at Berkeley. By 1985, an estimated 90% of

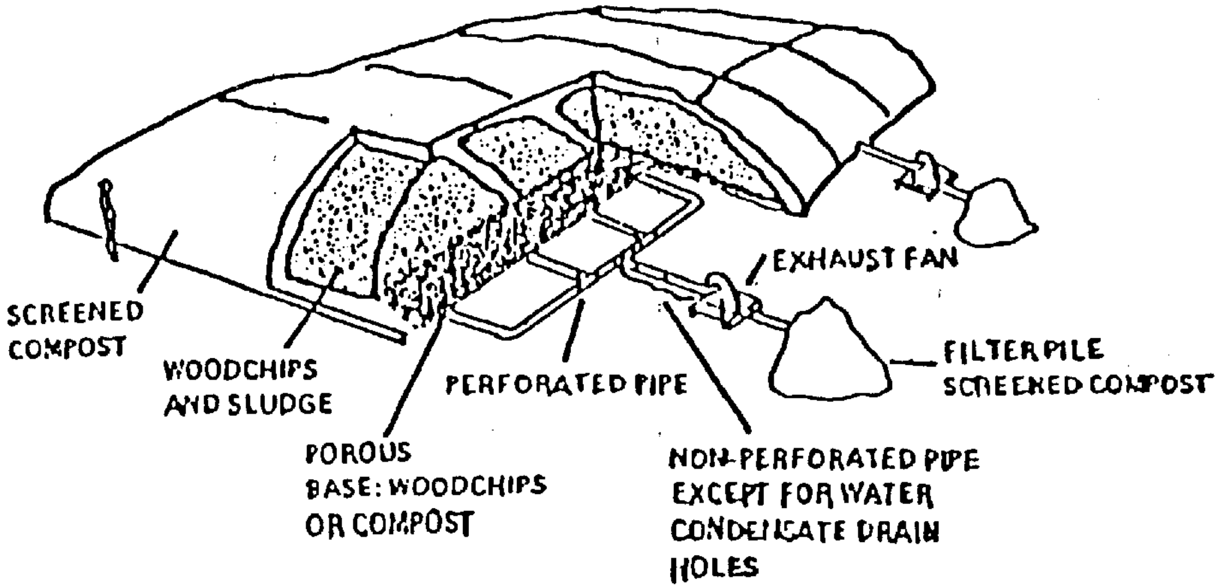

Figure 1: Aerated or Static Pile Method [65]

the 115 sludge composting facilities operating in the United States were using the static pile composting process [57].

The most recently developed method, in-vessel composting (also known as mechanical or enclosed reactor system) takes place in completely enclosed containers, in which conditions such as temperature, air flow and oxygen concentration can be monitored and controlled to minimize odors and process time. This process has higher capital costs than the above options. Because of the specialized mechanical systems used, there are process delays and higher maintenance costs during breakdowns [57]. This method is often used in municipalities with cold climates or where land is limited [58].

2.4. BENCH-SCALE RESEARCH

Many bench-scale research had been conducted trying to find the relation between the different variables affecting the composting process and its performance.

One of the first bench-scale studies of the composting process was made by K.L. Schulze. In an article in 1962, he studied the aerobic decomposition of mixed organic waste materials in the thermophilic temperature range under continuous operation [44]. He developed a bench-scale composter which consisted of a closed rotating Plexiglass cylinder, 10 in. in diameter and 19 in. long, which was used to establish quantitative data for the relationship between oxygen consumption, temperature and moisture content, using as the feed material a mixture of garbage and dewatered sludge cake [44]. From the experiments, he found that the oxygen consumption rate increased directly with temperature between 27°C and 63°C. From a regression of a logarithmic plot of the oxygen consumption rate versus temperature, he determined the following relation:

$$W_{O_2} = 0.10 \quad (1.066)^T \qquad 2\text{-}1$$

where W_{O_2} is the rate of oxygen consumption, in mg O_2/g volatile matter-hr and T is the temperature in °C. He also found that the activity of the composting process, as measured by the oxygen consumption rate, increased directly with the moisture content from a minimum of zero at a moisture content below 20% to a maximum at a moisture content of 60%.

By 1973, John S. Jeris and Raymond W. Regan finished a four year bench-scale study trying to control different environmental parameters to develop an optimum solid waste composting process [27,28,29]. Mainly, they studied the effect of paper content in the composting process, taking into account the following parameters: temperature, moisture content, free air space, paper content, detention time, recycle, pH and nutrients. They used different waste materials like newsprint, typical municipal refuse containing 60% to 70% paper, and composted refuse. They found that "for freshly collected municipal refuse, containing 60% to 70% paper, an optimum composting rate of 3.7 to 4.5 mmole of CO2 produced was measured at 59 ± 5 °C " [29]. Also "the optimum moisture content and free air space for composting typical mixed refuse were 67% and 30% respectively" [29]. By using controlled conditions, they found that maximum composting rates were obtained at a pH of 7.5 to 8.5.

From 1972 to 1976, C. Stuart Clark, Charles O. Buckingham, Derek H. Bone and Reginald H. Clark developed a "definable laboratory system for composting which would produce data sufficiently precise for research work" [7]. This laboratory system tried to improve on the low degree of reproducibility observed in past studies. They developed a synthetic garbage to reduce the differences due to the great variations in feed materials. The synthetic garbage was designed taking into account the approximate composition of domestic solid wastes in North America. The developed laboratory system is illustrated in Figure 2. In the laboratory test, they used CO_2 evolution to measure the biological activity. A high degree of reproducibility was achieved due to the controlled aeration system called "Impulse Aeration" [7]. This system is based on periodically removing, by partial evacuation,

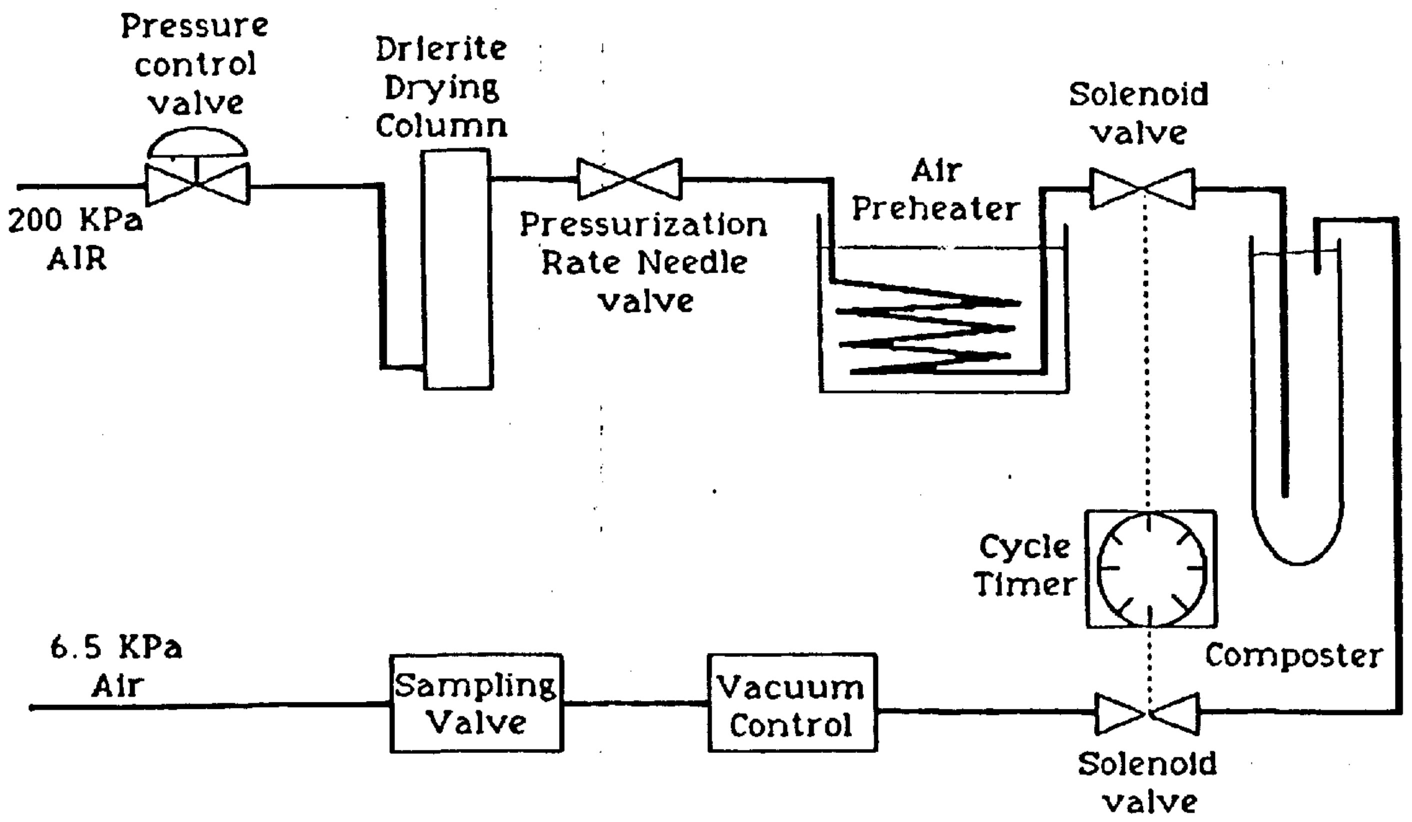

Figure 2 : Laboratory Composter by C. Stuart Clark (6)

most of the composting atmosphere and replacing it with fresh air from a preheated reservoir.

By 1976, D.J. Suler and M.S. Finstein studied the effect of temperature, aeration and moisture content on the CO_2 formation in bench-scale, continuously thermophilic composting of solid wastes [56]. Continuously thermophilic composting is a process in which fresh incoming material is boosted immediately into the thermophilic temperature range by the heat of the existing compost. This new material displaces a like volume of the oldest compost. They used the CO_2 formation as the parameter to measure compost activity. The waste material utilized was table residues from a student dinning facility, 92% of which was volatile matter. The experiments were conducted in a 96 hour period, approximately the retention time at a full-scale continuously thermophilic solid-waste composting installation. A high O_2 consumption was observed during the first day of the experiments. The ~~moisture~~ content also increased slightly during the experimental period. They observed that at higher temperatures (72°C), relatively acidic conditions appeared (pH=6.0), and little CO_2 was formed. They also found that a maximal formation of CO_2 was observed at a moisture content of 60%. They concluded that the optimum temperature for composting, based on CO_2 formation, was in the range of 56 to 60°C. They established that an optimum temperature may vary with different wastes, but it is certainly lower than the maximum that can be attained.

In 1977, Gudrum Bågstam from the Royal Institute of Technology in Stockholm, Sweden, finished a study in the composting of spruce-bark together with sewage sludge [5]. The feed mixture consisted of ground and screened spruce-bark and dewatered, aerobically stabilized sludge from a sewage treatment plant, which was equivalent to a dewatered fresh sludge. He made 13 experimental runs to determine parameters like the oxygen supply (depending on aeration and mixing of the material by rotation of the composter), temperature and moisture content of the material, the sludge/bark ratio and the influence of the pH level in the material. From the nitrogen balance, he determined that in a mixture containing 30% (dry weight) sludge, there was a loss in the nitrogen in the form of ammonia. An optimum range of sludge content was from 20 to 25% of dry weight. He established an optimun moisture content of 70 to 73%. At a moisture content higher than 74%, there was a decrease in the decomposition rate. He obtained a maximum decomposition rate in the composting of bark-sludge with an air flow of 60 l/hr, and the highest decomposition rate at 35 °C during the first 36 hr, followed by 45 °C during the next 5 days at 55 °C thereafter. He concluded that a sludge content of 30% dry weight resulted in low CO_2 production. This slow decomposition rate was due to the high moisture content in the initial mixture. He observed that a decrease in the sludge content from 30 to 20 % dry weight accelerated the decomposition rate. Also, in experiments with pH-adjustment at a sludge content of 20% dry weight an increase in the CO_2 production was observed.

By 1979, a group from the Université de Technologie in France developed a bench-scale reactor to study the "effects of different nitrogen additives including calcium cyanamide in view of improving the composting of solid urban wastes" [9]. The group was composed by A.M. Deschamps, P.Henno, C. Penelle, L. Caignault and J.M. Lebeault. The reactor was constructed of polyvinyl chloride, air-tight and thermally isolated in which the metabolic activity of the microflora was followed by the evolution of temperature and CO_2 released. The height of the reactor was 90cm (35.4in) and a diameter of 30cm (11.8in). About 10kg of municipal waste could be composted in the reactor. In the experiments, about 24g of nitrogen were provided in each one with the use of different additives: "ammonium sulfate, urea, calcium cyanamide ($CaCN_2$) and Scoramide (trademark of a ternary fertilizer sold in France by Ets LHomme and composed of calcium cyanamide, phosphate and potassium)"[9]. They found that for urban wastes, calcium cyanamide or fertilizers like Scoramide, could be used in soils, "improving the development of thermophilic cellulolytic fungi and destroying most of the pathogenic bacteria" [9].

By 1981, N.J. Ashbolt and M.A. Line of the University of Tasmania in Australia, finished a study in the composting of organic wastes in which they designed a bench-scale system [2]. The bench-scale composter was designed to provide strict control over the air composition, moisture content, temperature, and mixing in the composting of the eucalyptus bark. The composter was made of PVC and consisted of six units, each one having a capacity of 4 liters provided with a mixing paddle. The whole unit was summerged in a water bath (Figure 3), for temperature control. The compost mixture consisted of "150g of eucalyptus bark, 15g of composted inoculum, 15.04 or 8.32g of thawed fish waste, and distilled water to give a moisture content of 68%". [2] They analyzed the production rates of CO_2, NH_3, CH_4 and H_2S and the O_2 consumption by means of gas chromatography.

L.J. Sikora, M.A. Ramirez and T.A. Troeschel published in 1982 the design of a laboratory composter for use in studies "simulating the biochemical changes that occur during composting" [47]. The composter was a self-heating adiabatic unit consisting of a covered, double-walled, insulating tank; an air-tight cylinder; an inner screen mesh cylinder, which held the organic material with dimensions of 25cm height and 20cm diameter; a heater-circulator and a differential temperature control system. The mixture consisted of a raw, highly limed (pH = 11.0), filter cake sludge mixed with woodchips in a volumetric ratio of 1:1.8. Compressed

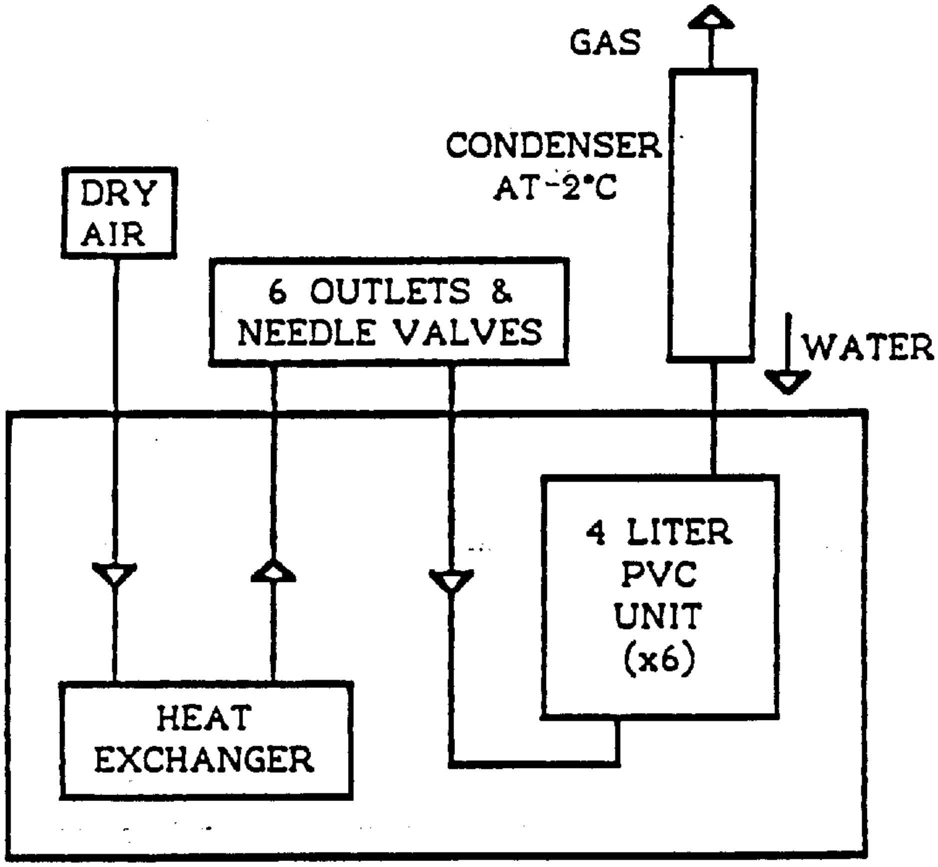

Figure 3: Scheme of the Bench-Scale Composter of Ashbolt & Line [2]

air, regulated at 74cm^3/min, passed through 1N H_2SO_4 to remove NH_3, 2N NaOH to remove CO_2, water for humidification to maintain aerobic conditions without drying the mixture, and a heat exchanger submerged in the water bath before entering the cylinder. After leaving the cylinder, the air passed through a condenser, a 1N H_2SO_4 trap to capture NH_3 and a 2N NaOH trap to capture CO_2. They established that variables, such as the aeration rate, oxygen levels, moisture content and temperature, could be studied using the designed laboratory composter. In the experiments performed, the mixture lost 33% of its wet weight and 9% of its dry weight after 49 days. Also, about 6 to 10% of the total nitrogen was lost.

By 1985, N.H. Frankos, F. Gouin and L.J. Sikora finished a study to determine if woodchips " of a specific low density tree species would improve the composting process performance by eliminating the screening after the process, yield more compost, and possibly conserve nitrogen." [16]. They used five different species of trees characterized as fast growing and with low bulk densities and lignin content. In this study, they designed a laboratory composter which consisted of polyvinyl chloride (PVC) cylinder (15.2cm ID and 50cm height) with the mixture, inside of an alumimun cylinder (20.3cm ID and 61.0cm height). Thermocouples were installed inside the PVC cylinder in contact with the mixture, at different levels. Another thermocouple was located in the air space between the PVC cylinder and the aluminum cylinder. Compressed air at 75cc/min was passed through 1N H_2SO_4 to remove the NH_3, 2N NaOH to remove the CO_2 and through water to humidify the air before entering in the PVC cylinder. After leaving the cylinder, the gas passed through a condenser, 1N H_2SO_4 to trap the NH_3 produced and 2N NaOH to trap the CO_2 produced (Figure 4). The mixture used consisted of raw, lime stabilized sludge mixed with the woodchips at a volumetric 1:2 ratio and about 2 kg of the fresh mixture was packed into the PVC cylinder. They observed that the CO_2 and NH_3 production curves were typical for almost all the tree species tested. A drawback in the composter design was that the dome-shaped cap used collected the water vapor and resulted in a low moisture content reduction. From the material balance, they determined that about ⅓ of the original woodchips needed to be replaced for recycle, due to the decomposition and physical breakdown during the process. They also found that for the species tested, the woodchips did not degrade to the point in which the screening after the process could be eliminated, and that the nitrogen content of the final mixture was not significantly affected.

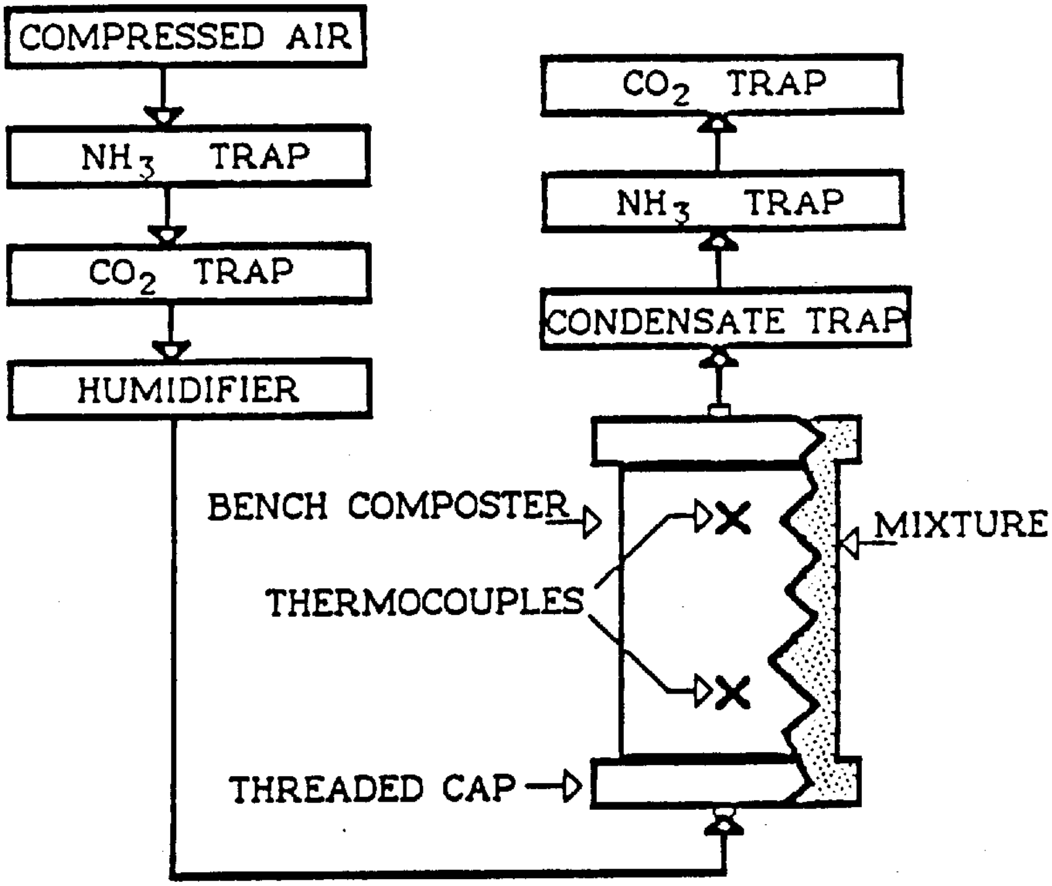

Figure 4: Air Flow Diagram of Bench Composter of Frankos, [16]

2.5. RESEARCH IN PUERTO RICO

In Puerto Rico, some studies have been developed to determine the feasibility of the composting process for the stabilization of sewage sludge.

By 1980, Toel E. Alpert, William Taffel and Eliot Epstein finished a study about the possibility of composting sewage sludge in Puerto Rico [1]. They made experimental trials and showed that a variety of bulking agents could be used and that the sludges can be effectively composted whether they were dry or wet, digested or raw. The scope of the study was divided into two phases; a field phase and an evaluation phase. In the field phase, they collected all the preliminary data related to the sludge and bulking agent, made eight different compost trials, performed compost market/utilization studies, and gathered the economic data related to the implementation of the process. In the evaluation phase they made a compilation of the findings of the field phase with a document for a possible implementation of the process by the Puerto Rico Aqueducts and Sewer Authority (PRASA).

As part of the preliminary data, they determined the physical properties (Table 1) and the metal content (Table 2) of the sludge from different sites in the southern part of Puerto Rico. Most of the sludge analyzed had a low moisture content, except for the Ponce raw sludge. They also identified various potential bulking agents (Table 3). Due to the low moisture content of the sludge,

TABLE 1 : Physical Properties of Sludges[1]

Sludge	Moisture (% of total)	Solids (% of total)	Organics (% of total)	Ash (% of total)	Annual Production (yd3/yr)
Ponce					
digested	7.8	92.2	29.6	70.4	2975
raw	73.1	26.9	43.4	56.6	
Adjuntas	42.6	57.4	45.8	54.2	113
Coamo	8.2	91.8	47.3	52.7	120
Guanica	7.3	92.7	39.6	60.4	66
Guayanilla	8.3	91.9	36.8	63.2	66
Peñuelas	4.0	96.0	19.5	80.5	36
Villalba	35.6	64.4	25.4	74.6	22
Yauco	29.8	70.2	46.2	53.8	336

[1] Table from [1]

TABLE 2: Sludge: Trace Metal Content (PPM dry weight)[1]

Sludge	Ca(%)	Cd	Cr	Cu	Hg	Mg(%)	Ni	Zn	Σ
Ponce									
digested	5.3	5.9	45	610	0.57	0.51	73	545	1295
raw	4.3	5.4	34	500	0.35	0.45	64	530	1040
Adjuntas	2.6	2.9	34	555	0.08	0.41	27	180	1140
Coamo	3.3	5.6	38	485	0.43	0.52	28	305	1510
Guanica	6.4	5.3	340	665	0.83	1.8	220	345	1635
Guayanilla	7.5	4.2	48	690	0.97	0.67	54	185	1295
Peñuelas	2.5	1.9	48	245	0.86	1.3	34	205	1035
Villalba	3.8	2.5	27	260	0.56	0.92	28	135	750
Yauco	3.7	4.8	110	515	0.63	1.2	97	260	1235
Santa Isabel	-	6.9	77	490	-	-	33	310	1750

[1] Table from [1]

TABLE 3: Potential Bulking Agents in Puerto Rico[1]

Bagasse
Rice hulls
Coffee hulls
Pineapple residue
Industrial solid wastes
Grass clippings
Plantain peels
Water hyacinths
Coconut shells
Wood shavings

[1] Table from [1]

bulking agents of high moisture content were used. For sludge, such as the Ponce raw sludge and the one used in this work, bulking agents with high moisture absorption capacity and which can provide structure and porosity to the mixture should be used to lower the moisture content and facilitate the proper aeration needed in the decomposition reaction. The metal content results showed in Table 2 do not limit the ability to compost the sludge or the commercial distribution of any of the compost produced.

From the experimental trials, the sludge used in Pile V (Table 4) had similar characteristics to the type of sludge used in this investigation. The chemical composition of Pile V compost is illustrated in Table 5. From the low values of nitrogen, phosphorous and potassium, the final product was considered a soil conditioner rather than a fertilizer due to its limited nutrient

TABLE 4: Test Pile V[1]

Composition:	Ponce raw wet sludge + bagasse Ratio 3:1, bagasse: sludge (v/v)
Volume (yd^3):	120
Aeration Rate:	6 min/hr

[1] Table from [1]

TABLE 5: Chemical Composition of Pile V Compost[1]

Soluble salts:	9,400
pH:	7.4
Ca(%):	3.1
Cd (ppm):	1.2
Cr (ppm):	26
Cu (ppm):	130
Hg (ppm):	2.0
Mg (%):	0.60
Ni (ppm):	39
Pb (ppm):	150
Zn (ppm):	220
P (%):	0.11
K (%):	0.13
N (wt %):	1.0

[1] Table from [1]

In the study, they compared the data for the total and fecal coliforms present in the sludge and compost samples for different regions (Table 6). They found a coliform reduction greater than 99% in most cases, which established the efficiency of the composting process for sludge stabilization.

TABLE 6: Pathogen Destruction During Composting of Puerto Rican Sludges'

	CFU''/g dry weight Coliforms			
	Total		Fecal	
Town	Sludge	Compost	Sludge	Compost
Guayanilla	≥3.3x10^{9}	1.1x103	6.0x104	<14
Peñuelas	3.4x109	5.9x103	7.2x106	<17
Guanica	<1x105	2.8x103	<1x103	<15
Adjuntas	≥5.3x109	3.0x102	>5.3x107	<16
Villalba	≥4.7x109	16	≥4.7x107	<16
Coamo	3.2x106	4.5x102	2.7x104	<12
Yauco	≥4.3x109	6.3x102	≥4.3x107	<14

'' CFU - colony forming units
' Table from [1]

They concluded that the composting of sludge in Puerto Rico was technically feasible and that the selection of the type of system and materials to be used depends on site-specific factors such as availability of bulking agents, available dewatering facilities, cost of transportation and equipment.

In 1983, Lorenzo Saliceti Piazza studied the method of aerated pile composting as a disposal alternative for the sludge produced by the Barceloneta Wastewater Treatment Plant [43]. At the time, there were doubts on the feasibility of composting the sludge from the Barceloneta Regional Wastewater Treatment Plant (BRWTP) because it could contain heavy metals and antibiotics in high concentrations proceeding from the different industries (mostly pharmaceutical) that discharge their effluents to this plant. These substances could inhibit or retard the biological activity in the composting process.

He conducted two full scale experiments using different bulking agents. In the first one, he used a mixture of sludge with bagasse (Table 7). The initial moisture content of the mixture was 75%, higher than the recommended of 60%. Also the C/N ratio was 15.51, lower than the 30 recommended; this low value caused the volatilization of the nitrogen. From the temperature profiles (Figure 5), the mixture was at a temperature of about 70°C in the second day of the composting cycle, and stayed over 55°C for the first 24 days; the experiment lasted 43 days.

TABLE 7: Analyses of Composting Experiment using Bagasse as Bulking Agent[1]

Analysis	Sludge	Bagasse	Initial Mixture	59 Days Mixture
Total Coliforms [MPN/g]	1,100	-	770	5
Fecal Coliforms [MPN/g]	1,100	-	770	0
Bulk Density, g/ml	1.04	0.11	0.37	0.11
% Water	87.83	45.49	75.22	54.97
% VS (dry basis)	73.30	92.23	85.72	80.32
% Carbon (dry basis)	40.72	51.24	47.62	44.62
% N (dry basis)	8.46	0.24	3.07	1.78
C/N Value	4.80	213.50	15.51	26.96
% Potassium (dry basis)	0.14	0.18	0.17	0.14
Total Phosphates ppm (dry basis)	1,251	4	433	27

[1] Table from [43]

In the second experiment, he used a mixture of sludge and rice straw (Table 8). The results were similar to the experiment made with bagasse. In Tables 7 & 8, it can be seen the great variability in the composition and amounts of total and fecal coliforms of the Barceloneta sludge. From the temperature profiles

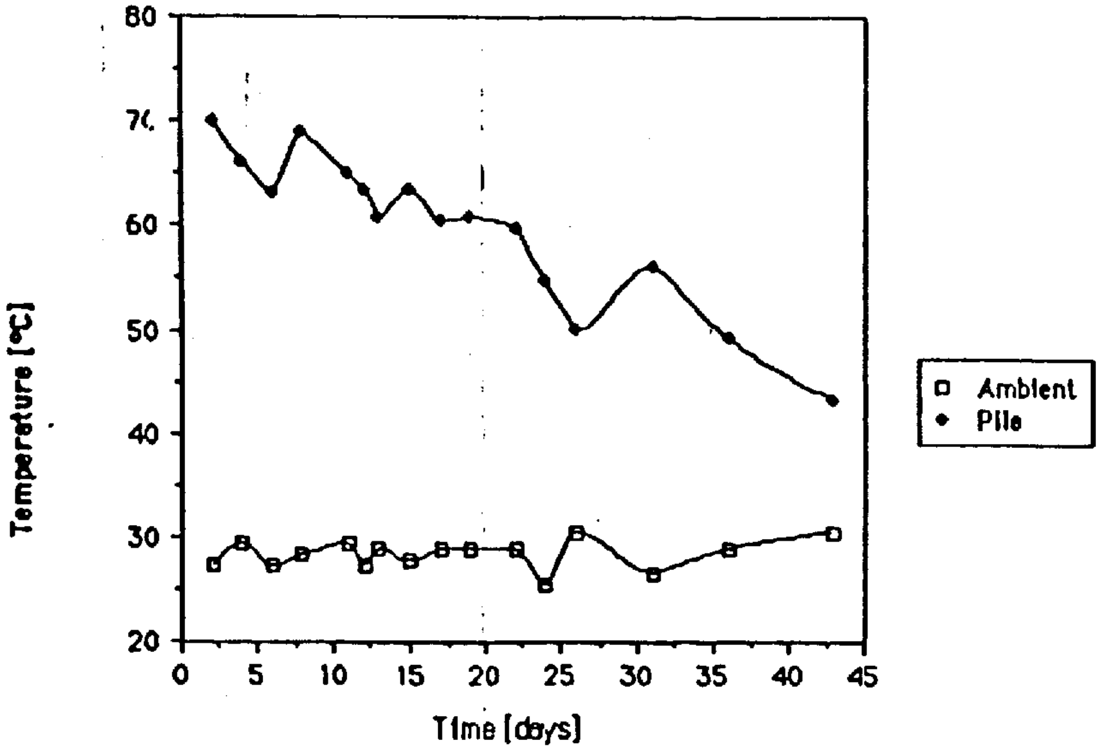

Figure 5: Temperature Profiles of Composting Experiment
Bagasse as Bulking Agent [43]

(Figure 6), the mixture started at a temperature of about 55°C in the second day of the composting cycle, and similar to the first experiment, stayed over 55°C for the first 28 days; the experiment lasted 59 days.

TABLE 8: Analyses of Composting Experiments using Rice Straw as Bulking Agent[1]

Analysis	Sludge	Rice Straw	Initial Mixture	95 Days Compost
Total Coliforms [MPN/g]	24,000	-	23,000	540
Fecal Coliforms [MPN/g]	24,000	-	23,000	0
Bulk Density, g/ml	0.64	0.014	0.33	0.30
% Water	81.65	15.85	78.80	50.90
% VS (dry basis)	78.69	78.26	78.62	58.37
% Carbon (dry basis)	43.72	43.48	43.68	32.43
% N (dry basis)	4.96	0.52	4.20	2.01
C/N Value	8.81	83.62	10.40	16.13
% Potassium (dry basis)	0.08	1.16	0.26	0.61
Total Phosphates ppm (dry basis)	1,454	204	1,240	269

[1] Table from [44]

He recommended that further "experiments with other mixing materials be conducted" [43], especially amending the mixture with a "particulate and degradable material to avoid high nitrogen loss" [43].

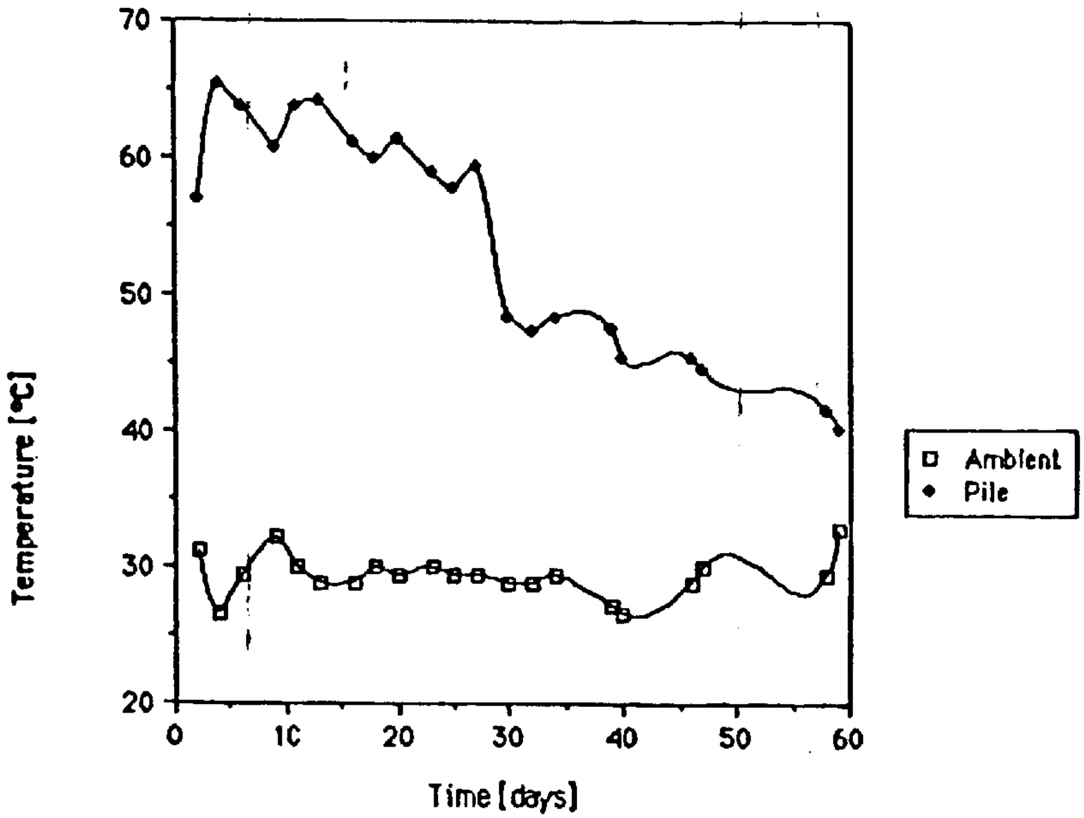

Figure 6: Temperature Profiles of Composting Experiment
Rice Straw as Bulking Agent [43]

3. THEORY

The composting process is a complex one due to the great number of variables which affect it. It depends on the type of organisms present and on how these organisms decompose the biodegradable matter available in the compost mixture. It also depends on physical variables like the moisture content, aeration, porosity, free air space, temperature of the composting mixture, pH and C:N ratio. All of these variables were studied to determine their importance in the composting process and a way to control their effect in the laboratory work performed.

3.1. AEROBIC METABOLISM REACTIONS

Aerobic metabolism reactions are used in cell respiration, upon which most forms of life are dependent for the release of energy stored in their food. Aerobic reactions use oxygen as an electron acceptor. An example of such reactions is the oxidation of glucose in presence of oxygen:

$$C_6H_{12}O_6(aq) + 6O_2(g) \gg 6CO_2(aq) + 6H_2O(l) \quad \Delta G_R^\circ = -2,834.5 \text{ kJ/mol} \qquad 3\text{-}1$$

where ΔGR° is the reaction's free energy change under standard state conditions [21]. There are other reactions in which other compounds are used as electron acceptors. One of such reactions is the anaerobic oxidation of glucose using sulfate [21]:

$$C_6H_{12}O_6(aq)+3SO_4^{-2}(aq)+6H^+(aq) \gg\gg 6CO_2(aq)+6H_2O(l)+3H_2S(aq) \qquad 3\text{-}2$$

$$\Delta G_R^\circ=-448.0 \text{ kJ/mol}$$

From the free energy changes for both reactions, the aerobic reaction releases more energy than the anaerobic one. This higher energy available contributes to the rise in temperature and further inactivation of pathogenic organisms in the composting mass under the static pile method.

3.2. ORGANISMS

The micoflora present in the composting mixture are responsible for the decomposition of degradable matter and heat released as a by-product of decomposition. Depending on the temperature of the composting mixture, different types of organisms are responsible of the decomposition process.

3.2.1. BACTERIA

Bacteria are simple, colorless, one-celled organisms that use soluble food and are capable of self-reproduction without sunlight. They range in size from 0.5 to 5 μm, and are only visible through a microscope. Because of their small size, they have a very high surface-to-volume ratio. This allows for a rapid transfer of soluble substrates into the cell and high rates of metabolic activity. Their shape can be in spheres (cocci), rods (bacillus) and spirals (spirillum) or intermediate forms as coma-shaped (vibrio) and spindle-shaped (fusiform). They may appear in pairs, packets or in chains. Bacteria reproduce by binary fission, the cell divides into two new cells each of which matures and again divides.

Bacteria are classified in two major groups; heterotrophic and autotrophic, depending on their source of nutrients. Heterotrophic bacteria use organic matter as both an energy and as a carbon source for synthesis. The primary reason heterotrophic bacteria decompose organics is to gain energy for the synthesis of new cells, and for respiration and motility. These bacteria are subdivided into three groups depending on their action toward free oxygen: aerobes, anaerobes and facultative. Aerobe bacteria require free dissolved oxygen in decomposing organic matter to gain energy for growth and multiplication. Anaerobe bacteria oxidize organics in the complete absence of dissolved oxygen by using oxygen bound in other compounds, such as nitrate and sulfate. Facultative bacteria use free dissolved oxygen when available, but can also live in its absence by gaining energy from anaerobic reactions.

Autotrophic bacteria oxidize inorganic compounds for energy and use carbon dioxide as a carbon source.

Bacteria are also classified according to the range of environmental temperatures that they can tolerate. Mesophilic bacteria grow in a temperature range from 25° to 40°C. Thermophilic bacteria grow at temperatures higher than 45°C [48].

During the composting process, a large number of aerobic mesophilic bacteria are initially present . They multiply during the first stage, but the increase in biological activity causes an elevation in temperature, thereby decreasing the number of mesophilic bacteria. They utilize the most readily accessible carbohydrates and decomposable proteins. Their primary role is to raise the temperature for the thermophilic bacteria that follow.

The elevation in temperature promotes an increase of the population of thermophilic bacteria (temperatures higher than 40°C). The population of thermophilic bacteria follows an inverse pattern from that of the mesophilic population, increasing to a maximum at the thermophilic stage (40°–70°C), and then gradually decreasing as the temperature drops. They initially decompose the protein and non–cellulose carbohydrate components, and will also attack the lipid and hemicellulose fractions.

3.2.2. FUNGI

Fungi are "filamentous or simple–celled primitive plants, with a discrete nucleus, a protoplasmic vacuole, lacking chlorophyll"[49]. The vast majority are saprophytic, decomposing organic matter in soil and aquatic environments. Fungi can be divided in molds and yeasts. Molds are aerobic, while in yeasts both aerobic and anaerobic metabolism are observed. Molds tend to form filamentous structures while yeasts tend to be unicellular. They are distinguished from bacteria by their eucaryotic cell type, generally of a larger size and a more sophisticated method of reproduction [21].

Fungi are less affected by low moisture environments and can often grow on dry substrates. They can withstand a broad range of pH conditions, and often have a lower nitrogen requirement than bacteria. Due to this lower nitrogen requirement, fungi has a competitive edge over bacteria in nitrogen deficient environments [21].

During the composting process, mesophilic fungi compete with the rest of the micoflora only for a short time as the compost heats up. They use the simple carbon substrates and are quickly replaced by thermophilic fungi. As the pile cools again below 40°C, they reappear in large numbers.

Thermophilic fungi occur in the 40°C to 60°C range, but die when the temperature reaches 60°C [40]. Like the mesophilic fungi, they survive in the external area of the pile and re-invade when the temperature declines. They decompose hemicellulose and cellulose.

3.2.3. PATHOGENIC ORGANISMS

Pathogens are disease producing organisms. The ones of most concern in regard to composting are *Aspergillus fumigatus* and Salmonella.

Aspergillus fumigatus is a pathogenic fungus that causes bronchial disease and seems to be the dominant fungal colony in composting. It appears in the composting piles when the moisture content of the pile decreases and the environment becomes too dry for bacteria [48].

Salmonella are disease causing bacteria that affect humans and warm blooded animals. The most common diseases caused by Salmonella are typhoid fever and gastroenteritis, which are transmitted from person to person in food or water, usually contaminated from fecal sources [48].

The health hazard these organisms present is normally reduced by the composting process, if the minimal time-temperature conditions suggested by prevail during the process [41]: the temperature of the pile is maintained at 55°C for at least three consecutive days. The thermal death points of some pathogens common to sewage sludge are presented in TABLE 9 [39].

TABLE 9: Thermal Death Points of Some Pathogens Common to Sewage Sludge[1]

Pathogen	Thermal Death Points
Brucella abortus	60°C for 3 min
Necator americarus	45°C for 45 min
Esherichia coli	55°C for 60 min
Trichinella spiralis	55°C for 60 min
Corynebacterium diptheria	55°C for 45 min
Salmonella spp.	55°C for 60 min
Salmonella typhosa	55°C for 30 min
Salmonella newport	55°C for 30 min
Ascaris Lumbricoides ova	60°C for 60 min

[1] TABLE from [39]

3.3. KINETICS OF MICROBIAL GROWTH

The rate of substrate utilization by microbes can be represented by the Monod equation developed in 1942:

$$\frac{dS}{dt} = - \frac{k_m S X}{Ks + S} \qquad 3\text{-}3$$

where:
dS/dt = rate of substrate utilization, mass/volume-time
X = concentration of microbes, mass/volume
k_m = maximum rate of substrate utilization at high substrate concentration, mass substrate/mass microbes-day
Ks = half-velocity coefficient, mass/volume
S = concentration of the rate limiting substrate, mass/volume.

The negative sign indicates that the substrate concentration decreases due to the microbial activity. This equation assumes that the concentration of a limiting substrate S is the one that controls the kinetics. This equation is best applied to soluble substrates.

The rate of substrate utilization is related to microbial growth by [21]:

$$\frac{dX}{dt} = Ym \left[\frac{-dS}{dt}\right] - k_e X \qquad 3\text{-}4$$

where:
dX/dt = net growth rate of microbes, mass/volume-time
Ym = growth yield coefficient, mass of microbes/mass of substrate
k_e = endogenous respiration coefficient, $time^{-1}$ or mass of microbes respired/mass of microbes-time.

The endogenous respiration term is included to take into account that the cellular mass decreases if no substrate is available.

Both equations can be combined to give:

$$\mu = \frac{\mu m\, S}{Ks + S} - k_e \qquad 3\text{-}5$$

where:
μ = net specific growth rate $[(dX/dt)/X]$
μm = maximum net specific growth rate $[Ym\ km]$.

The term μm is obtained at a high substrate concentration and a low endogenous respiration rate [21]. This equation is used to describe microbial growth and substrate use in aqueous solutions.

It has been applied to a variety of biological processes used in sanitary and biochemical engineering practice, including activated sludge processes and anaerobic digesters.

3.4. KINETICS OF HEAT INACTIVATION

The kinetics of heat inactivation are often modelled as a first order decay of the form:

$$\frac{d\eta}{dt} = -kd\ \eta \tag{3-6}$$

where: η = viable cell population
kd = thermal inactivation coefficient.

This expression is also known as "Chick's law" after Harriet Chick who reported it as an expression for the exponential die-offs in 1908 [21].

The thermal inactivation coefficient kd is a function of temperature and is often modelled as an Arrhenius expression of the form:

$$kd = C\ e^{-Ed/(R\ Tk)} \tag{3-7}$$

where: Tk = temperature, K
Ed = inactivation energy, kJ/mol

The range for the inactivation energy Ed for many spores and vegetative cells lies between 209 and 418.7 kJ/mol.

Performing a logarithmic transformation of the above equation yields:

$$\ln kd = \ln C - \frac{Ed}{R}(1/Tk) \qquad 3\text{-}8$$

From a plot of ln kd versus 1/Tk, the constant C and the inactivation energy Ed can be determined.

3.5. LIMITATIONS ON MICROBIAL DESTRUCTION

There are limitations on the microbial destruction that can be achieved during the composting process. The clumping of solids, spore forming bacteria, nonuniform temperature distribution and bacterial regrowth are examples of these limitations.

Temperatures observed during the composting process should be effective in the reduction of the pathogenic organisms present in the sludge, but some organisms (such as the endospores formed by spore forming bacteria), would not be inactivated by the process.

In the clumping of solids, heating time for particles of 1 - 10cm radius would be insignificant. On the other hand, if the clumps are larger than 20cm radius, the heating time becomes significant, limiting the destruction of the pathogenic organisms present inside the clumps.

It is impossible to achieve uniform temperatures throughout the entire composting mass. The development of cold zones may allow the pathogenic organisms to survive the composting process. It is necessary to know the temperature distribution throughout the composting mass to limit the development of cold zones.

Once the temperature of the composting mass is reduced to sublethal levels, certain type of bacteria may regrow. This phenomenon has been observed with coliforms and Salmonella in liquid wastes and even composted material with a moisture content less than 40%. However, if the composting material is not subjected to any contamination with pathogenic organisms, regrowth is restricted by the competition with the natural microbial flora [21].

3.6. AERATION REQUIREMENTS

The function of aeration of the composting mass is to supply the oxygen needed for the organic decomposition, to pick up moisture and to remove heat to promote optimum conditions for the decomposition.

The oxygen requirements for organic decomposition was determined from a generalized chemical composition for primary sludge and the extent of the degradation during the composting process. The generalized chemical composition for the sludge was found to be $C_{10}H_{19}O_3N$ [21,48] and the decomposition reaction in presence of oxygen was:

$$C_{10}H_{19}O_3N + 12.5\ O_2 \gg 10\ CO_2 + 8\ H_2O + NH_3 \tag{3-9}$$

From the stoichiometry, 2.0 g of oxygen are needed per gram of sludge organic oxidized.

The average composition of woodchips is $C_6H_{11}O_3$ [48], and the decomposition reaction is:

$$C_6H_{11}O_3 + 7.25\ O_2 \gg 6\ CO_2 + 5.5\ H_2O \tag{3-10}$$

From the stoichiometry, 1.77 g of oxygen are needed per gram of woodchips oxidized [48].

Not all of the sludge will be degraded by the composting process. Therefore, it is necessary to define a degradability coefficient, defined as the fraction of organics that actually degrade during composting. The degradability coefficients for the sludge and bulking agent, respectively, during composting conditions will be defined by the variables k_c and k_b.

3.7. POROSITY AND FREE AIR SPACE

The composting mass is a network of solid particles that contain void spaces and interstices of varying size. The void spaces between the particles are filled with air, water or a mixture of air and water. When these void spaces are completely filled with water, the sludge will behave as a plastic material. The oxygen transfer is restricted and aerobic conditions diminish without constant agitation. As the void spaces become filled with air, the oxygen transfer improves and aerobic conditions are reestablished.

The porosity and the free air space determine the quantity of void spaces present in the composting mass. Porosity, n, is defined as the ratio of void volume to the total volume [21]:

$$n = \frac{Vv}{Vt} = 1 - \frac{Vs}{Vt} \qquad 3\text{-}11$$

where:
Vv = void volume
Vs = volume of solids
Vt = total volume of solids, water and gas in the composting mass.

The free air space, f, is defined as the ratio of gas volume to the total volume [21]:

$$f = \frac{Vg}{Vt} = \frac{Vt - Vs - Vw}{Vt} \qquad 3\text{-}12$$

where Vw is the volume of water in the composting mass.

The free air space is important in determining the quantity and movement of air through the composting mass. The bulking agent used must be able to provide the structural support for the sludge, assume adequate free air space and increase the size of the void spaces to allow an easier air movement through the mixture. The sludge can be viewed as occupying void spaces between bulking particles.. Therefore, sufficient bulking agent must be added to the sludge in order to assure that sludge volume does not exceed the available void space. Also, the use of a dry bulking agent is advantageous because moisture will be absorbed from the sludge, thus increasing the available free air space.

3.8. MOISTURE CONTENT

Micro-organisms require a certain amount of water for their metabolic activities as it provides a medium for transport of dissolved nutrients. In the composting mass, proper moisture levels must be maintained. If the moisture content is too low (<40%) stabilization will be slowed down because of the limited amount of water, essential for microbial growth. At a high moisture content (>70%), water may displace air from the void space and lead to anaerobic conditions. Therefore, an optimal moisture content is around 50 to 60%.

The moisture level is closely linked with the void spaces and aeration. A decrease in the particle size will decrease the diffusion of oxygen, reducing the composting rate; it will also reduce the size of the void spaces. On the other hand, a reduction in the particle size will increase the surface area available for microbial attack.

3.9. Temperature

Temperature affects the growth and activity of microorganisms present in the composting mass, and determines the rate at which organic materials are composted. The initial elevation of temperature is due to the heat released in the decomposition of the most readily decomposable carbohydrates and proteins by mesophilic bacteria present in the sludge. The heat released is conserved by the composting mass because of the insulating properties of the organic materials present.

As the temperature continues to increase (45° to 60°C), the thermophilic bacteria become predominant, generating enough heat to destroy human pathogens.

The slope of the temperature versus time curve depends on the nature of the organic matter being composted, the availability of the nutrients, the moisture content, insulation, particle size and degree of aeration. The amplitude of the temperature versus time curve will be greater with a higher proportion of easily degradable materials. This will also accelerate the rate of decomposition [8].

In large scale processes, the thermophilic stage is reached usually between days 2 - 7 of composting. Typically, after the temperature of the composting mass reaches 70° C, it begins to cool down to ambient temperatures. The optimal ceiling temperature, based on the oxidation of the organic matter into CO_2 and H_2O has been found to be 60° C [40, 44, 61].

3.10. CARBON:NITROGEN RATIO

The carbon:nitrogen ratio provides a useful indication of the probable rate of organic matter decomposition; microorganisms require a carbon source for growth as well as a source of nitrogen for protein synthesis. An initial C:N ratio of 20 to 35 would be the most favorable for rapid conversion [61]. Ratios below 20 result in the loss of nitrogen as ammonia, and a ratio above 35 lead to progressively longer times of composting [40]. Sewage sludge usually has a C:N ratio of less than 15 [63]. The addition of a bulking agent, like woodchips, raises the C:N ratio, ensuring the conversion of the available nitrogen into organic constituents of the composting mass. After the removal of the woodchips, the C:N ratio lowers and the nitrogen is allowed to mineralize [65].

3.11. pH

Sewage sludges can be composted from a pH range of 5 to 10. A pH value outside this range will retard the process. The most favorable range is from 6 to 8, in which the microorganisms present exhibit maximum growth and activity [61].

During the composting process, the pH will change from 5.0 to 5.5 during the mesophilic stage, to 8.0 to 9.0 during the thermophilic stage, and to neutrality during the cooling stage. This pattern is observed due to the strong influence of the evolution of ammonia [8].

4. EXPERIMENTAL PROCEDURE

4.1. EXPERIMENTAL DESIGN

A two level experimental design was used in order to find the relation between the degree of stabilization of the primary sludge achieved through composting and the type of bulking agent used and temperature control (Table 10) [3]. The two levels for the bulking agent variable were: runs with only woodchips from the African tuliptree (<u>Spathodea campanulata</u>), and runs with a combination of woodchips and cut spent rubber tires. For the temperature control variable, runs were made with (+) and without (-) temperature control. Temperature control meant limiting the maximun temperature of the mixture to 60°C.

TABLE 10: Experimental Design

Bulking Agent	Temperature Control	Trial Number
woodchips	+	3
woodchips	-	1
woodchips & rubber	+	2
woodchips & rubber	-	4

Due to various factors, it was not possible to make duplicate runs in the experimental design. First, there were difficulties in obtaining the sludge from the Barceloneta Regional Wastewater Treatment Plant (BRWTP), because the plant decided to stop using the press filters for sludge dewatering; second, due to installation and proper operation problems with the bench-scale composter concerning leaks in the aeration lines; and third, because each experimental run lasted from 21 to 28 days plus 2 to 3 weeks of preparation and analysis of samples.

4.2. EQUIPMENT DESCRIPTION

Two bench-scale composters were used in the experiments, their design based on the one designed by Frankos (Figure 7) [16]. Each consisted of a polyvinil chloride (PVC) cylinder (Sch. 40) with a height of 61cm (2ft) and a nominal diameter of 15.24cm (6in). The PVC cylinder was closed at both ends with PVC end plugs. Aeration lines of 0.952cm (3/8in) O.D. stainless steel tubing were connected to the end plugs by Swagelok pressure fittings. Two type K thermocouples (Omega Engineering) were passed through the PVC end plugs also by Omegalok pressure fittings, one placed at 15.24cm (6in) and the other at 45.72cm (18in) inside the composter. The whole PVC unit was placed inside an aluminum cylinder with two end flanges with a height of 91.44cm (3ft) and an inside diameter of 20.32cm (8in) (Figure 8). A Fisher Scientific silicone rubber extruded heating tape (2.54cm x 2.438m, 1in x 8 ft), connected to a VARIAC® variable transformer, was wrapped around the aluminum cylinder to serve as a heat source. The aluminum cylinder was covered with a 5.08cm (2in) thick sodium carbonate

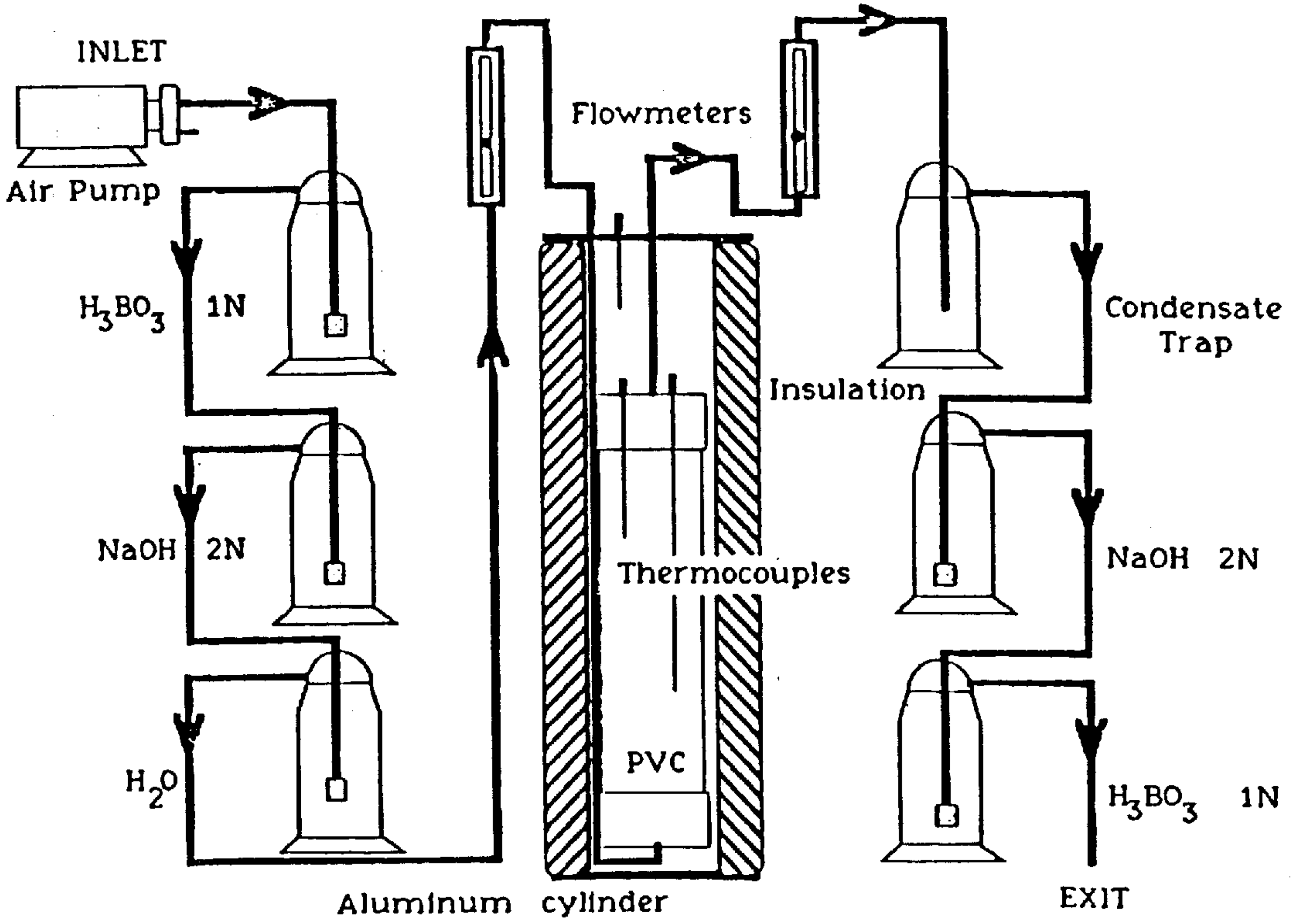

Figure 7: Bench-Scale Composter Layout

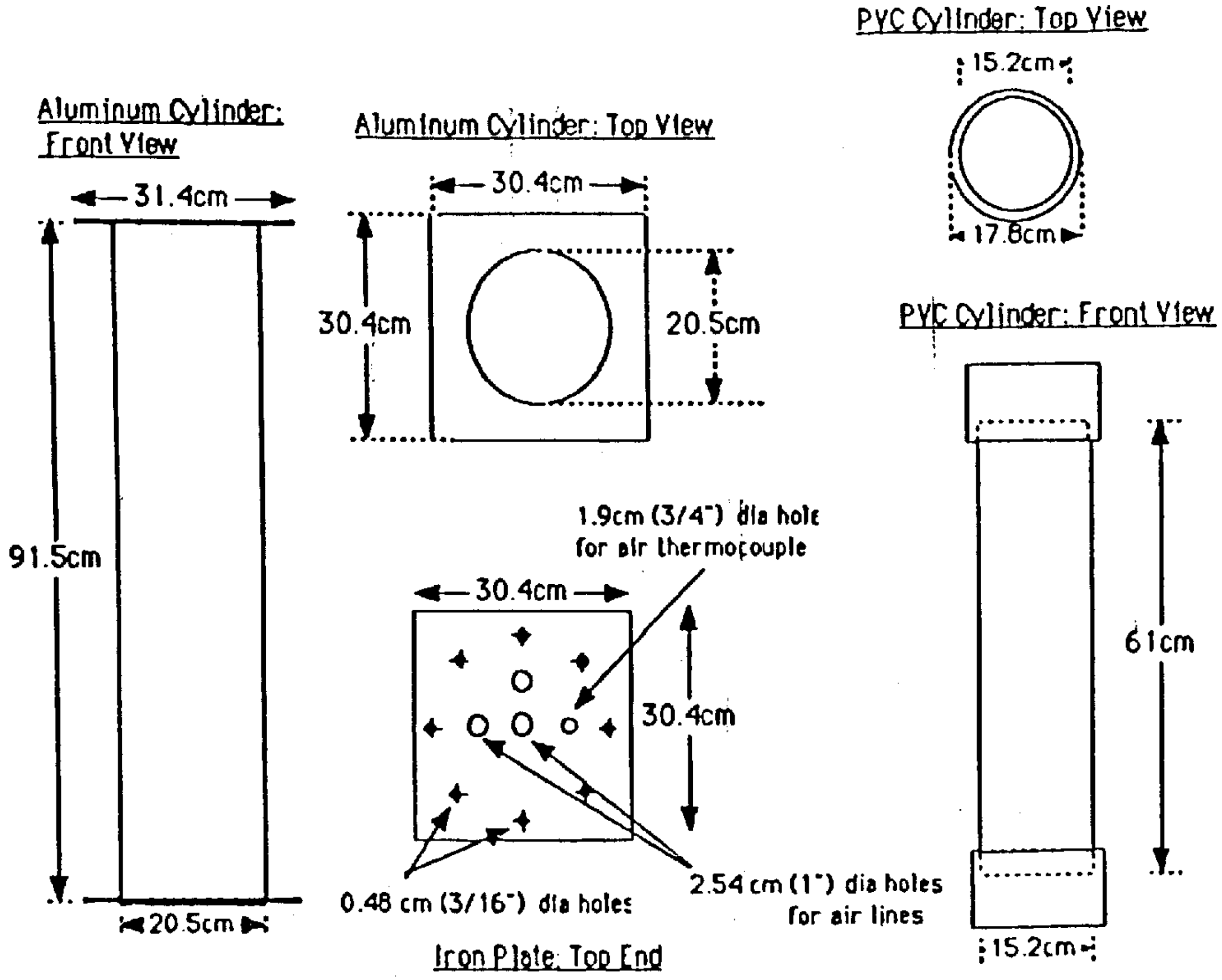

Figure 8: Scale Drawing of Bench-Scale Composter

base insulation, which was covered with insulation cloth to avoid dust accumulation. A surface type thermocouple (Omega Engineering) was attached to the internal wall of the aluminum cylinder. The aluminum cylinder was sealed with iron plates which were bolted to the flanges, with Swagelok pressure fittings connected to the aeration lines and the thermocouples wires. A type K air thermocouple was located in the air space between the PVC cylinder and the aluminum cylinder. The thermocouple wires were connected to a multiple selector and an Omega 2170A digital thermometer.

The aeration system consisted of a Gast vacuum-pressure pump (Fisher Scientific) connected to a pressure stabilization tank (4 l Erlenmeyer). Before entering the composter, the air was forced through three Kimble 500 ml gas washing bottles (Fisher Scientific), the first one contained a 1N solution of H_3BO_3, the second contained a 2N solution of NaOH, and the third contained H_2O. The H_3BO_3 solution was used to strip the ammonia (NH_3) from the air; the NaOH solution removed the CO_2 contained in the air; and the H_2O bottle saturated the air entering the composter. A polyethylene check valve was placed after each gas washing bottle to eliminate any air backflow due to pressure changes. The air was then passed through Gilmont calibrated rotameters (Cole Palmer), one before and one after the composter to measure air flow and any loss that could occur through the composter. The effluent air was passed through a condensate trap, a gas washing bottle with H_3BO_3 1N, and another with NaOH 2N. In this case, the bottle were used to retain all the NH_3 and CO_2 produced by the decomposition reaction for later analysis. All the aeration lines were made of Tygon® tubing (0.635cm, ¼in I.D.) except the aeration lines inside the composter, which were made of 0.952cm O.D. (3/8in) stainless steel tubing.

4.3. EXPERIMENTAL PROCEDURE

The feed material used in the experiments was primary sludge from the Barceloneta Regional Wastewater Treatment Plant. It had a pH around 7.0 and variable properties depending on the day of the sample collection.

The bulking agent used consisted of woodchips from the african tuliptree (S. campanulata) or a combination of woodchips and cut spent rubber tires. The wood was obtained locally and shredded with a 5-hp W.W. Grinder, model 5-14-4 shredder. Table 11 present the size distribution by weight of the woodchips. The rubber tires were cut in pieces of approximately 5.0 - 7.5cm of length and 4cm width with a metal cutting vertical band saw.

For both the primary sludge and woodchips, laboratory analyses were made to determine the moisture content, volatile solids, total and fecal coliforms, total nitrogen, phosphorus, potassium, and heavy metals (nickel, chromium, lead and cadmiun). The moisture content determination was made by heating a sample at 108°C for 24 hr. The volatile solids content determination was made by incinerating the already dry sample at 550°C for 4 hr. The total and fecal coliforms were analyzed by the standard most-probable number (MPN) method [52]. These tests were made by a local private laboratory. The total nitrogen was determined by the Kjeldahl method, with Hibbard reagent digestion [52]. Potassium and heavy metal analyses were determined with an atomic absorption unit [52].

TABLE 11: Size Distribution by Weight for S. campanulata woodchips

sieve opening, cm (in)	weight %
1.27 (½)	2.22
0.9525 (3/8)	9.44
0.3125 (5/16)	9.07
0.1410 (0.0555)	69.29
0.100 (0.0394)	3.13
0.0706 (0.0278)	2.79
< 0.0706 (0.0278)	4.14

Based on an average moisture content for the sludge and the woodchips, a volumetric mixing ratio was established of 3:2 v/v (woodchips:sludge). This mixing ratio also provided a C:N ratio higher than the recommended value of 30, and created the porosity and free air space needed for the degradation reaction. When shredded rubber tires were used, the volumetric mixing ratio was 2:2:1 (sludge:shredded rubber:woodchips). Although the cut spend rubber tires provided the necessary porosity and free air space, the woodchips were added to help in the nutrient balance (C:N ratio).

After mixing the sludge and the bulking agent, a sample of about 75g was obtained for moisture and volatile solids content determination and pH. The pH of the mixture was determined from a solution of 20 g of mixture in 20 ml of water, using a Pope 501 pH meter with a Sensorex combination pH electrode (Joluvar).

The PVC unit was filled with the composting mixture, and closed tightly using a silicone rubber sealant (3C Company) at the end plugs. The composter was then weighted. Thermocouples and air lines were connected to the composter. The aluminum cylinder was closed with iron end plates, placing a neoprene gasket between the ends. Thermocouple wires and aeration lines were connected to the aluminum cylinder. The solutions of H_3BO_3 1N, NaOH 2N and H_2O were poured in their corresponding gas washing bottles. The aeration lines were connected to the rotameter, gas washing bottles, and the vacuum-pressure pump. An air flow of 100 ml/min was established based on the stochiometric requirements for the degradation reaction. The aeration was distributed with a flow of 500 ml/min for 6 min every 30 min with a time switch (Dayton Electronic) connected to the vacuum-pressure pump.

At the beginning of the experiment, the variable transformer was set to obtain an initial temperature of 40°C in the composter aluminum wall. After the temperature of the composting mixture exceed the temperature of the aluminum wall, the variable transformer was reset so that the temperature of the aluminum wall was 2°C lower than that of the composting mixture to minimize heat losses.

Three times each day, temperature and air flow data were recorded. Every other day, the H_3BO_3 and NaOH solutions were changed. The spent solutions were refrigerated and later analyzed to determine the NH_3 and CO_2 generated by the degradation reaction. The CO_2 generated was determined by direct titration with NaOH [16] and the NH3 by direct titration to an endpoint pH of 8.30 using a 1N-HCl tritant [35].

Every seven days, the composter was opened to weight the PVC cylinder and to obtain a sample of the composting mixture. After being weighted, the direction of the air flow was inverted, to get a uniform degradation through the composter. The sample was analyzed for moisture, volatile solids content and pH.

The experiment trials were ended when the temperature of the composting mixture began to diminish. This was usually after 21 to 28 days of composting. A sample was obtained of the final composting mixture to determine the moisture and volatile solids content, pH, total and fecal coliforms, total nitrogen, phosphorus, potassium and heavy metals.

The final mixture was cured for about 3 to 4 additional weeks, leaving the mixture at room temperature in the laboratory fumes hood. During this process the moisture content of the mixture was reduced significantly. The final mixture was separated in different size fractions using a portable sieve shaker (EC, model RX-24) with USA standard testing sieves of sizes 1.9050cm (3/4"), 0.79cm (5/16"), 2.80mm (0.111in), 2.0mm (0.0787in) and 710µm (0.0278in). The purpose of the size separation was to determine the fraction of the final mixture that could be used as a soil conditioner and the fraction that could be recycled.

5. RESULTS AND DISCUSSIONS

5.1. MIXING RATIO DETERMINATION

The volumetric mixing ratio of sludge and woodchips was determined from the moisture balance for the mixture, establishing a final moisture content of 60%. The formula for the mixture moisture content was [48]:

$$Mm = \frac{a/(a+b) \bullet Mc \bullet Xc + b/(a+b) \bullet Mw \bullet Xw}{a/(a+b) \bullet Xc + b/(a+b) \bullet Xw} \qquad 5\text{-}1$$

where:
Mm = moisture content of the mixture
Mc = moisture content of the sludge
Xc = bulk weight of sludge [kg/l]
Mw = moisture content of woodchips
Xw = bulk weight of woodchips [kg/l]
a = part of sludge in the mixing ratio
b = part of bulking agent in the mixing ratio

Establishing a final mixture content (Mm) of 60%, an initial moisture content for the sludge (Mc) of 75%, an initial moisture content for the woodchips (Mw) of 50%, a sludge density of 0.36 kg/l, and for the woodchips of 4.8×10^{-2} kg/l, the mixing ratio was determined from equation 5-1 to be 1.2:1 v/v woodchips:sludge. To ensure the best porosity and free air space, the mixing ratio was established at 1.5:1 v/v woodchips:sludge.

For the experimental trial using cut spent rubber tires as bulking agent, the volumetric mixing ratio was established at 2:1:2 rubber:woodchips:sludge [23].

5.2. AERATION REQUIREMENTS

The aeration needed in an experimental run was determined from the stoichiometric requirements based on the decomposition reactions for both the sludge and the bulking agent. As stated by equation 3-9, 2.0 grams of O_2 are needed per gram of sludge oxidized, and by equation 3-10, 1.77 grams of O_2 are needed per gram of woodchips oxidized. Using a degradability coefficient for the sludge (Kc) of 0.40 [21,48], and for the woodchips (Kw) of 0.10 [21,48], about 685 gr of dry O_2 are needed for the degradation of the mixture inside the bench composter. Using saturated air at 20°C and 1 atm, a flow of 82 ml/min was needed. A flow of 100 ml/min was used to assure an excess of O_2 in the composter.

5.3. PROBLEMS WITH NH_3 AND CO_2 DETERMINATION

The aeration system of the bench-scale composter was connected to the gas washing bottles to determine the NH_3 and CO_2 produced by the degradation reaction. The gas washing bottles created a pressure resistance to the air flow. This pressure resistance increased the air pressure inside the PVC cylinder, causing the leakage of air through the PVC cylinder end plugs. Although silicone rubber sealer was used to seal the end plugs, the air continued to leak through little deformations of the PVC end plugs due to the high pressure and temperature (50 - 60°C) Because of this leakage, the data for the determination of the CO_2 and NH_3 was not reliable.

5.4. EXPERIMENTALS TRIALS

Four experimentals trials were made based on a two level experimental design as described in section 4.1 and 4.3. The experimental trial 1 was made with primary sludge from the Barceloneta Regional Wastewater Treatment Plant and woodchips from the African tuliptree, without any temperature control Experimental trials 2 and 3 were done simultaneously and both with temperature control. The sludge and woodchips used in this trials were from the same source as trial 1, but were collected on another date. The bulking agent for trial 2 was a combination of cut spent rubber tires and woodchips from the African tuliptree, and trial 3 only used woodchips. Experimental trial 4 was made with primary sludge and woodchips from the same source as the preceding trials, but were collected on another date. It was made without temperature control, and the bulking agent used was a combination of cut spent rubber tires and woodchips from the African tuliptree. The cut spent rubber tires for trial 4 were obtained from the same tire as the ones used in trial 2.

5.4.1. Experimental Trial 1

The experimental trial 1 consisted of a mixture of primary sludge and woodchips at a volumetric mixing ratio of 1.5:1 (woodchips:sludge). The characteristics of the sludge, woodchips and the initial composting mixture are presented in Table 12. For the preparation of the initial composting mixture, 4.14kg of primary sludge with an apparent density of 0.73kg/l, was mixed with 1.10kg of woodchips from the African tuliptree with an apparent density of 0.146kg/l. Of the resulting mixture, 4.6565kg were placed inside the PVC cylinder, with an apparent density of 0.416kg/l.

Figure 9 presents the temperature profile for the experimental trial 1. The mixture temperature increased gradually during the first 16 days, reaching temperatures higher than 55°C. These higher temperatures were maintained for about 6 days, which is greater than the minimum of three days required by EPA for pathogen destruction [14]. Because the experimental trial 1 did not have temperature control, the maximun temperature achieved was around 65°C. Figure 10 shows that the temperature of the composting mixture inside the PVC cylinder was higher than

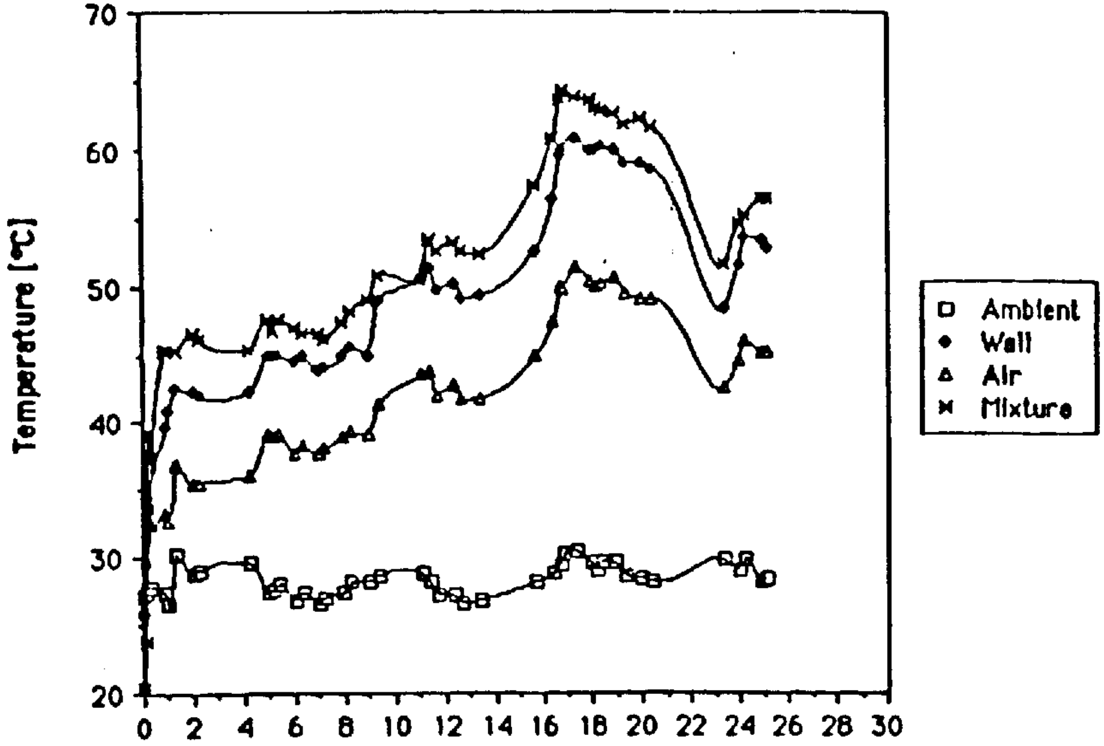

Figure 9: Temperature Profile for Trial 1
Sludge and Woodchips [without Temperature Control]

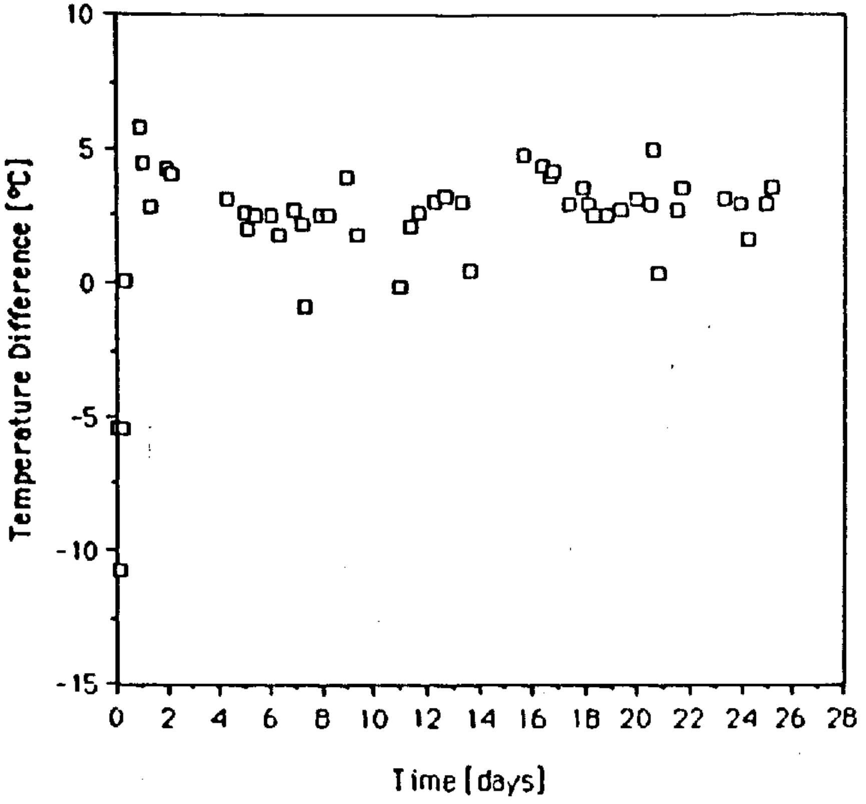

Figure 10: Temperature Difference for Trial 1
T(in, ave) - T(wall)

the temperature of the aluminum cylinder wall. This difference in temperatures was not observed at the beginning of the experimental trial because the heat source at the aluminum wall was used for the start-up. Also, it was not observed when the composter was opened for sample collection and change of direction in air flow every 7 days.

TABLE 12: Characteristics of the Sludge, Woodchips and Initial Mixture for Experimental Trial 1

	Sludge	Woodchips	Mixture (initial)
Moisture (% wt)	71.23	55.0	69.90
Volatile Solids'(%wt)	73.22	95.4	84.61
Total N' (mg/kg)	7059	4400	6501
Potassium' (mg/kg)	352.4	724.4	430
Total PO_4' (mg/kg)	2.448	1.21	2.18
pH			7.1
Carbonϕ (mg/kg)			470056
C/N Ratio			72
Chromium' (ppm)	75.3	3.2	
Lead' (ppm)	47.7	2.0	
Nickel' (ppm)	48.2	2.1	
Cadmium' (ppm)	3.8	0.2	

' dry basis
ϕ Carbon (%) = [Volatile solids (%)]/1.8 [21,43]

The change in moisture and volatile solids content is presented in Figure 11. The moisture content of the composting mixture increased after the second week because the air was

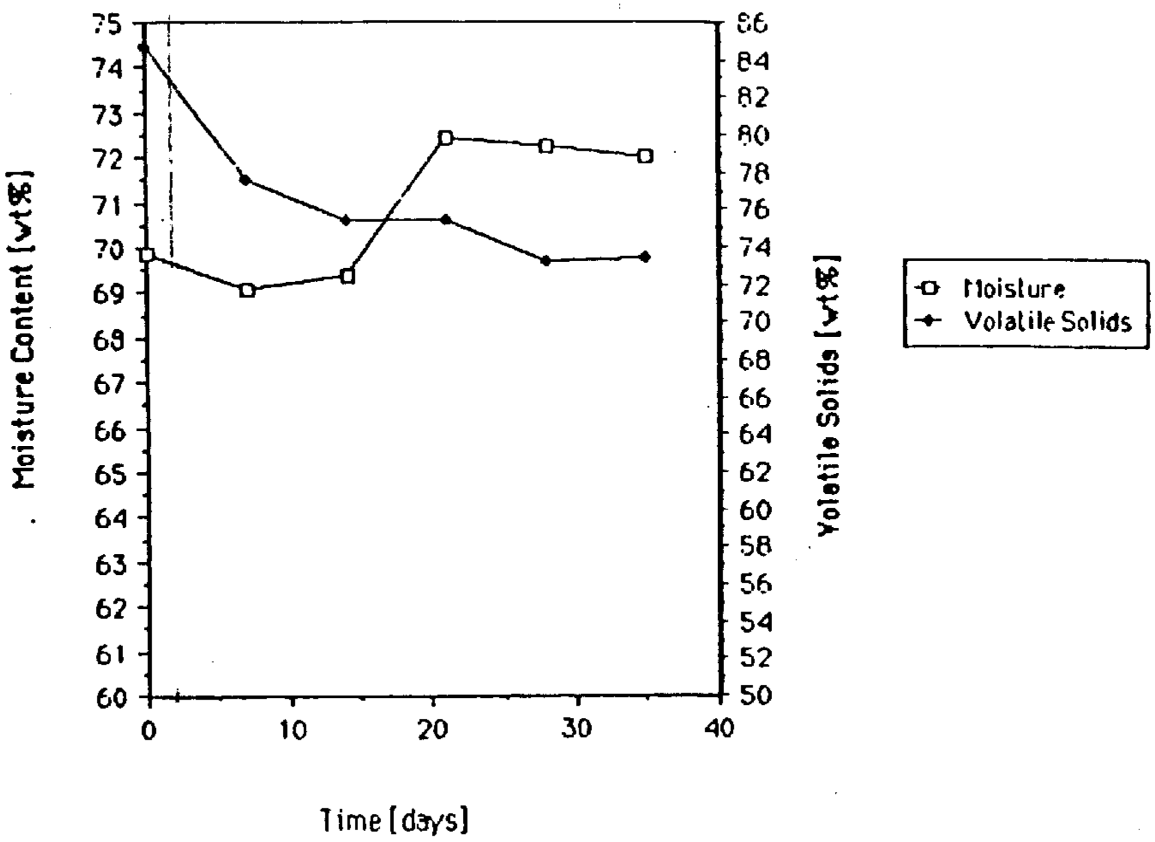

Figure 11: Change in Moisture and Volatile Solids Content for Trial 1

saturated before entering the composter. This caused no moisture reduction in the composting mixture due to aeration, stabilizing the moisture content in an average of 70.84%. A gradual reduction in the volatile solids content was observed, evidence that the degradation reaction was taking place. The greatest change in volatile solids content was observed during the first week (from 84.61% to 77.72%), mainly due to the decomposition of the most degradable materials present. The progress of the degradation reaction was also observed in the weight loss, represented by Figure 12. Although samples were taken every 7 days, a weight loss was observed between composter openings. During the first three weeks, an average change of 0.0767kg per week was observed in the composting mixture weight.

After curing the mixture for 30 days, it was sieved to determine the final product and the recyclable portions. Figure 13 represents the size fractions in weight percent. Fractions corresponding to sieve sizes less than 2.800 mm were considered appropiate for utilization purposes. This correspond to about 24.16% wt of the mixture. The remaining 75.84% wt can be recycled as bulking material.

The nutrient and heavy metal content of the final composting mixture is presented in Table 13.

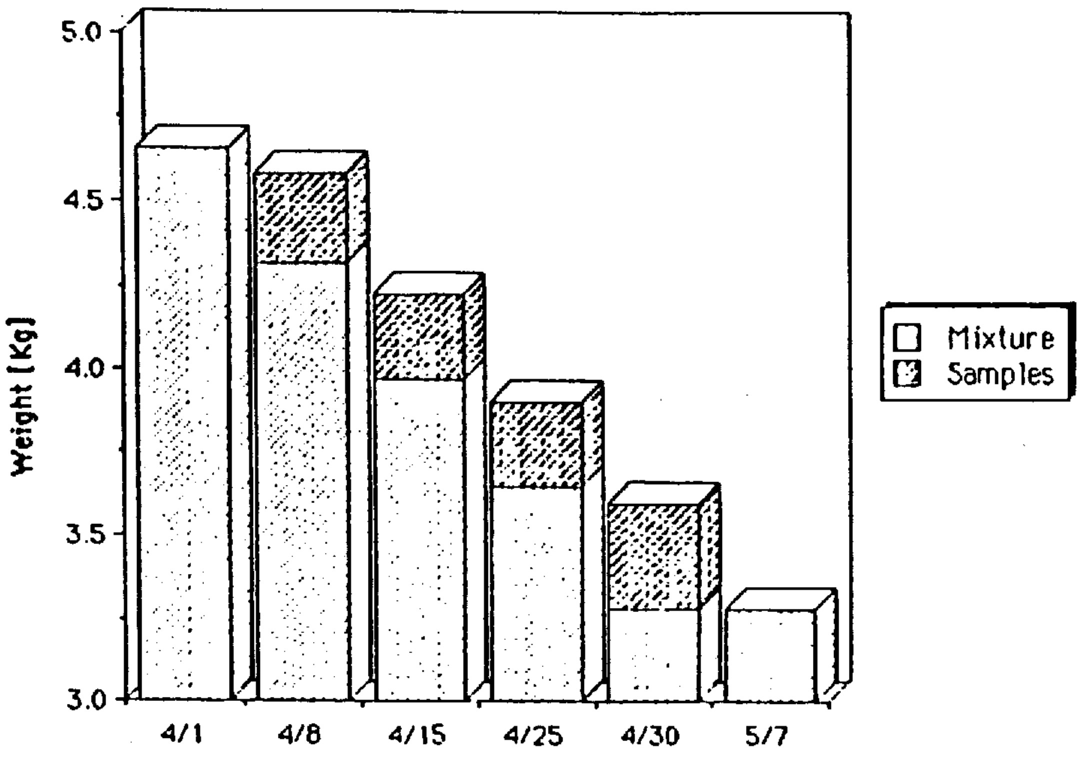

Figure 12: Weight Loss for Trial 1

Sludge and Woodchips [without Temperature Control]

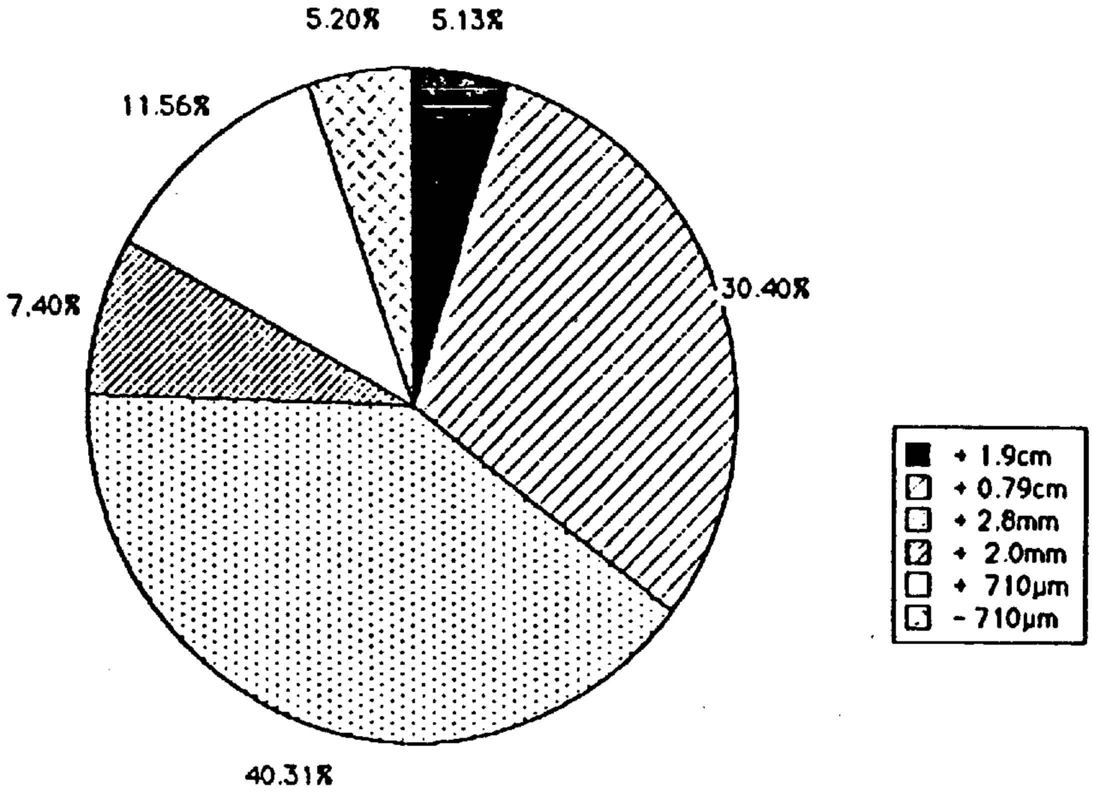

Figure 13: Particle Size Distribution for Trial 1
Sludge and Woodchips (without Temperature Control)

TABLE 13: Nutrient and Heavy Metals Content for the Final Mixture in Experimental Trial 1.

Total K Nitrogen[†]	5747
Total Phosphates[†]	0.433
Potassium[†]	1.571
Chromium (ppm)	11.2
Lead (ppm)	5.3
Nickel (ppm)	5.8
Cadmium (ppm)	0.5

[†] units [mg/kg]

5.4.2. EXPERIMENTAL TRIAL 2

The experimental trial 2 consisted of a mixture of primary sludge and woodchips and cut spent rubber tires at a volumetric mixing ratio of 2:2:1 (sludge:rubber tires:woodchips). The characteristics of the sludge, woodchips and the initial composting mixture are presented in Table 14. For the preparation of the composting mixture, 4.27kg of primary sludge with an apparent density of 0.738kg/l, was mixed with 0.34kg of woodchips from the African tuliptree with an apparent density of 0.145kg/l and with 2.0173kg of cut spent rubber tires with an apparent density of 0.44kg/l. Of the resulting mixture, 5.45kg were placed inside the PVC cylinder, with an apparent density of 0.487kg/l.

TABLE 14: Characteristics of the Sludge, Woodchips and Initial Mixture for Experimental Trial 2

	Sludge	Woodchips	Rubber''	Mixture (initial)
Moisture (% wt)	72.40	53.0		67.35
Volatile Solids' (% wt)	65.82	96.3	94.3	71.42
Total N' (mg/kg)	143.5	4212		428.4
Potassium' (mg/kg)	475	694	162	490.3
Total PO4' (mg/kg)	2.446	1.155		2.36
pH	6.8			7.1
Carbonϕ (mg/kg)				396778
C/N Ratio				926
Chromium' (ppm)	115.6	3.2		
Lead' (ppm)	27.8	2.0	17.5	
Nickel' (ppm)	54.7	2.1	5.6	
Cadmium' (ppm)	8.0	0.2	4.12	

' dry basis
'' data by Dr. Narinder K. Mehta
ϕ Carbon (%) = [Volatile solids (%)]/1.8 [21,43]

Figure 14 presents the temperature profile for the experimental trial 2. The mixture temperature increased gradually during the first 7 days, and reached a temperature in the range of 55 to 60°C. This temperature was maintained for about 14 days. Figure 15 shows that the temperature of the composting mixture inside the PVC cylinder was higher than the temperature of the aluminum cylinder wall. As in the previous experiment, this difference in temperatures was not observed at the beginning of the experimental trial because the heat source at the aluminum wall was used for the start-up. Also, it was not observed when the

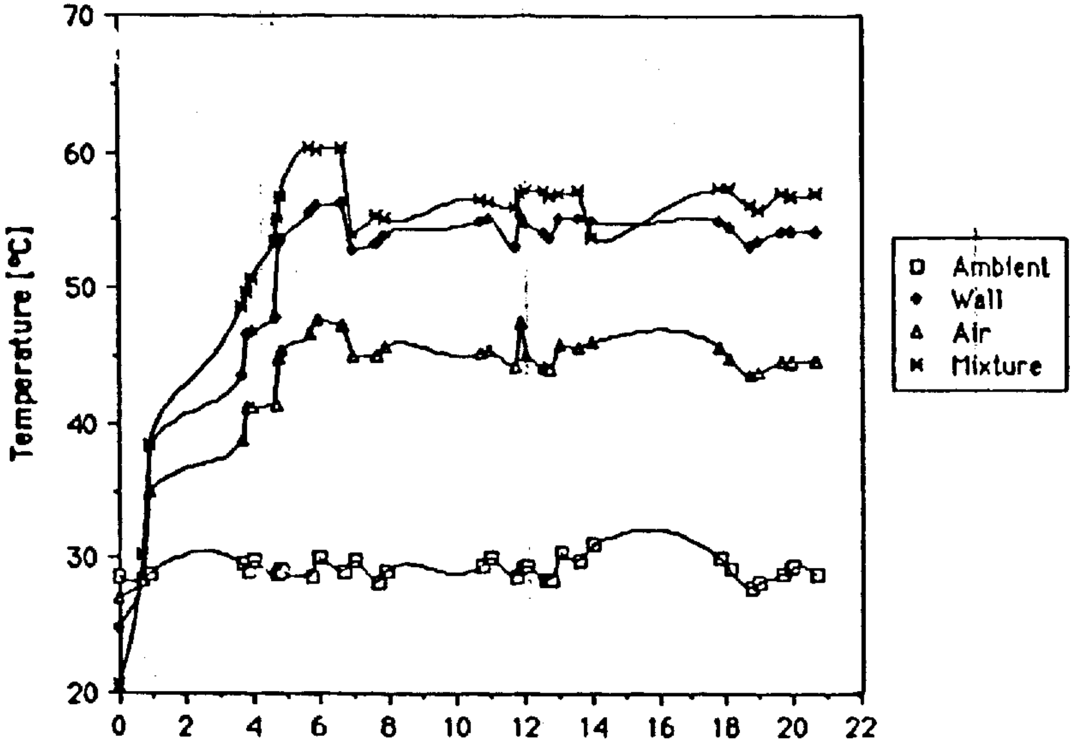

Figure 14: Temperature Profile for Trial 2

Sludge, Rubber and Woodchips [with Temperature Control]

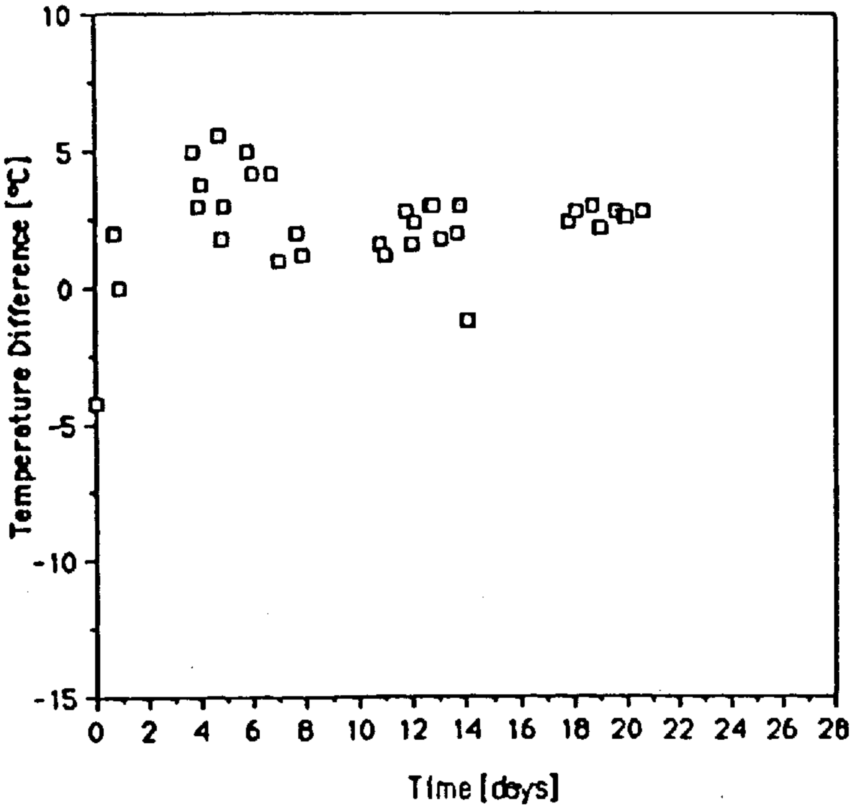

Figure 15: Temperature Difference for Trial 2
T(in, ave) - T(wall)

composter was open for sample collection and change of direction in air flow every 7 days.

The change in moisture and volatile solids content is represented in Figure 16. The moisture content of the composting mixture increased after the first week because the air was saturated before entering the composter. This caused no moisture reduction in the composting mixture due to aeration, stabilizing the moisture content in an average of 74.76%. A sharp reduction in the volatile solids content was observed, evidence that the degradation reaction was taking place. The greatest change in volatile solids content was observed during the first week (from 71.42% to 60.79%), mainly due to the decomposition of the most degradable materials present. The progress of the degradation reaction was also observed in the weight loss, represented by Figure 17. Although samples were taken every 7 days, a weight loss was observed between composter openings. During the first week, a weight change of 0.226 kg was observed, and for the second and third week an average weight change of 0.0946 kg per week was seen.

After curing the mixture for 30 days, it was sieved to obtain the final product and the recyclable portions. Figure 18 presents the size fractions in weight percent. Fractions corresponding to sieve sizes less than 2.800mm (about 8.47%) were considered appropiate for utilization purposes. The remaining of the mixture

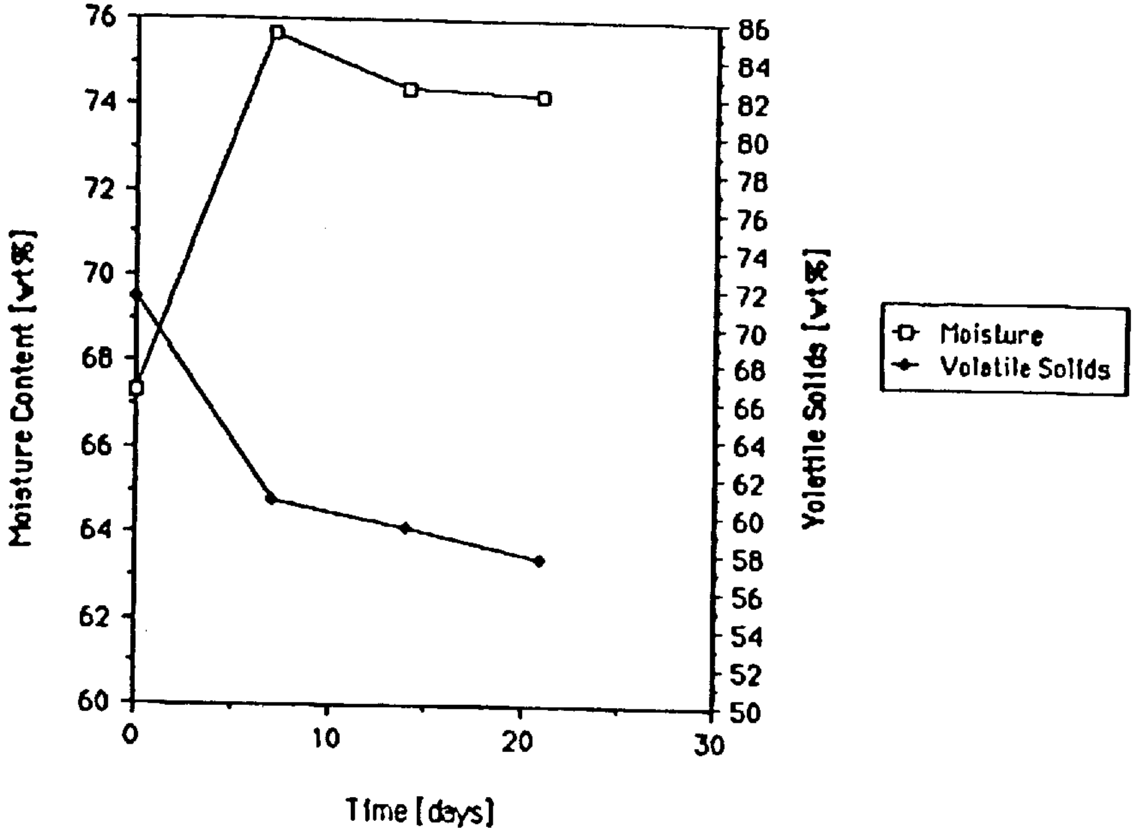

Figure 16: Change in Moisture and Volatile Solids Content for Trial 2

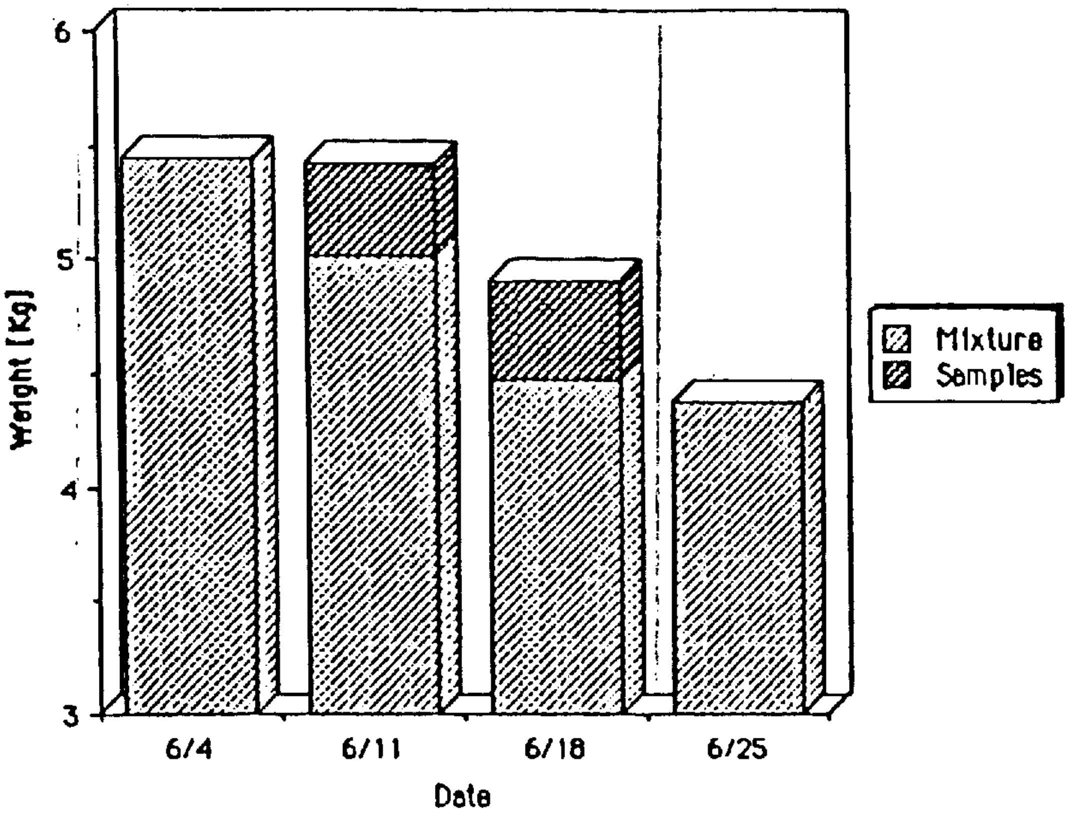

Figure 17: Weight Loss for Trial 2

Sludge, Rubber and Woodchips [with Temperature Control]

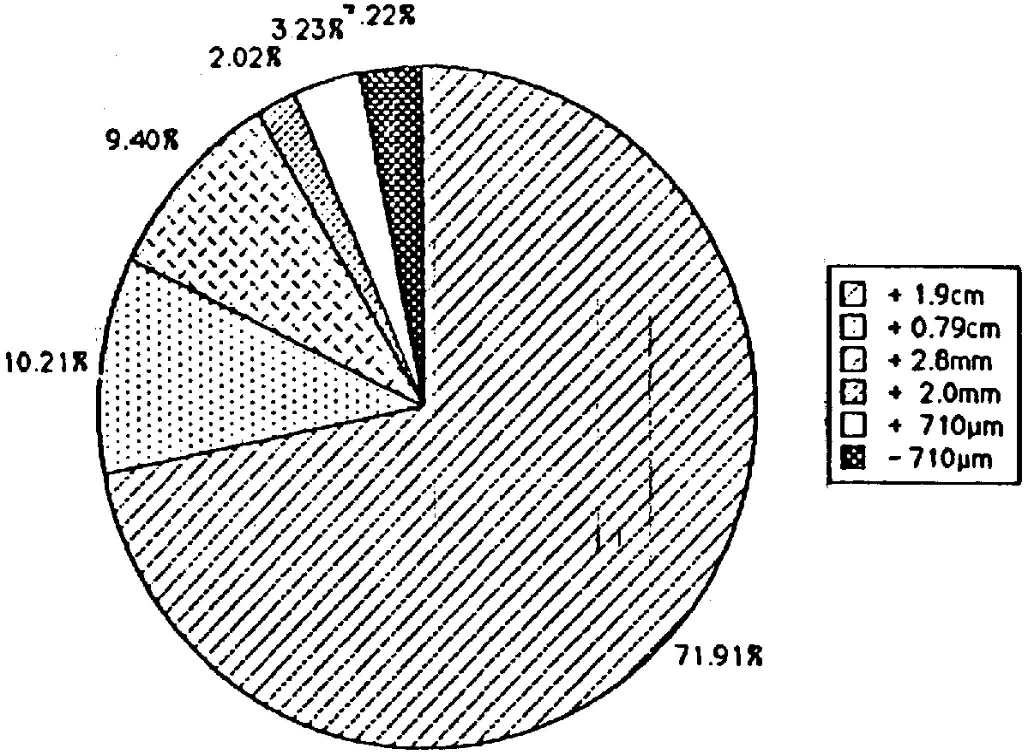

Figure 18: Particle Size Distribution for Trial 2 Sludge, Rubber and Woodchips [with Temperature Control]

(91.53% wt) could be recycled as bulking material. This low value for the final product was due to the presence of cut spent rubber tires, which accounted for 71.91% wt of the mixture.

The nutrient and heavy metal content of the final composting mixture is presented in Table 15.

TABLE 15: Nutrient and Heavy Metals Content for the Final Mixture in Experimental Trial 2'.

Total K Nitrogen'	28.5
Total Phosphates'	0.629
Potassium'	1702
Chromium(ppm)	10.3
Nickel(ppm)	7.4
Lead(ppm)	3.3
Cadmium(ppm)	0.7

' units [mg/kg]

5.4.3. EXPERIMENTAL TRIAL 3

The experimental trial 3 consisted of a mixture of primary sludge and woodchips at a volumetric mixing ratio of 1.5:1 (woodchips:sludge). The characteristics of the sludge, woodchips, cut spent rubber tires and the initial composting mixture is presented in Table 16. For the preparation of the composting mixture, 3.437kg of primary sludge with an apparent density of 0.736kg/l, was mixed with 1.04kg of woodchips from the African tuliptree with an apparent density of 0.148kg/l. Of the resulting mixture, 4.2535kg were placed inside the PVC cylinder, with an apparent density of 0.379kg/l.

TABLE 16: Characteristics of the Sludge, Woodchips and Initial Mixture for Experimental Trial 3

	Sludge	Woodchips	Mixture (initial)
Moisture (%wt)	72.4	53.0	68.59
Volatile Solids'(%wt)	65.82	96.3	82.75
Total N' (mg/kg)	143.5	4213	1087.6
Potassium' (mg/kg)	475	694	526
Total PO4' (mg/kg)	2.45	1.15	2.14
pH	6.8		7.1
Carbonϕ (mg/kg)			405000
C/N Ratio			372.4
Chromium' (ppm)	115.6	3.2	
Lead' (ppm)	27.8	2.0	
Nickel' (ppm)	54.7	2.1	
Cadmium' (ppm)	8.0	0.2	

' dry basis

ϕ Carbon (%) = [Volatile solids (%)]/1.8 [21,43]

In Figure 19, the temperature profile for the experimental trial 3 is presented. The mixture temperature increased gradually during the first 5 days, reaching temperatures in the range of 55 to 60°C. This high temperature was maintained for about 13 days, because the trial had temperature control. Figure 20 demonstrates that the temperature of the composting mixture inside the PVC cylinder was higher than the temperature of the aluminum cylinder wall. This difference in temperatures was not

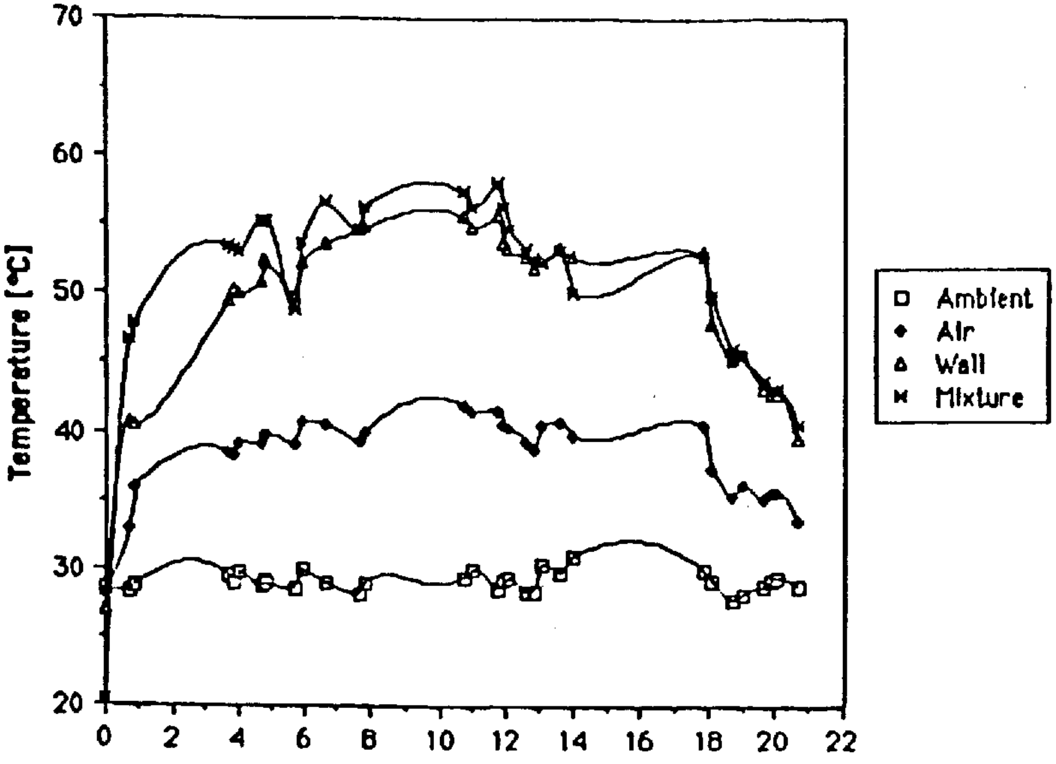

Figure 19: Temperature Profile for Trial 3
Sludge and Woodchips [with Temperature Control]

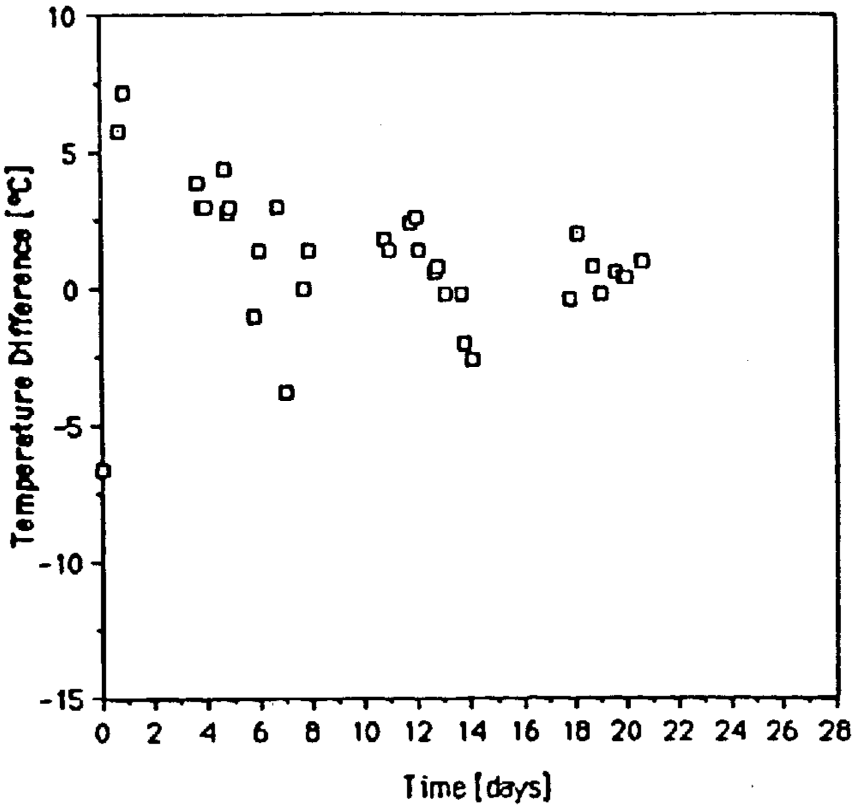

Figure 20: Temperature Difference for Trial 3
T(in, ave) - T(wall)

observed at the beginning of the experimental trial because the heat source at the aluminum wall was used for the start-up. Also, it was not observed when the composter was open for sample collection and change of direction in air flow every 7 days.

The change in moisture and volatile solids content is presented in Figure 21. The moisture content of the composting mixture increased after the first week because the air was saturated before entering the composter. This caused no moisture reduction in the composting mixture due to aeration, stabilizing the moisture content in an average of 73.24%. A gradual reduction in the volatile solids content was observed, evidence that the degradation reaction was taking place. The greatest change in volatile solids content was observed during the first week (from 82.75% to 69.69%), mainly due to the decomposition of the most degradable materials present. The progress of the degradation reaction was also observed in the weight loss, represented by Figure 22. Although samples were taken every 7 days, a weight loss was observed between composter openings. During the first two weeks, an average change of 0.1122kg per week was observed, and a change of 0.0627kg for the third week.

After curing the mixture for 30 days, it was sieved to obtain the final product and the recyclable portions. Figure 23 presents the size separation in weight percent. About 24.96% wt of the final

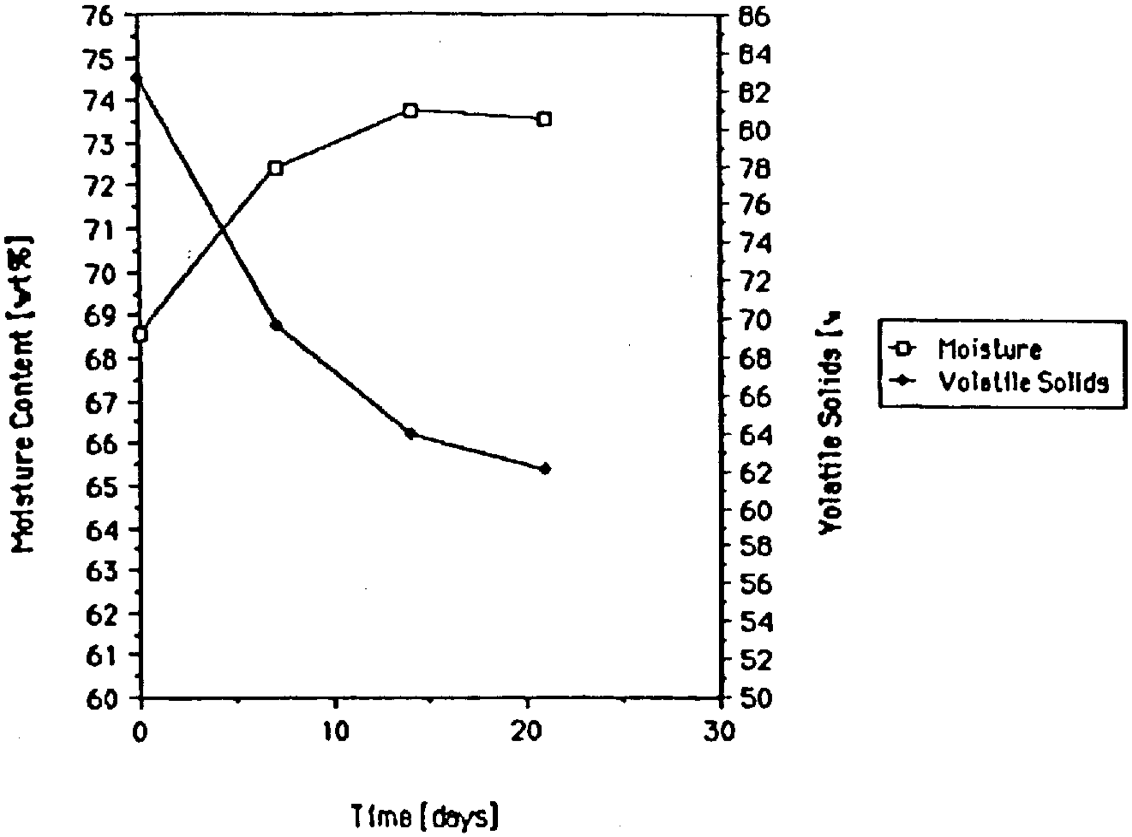

Figure 21: Change in Moisture and Volatile Solids Content for Trial 3

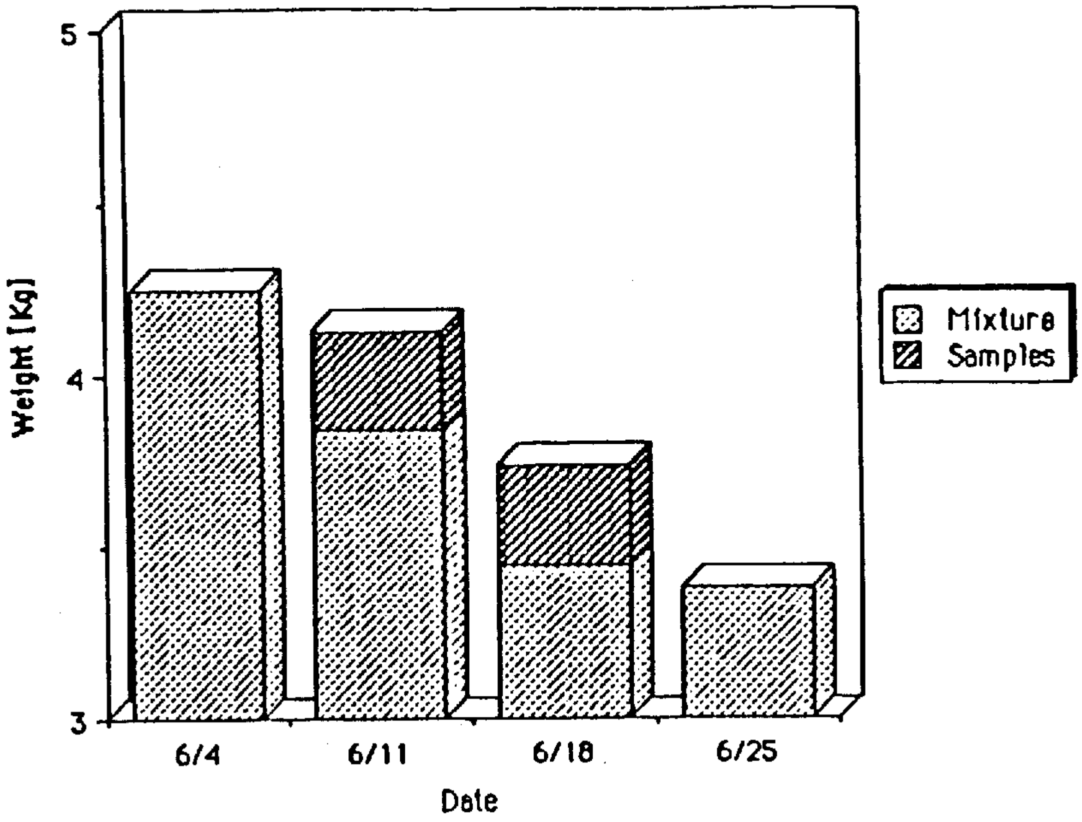

Figure 22: Weight Loss for Trial 3
Sludge and Woodchips (with Temperature Control)

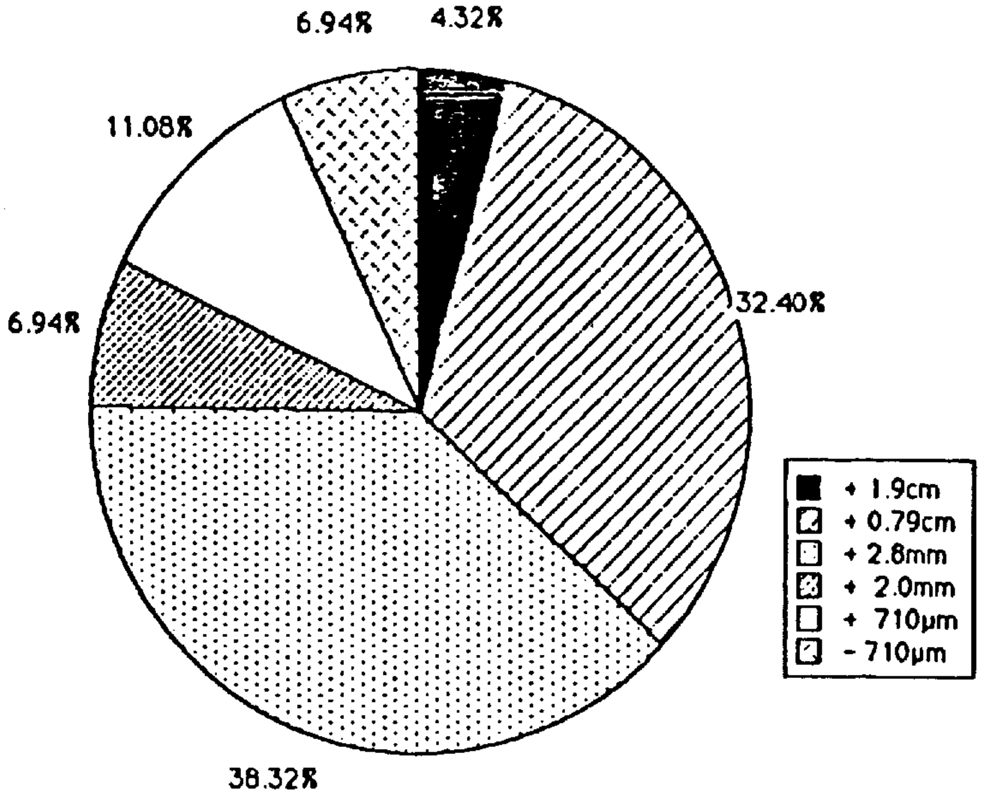

Figure 23: Particle Size Distribution for Trial 3
Sludge and Woodchips (with Temperature Control)

composting mixture after curing, corresponding to sieve size less than 2.80mm, could be used for utilization purposes. The remaining of the mixture (75.04% wt) could be recycled as bulking material. The nutrient and heavy metal content of the final composting mixture is presented in Table 17.

TABLE 17: Nutrient and Heavy Metals Content for the Final Mixture in Experimental Trial 3.

Total K Nitrogen'	13440
Total Phosphates'	0.565
Potassium'	3983
Chromium(ppm)	8.9
Nickel(ppm)	4.1
Lead(ppm)	3.0
Cadmium(ppm)	0.5

' units [mg/kg]

5.4.4. EXPERIMENTAL TRIAL 4

The experimental trial 4 consisted of a mixture of primary sludge and woodchips and cut spent rubber tires at a volumetric mixing ratio of 2:2:1 (sludge:rubber tires:woodchips). The characteristic of the sludge, woodchips, cut spent rubber tires and the initial composting mixture is presented in Table 18. For the preparation of the composting mixture, 3.59kg of primary sludge with an apparent density of 0.769kg/l, was mixed with 0.274 kg of woodchips from the African tuliptree with an apparent density of

0.117kg/l and with 1.8185kg of cut spent rubber tires with an apparent density of 0.389kg/l. Of the resulting mixture, 5.34kg were placed inside the PVC cylinder, with an apparent density of 0.477kg/l.

TABLE 18: Characteristics of the Sludge, Woodchips and Initial Mixture for Experimental Trial 4

	Sludge	Woodchips	Rubber''	Mixture (initial)
Moisture (%)	76.59	52.71		72.63
Volatile Solids' (%)	53.66	96.5	94.3	55.82
Total N' (mg/kg)	11538	4186		11023
Potassium' (mg/kg)	210.7	689	162	244
Total PO4' (mg/kg)	2.14	1.15		2.07
pH	7.5			7.1
Carbonϕ (mg/kg)				310111
C/N Ratio				28
Chromium' (ppm)	133.2	3.2		
Lead' (ppm)	42.4	2.0	17.5	
Nickel' (ppm)	45.3	2.1	5.6	
Cadmium' (ppm)	2.1	0.2	4.12	

' dry basis

'' data by Dr. Narinder K. Mehta

ϕ Carbon (%) = [Volatile solids (%)]/1.8 [21,43]

In Figure 24, the temperature profile for the experimental trial 4 is presented. The mixture temperature increased gradually during the first 3 days, and reached a temperature around 75°C. The mixture temperature remained above 70°C for about 4 days. Because the experimental trial 4 did not have temperature control, the composting mixture reached temperatures of around 80°C. Figure 25 demonstrates that the temperature of the composting

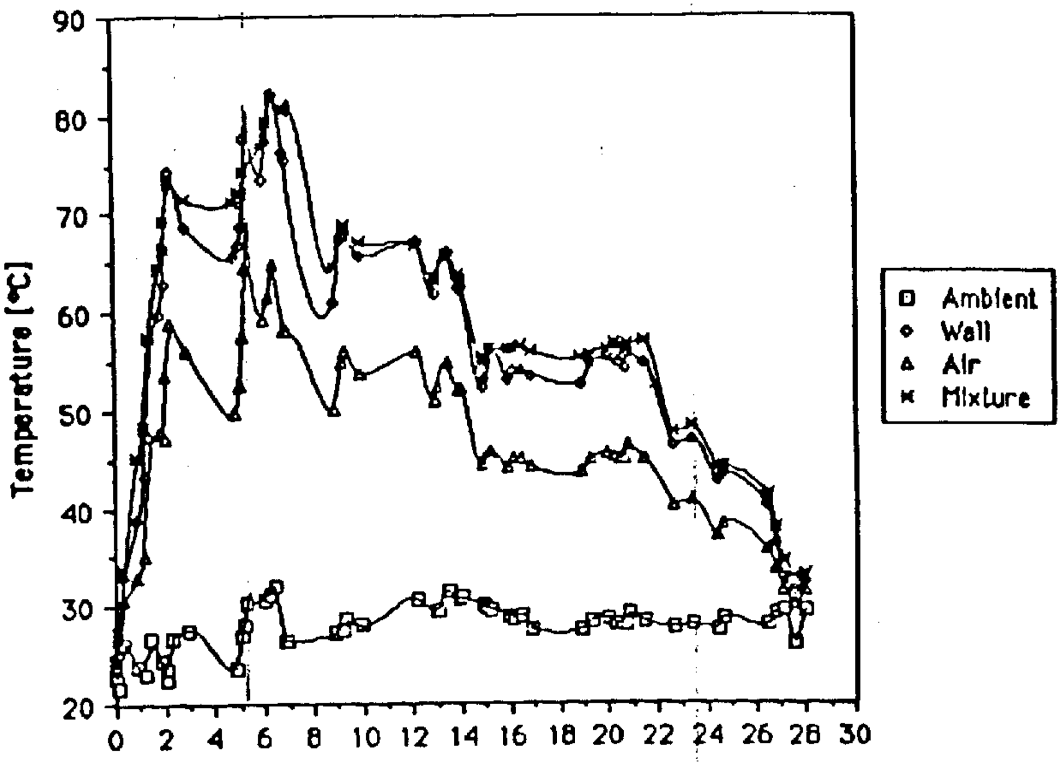

Figure 24: Temperature Profile for Trial 4
Sludge, Rubber and Woodchips [without Temperature Control]

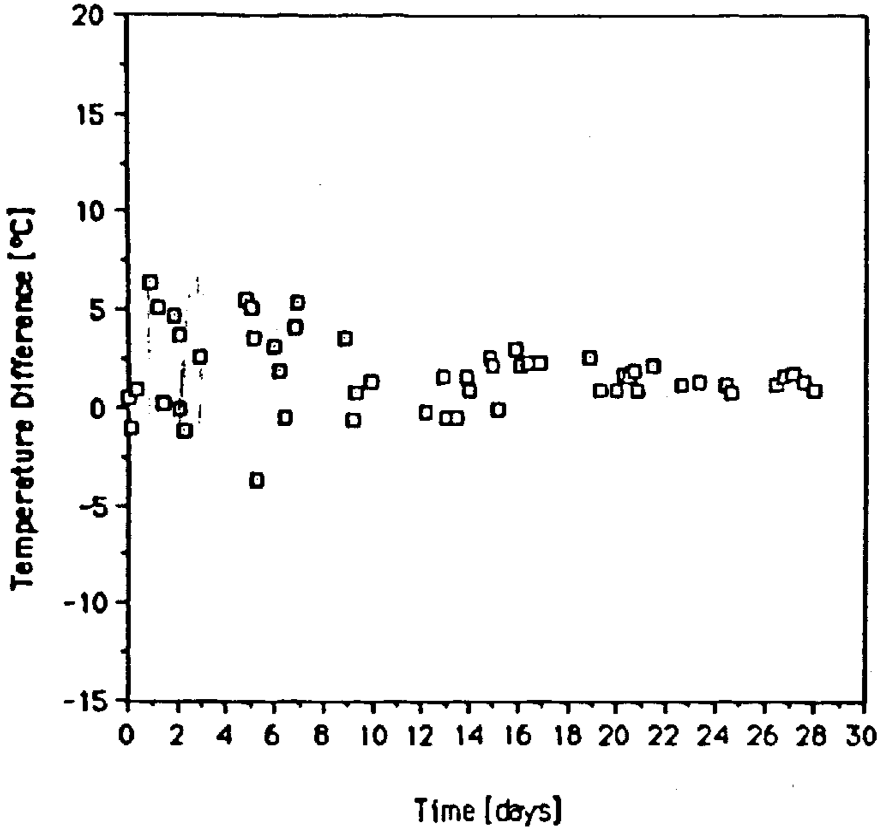

Figure 25: Temperature Difference for Trial 4
T(in, ave) - T(wall)

mixture inside the PVC cylinder was higher than the temperature of the aluminum cylinder wall. This difference in temperatures was not observed at the beginning of the experimental trial because the heat source at the aluminum wall was used for the start-up. Also, it was not observed when the composter was open for sample collection and change of direction in air flow every 7 days.

The change in moisture and volatile solids content is represented in Figure 26. The moisture content of the composting mixture decreased during the first two weeks because of the high temperatures reached by the mixture. At this high temperatures, the air entering saturated at ambient temperature was able to significantly remove moisture from the mixture. No significant reduction in the volatile solids content was observed, which demonstrates that the degradation reaction was not taking place properly and efficiently as in the other trials. The volatile solids content was maintained in the average of 54.98% during the experimental trial. The effect of moisture removal was observed in Figure 27 for the weight loss. The weight loss observed for the first week was 0.437kg, 0.2787kg for the second week and 0.1549kg for the third week. All this weight loss was the product of moisture removal by the air flow.

After curing the mixture for 30 days, it was sieved to obtain the final product and the recyclable portions. Figure 28 shows the size fractions in weight percent. About 13.06% wt of the final

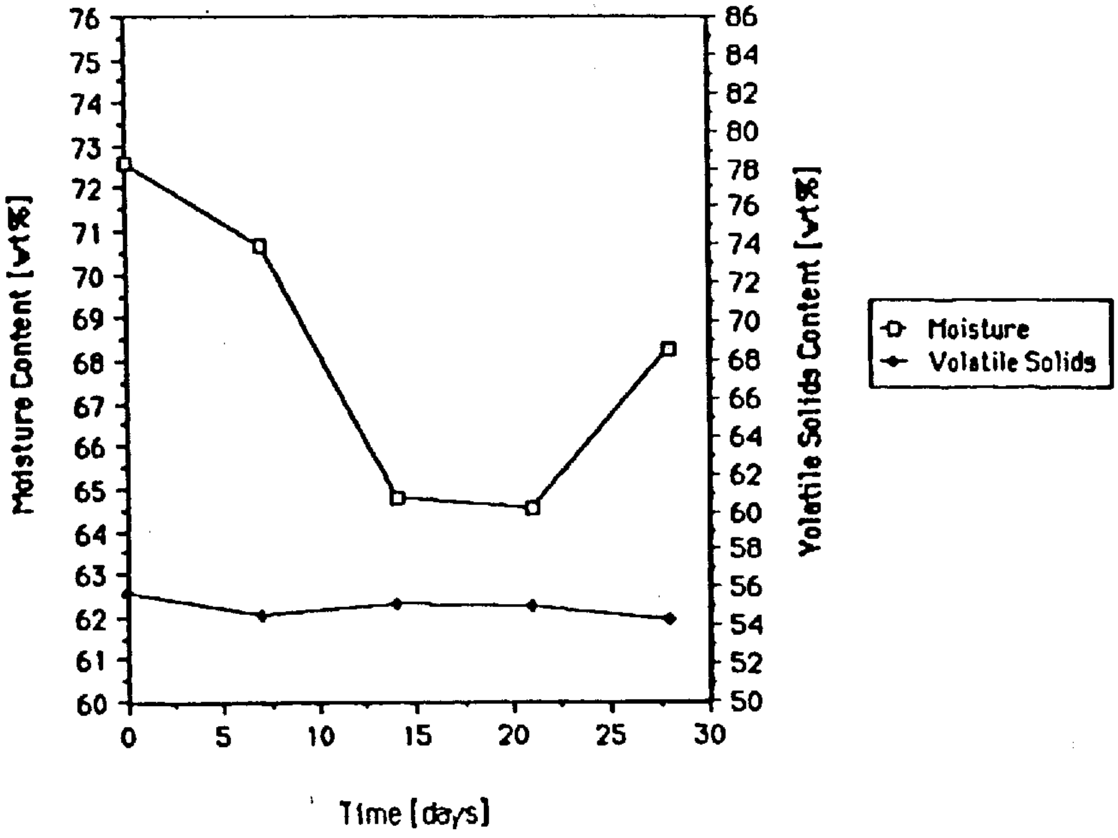

Figure 26: Change In Moisture and Volatile Solids Content for Trial 4

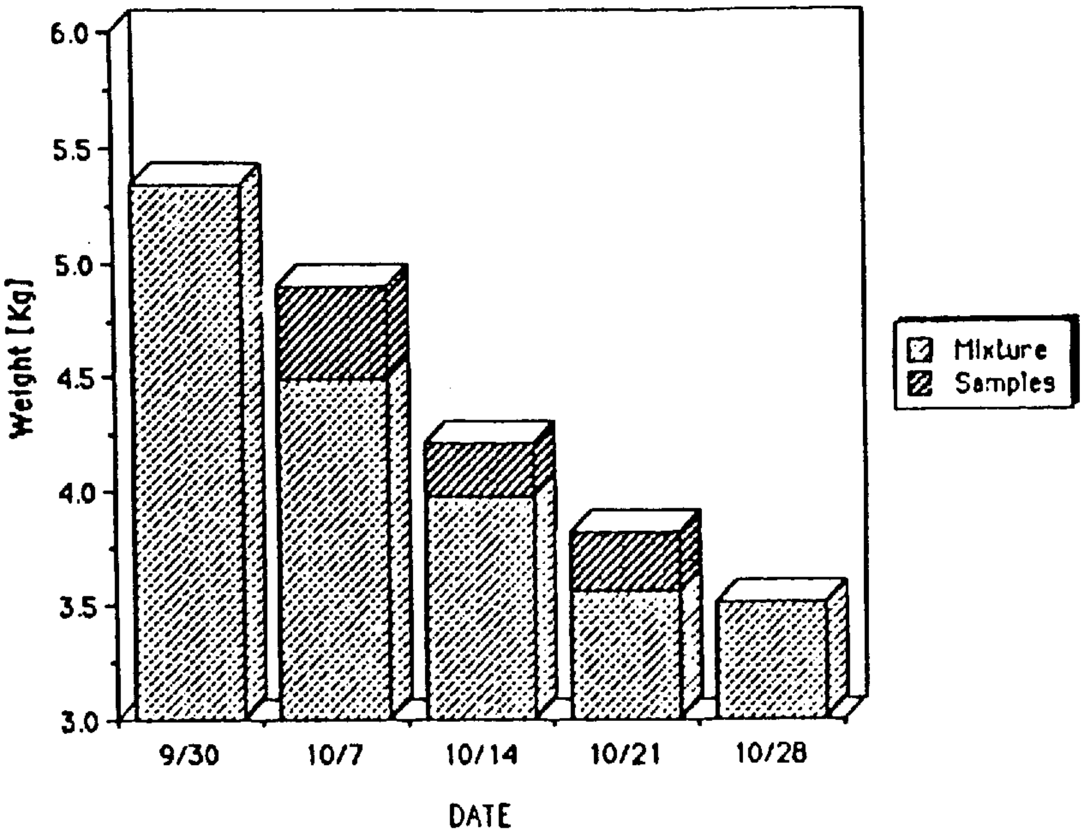

Figure 27: Weight Loss for Trial 4

Sludge, Rubber and Woodchips [without Temperature Control]

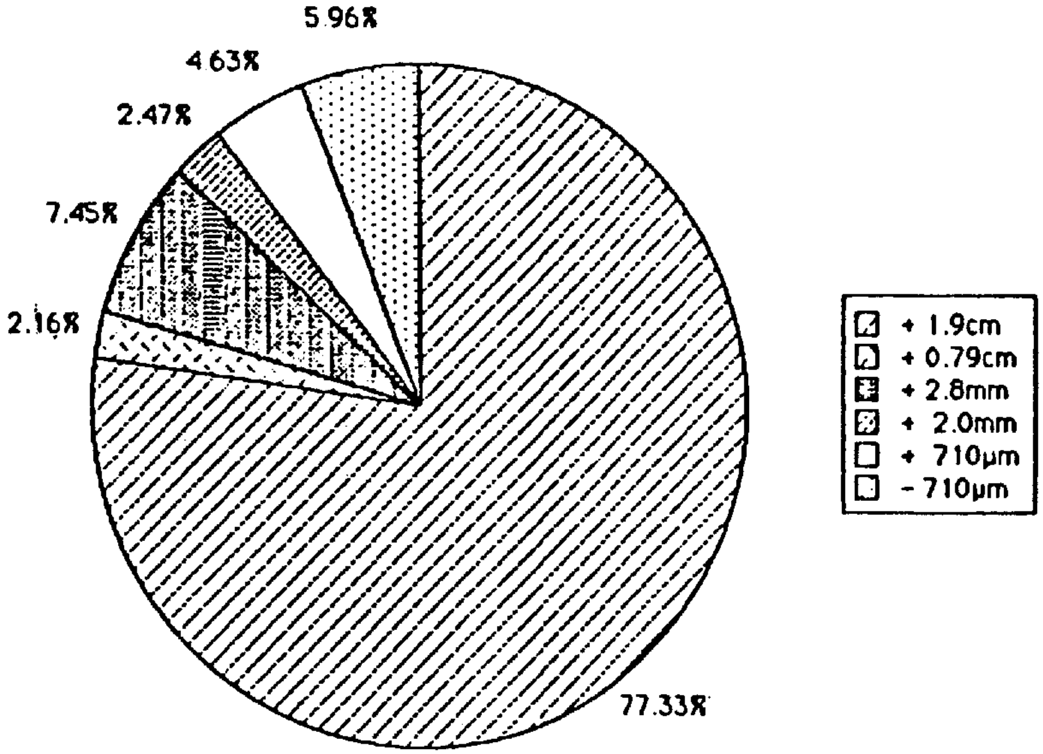

Figure 28: Particle Size Distribution for Trial 4

Sludge, Rubber and Woodchips (without Temperature Control) composting mixture after curing, fraction corresponding to sieve size less than 2.80mm, could be used for utilization purposes. The remaining of the mixture (76.94% wt) could be recycled as bulking material. This low value for the final product was due to the presence of cut spent rubber tires, which accounted 77.33% wt of the mixture.

The nutrient and heavy metal content of the final composting mixture is presented in Table 19.

TABLE 19: Nutrient and Heavy Metals Content for the Final Mixture in Experimental Trial 4.

Total K Nitrogen'	11520
Total Phosphates'	0.472
Potassium'	136
Chromium(ppm)	11.8
Nickel(ppm)	5.6
Lead(ppm)	4.3
Cadmium(ppm)	0.9

' units [mg/kg]

5.4.5. TOTAL AND FECAL COLIFORMS, AND PH

The change in total and fecal coliforms is presented in Table 20. All four trails showed a significant reduction in the total and fecal coliforms, without any significant difference observed for the type of bulking agent used, or for trials with or without temperature control.

TABLE 20: Total and Fecal Coliforms for the Experimental Trials[1]

	Fecal		Total	
Trial	Sludge	Compost	Sludge	Compost
1	90	<30	≥ 24,000	90
2	≥240,000	<30	≥240,000	70
3	≥240,000	<30	≥240,000	70
4	≥24,000	30	≥24,000	90

[1] MPN/100 mls

The change in pH for all the four experimental trials is presented on Figure 29. Trial 1, 2, and 3 showed similar behavior in the increase of pH as the degradation proceeded. As already explained in Chapter 3, the increase in pH probably was due to the production of NH_3 by the degradation reaction. In trial 4, the pH oscillated and not reached the same final pH as the preceding trials. This type of behavior was caused by the high temperature reached during the first 5 days, which killed the degradation reaction.

5.5. Statistical Analysis

A statistical analysis was performed based on the percent change in the volatile solids (Table 21). The experimental trial 3 showed the greatest change in volatile solids (Figure 30).

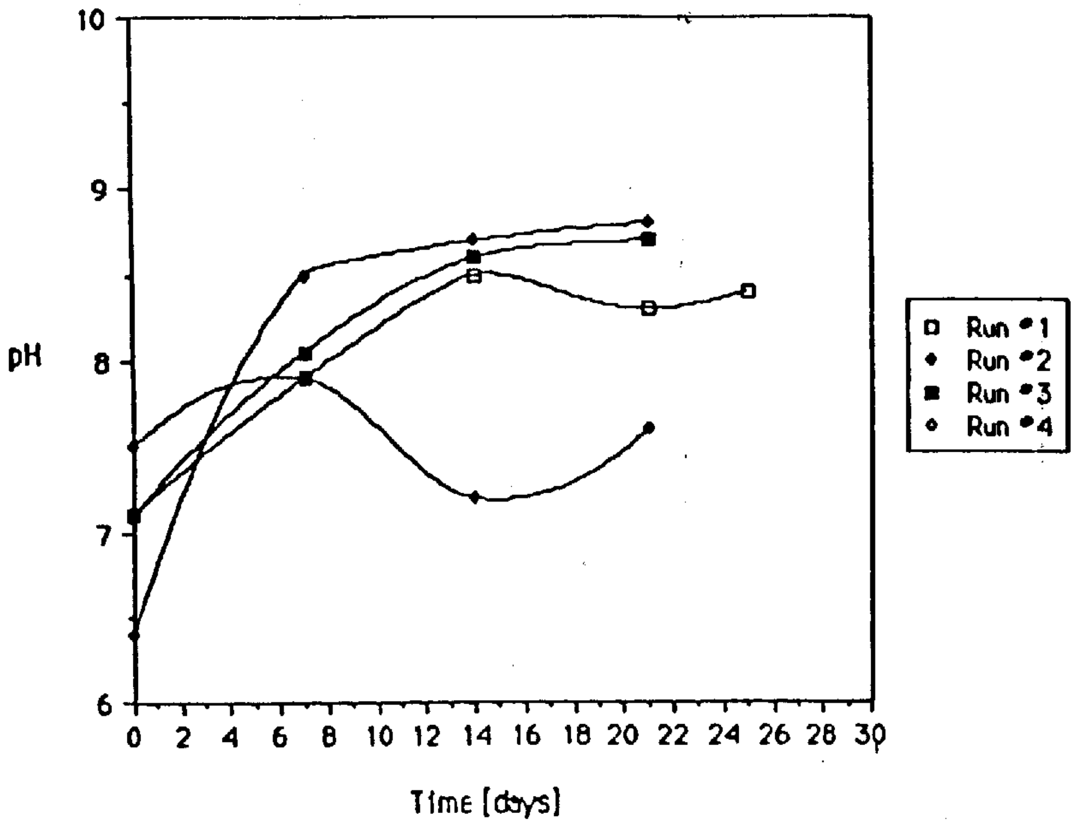

Figure 29: Change in pH vs Time for Each Trial

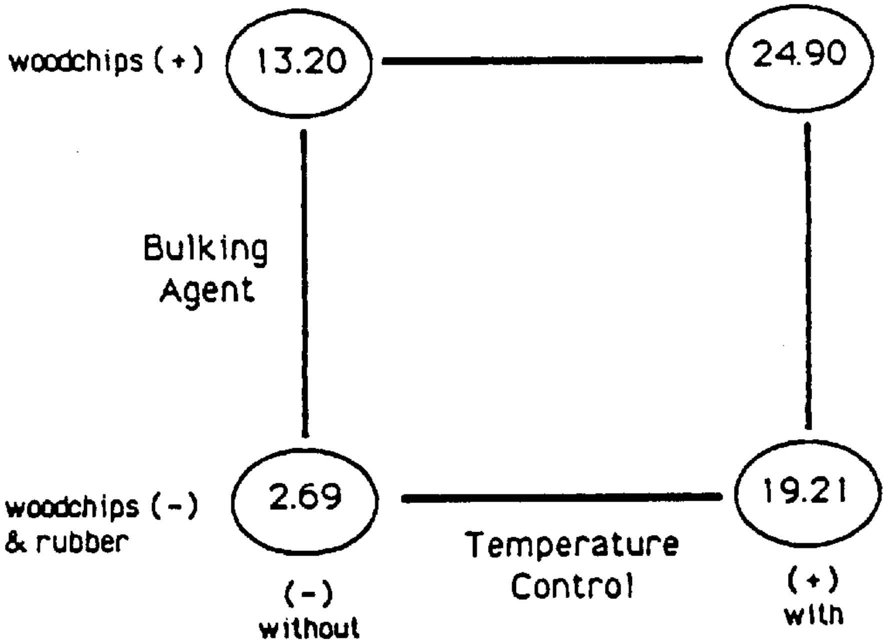

Figure 30: Type of Bulking Agent and Temperature Control interactions based on the Change Percent of the Volatile Solids.

TABLE 21: Change Percent in Volatile Solids Content for the Experimental Trials

Bulking Agent	Temperature Control	Volatile Solids ($\Delta\%$)
Woodchips	No	13.20
Woodchips and Rubber	Yes	19.21
Woodchips	Yes	24.90
Woodchips and Rubber	No	2.69

The main effect of the type of bulking agent was calculated to be 8.1. The main effect measures the average effect of the type of bulking agent over the conditions of with or without temperature control. The main effect of the temperature control was calculated to be 14.11.

A value of "1" was assigned to the bulking agent using only woodchips, an "0" for the ones using woodchips and rubber. For the temperature control, a value of "1" was assigned when the temperature control was used, and "0" when not. Using these assigned values, the correlation coefficients of the variables with respect to the change percent of volatile solids were calculated. For the type of bulking agent used, the covariance was found to be 2.7, with a correlation coefficient of 0.492. For the temperature control, the covariance was found to be 4.703, with a correlation coefficient of 0.858. This data shows that the significant variable for the best performance of the composting process is the temperature control. The type of bulking agent showed to be not so important, if basic conditions as moisture content, and the necessary free air space and porosity were available.

6. CONCLUSIONS AND RECOMMENDATIONS

The existence of a temperature control system was the most important variable in the performance of the composting process based on the change percent of volatile solids content, the reduction in the total and fecal coliforms, and the change in nutrients content (nitrogen, phosphorus and potassium).

Table 22 showed the change in nutrient content for all the experimental trials. No specific pattern could be inferred from this data. Trial 3 showed the greatest change, with a significant increase in the total Kjeldahl nitrogen and potassium content. Also trial 4 showed no change in the nutrient content, evidence that the degradation reaction did not proceed. The negative values indicate that the nutrients increased after composting. This variability was associated to the difficulty to obtain homogeneous mixture for nutrient determination; it was impossible to establish the same sludge:bulking agent ratio in the final compost samples.

Table 22: Change in Nutrients Content for All Experimental Trials

Trial	Nitrogen(%)	Potassium(%)	Phosphates(%)
1	-11	-99.6	-80.1
2	-93.35	247	-73.35
3	1135	653.5	-75.6
4	4.5	-44.26	-22.8

The C:N ratio for the first three trials was too high, due to the low nitrogen content of the sludge. This will establish longer times of composting and help in the mineralization of nitrogen, but could not be demonstrated from the experimental data. The final composting mixture showed low concentration of heavy metals. Based on the concentration limits in Table 23, the final product could be used safely as a soil conditioner.

Table 23: Sludge Contaminant Concentration Limits[1]
[Marketing and Distribution]

	Cadmium (mg/kg)	Lead (mg/kg)	Nickel (mg/kg)
Range	2 - 40	300 - 4800	100 - 1250
Mode	25	500	200

[1] Table from [51]

Although some data showed a great variability, there is a trend that shows that the best alternative is the use of temperature control and only woodchips as the bulking agent. The reduction in the volatile solids was greater for the experimental trial with woodchips and temperature control. This also showed a significant reduction in process time, as was shown by the temperature profile. In the matter of pathogen reduction, all the trials showed the same significant decrease after composting, due to the elevated temperatures.

Based on the results obtained, it is recommended to re-design the bench-scale composter to eliminate leakages to make possible the determination of NH_3 and CO_2 produced in the degradation reaction. This includes the utilization of a method of analysis different from the gas washing bottles, due to the high pressure resistance. Also, a more effective system to close the PVC cylinder and which will allow for sample collection is needed.

Experiments should be made in the area of the degradability coefficient for the sludge and bulking agent used. These data will help in the development of a computer simulation model of the bench-scale composter. This computer simulation will enable comparisons between different types of bulking agents and mixing ratios without a long time of experimentation.

It is also recommended to study the effect of recycle in the composting process performance. As demonstrated in Chapter 5, almost 75% wt of the final composting mixture could be recycled. It is necessary to study the effect of recycle in the nutrients availability, the C:N ratio, and how many times could it be recycled.

Continuation of studies in these areas will help in the establishment and operation of already designed composting plants in Mayagüez and Arecibo. The utilization of composting process offers a solution to the problem of stabilization of the sludge produced in the wastewater treatment plants, and will help in the conditioning of the Puerto Rican soils.

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