SEWAGE SLUDGE DISPOSAL: THE COMPOSTING OPTION

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ABSTRACT

The objective of the present studies was to explore the possibility of employing composting as a mean of sewage sludge stabilization. A series of composting experiments were performed using dewatered secondary activated sewage sludge from a domestic wastewater treatment plant in New Plymouth, New Zealand. These trials have been carried out treating the sludge in both open and closed composting systems on a laboratory scale. Two open system methods, one aerated windrow and one static pile, and three closed experiments using a compostumbler were performed. Throughout the whole study woodchips (in varying ratios) were used as a bulking agent.

An initial moisture content of nearly 60% in the sludge - woodchips mixture produced the highest degree of composting activity over a three week period.

Biological drying during the process was indicated by an increase in total solids up to values between 17% and 27%.

Partial stabilization of the organic fraction was indicated by a decrease in volatile solids of 28% - 50%. In two closed system trials a total carbon decrease of 26% - 42% was observed, serving as an additional indication that there had been a reduction in organic matter.

Total nitrogen losses were substantial in all experiments. Reductions were in the range of 14% - 58% with the highest

losses observed in the static pile experiment.

Phosphorus was found to be stable with only minor concentration changes observed.

Temperature development in the composting material followed the well known pattern, provided that the factors influencing the composting process were close to optimal. Temperatures approaching 70^{O}C in the initial stage of the process were measured.

Bacteriological studies indicated, that the final composted product was not free from microbial hazard. In one closed system trial, however, no entero-streptococci were observed, indicating a complete inactivation of these indicator microorganisms.

Ongoing development of the composting systems used, including improvements of methodologies employed is necessary in conducting further investigations.

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ABBREVIATIONS AND SYMBOLS USED IN THE TEXT

$B_{95\%}$:	95% confidence interval on the mean
BEA:	Bile Esculin Azide
C:	Carbon
°C:	Degree Celsius
CFU:	Colony Forming Units
C/N:	Carbon to nitrogen ratio
F:	F-ratio of mean sums of squares
g:	Gram
h:	Hour
kg:	Kilogram
l:	Liter
m:	Meter
ml:	Milliliter
MPN:	Most Probable Number
N:	Nitrogen
P:	Phosphorus
PCA:	Plate Count Agar
s:	Standard deviation
TS:	Total solids
VS:	Volatile solids
v/v:	Volume/Volume
w/w:	Weight/Weight

CHAPTER 1

INTRODUCTION

Wastewater treatment processes produce substantial quantities of sludges requiring further treatment and disposal. Sewage sludge contains recyclable nutrients, but it also contains parasitic and pathogenic organisms. For these reasons digestion and incineration of sewage sludge have been employed in dealing with sludges satisfactorily, however, they are generally not economical.

Liquid or semi-solid sewage sludge has also been directly reused in agriculture, but this practice is becoming rare with increasing public awareness of environmental problems. It is now generally accepted, that for recycling of sewage sludge, its organic matter must be stabilized and, for specific situations, sanitized to eliminate risks of animal and human infection.

Current treatment technologies to stabilize the organic fraction of sewage sludge include mesophilic or thermophilic aerobic and anaerobic digestion. Problems associated with these technologies are incomplete removal of pathogens in the first and high costs in maintaining thermophilic temperatures in the second case. Sanitation of sludge using lime or chlorine treatment is also inefficient, whereas pasteurization and irradiation present serious post-processing contamination problems, and are expensive upstream and downstream processes. The product of thermally dried sludge can be stored for long periods. However, it is very expensive to produce and, since it is not biodegraded, it is also prone to moisture resorption and recontamination.

Aerobic composting is a biological process, which can serve as a treatment component of an overall sewage management plan. It provides a stable product, usable as a soil conditioner. It achieves significant volume reduction through biological drying. Proper process conditions and a thermophilic phase during processing lead to the volatilization of organic compounds as well as to inactivation of bacterial pathogens and parasites. Composting has been widely investigated and the basic process mechanisms have been established.

The city of New Plymouth, New Zealand, is currently evaluating different treatment systems for excessive amounts of activated sewage sludge. The objective of this work was to investigate the feasibility of composting as a means of stabilizing dewatered activated sewage sludge, originating form the city's municipal wastewater treatment facility. Of concern was the monitoring of the temperature development, the reduction of volatile organic matter, the change in nitrogeneous and phosphorous compounds and the reduction of indicator microorganisms during the operation. The relative performances of open and closed systems was also investigated.

CHAPTER 2

SLUDGE TREATMENT AND DISPOSAL - AN OVERVIEW

Liquid waste, resulting from the domestic and industrial activities of a community, is described as sewage. Raw sewage usually contains mostly water (greater than 99.5%, v/v). It can be defined as a turbid liquid consisting of a dilute complex mixture of inorganic and organic matter in many forms. These forms include:

(i) Substances in true solution,

(ii) floating and suspended, large and small particles of solid matter, and

(iii) finely divided, colloidal matter.

Domestic sewage contains living microorganisms, and is an excellent growth medium for bacteria. The composition of sewage depends largely on the ratio between the domestic and the industrial wastewater present.

The object of sewage treatment is to separate the pollutants from wastewater in order to produce water of the appropriate discharge specifications and a minimum quantity of essentially non-noxious solid residue.

Wastewater treatment involves a series of processes. A possible overall block diagram of treatment steps involved is given in Figure 2.1. The treatment process invariably results in sludges containing suspended solids in the influent wastewater and the solids generated during treatment. The sludges need further treatment before disposal to minimize detrimental environmental impact.

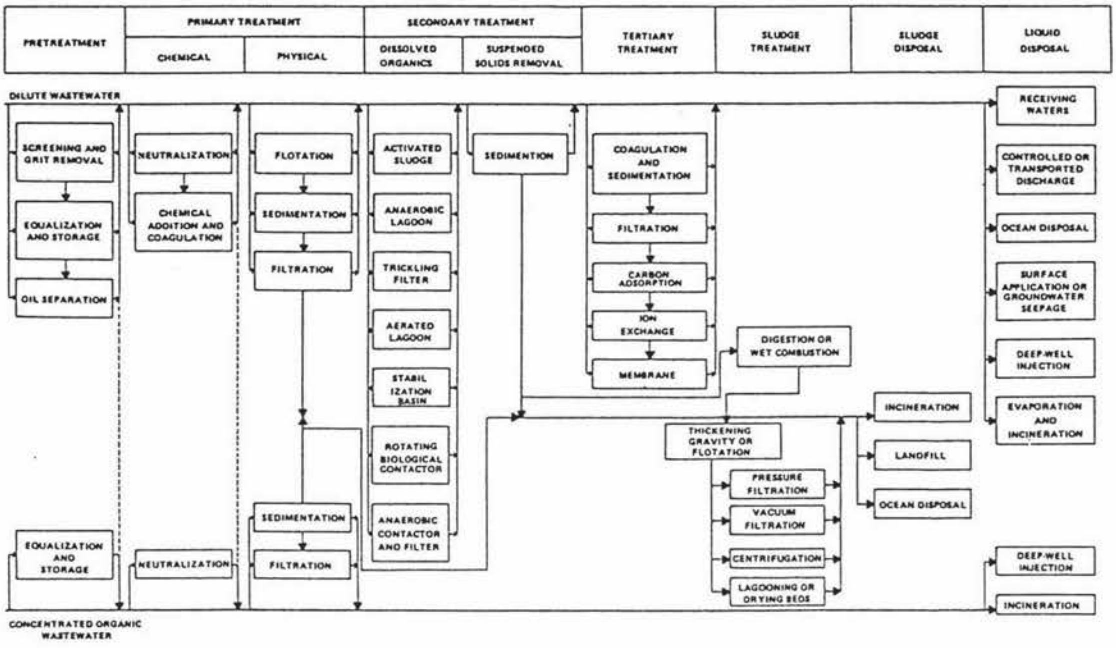


FIGURE 2.1: Diagram of wastewater treatment processes. (Source: Eckenfelder, 1980).

2.1 GENERAL ASPECTS OF SLUDGES

The more efficient wastewater plants of today produce quantities of sludge that are difficult to handle. Complex waste sludges which originate from industrial or municipal wastewater are usually produced by one of a variety of treatment systems. These sludges include process sludges and residuals from mining, manufacturing and agriculture. Eckenfelder and Santhanam (1981) state that sludges may be defined as a solid-liquid waste mixture having a total solid concentration that may range from as low as 2000 parts per million (ppm) to hundreds of thousands of ppm in some industrial sludges. A further clarification of the meaning of sludge is given by the following description:

Sludge is a combination of pure water, soluble and insoluble substances and either of them can be organic or inorganic in nature (Dillard, 1981).

With any characterization of a sludge one should therefore include the following details, viz.

- The source of the sludge;
- The processing which has been used on the sludge prior to characterization; and
- Analytical methods used to determine sludge characteristics.

Differences in the types of wastewaters and in design and operation of treatment plants result in a great variation of characteristics of sludges. Operation and design of treatment require the measurability of several of these characteristics (Vesilind, 1980).

Typical data on the chemical composition of different sludges as well as physical characteristics are well established (Tchobanoglous, 1985). A large proportion of industrial solid wastes occur in the form of sludges. These are environmentally significant and are produced in greater amounts than municipal solid wastes or sewage sludges. Quantities of municipal and industrial sludges are likely to increase significantly (Eckenfelder and Santhanam, 1981).

Problems in sludge treatment based upon the reduction of water and organic content of sludges are complex due to many reasons:

- Sludge is composed largely of the substances responsible for the offensive character of untreated wastewater;
- Sludge produced through biological treatment is composed of the organic matter contained in the wastewater but in another (i.e. cellular) form. After disposal this sludge will decompose and become offensive;
- A small part of the sludge consists of solid matter.

The operations of sludge treatment and disposal generally account for as much as 50 percent of the total running cost of a sewage treatment work site, although the volume of liquid sludge which is produced through the treatment usually represents only 1-2 % of the total flow of sewage (IWPC, 1979). Sludges may be subjected to various unit operations, treatment stages and forms of final disposal (Figure 2.2). These treatments may be combined depending upon many factors.

During the year 1984 the annual sewage sludge production in Western Europe was reported to be about 5.5 million tonnes (expressed in dry solids), which is expected to rise further in the near future (Matthews et al., 1986). It is clear that these increasing volumes of sludges from domestic and industrial sources together with a decreasing availability of land for sludge disposal purposes as well as a decreasing public tolerance of environmental pollution poses serious long term problems for municipal authorities. As an example one could consider agricultural use of sewage sludge as a possible disposal means. In this case serious difficulties arise with regard to the protection of the environment. In order to overcome such limitations, an improvement of the treatment of sludge at reasonable cost is necessary to obtain products which could serve as soil additives and to minimize the environmental pollution and harmful effects on human and animal health.

As with other wastes a main problem of sewage sludge and its disposal is the often high content of trace metals. Nriagu and Pacyna (1988) present an inventory of industrial/municipal discharge of trace metals into soils and the aquatic ecosystem. This report also indicates the problem of toxic metal pollution as a global and regional issue and mentions the possible transfer of toxic metals through air, soils and water to the human food chain.

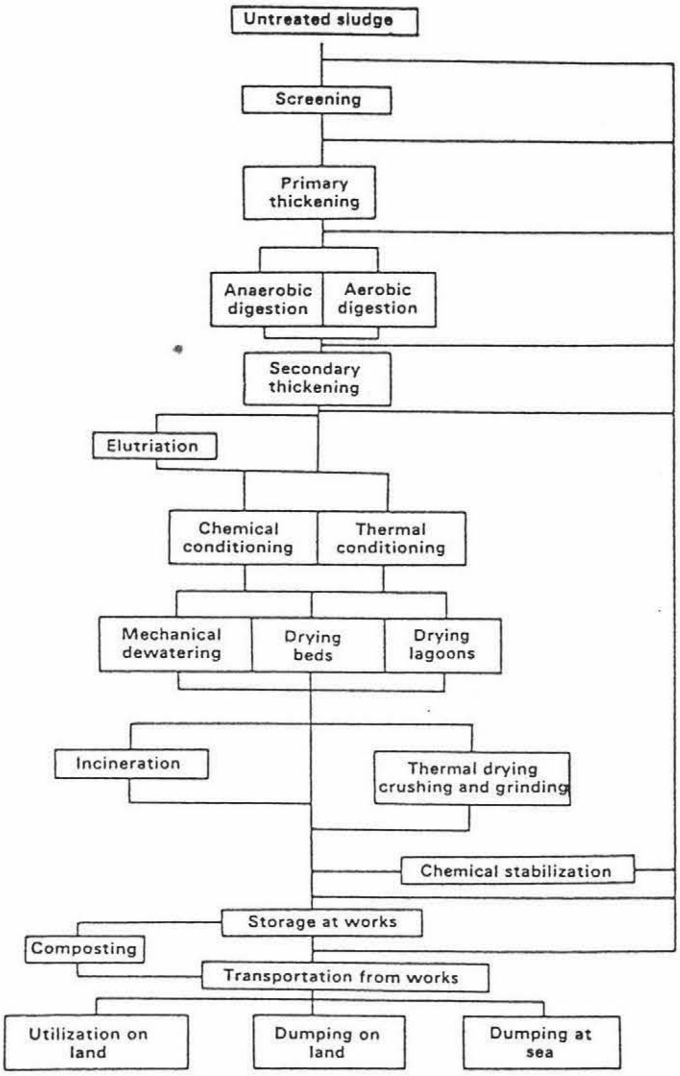


FIGURE 2.2: Unit processes and operations employed in treatment, utilization and disposal of sewage sludge. (Source: IWPC, 1979).

2.2 MUNICIPAL WASTEWATER SLUDGES

Sludges from municipal wastewater treatment plants vary markedly in moisture content, decomposable organic matter, chemical ingredients and microbial populations. Although such material may be produced by efficient treatment plants, their disposal practices are becoming a crucial problem especially with regard to the maintenance of environmental acceptability.

Although municipal sewage sludge may not be a particularly important source on a global scale its trace metal content is often so high, that it is sometimes unsuitable for disposal on land. For a particular region sewage sludge may represent one of the most important sources of metal contamination of soils (Nriagu and Pacyna, 1988).

2.2.1 SOURCES AND PRODUCTION

Sludges from conventional sewage treatment plants originate from primary, secondary and tertiary treatment processes and are known as primary sludge, secondary sludge, and tertiary sludge, respectively.

Raw sludge is defined as primary sludge or secondary sludge or a mixture of the two prior to modification of its nature by some other treatment. Digested sludge is defined as sludge which has been subjected to either aerobic or anaerobic digestion.

The combination of primary and secondary sludges is referred to as mixed sludge. Sludge production usually results from a solids-liquid separation process such as sedimentation or flotation. Environmentally satisfactory sludge disposal options require the optimization of those operations generating the sludge.

The sludges undergo in most cases a series of treatment steps involving thickening, dewatering and biological degradation prior to final disposal. These treatment processes are alternative technologies chosen according to nature and characteristics of the sludge and the final disposal method used.

2.2.1.1 Primary Sludge

When raw sewage enters a municipal sewage works, it is first subjected to either two or three preliminary treatment steps. These steps remove solid materials, gritty matter,and additionally also some oil and grease. After this preliminary treatment stage, the supernatant enters the primary treatment step, which in most cases involves a sedimentation operation.

At most sewage treatment plants about 60-70 percent of the suspended solids and 25-40 percent of the biochemical oxygen demand in the sewage entering the work are removed by primary sedimentation in a clarifier. These solids are known as raw primary sludge. Sludge production in sewage treatment works consists mostly of primary sludge. The presence of industrial effluents may have a marked influence on the characteristics of the primary sludge, which will depend upon the types of industry involved. Primary sludges are often anaerobically digested and after being dewatered they are subjected to ultimate disposal (Eckenfelder and Santhanam, 1981; Vesilind, 1980; WPCF, 1971; IWPC, 1979; Tchobanoglous, 1985; Ramalho, 1983).

2.2.1.2 Secondary Sludge

Secondary sludge is the product of the biological treatment process in which microbial flocs or cell aggregates biochemically oxidize the biodegradable components present in the sewage after the preliminary and primary treatment. A schematic of different activated sludge processes, possibly the most popular of the secondary treatment processes, is shown in Figure 2.3. Chemoheterotrophic bacteria are the predominant microbes in the activated sludge treatment process (Hamer, 1985). The biochemical oxidation process involves the growth and respiration of the microorganisms that comprise the flocs. Two distinct stages occur in the activated sludge process, these are: (1) the bio-oxidation of the degradable components present in the sewage and (2) the sedimentation (settling) of the biomass produced as a result of the microbial growth process. As a consequence the effluent is low in microbial solids while the settled flocs become the secondary sludge for further processing.

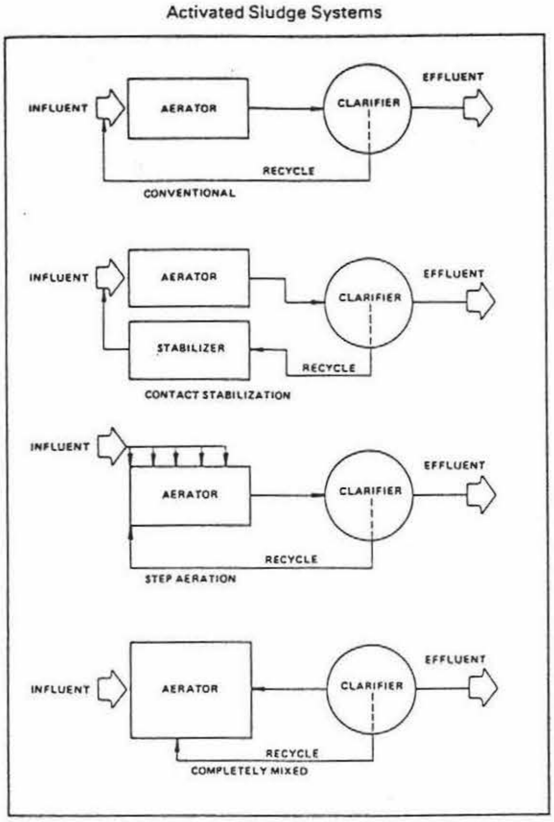


FIGURE 2.3: Schematic representation of different activated sludge systems. (Source: Eckenfelder, 1980).

It is known that there occur also several non-biological, physico-chemical processes during biotreatment (Tchobanoglous and Schroeder, 1985; Hammer, 1986; White, 1987). A detailed description of the activated sludge process can be found elsewhere (Grady and Lim, 1980) and the complexities of its microbial ecology are presented by Hamer (1985).

Secondary sludges also accumulate during secondary treatment in aerobic lagoons. In New Zealand, this process is often used in the biological treatment of meat wastes (Massey University, 1987).

The mass of microorganisms produced in the activated sludge process exceeds the amount required by the system. Consequently, much of the secondary sludge must be removed and treated. The disposal of this material represents one of the most important problems in the field of wastewater treatment. Composting is one of the most promising means of disposing of this material and is the topic of the work herein.

2.2.1.3 Digested Sludge

There are two types of digested sludge; they are products of anaerobic and aerobic digestion and it is the former that is more common (IWPC, 1979). Details of the principles of anaerobic and aerobic digestion can be found elsewhere (Vesilind, 1980; Kugelmann and Jeris, 1981; Adams and Eckenfelder, 1981).

2.3 SLUDGE TREATMENT

2.3.1 INTRODUCTION

As previously described, wastewater operations lead to the generation of sludge. Disposal problems of sludge can be reduced by eliminating some of the water content, which lies in the range of 94 % to 98 % in case of raw sludge. Most sludge-treatment processes have therefore the objective of water reduction. The selected treatment methods depend primarily on the nature and characteristics of the sludge and on the final disposal method employed (Vesilind, 1980). It is important to note that the treatment method used before final disposal should also include consideration of environmental and public health impact. A possible configuration of alternative forms of sludge treatment is shown in Figure 2.4.

The volume of sludge can be reduced to one-tenth by reducing the moisture from 96% to 60% (White, 1987). However, sewage sludges are difficult to dewater. The small size of the particles, electrostatic and capillary forces and the existence of some water in the form of a gel may be reasons for the slow rate of water removal (White, 1987).

In order to facilitate water removal during subsequent thickening and / or dewatering operations, the sludge is pretreated by conditioning. The subsequent water drainage and solids separation is thereby increased. Also filtration, centrifugation and other separation processes can be enhanced through conditioning. Thickening by gravity or by dissolved air flotation is the first step in most sludge treatment processes. Thickening increases the efficiency of further treatment through a considerable reduction in volume and a concentration of solids up to 15% (w/w).

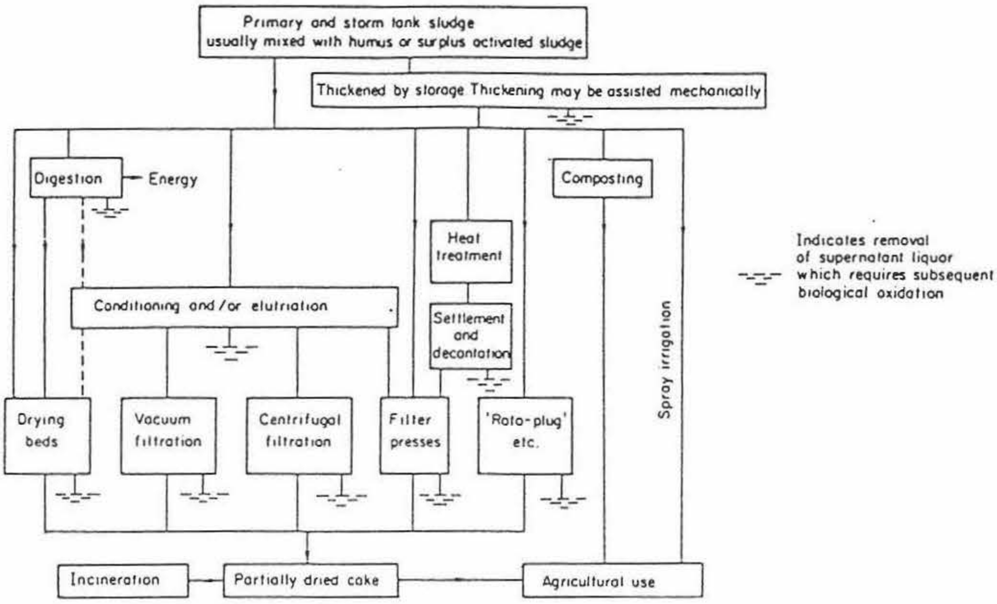


FIGURE 2.4: Schematic relationship of different alternative sludge treatment forms. (Source: White, 1987).

Sedimentation in tanks leads to a small degree of dewatering by consolidation. Often the provision of a slow stirring mechanism encourages the growth of particle size by flocculation. The liquor is then decanted from the surface (IWPC, 1979).

Sludge dewatering brings the concentration of solids to greater than 15% (w/w) and leads to the characteristic flow behaviour of sludge as a solid. Enough water should be removed from the sludge to enable disposal (IWPC, 1981).

Sludge stabilization includes various chemical, physical and biological methods and leads to a stable and disposable product without having detrimental effects on the environment (Vesilind, 1980).

Lime or chloride treatment of sludges stops biodegradation for a limited period only and is an inefficient sanitation method (WPCF, 1984).

Pasteurization and irradiation require a digestion phase upstream or downstream and present serious recontamination problems (WPCF, 1984).

Thermal drying provides a product which is not degraded and can be recontaminated with increasing humidity (WPCF, 1984).

Anaerobic sludge digestion results in the production of combustible gases, e.g. methane but the difficulties of process control is still a major disadvantage in this process.

The basic reaction bringing about aerobic sludge stabilization is the decomposition of complex organic molecules to CO_2 and H_2O through the metabolism of aerobic organisms. Aerobic digestion is suited better to the excessive amounts of biological sludges than it is to primary sludges. Usually this treatment follows a solids-liquid separation process (Kugelmann and Jeris, 1981).

Composting is another form of an aerobic conversion process. Dewatered sewage sludge is usually mixed with a bulking agent to provide additional carbon source and porosity for better aeration (Haug, 1980). The end product has a high utility as a soil conditioner and has a low health risk due to a thermophilic stage in the process (Haug, 1980).

To obtain a dry sludge thermal energy can be used to further treat the sludge after dewatering. Drying of the sludge results in a product containing a high volatile solids content while sludge combustion or incineration involves complete oxidation of all volatile matter. The product is thereby an inert residue. Incineration of refuse, however, has been found to be a very important source of trace metals in the atmosphere (Nriagu and Pacyna, 1988).

A method of producing crude oil from sewage sludge has been investigated in a study, involving thermochemical liquefaction (Anonymous, 1988a).

It has been reported that marine dumping of sewage sludge and domestic wastewater effluents are the major sources of trace metal pollution in aquatic ecosystems including the oceans (Nriagu and Pacyna, 1988).

Looking at the different sludge treatment methods, there exists an extensive variety of possibilies as to how a particular method may be realised technically (James, 1976).

2.3.2 SLUDGE CONDITIONING

2.3.2.1 General Considerations

Sludge conditioning is a physical or chemical treatment of sludge and the objective of which is to facilitate dewatering. Conditioning methods involve the transformation of small and amorphous gellike particles into larger and more strongly bound aggregates. Many sludge conditioning methods as well as tests for assessing their efficiency exist (Englande and Reimers, 1981). The use of a particular conditioning process depends on the solids concentration operation which follows after conditioning. The two major classes of sludge conditioners are physical and chemical conditioners. Other conditioning techniques involve heat treatment, freezing, elutriation, irradiation, solvent extraction, electrolytic processing, ultrasonic treatment and biological conditioning. Detailed information on these methods are given elsewhere (Englande and Reimers, 1981).

2.3.2.2 Chemical Conditioning

Conditioning requires the adjustment of physico - chemical conditions to reduce particle charge. Reduction of colloidal charge is achieved mainly by the addition of inorganic chemicals with charges opposite to that of the colloid, such as ferric and ferrous salts, aluminium salts and lime. Organic synthetic polymers such as polyacrylic acid (PAA), hydrolyzed polyacrylamide (HPAM), and polystyrene sulfonate (PSS) are other compounds used for chemical conditioning.

The predominant forces leading to aggregation and desorption of bound water are Van der Waals forces (Englande and Reimers, 1981; Vesilind, 1980).

Dissolved oxygen, pH-value, redox potential and the concentration of carbonates, detergents, oil, greases and degradable organics are all auxilliary factors affecting conditioning effectiveness (Englande and Reimers, 1981).

In order to obtain effective conditioning of the sludge it is necessary to carry out laboratory tests such as the beaker's test, the gravity drainage test, the capillary suction time test, the Buchner funnel test and others to evaluate the worth of a chemical as a conditioner. A description of these methods is given in IWPC (1981). Generally, these tests simulate on a laboratory scale the physical conditions which will occur in the real dewatering process.

2.3.2.3 Physical Conditioning

An increase in filtration rate of sludge is achieved by the addition of inert materials such as filter aids. These physical conditioners are used if vacuum or pressure filtration is to follow the conditioning.

The use of physical conditioners offers advantages which include reduced chemical conditioning requirements, an increase in cake solids concentration and improvement in cake release (Englande and Reimers, 1981). A disadvantage is however, the increase of the volume of sludge to be dewatered and ultimately disposed.

2.3.2.4 Thermal Pretreatment of Sludges

Thermal pretreatment is a process in which sludge is thermally treated at temperatures of about 170°C and then anaerobically digested. It has several potential advantages which include improved dewaterability of the sludge, increased biodegradability of sludges during anaerobic treatment and sludge sterilization due to the effect of high temperatures (Haug et al., 1983).

2.3.3 MOISTURE REDUCTION AND CONCENTRATION OF SOLIDS

2.3.3.1 Sludge Thickening

To increase the efficiency of further sludge treatment such as dewatering, digestion, heat treatment, transportation etc., different type of sludges are subjected to thickening. This operation results in a noticeable volume reduction which is achieved with even low increase in solids concentration. For a unit weight of solids, a sludge containing 98% water occupies only half the volume of a sludge containing 99% water (IWPC, 1979). Potential advantages of the thickening process can be summarized as follows:

(i) volume reduction of sludge, thereby reducing the costs of subsequent treatment;

(ii) sludge can be withdrawn from thickening equipment more frequently which leads to its improved performance; and

(iii) ease of blending of sludges.

Depending on the subsequent method of treatment there exist limits to which sludge should be concentrated.

The most common method of thickening is gravity sedimentation followed by flotation and to a lesser degree centrifugal thickening. Also gravity filtration and elutriation/decantation have been used to thicken sludges (Tchobanoglous, 1985; Albertson et al., 1981).

Gravity Thickening

Gravity separation occurs in tanks called thickening and consolidation tanks (IWPC, 1979). Particles of solid matter gravitate towards the floor of the clarifier tank according to the theory of sedimentation. The thickened sludge is withdrawn from the bottom of the tank and then pumped to the digesters or dewatering equipment as required. The continuous supernatant flow resulting in such devices is returned to the primary settling tank which might be seen as a disadvantage because of additional loading on the sewage treatment plant.

Flotation Thickening

Flotation is usually applied to secondary sludges. Flotation results in the reduction of the specific gravity of particles due to their attachment to air bubbles so that they will float rather than settle. The method consist of the introduction of air into a solution which is being held at an elevated pressure. When the solution is depressurized, the dissolved air is released as fine bubbles carrying the sludge to the top where it is removed. Dissolved air flotation and dispersed air flotation are two methods commonly employed (Tchobanoglous, 1985).

2.3.3.2 Dewatering of Sludge

The moisture reduction by dewatering fulfills requirements for many other subsequent sludge handling processes which are better to operate when the sludge contains more than 20% solids (w/w). Sludge dewatering is usually preceded by thickening and conditioning and may be followed by further treatment. The dewatering operation can be accomplished by many processes. Mechanical dewatering includes the use of various mechanically assisted physical means such as filtration, squeezing, capillary action, centrifugal action, etc. Natural evaporation and percolation to dewater the solids is another technique used quite often. Available dewatering equipment thus include vacuum filters, centrifuges, filter presses, horizontal belt filters, drying beds and lagoons (Vesilind, 1980; IWPC, 1981; Santhanam *et al.*, 1981).

2.3.4 SEWAGE SLUDGE STABILIZATION AND DISINFECTION

Sludges are stabilized for the following reasons:

(i) to reduce pathogens;

(ii) to eliminate offensive odors;

and

(iii) to inhibit, reduce or eliminate the potential for putrefaction.

Stabilization thus prevents microorganisms from growing in the organic fraction of the sludge.

Different chemical, physical as well as biological technologies for sludge stabilization and/or disinfection are available. Many variations of these methods exist. Most of them have been widely investigated with respect to microbiological, technical and also economical aspects (Bruce *et al*., 1983; Strauch *et al*., 1985; USEPA, 1979). Some chemical, physical and biological treatment processes are discussed further in the following sections. Not all treatment methods discussed in this chapter are considered as sterilizing in their effect, however, because some degree of pathogen reduction occurs during these treatments, one can class them as disinfection processes.

2.3.4.1 Chemical Sludge Stabilization

Chlorine Oxidation

Chlorine oxidation results in chemical oxidation and disinfection of any biological sludge. In this method, high doses of chlorine gas are used in a special chlorine stabilization unit (WPCF, 1984). Putrescibility and pathogen concentration are reduced by the treatment. The process is followed by dewatering. Many aspects of handling with high acidity, high chloride content and heavy metal contaminated by-products, e.g. supernatants and filtrates from chlorine-oxidized sludges are of concern (WPCF, 1984).

Lime Stabilization

The addition of lime to untreated sludge leads to pH-values up to 12 or higher. Under these conditions microorganisms including pathogens and possibly polioviruses are inactivated or destroyed thereby disinfecting the sludge (WPCF, 1984).

As the treatment simplifies subsequent dewatering, it has been practised for this purpose for many years. The pH level should be maintained at high values for a sufficiently long period to stabilize the sludge and to prevent microbial regrowth. However, lime treatment does not reduce the organic content of the sludge to any significant extent. Also the mass of dry sludge solids is increased by addition of lime and by the chemical precipitates that form during the treatment. The quantities of lime added and the time of exposure need to be optimised.

2.3.4.2 Physical Sludge Stabilization

Pasteurization

Pasteurization is a method to achieve sludge disinfection beyond that attained by normal stabilization. It is based on maintaining the sludge at or above a predetermined temperature for a minimum time period, for example 30 minutes at 70^{o}C. Direct steam injection is the most feasible method and is used to prevent organic fouling and inorganic scaling otherwise occuring if indirect heating is used (Tchobanoglous, 1985).

A new approach in pasteurizing sewage sludge has been made through the use of submerged combustion (Anonymous, 1988b), where gas from the sludge digester, which is about 65% methane, is burned within the sludge.

Thermal Reduction

The principal application of thermal reduction processes are the destruction of solid matter i.e. carbonaceous compounds and a reduction in the volume of dewatered untreated sludges. These treated sludges can then be disposed safely. In other cases the main purpose of the treatment method might be the recovery of valuable chemicals or precious metals.

The most common thermal reduction processes for sludge treatment include different incineration methods, wet-air oxidation, pyrolysis, flash combustion, cyclonic burning and molten salt combustion. Detailed information on current technical applications is given by James (1976). In addition, more general descriptions of such processes have been discussed by several authors (Tchobanoglous, 1985; Vesilind, 1980; Stevens and Santhanam, 1981; WPCF, 1984).

Thermal reduction processes usually require a high energy input because most operations need auxiliary fuel for heating purposes (Vesilind, 1980). This is of concern looking at the ever increasing costs of energy. Often other more economical methods for sludge treatment are evaluated due to this reason.

Heat Drying

The objective of heat drying is to remove the moisture from the wet sludge so that it can be processed by further treatment; for instance incineration. Dried sewage sludge can also be used as soil conditioner and fertilizer.

Drying is achieved through vaporization of water from the sludge to the air. The theory of drying is well established and extensive and beyond the scope of this work. Technically, the treatment by drying is accomplished by application of drying equipment such as flash dryers, spray dryers, rotary dryers or multiple hearth dryers. Other methods are described by James (1976).

A major problem also encountered using this method is that energy requirements and hence costs are high, even with reasonable heat recovery (Stevens and Santhanam, 1981).

Air Drying

Sludges can be dried in drained drying beds, but the constraints imposed by odour control limit this method to digested sludges. The time required varies from several weeks to several months. Newer regulations in the U.S. specify the temperature, depth of sludge in drying beds and drying time (WPCF, 1984).

Many conditions may vary in using drying beds, such as type of sludge, stabilization method used before drying, temperature to which the sludge is exposed, whether the beds are covered or uncovered. These facts all have an influence on pathogenic microorganism present after drying. In arid regions air drying is accomplished in lagoons.

Irradiation

Gamma or beta irradiation can be used as processes to further reduce pathogens once the sludge has been stabilized (Englande and Reimers, 1981). Sludges subjected to irradiation cannot become radioactive (WPCF, 1984). However, this technique has not proved popular for cost and other considerations.

2.3.4.3 Biological Sludge Stabilization

To determine an acceptable degree of sludge treatment and the risk of health implications through different disposal methods, the U.S. Environmental Protection Agency (EPA) defined two process classifications; processes to significantly reduce pathogens (PSRP) and processes to further reduce pathogens (PFRP). Under specified conditions anaerobic digestion, aerobic digestion and composting are considered PSRPs or PFRPs. (Appleton et al., 1986).

Anaerobic Digestion

A major use of anaerobic digestion is in the treatment of excess sludge solids produced in sewage treatment. The concentrated sludge originates from waste particulates removed in the screening and primary sedimentation units and also the biomass grown in the secondary biological oxidation process. After digestion, the sludge is easier to treat by subsequent methods such as dewatering , drying or incineration. During digestion the sludge solids content is reduced by as much as 50% to 60% (w/w) (Bailey and Ollis, 1986).

During the first step of the anaerobic digestion process, a variety of bacteria synthesize extracellular enzymes which solubilize or disperse solid sludge material. In the next step these soluble organics are digested by acid forming, facultative and obligate heterotrophic anaerobic bacteria. The major product is acetic acid, although propionic acid and butyric acid can also be produced. During the final reaction (methane production) acetic acid serves as the preferred substrate for strict anaerobic methanogenic bacteria (Hamer, 1985). It has been shown that about 70% of the methane produced is derived from acetic acid. The remaining 30% of the methane is produced from H_2 and CO_2 by another group of methanogens. The methanogenic bacteria are very sensitive to changes in environmental conditions and have a slow growth rate, i.e. in the range of 0.011 h^{-1} to 0.053 h^{-1} at mesophilic temperatures (Grauer, 1985).

Methane can be used as raw energy supplier in wastewater treatment plants.

Anaerobic digestion can be achieved using different temperature ranges. Mesophilic anaerobic digestion occurs between 16°C and 38°C whereas thermophilic anaerobic digestion occurs between 38°C and 65°C. Thermophilic digestion normally requires the addition of extra heat. Optimal temperatures for high digestion rates lie between 30°C and 35°C for the mesophilic range . For thermophilic digestion the optimum lies at about 55°C. Rather long time periods, for instance about one year, are often needed in order to establish a stable thermophilic anaerobic digestion process, as shown in a study by Rimkus et al. (1982).

Many variations in design and operation of anaerobic digestion systems are in use (Kugelmann and Jerris, 1981). A dual digestion system consisting of a 1-day detention time, pure oxygen using aerobic digester (step I) followed by an 8-day detention time anaerobic digester (step II) is described by Appleton and Venosa (1986).

Stabilization occurs in each digestion system. Disinfection is achieved to a certain extent and depends mainly on the temperature time course of the process. Lenze et al. (1985) and Saier et al. (1985) describe experiments of the influence of different anaerobic digestion treatment methods on viruses in sewage sludge.

Aerobic Digestion

The major objectives of aerobic digestion are the destruction of insoluble, biodegradable organic matter in an aerobic environment and hence the production of a biologically stable end product suitable for disposal or subsequent treatment. Aerobic digestion is generally better applied to excess biological (i.e. secondary) sludges than to primary sludges. The mechanisms of aerobic microbial degradation and the degree of stabilization of volatile solids are different for the various individual mixtures of sludges.

The resulting overall reaction can be presented by the following equation (Tchobanoglous, 1985):

$$C_5H_7NO_2 + 7O_2 \text{ ----> } 5CO_2 + NO_3^- + 3H_2O + H^+ \qquad (2.1)$$

In order to obtain energy for cell maintenance reactions, the microorganisms start to decompose their own protoplasm after the supply of available substrate is depleted. This stage is known as the endogenous respiration phase (Kugelmann and Jerris, 1981). An extremely complex heterogeneous population of microorganisms is responsible for the metabolism of the aerobic digestion process (Hamer, 1985).

Three variations of aerobic digestion operations , described in more details by Tchobanoglous (1985), are currently in use:

(1) conventional aerobic digestion;
(2) pure oxygen aerobic digestion;
and
(3) thermophilic aerobic digestion.

Thermophilic aerobic sludge treatment is also proposed as a pre-treatment process to increase the efficiency of conventional sludge treatment technologies with respect to the removal of potentially pathogenic microorganisms (hygienization) and sludge stabilization (Mason, 1987).

Investigations on the hygienic effect of different processes are presented by Langeland *et al*. (1985) and Strauch *et al*. (1985).

Composting

Composting is an aerobic biological method of sludge stabilization. It can produce a product which has high utility, is reasonably safe and aesthetically acceptable. It is classified as PFRP treatment (Process to further reduce pathogens) under the following conditions: Minimum operating conditions at 55°C for 3 days for in-vessel and aerated static pile methods, minimum temperature of 55°C for at least 15 days for windrow methods (Appleton *et al.*, 1986).

The use of this technique for the treatment of secondary sludge is the topic of this study. The process is discussed further in the next chapter.

2.4 COMPOSTING OF SEWAGE SLUDGE: PREVIOUS WORK

2.4.1 INTRODUCTION

Composting is a controlled biooxidative process that:

1) involves a heterogeneous organic substrate in the solid state;
2) evolves by passing through a thermophilic phase and a temporary release of phytotoxin (Zucconi et al., 1985); and
3) leads to production of carbon dioxide, water, minerals and stabilized organic matter (compost) (Zucconi et al., 1987).

In order to stabilize the waste, composting requires special conditions of moisture and aeration to produce thermophilic temperatures. High temperatures in the range of 75°C to 80°C might be desirable from a hygienic viewpoint but they do not support biooxidation. Temperatures above 70°C lead to conditions which are inhibitive for microorganisms required to breakdown the organic material (Gotaas, 1956).

The process is a familiar one from the product oriented perspective of producing an organic compost for application to soil. This degradation normally takes place slowly on the surface of the ground at ambient temperatures and mainly under aerobic conditions. A schematic diagram of the overall process is illustrated in Figure 2.5.

Wastes treatable by composting vary from the highly

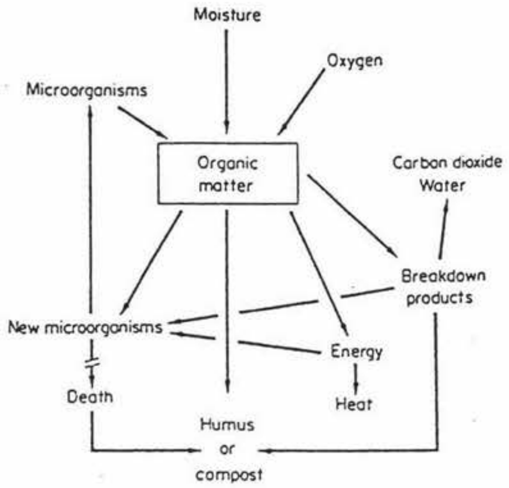


FIGURE 2.5: Schematic overview of the composting process. (Source: Biddlestone and Gray, 1985).

heterogeneous organic / inorganic mixture in urban refuse to the more homogeneous farm manures (Hummel and Willson, 1975; Stombaught and White, 1975; Willson and Hummel, 1975; Singley et al., 1975; Viel et al., 1987), crop residues and primary and secondary sewage sludges (Golueke, 1972; Golueke, 1977). During the composting process, provided enough oxygen is available, the organic materials are converted to more stable products such as humic acids and carbon dioxide and water is evolved. In general terms, the composting process can be represented by the following equation (Finstein et al., 1986b):

$$\text{Fresh org. waste} + O_2 \xrightarrow[\text{metabolism}]{\text{microbial}} \text{stabilized org. residue} + CO_2 + H_2O + \text{heat} \quad (2.2)$$

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

Composting includes a thermophilic phase, which is useful due to its disinfective effect on pathogenic organisms present in raw material such as sewage sludge (Haug, 1980).

Less familiar is the treatment-oriented perspective, in which composting serves as the treatment component of an overall waste management plan, and whose objectives are the biological conversion of putrescible organics to a stabilized form free of pathogenic organisms. Wet substrates such as sewage sludge can also be significantly dried during composting, another valuable factor from the subsequent disposal point of view. Thus, composting has come into widespread use as a wastewater sludge treatment process during the last several years (Sayag and Andre, 1987; Goldstein, 1985, 1987a and 1987c; Walker, 1987). Of particular interest to New Zealand is that the cost of composting has been shown to be one-third to one-half less than alternative sludge treatment methods, such as incineration (Goldstein, 1987b).

The sludge composting process proceeds satisfactorily only within a well defined range of conditions. The key design features in recent composting technology are known to be a suitable microbial population,the volatility and type of material, the moisture content, the oxygen concentration, the carbon/nitrogen ratio, the temperature and the pH-value; some of these factors are discussed by Golueke and Diaz (1987). These factors influence the activities of the bacteria, fungi, and actinomycetes responsible for decomposition and thus affect the speed and course of the composting process.

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

It has been demonstrated that the application of compost to soil improves some important physical properties of soil and increases the percentage of organic matter and cation exchange capacity. Occasionally, negative aspects can emerge from compost incorporation into soil such as an increase in organic pollutants and heavy metals (Gallardo-Lara and Nogales, 1987).

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

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

Section 2.4.3 provides a more detailed discussion of the different composting systems currently in use.

2.4.2 PRINCIPAL FACTORS

Numerous factors affect the course of a composting process but their contributions to the overall process are not specifically defined. The complex reactions of microbiological cell metabolism involved, lead to the difficulty in obtaining close replication of results, although similar trends can be observed in composting trials carried out under similar conditions. This can be seen in comparing the various literature references.

2.4.2.1 Process Fundamentals

The microorganisms responsible for composting are varied, widespread and usually present in organic materials (Finstein et al., 1986a). The addition of special inocula to the composting mass has been shown by Golueke (1977) to be not beneficial to the composting process. This finding, although interesting is certainly worthy of confirmation.

When the moisture content of the wastes is brought to a suitable level and the mass aerated, the rate of microbial action increases and the material undergoes stabilization. As well as oxygen and moisture, the microorganisms require for their growth a source of carbon, which is the organic fraction of the waste. Macronutrients such as nitrogen, phosphorus and potassium and certain trace elements are also needed. In attacking the organic matter, the microorganisms reproduce themselves and liberate CO_2, H_2O, other organic products and energy, some of which is used in metabolism, the remainder is given off as heat. The end product, compost, consists of resistant organic residue, breakdown products, dead and some living microorganisms together with products from further chemical reactions occuring between these materials.

The raw material to compost is assembled into a mass sufficiently large to store heat despite losses to the surroundings. Bulking agents for porosity and moisture control (for example recycled compost, wood chips, etc.) are added to dewatered sludge to provide a porous, structurally stable mixture, of about 40% to 70% solids, and which enables the sludge to self-sustain the aerobic respiration reactions. The whole composting process, depending on the ambient conditions, generally involves the following four basic stages:

(1) mesophilic phase with temperatures up to $40^{o}C$;

(2) thermophilic phase, $45^{o}C$ to $65^{o}C$;

(3) cooling;

and

(4) maturing.

Figure 2.6 shows a temperature versus time schematic of the composting process.

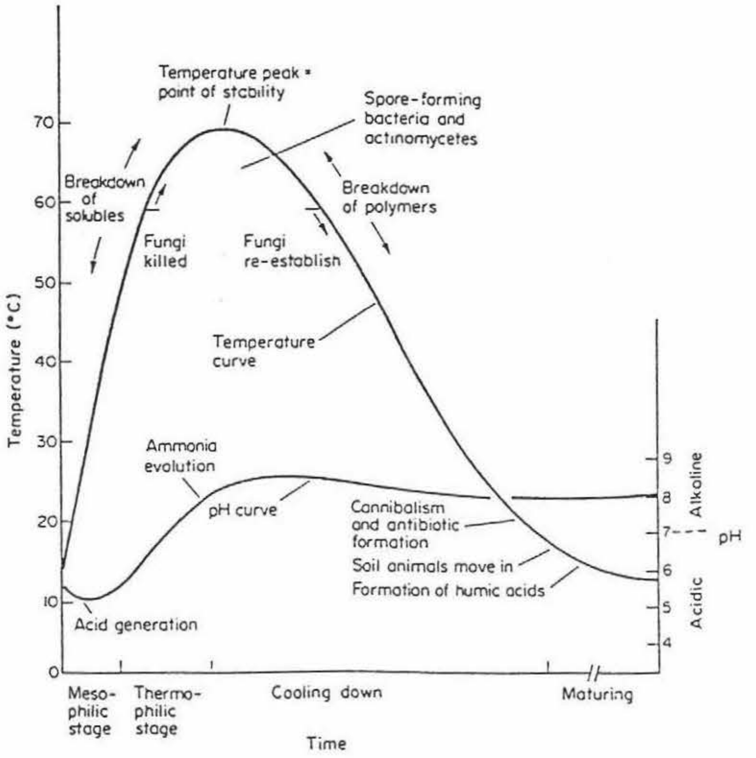


FIGURE 2.6: Schematic diagram of temperature versus time course during the composting process. (Source: Biddlestone and Gray, 1985).

2.4.2.2 <u>Biochemical Aspects</u>

Organic wastes, whether of agricultural or industrial origin, e.g. food processing wastes (Katsuyama, 1979; Keeley and Skipper, 1988) or municipal sewage sludges, are mixtures of sugars, proteins fats, hemicelluloses, celluloses, lignin minerals and other compounds in a wide variety of concentrations and may serve as starting material for composting (Genevini and Negri, 1986; Zucconi and De Bertoldi, 1987). The organic matter in wastewater sludges is ordinarily not susceptible to total oxidation. However, Higgins _et_ _al_. (1982) have shown in a comparative study with other biological treatments that composting can achieve a significant reduction in volatile solids and other indicators of the effectiveness of biological treatment. The maturity of the final compost product is important for the assessment of its quality and possible use. Analytical methods and definitions of product quality and maturity have been reported by several workers (Morel _et_ _al_., 1985; Penninck and Verdonck, 1987; Witter and Lopez-Real, 1987; Zucconi and De Bertoldi, 1987; Mooijman and Lustenhouwer, 1987).

Composting is both a breaking down process (catabolism) and a building up process (anabolism). Low molecular weight materials, the water solubles, can pass through the cell wall easily and take part in cell metabolism, providing energy and being synthesized into larger polymers. The higher molecular weight components of the organic wastes cannot pass through the microbial cell membrane and cannot be used without being first degraded. In these cases, the microorganisms can secrete extracellular enzymes which hydrolyse the polymers into their respective short chain units. Subjected to these reactions for example are celluloses and hemicelluloses, the former of which, as well as lignin are most resistant to microbial attack (Golueke, 1977).

Carbon and energy source, supply of nitrogen for cell proteins and requirements for phosphorus, potassium, calcium, sodium, magnesium, sulfur, iron, and traces of other elements such as cobalt and zinc, (symbols C, N, P, K, Ca, Na, S, Fe, Co, Zn respectively), are in most wastes adequately met. The composition of sewage sludge is given in IWPC (1978).

With low C/N ratios, 8:12 in the case of sewage sludge (Stentiford, 1987), nitrogen will be lost as ammonia during composting. Optimum C/N ratios are reported to be about 25:30 for sewage sludge composting (De Bertoldi _et al_., 1985a; Zucconi and De Bertoldi, 1987).

Despite quite controversial comments in literature, Witter and Lopez-Real (1987) have stated, that the C/N ratio does not accurately reflect the decomposition process. Instead, the final value is an important characteristic of organic matter in relation to its agricultural use.

High water containing substrates such as sewage sludge pose special problems to alternative treatment methods. Thermal processes for example become less efficient for high moisture organic substrates and make composting more attractive as a method to biologically dry and convert wet materials to a more usable form. Outside energy input for composting is often minimal compared with other treatment methods (Haug, 1980). Due to its water content of 70% to 80% dewatered sewage sludge lacks porosity, and also tends to compact. Because gas exchange is hindered by high moisture content, sewage sludge requires adequate handling for a successful composting process, e.g. bulking agent addition, aeration, etc.

Most of the carbon in the bulking agent (e.g. woodchips) becomes available to bacteria at a very slow rate, since it forms part of the xylem. For the most part the xylem is lignaceous and therefore highly resistant to microbial attack. Woodchips and other bulking agents should consequently be considered almost entirely as bulking and moisture absorption agents, and very little, if at all, as sources of carbon (Golueke and Diaz, 1987).

2.4.2.3 Microbiology

The main classes of organisms involved in composting are bacteria, algae, and fungi. Additionally other microbes such as protozoa and viruses may also be present (Haug, 1980). Golueke (1977) stated that the bacterial metabolism during the decomposition is limited by the genotype of the respective microorganisms, assumed that all environmental conditions and also the equipment design are optimal for the process. The bacteria are responsible for a large part of the heat released and also for the initial breakdown of the organic matter. A wide variety of actinomycetes species in the composting mass can be detected visually and olfactorily a few days after the process has been started (Golueke, 1977). Actinomycetes species decompose mainly cellulosic as well as some lignaceous components. However, many other organic substrates can also be metabolised by these microorganisms.

Fungal microorganisms occur in the mass at about the same time as actinomycetes. Golueke (1977) reports on a study where it was possible to isolate 304 unifungal cultures from one batch of compost. Fungi are also able to use many different substrates as carbon and energy sources. Their existence after a certain period of time is closely related to that of the actinomycetes due to the similarity of substrate utilization. Large numbers of the actinomycetes and most of the fungi are obligate aerobes, which emphasises the importance of adequate aeration.

Biddlestone and Gray (1985) and Duvoort-van Engers and Coppola (1986) have quoted studies on the population number and the occurrence of bacteria, actinomycetes and fungi in composting processes.

It has not been proved useful to determine the optimal environmental conditions for the maximum activity of isolated organisms. Instead, this complex microbiological ecosystem should be treated as an integrated whole for which the optimum design for equipment and operational procedures should be established (Golueke, 1977).

The microbial activity is influenced by many critical parameters during composting (Golueke and Diaz, 1987). McKinley et al. (1985) have shown, that temperature seems to be the dominant physical-chemical parameter which controls the microbial activity and biomass during composting of sewage sludge. Samples from the 35°C to 50°C areas of a compost pile generally exhibited the greatest microbial activity in this study.

2.4.2.4 Heat Generation and Temperature

Basic Reaction Pattern

Composting of organic wastes leads to the generation of heat and a rise in temperature achieved by the insulating effect of the material. The gas exchange inside the material is usually sufficiently effective to prevent gross oxygen starvation. The increase in temperatures up to 40°C is due to mesophilic microorganisms which generate heat at a rate exceeding its loss to the surroundings. The temperature continues to rise (thermophilic stage) and at 60°C the predominating respiratory reactions are those of the actinomycetes and spore forming bacteria. The slowing of respiration marks the end of the thermophilic phase. The maximum temperature achieved in composting depends on the quantity of material processed as well as on other factors. Following the achievement of the peak temperature the cooling phase commences. Certain thermophilic fungi reinvade the mass and together with actinomycetes the decomposition of residual organic compounds proceeds until the rate of energy liberation becomes very small and the temperature of the mass falls to ambient. This marks the beginning of the maturing stage during which final biooxidation reactions take place often lasting several months. Finally the food supply for the microbes becomes exhausted.

Heat Generation - Temperature Interactions

Finstein et al. (1986a) state that higher temperatures are at first biologically favourable, increasing the rate of growth and heat generation. This establishes a positive interaction between heat generation and temperature (i.e. both increasing). When the temperature begins to exceed values which lead to maximal growth rates of mesophiles (approximately 38°C), the interaction becomes negative because higher temperatures are unfavourable to this microbial community. This slows the temperature increase and would, in the absence of subsequent events , soon terminate it. However, the temperature increase is renewed with the initiation of thermophilic growth, starting at approximately 45°C. This reestablishes a positive interaction between heat generation and temperature. Since the thermophilic community in self-heating organic masses is most active at approximately 55°C to 60°C, the interaction again becomes negative when the temperature exceeds this range. The temperature increase again slows, with values typically peaking at approximately 80°C. At this temperature the rate of heat generation is low.

During the composting of waste a basic problem is to prevent the inactivation of microbial activity which occurs at thermophilic temperatures, usually obtained if no aeration control is employed (Finstein _et_ _al_., 1987a-d). This necessitates enhanced heat removal in a controlled (e.g. feedback-control) fashion to avoid temperatures greater than 60°C which weaken the microbial community and thereby suppressing decomposition, heat output, and water removal (MacGregor _et_ _al_., 1981). Temperatures around 60°C have been shown to produce the greatest amount in total CO_2 from a composting mass (Nakasaki _et_ _al_., 1985). Other studies and reviews dealing with sewage sludge composting have shown that temperatures between 40°C to 60°C favour microbial activity and decomposition (Hoitink _et_ _al_., 1984; Kuter _et_ _al_., 1985; Sikorah and Sowers, 1985; McKinley and Vestal, 1984; Pereira-Neto _et_ _al_., 1987a; Finstein _et_ _al_., 1986a and 1986b).

2.4.2.5 Aeration, Heat and Moisture Removal

The heat removal mechanisms involved in composting are radiation, conduction, vaporization of water (evaporative cooling, e.g. removal of heat and water vapour are linked functions) and sensible heating (temperature increase of dry air).

Radiant heat loss is generally considered to be negligible in the case of composting piles. Conductive removal of heat is slow relative to the potential rate of heat generation, owing to the low thermal conductivity of composting materials (Finstein et al., 1986a).

Optimum composting rates are obtained at temperatures of about 55°C (as discussed in the previous section). Calculations have shown, that these temperatures can be reached using the effects of ventilative heat removal (Finstein et al., 1986a; Finstein and Miller, 1985), through which the main part of heat in composting will be released. This method includes the use of a blower which should operate in the forced-pressure direction rather than in the induced vacuum direction. Also, Biddlestone et al. (1986) concluded that forced aeration is desirable when sewage sludge is composted. The blower is thereby feedback controlled, which provides timevariable ventilation on demand and matches ventilative heat removal to heat generation in reference to biologically favourable temperatures below 60°C in order to maximize decomposition rate (Finstein et al., 1986b). The aim of a maximum decomposition rate also facilitates the prevention of odour development in the composting mass, which is regarded from the public standpoint as the worst impact of a composting facility (Finstein and Miller, 1985; Haug, 1980). Ventilation also supplies oxygen for the microbial decomposition processes and removes metabolic CO_2. About nine times as much air is required to remove heat than to supply oxygen (Finstein et al., 1986a and 1987a).

The amount of water removed generally exceeds that produced metabolically, because water is vaporized extensively at composting temperatures (Finstein et al., 1986b). It is desirable to achieve a 15% to 20 % moisture reduction during composting in order to facilitate the subsequent screening operation (Haug, 1980).

The mechanisms of ventilative heat removal are vaporization and sensible heating of air. Stahlschmidt (1987) presented a method to calculate the quantity of heat produced and also the rate of heat production during the composting of a given mixture.

A consequence of vaporization is that the material tends to dry as composting progresses. Whether dryness or depletion of readily available substrate becomes the activity limiting factor depends on the starting material's substrate and water content (Finstein et al., 1986b).

Kuter et al. (1985) have shown that high composting rates were achieved when compost temperatures were maintained below 60°C at high airflow rates using a feedback controlled aeration. Adjusted aeration in response to temperature resulted in stabilized and dry compost in a study carried out by Sikorah and Sowers (1985). Similar studies and reports involving controlled aeration modes in composting systems are stated elsewhere (Pereira-Neto et al., 1987a and 1987b; Donovan, 1985; Kuchenrither et al., 1985; Appel and

Hettmann, 1988; Eccles and Stentiford, 1987; Higgins, 1982).

Aeration requirements can also be met through agitation and turning of the compost mass. However, too much agitation can lead to excessive cooling and drying of the wastes and shearing of actinomycete and fungal mycelium.

2.4.2.6 Pathogenic Organisms

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

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

Secondary sludges generally contain fewer pathogens than primary sludges, unless originating from high rate systems without subsequent sedimentation (IWPC, 1978).

The following is a summary of comments made by Finstein *et al.* (1987b) concerning the main objectives of sanitation:

The first objective is the prevention of growth and spread of mainly fungal (mold) pathogens and thus the mass production of dangerous spores during composting. Here, Aspergillus fumigatus which can grow on wood chips, is of particular concern. In order to decrease the risk of growth of this fungus, the use of recycled compost as bulking agent instead of wood chips has been suggested.

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

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

Pereira-Neto et al. (1987) state that a widely used minimum standard for sanitisation is to maintain a temperature of 55^{o}C for at least 3 days. However, De Bertoldi et al. (1988) suggest a temperature of 65^{o}C for 3 consecutive days.

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

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

- Pathogenic bacteria: salmonellae, shigellae, pseudomonds, Mycobacterium spp., Candida albicans, Aspergillus fumigatus;
- Enteric viruses: Enterovirus and its subgroups (polioviruses, echoviruses and coxsackieviruses), reovirus and adenovirus;
- Parasites: Entamoeba histoytica, Ascaris lumbricoides, Taenia spp., Schistosoma spp., and others.

Another list of pathogens likely to be found in solid urban waste and wastewater sludge is presented in a report by De Bertoldi et al. (1988). According to Spillmann et al. (1987), the most favourable treatment to render sludge hygienically safe from the virological point of view would be a treatment at 60°C to inactivate thermolabile viruses followed by another sludge treatment step, such as anaerobic mesophilic digestion to eliminate thermostable viruses, which are more sensitive to chemical and microbial inactivation.

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

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

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

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

At present, it is not possible to measure adequately the safety status of treated sewage sludge. Also, the degree of the principal pathogen reduction that should be attained has still to be defined (De Bertoldi et al., 1988). No reliable standard indicator system is available although many investigations concerning this problem are in progress (Strauch, 1987).

2.4.3 COMPOSTING TECHNOLOGIES

2.4.3.1 General Aspects

High moisture content feeds such as sewage sludges demand one of three possible procedures in order to be treatable by composting:

(i) Recycle of compost and blending with the dewatered sludge before composting;

(ii) Addition of an organic amendment such as sawdust, straw, peat, refuse, etc., to reduce bulk weight and increase air voids for proper aeration and to increase also the organics in the mixture;

(iii) Addition of an inorganic or organic (usually wood chips) bulking agent to provide structural support and maintain airspace in the mixture.

The mixing process should result in a uniform, homogeneous mix without the formation of lumps or balls. Figure 2.7

represents a generalized schematic of the composting process. The block "composting process" can stand for many different systems, showing that the fundamentals of this sludge treatment remain the same for all systems used.

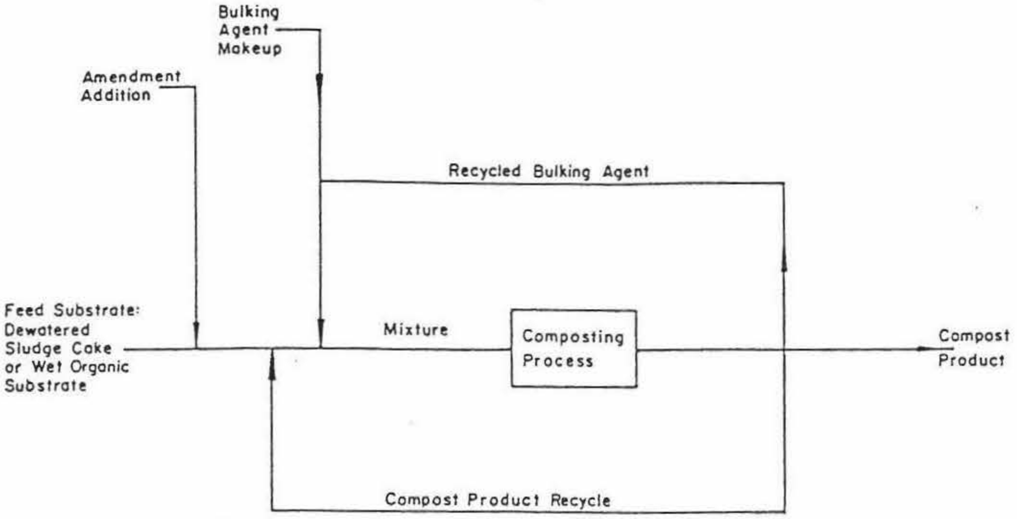


FIGURE 2.7: Generalized schematic for the composting process showing inputs of feed substrate, compost product recycle, amendment and bulking agent. (Source: Haug, 1980).

Composting systems can be classified according to the reactor type, solids flow mechanisms, bed conditions in the reactor and manner of air supply (Haug, 1980). A more basic distinction for the process is widely used in literature; it is made in terms of reactor systems (also called closed systems or in-vessel systems) and non-reactor systems (also called open systems) (Robinson and Kuchenrither, 1985; Stentiford, 1987). Non-reactor systems can be further divided into conventional windrow process, aerated windrow process and extended aerated static pile process (Benedict <u>et</u> <u>al</u>., 1986).

In a comparative study by De Bertoldi et al. (1982), composting trials were carried out using three different windrow systems. The physical, chemical, microbiological and pathogenic results showed that forced pressure ventilation in conjunction with temperature feedback control (i.e. aerated static pile system), seemed to be the most rapid process. The same study and also earlier experiments from the same authors showed that static pile systems were superior to turned systems (i.e. windrow systems). Aerated static pile composting trials also achieved a more effective inactivation of pathogens than windrow processes in a comparative study carried out by Pereira-Neto et al. (1987b). However, these authors did not find significant differences in organic breakdown and pathogen inactivation concerning the aeration mode of the static pile system, i.e. variable rate aeration timer and temperature feedback system were equally effective. Concerning the use of windrow systems, these authors conclude that the surface layers of the windrow which are near ambient temperature, may act as reservoirs for pathogens. After mixing the heap these organisms could reinfect materials which had already been subjected to high temperatures.

2.4.3.2 Conventional Windrow Process

Conventional windrow composting involves mixing of dewaterd sludge (15% to 25% solids, w/w) with a sufficient quantity of previously composted material (recycled compost) of about

60% solids (w/w). A starting solids content of approximately 40% (w/w) is thus achieved. Alternatively an external amendment or bulking agent can be added. Systems without the use of recycled compost also exist. After mixing, the fresh material is formed into windrows of variable length. The composting period lasts at least 30 days during which the windrows are turned by mechanical equipment according to different criteria such as moisture content, and the temperature distribution in the heaps. The turning provides remixing and gas exchange. Natural ventilation occuring through upwards movement of hot gases and water vapour in the windrow is another means of oxygen supply. After the active windrow composting period, the composted material is usually subjected to curing for at least another 30 days. A portion of the finished compost is then recycled and the rest is stockpiled for distribution.

2.4.3.2 Aerated Windrow Process

The aerated windrow process is similar to the conventional windrow process except that oxygen supply into the windrow is supported by forced or induced aeration (Kuchenrither et al., 1985). Periodic agitation by turning is used to restructure the windrow (Haug, 1980; Benedict et al., 1986).

2.4.3.3 **Aerated Static Pile Process**

Process Description

The aerated static pile process involves mixing dewatered sewage sludge with a bulking agent, such as recycled and new woodchips at typical (v/v) ratios of 3.5 to 4.5 in order to achieve a minimal solids content of about 40% (w/w) in the woodchips - sludge mixture (Benedict et al., 1986). Wood chips or other base material are used to cover a perforated aeration piping layout to improve air distribution and prevent blocking of the holes in the pipe. A method to determine the distribution and size of air ducts in a composting ventilation system was presented by Psarianos et al. (1983) and Higgins (1982). The mixture to be composted is placed on the base material in an extended pile configuration which is triangular in cross section if a single pile is used. Insulating cover material is applied as last layer at the surface of the pile. Apart from insulation this cover should also reduce odour development.

A blower is connected by a manifold to the aeration piping. Ventilation of the piles can be accomplished in several ways, such as air suction, air blowing, alternating ventilation, and air blowing in conjunction with temperature control (Willson, 1983).

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

Process Control

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

To keep the temperature in the optimum range of 55°C to 60°C, the accumulating heat must be removed. Studies have shown that a practical means of removing heat, maintaining the optimal temperature and thus reaching high composting rates is the application of ventilation in a controlled fashion (Donovan, 1985; Finstein *et al.*, 1987d). Control is best achieved by temperature feedback control, used for instance also by Pereira-Neto *et al.* (1987a), in conducting static pile composting trials. A reduction in the number of *Escherichia coli* from 10^7 CFU/g to less than 10^2 CFU/g was reached within 2 weeks. A similar result was found in the number of faecal streptococci.

Two different methods to control a static pile composting process were investigated by Miller and Finstein (1985). Faster decomposition rates and higher reduction in total sludge solids as well as in sludge volatile solids were achieved in the so - called "Rutgers strategy" where temperature feedback control was applied. A summary of the important influence of ventilation on the biological activity during composting is shown in Figure 2.8.

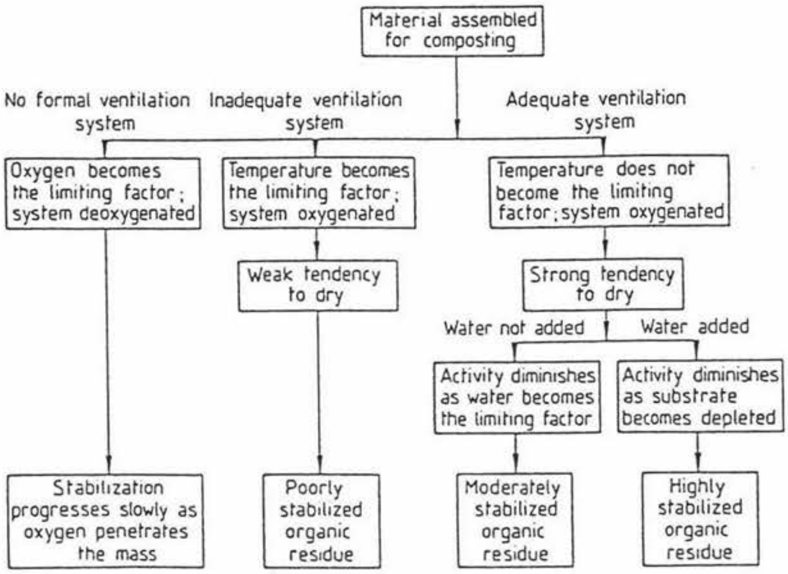


FIGURE 2.8: Biological activity of composting systems and their limitations induced by different ventilation systems. (Source: Finstein et al., 1986a).

Aeration rates most commonly used range from 9 to 15 m^3 per hour per U.S. dry ton of material, although different values can also be found in literature (Haug, 1980).

According to Pereira-Neto et al. (1987b) and De Bertoldi et al. (1985b) the temperature distribution through a compost pile or windrow varies depending upon many operational factors for example the height of the pile. Temperature variations occur throughout the whole composting period. Compost heaps develop their coolest zones normally either at the outer surface layers or at the boundary with the base material on the ground. Pereira-Neto et al. (1987a) showed that concerning these areas of the compost material, it is not possible to guarantee that the finished product presents no risk of pathogen survival or pathogen regrowth.

2.4.3.4 In-Vessel Systems

There exist numerous systems of in-vessel or reactor systems for composting of sewage sludge. For most of these systems the process parameters are identical to those of the static pile process, however, some main differences mentioned by Haug (1980) as well as in Anonymous (1986), a report recently published in the U.S.A., presenting details of various types of reactor systems, their evaluation in specific cases and also design and operational parameters.

The main features of different systems are summarized below.

Vertical Flow Reactor

Conditions and movement of the mixture in the reactor lead to further division of vertical flow reactors. Moving agitated bed reactors allow for agitation of solids during the passage down the reactor, which provides some mixing. Forced aeration is applied. The mixture to compost is usually fed on either a continuous or intermittent basis.

The entire bed volume of moving packed bed reactors is filled with the sludge - bulking agent mixture, which is not agitated during composting, resulting in plug flow behaviour. Forced aeration is applied. This type of reactor can be fed on either a continuous, intermittent or batch basis. Within this group of systems there exists a system in which periodic transfer of solids from the bottom to the top of the reactor via an external loop permits agitation of the mixture. The bed solids as a whole, however, remain unagitated during the batch cycle until their withdrawal from the bottom of the reactor at the end of the cycle.

Horizontal and Inclined Flow Reactor

Based on the solids flow pattern within the reactor, at least three different tumbling solids bed reactors (or rotating drum reactors) can be distinguished:

1) Dispersed flow pattern: Dispersion is provided by constant tumbling action. Material inlet and outlet are located on opposite ends of the drum. The flow pattern resemble plug flow except for the material dispersion.

2) Cells in series: Solids flow is provided by periodic emptying and transfer of material from one cell to another. Each cell is well mixed, which ensures that material does not short circuit through the reactor. The product is discharged from the last cell and feed is added intermittently to the first cell once it has been emptied.

3) Complete mix: Uniform feed and discharge along the length of the reactor are maintained along with a high level of mixing. In case of continuous operation, further compost

processing to ensure pathogen reduction is required due to the short detention time of a large proportion of material in the reactor. Intermittent feeding and withdrawal can avoid this problem.

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

Agitated solids bed reactors (or bin reactors) use forced aeration and mechanical agitation of solids during composting. Solids feed occurs on a continuous, intermittent or batch basis.

2.4.4 CONCLUDING REMARKS

Composting under appropriate conditions renders sludge to a valuable soil conditioner without dangerous impacts on human and animal health if applied as landfill. It is also one of the best available solutions for the recycling of nutrients occurring in sewage sludge without causing undesirable environmental effects. For these reasons high temperature composting of secondary sewage sludge has been investigated in this study.

Woodchips could be used as the bulking material as it is readily available at low cost in New Zealand although there exist certain disadvantages. For example, woodchips contain a wide range of size distribution and it is also necessary to treat them by additional unit operations for recycling and recovery. In addition, their use is associated with the occurence of the pathogenic fungus Aspergillus fumigatus. Other materials which could be used as bulking agents are sawdust, recycled compost from previous composting processes (Klees and Silverstein, 1986), shredded tyres, municipal refuse and others.

Finally, it is to note that a special economical feasibility study is necessary for every composting facility to be planned. Investigations have shown that it is not generally possible to transfer conclusions from economical evaluation studies between different composting facilities.

CHAPTER 3

MATERIALS AND METHODS

3.1 EQUIPMENT AND MATERIALS

3.1.1 SLUDGE: SOURCE AND CHARACTERISTICS

The secondary waste activated sludge used in all composting trials was generated in the extended aerated activated sludge treatment plant New Plymouth, New Zealand. The sludge was thickened in a clarifier, then subjected to mechanical dewatering in a belt filter press resulting in a final water content in the range of 82% to 87%. A polyelectrolyte conditioning agent (Zetag 57) was added to the wet sludge to facilitate the dewatering process. The sludge settling characteristics, based on Sludge Volume Index, were reported to be excellent (Bhamidimarri, 1987). However, the index value that is characteristic of a good settling sludge varies with the characteristics and concentration of the mixed liquor solids, so observed values at a given plant should not be compared with those reported for other plants or in the literature (Tchobanoglous, 1985).

The sludge was transported in 220 liter drums to the site of the experiments. Fresh sludge was used for each experiment.

3.1.2 BULKING AGENT

In all composting experiments, woodchips were used as the bulking agent in order to provide porosity to the sludge. The woodchips were obtained from a local (Tiritea) sawmill. They consisted predominantly of pine (Pinus radiata) wood mixed with some chips of a related species of pine, macrocarpa. Woodchips were taken from logs that had not been preserved with usual agents. The shape of the chips was not uniform and their length and width varied, ranging from approximately 0.02m to 0.2m and 0.01m to 0.02m, respectively. The woodchips were exposed to all weather conditions due to their storage in an open air outside the sawmill. In some of the trials the woodchips used were dried before mixing with the sludge while in some trials they were used undried.

3.1.3 SITE CONDITIONS

The environmental conditions in the room used for composting were not temperature and humidity controlled and were subjected to normal fluctuations. The composting trials were conducted indoors to minimize these fluctuations.

3.1.4 AERATION EQUIPMENT

3.1.4.1 Piping Materials

The piping materials were purchased from a local plumbers supply firm. The piping layout used in both static pile experiments consisted of the following parts with their indicated sizes:

- Low pressure PVC-pipe, 15mm inner diameter (i.d.), (P.a)
- T-piece, PVC, 40 x 15mm i.d., (T)
- T-piece, PVC, 40 x 40mm i.d., (T)
- Low pressure PVC-pipe, 40mm i.d., (P.b)
- 40mm PVC end cap , (C)
- 15mm PVC ball valve, (V)
- Air ducting pipe i.d. 260mm
- PVC reducing sleeve

The letters in brackets above refer to Figure 3.1. The pipes which were covered with woodchips and compost mixture had 4.0 mm diameter holes. Plates 3.1 and 3.2 show the layout of the pipes employed in the aerated static pile trial.

3.1.4.2 Fan and Compressor

For the purpose of aeration a centrifugal fan (ILC/5, 190 Watt, Woods Air Movement, GEC (New Zealand) Ltd. Woods/Satchwell Division) was installed. Since the fan could not deliver air at sufficient pressure during the first trial, it was decided to use compressed air as the means of aeration supply. The compressor capacity used was approximately $0.17m^3/min$. Both fan and compressor were switched on and off according to a timer setup shown in Figure 3.2.

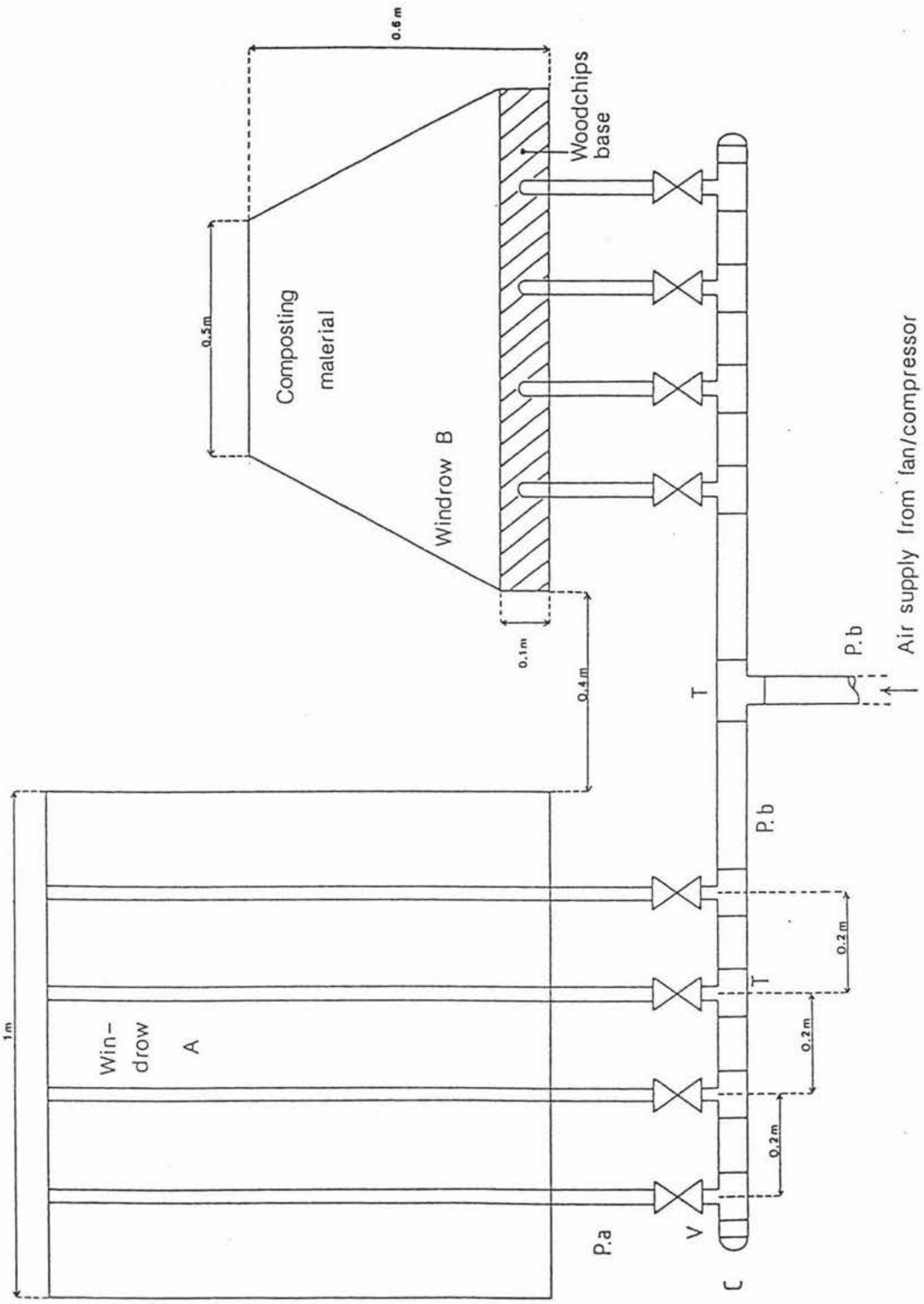


FIGURE 3.1: Schematic representation of the aeration piping layout used in the aerated windrow trial (not to scale). Windrow A is shown in plan view and windrow B in elevation. For details refer to section 3.1.4.1.

3.1.5 COMPOSTUMBLER

The sludge and woodchips were mixed using a 420 L Compostumbler (Suttons Industries Limited, Christchurch), shown in Plate 3.3 and Figure 3.3. The same equipment was also employed to carry out the three in - vessel composting trials.

SPF high density foam rubber was used to insulate the compostumbler.

Further details of the use of the compostumbler are given in the next chapters.

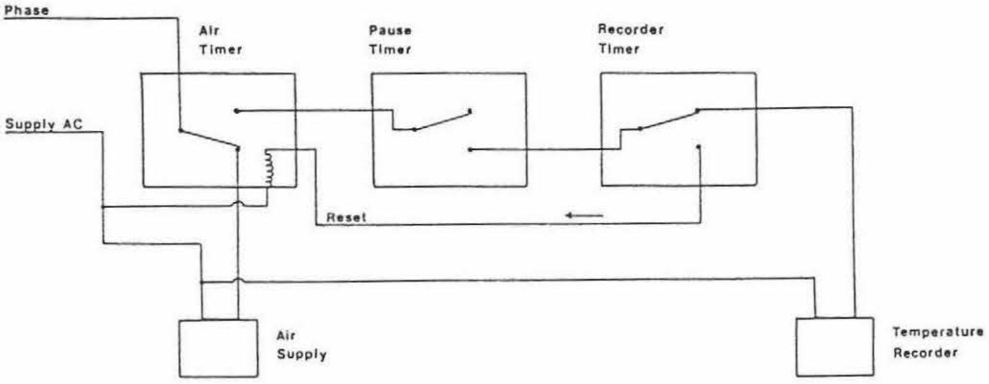


FIGURE 3.2: Timer configuration for the 'on - off' - regime of the aeration and the temperature measurement. Mode of timer shown: Air supply.

3.1.6 TEMPERATURE RECORDING

The ambient temperature and the temperature during the third in - vessel trial have been recorded using a Honeywell Versaprint 6 point recorder to which two type K thermocouples were connected. A Taylor Multi-scan recorder (Model 3141 J) was employed to measure the temperature in the composting mixture during the composting experiments.

Here, the thermocouples were also of the type K.

The measurement cycles of the temperature recorder measuring compost temperatures were activated by a series of timers, setup in a layout shown in Figure 3.2. The timers used were SAIA Multitimer (Air timer) and Kasuga MST (Pause and Recorder timer), respectively.

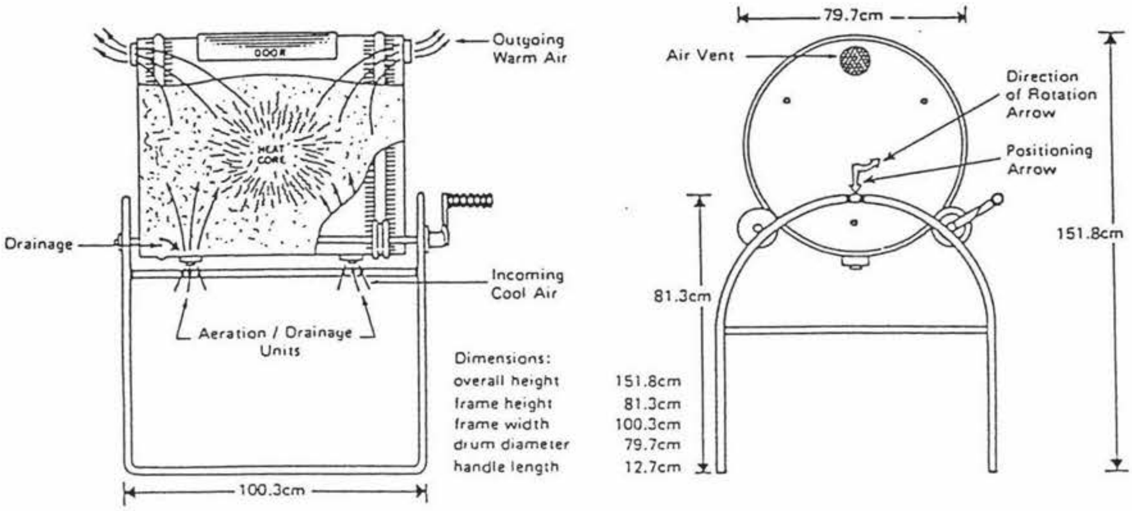


FIGURE 3.3: Compostumbler, used as mixing device and as equipment for the drum tumbler trials. The compostumbler has a volume of 420 l.

3.1.7 SAMPLING

A remote handling tong was used to collect grab samples from within the compost mass during the aerated static pile experiment and to grasp composite samples from the closed system which was assumed to be well mixed. Figure 3.4 is an illustration of a sampling device which is very similar to the one actually used in the experiments. The tong was introduced in the closed stage into the pile. Then it was opened and turned around a few times in order to force the sampled mass to become loose enough to be grasped, and finally, after closing the tong, it was pulled out from the compost pile. A sampling mass of about 50g to 100 g was taken from the mass by using this procedure.

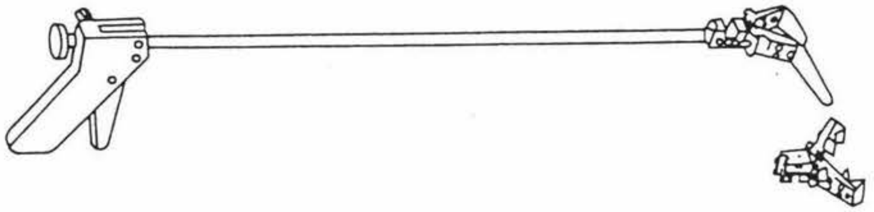


FIGURE 3.4: An example of a remote handling tong, a sampling device similar to the one actually used in the experiments.

3.2 EXPERIMENTAL PROCEDURE

Five compost trials, using different methods were performed during the period between mid-October 1987 and mid-April 1988. The first two trials were carried out using two different open system methods; the aerated windrow and the aerated static pile method. Trial three, four and five investigated the use of a closed composting system with varying ratios of woodchips to sludge. The description of the experimental procedures for these trials are given later in the sections.

3.2.1 MIXING OF THE COMPONENTS

The dewatered activated sludge and the woodchips were mixed using the compostumbler. In order to achieve a mixture as uniform as possible, the drum was filled alternately with layers of sludge and woodchips and turned for a few revolutions in clockwise then counterclockwise direction, before filling the next layers of sludge and woodchips.

3.2.2 AERATED WINDROW TRIAL

3.2.2.1 Windrow Construction

The aim of this experiment was to gain some experience in dealing with composting of sewage sludge.

32 kg of woodchips and 162 kg of sludge were placed in the

compostumbler and mixed according to the procedure described previously in section 3.2.1. This mixture resulted in a ratio of approximately one part woodchips to five parts sludge on weight basis. The aeration piping layout used in this trial is presented in Figure 3.1. A layer of woodchips of about 0.10m thickness was employed as a pile base material over the concrete floor. This layer also prevented the air ducts in the aeration pipes from being blocked and provided structure for a better air distribution throughout the composting mass.

After mixing the components, the fresh material was formed into two small piles A and B over the piping layout. The shape of both piles was trapezoidal and approximately 1m wide at the base, 0.5m wide at the top, 0.6m high and 1m long, as shown in Figure 3.1.

In order to record the temperature throughout the composting mass, 12 thermocouples were placed in different positions within the windrows and connected to a temperature recorder. Thermocouples number 1-6 were positioned in windrow A and thermocouples 7-12 in windrow B as illustrated in Figure 3.5.

3.2.2.2 **Aeration Pattern**

The timer setup as shown in Figure 3.2 was programmed to switch on a fan which provided a fixed rate of aeration. During the first four days of the experiment, the 'fan - on' time was set to four hours after which a break of 1.5 hours followed. When the first 0.5 hour of the break had passed, the temperature recorder was activated and recorded the temperatures, measured by the thermocouples in an alternating fashion for the rest of the 'fan-off' time, i.e. 1 hour. Then the fan was reactivated again.

The aerobic conditions throughout the pile were intended to be maintained by the 'on - off' setup of the fan chosen for this trial. However, with this arrangement an optimal temperature time pattern was not obtained due to the lack of a temperature feedback control system. The efficiency of time - variant feedback control of the aeration rate as a function of the temperature development in the pile was shown by many authors, as discussed in section 2.4.2.

Four days after startup the fan was replaced by the use of compressed air for aeration. The same 'on and off' cycle has been employed up to the end of four weeks. The timer setup reactivated a solenoid valve instead of the fan. On the fifth day of the experiment, ten litres of water were added to each pile because of the impression that the material on the outer surface was becoming too dry for a successful composting.

3.2.2.3 **Sampling Procedure**

To follow the decomposition of the sludge, the first sampling series was collected after pulling down both piles.

For each pile a total of six samples were taken; three of which in a diagonal manner across a horizontal area of the pile after removing a layer of about 0.1m of unfinished compost material. The other three samples (from the same pile) were collected after removing another o.1m to o.2m of material, again in a diagonal manner. After sampling, the bulk material from each pile was then remixed and formed into a new pile in the same place.

Sampling during the composting period was undertaken for a total of three sampling series at approximately weekly interval. After 30 days, the composting trial was terminated and the mass was removed from the site.

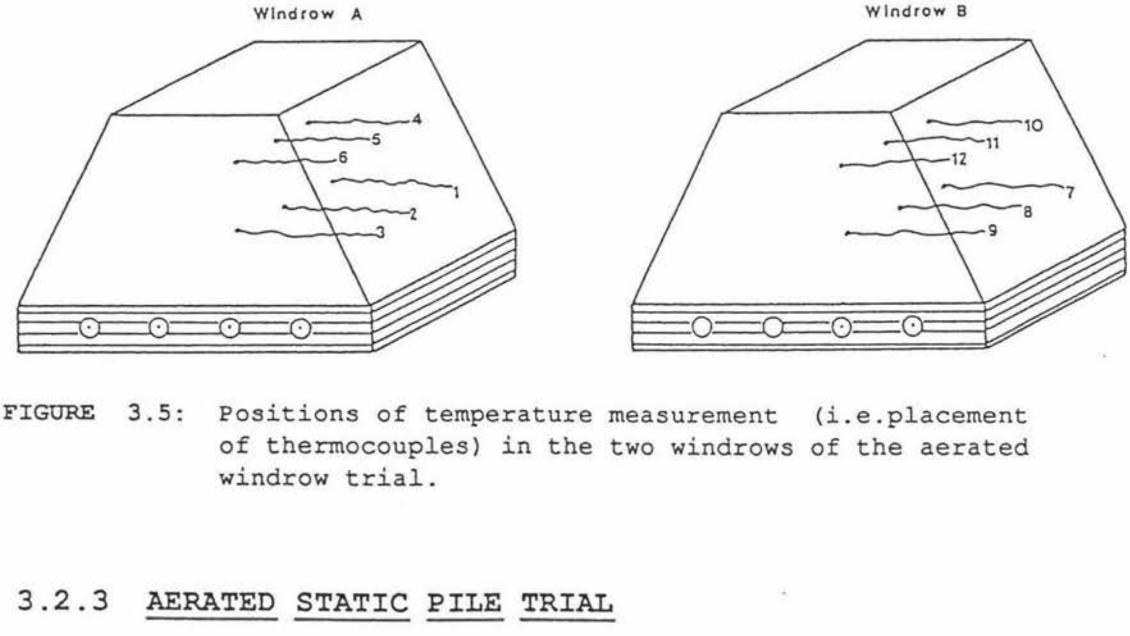


FIGURE 3.5: Positions of temperature measurement (i.e.placement of thermocouples) in the two windrows of the aerated windrow trial.

3.2.3 AERATED STATIC PILE TRIAL

3.2.3.1 Pile Construction

The perforated piping layout for this experiment is shown in Plates 3.1 and 3.2. The procedure of construction of the pile was the same as previously described in section

3.2.2.1. Sludge and woodchips were mixed in a ratio of 3.8 to 1 on a weight basis. The mixture was then placed over the perforated pipes to form a pile which was trapezoidal in cross section (Plate 3.4). The dimensions of the pile were approximately 1m wide at the base, 0.5m wide at the top, 0.6m high and 2.2m long (Figure 3.6). In order to follow the temperature time course of the experiment, 12 thermocouples were positioned within the pile as illustrated in Figure 3.6. The coverage of the compost pile usually applied in static pile systems (Pereira-Neto et al., 1987; Donovan, 1985; Stentiford, 1987), was not employed in this trial.

3.2.3.2 Aeration Pattern

Aeration by means of compressed air was used at the beginning of the period alternating an 'on' and 'off' regime. The initial 'on' period was short, i.e. five minutes after every ten hours in order to retain heat of reaction. After the aeration had been stopped by the timer, the temperature measurement cycle was reactivated for eight minutes following by ten hours without aeration. On the third day of this run, the aeration arrangement was changed as follows: 12 minutes aeration, eight minutes temperature measurement without aeration followed by five hours without aeration.

3.2.3.3 Sampling Procedure

During the ninth day, the first sampling series from the pile has been collected and treated according to the procedures and methods described in sections 3.1.7 and 3.3 respectively. The ports of sampling are indicated in Figure 3.6. The second sampling series was carried out on the 16th day and the third samples were taken on the 23rd day of the experiment.

Due to time constraints, this second composting trial was terminated after only three weeks.

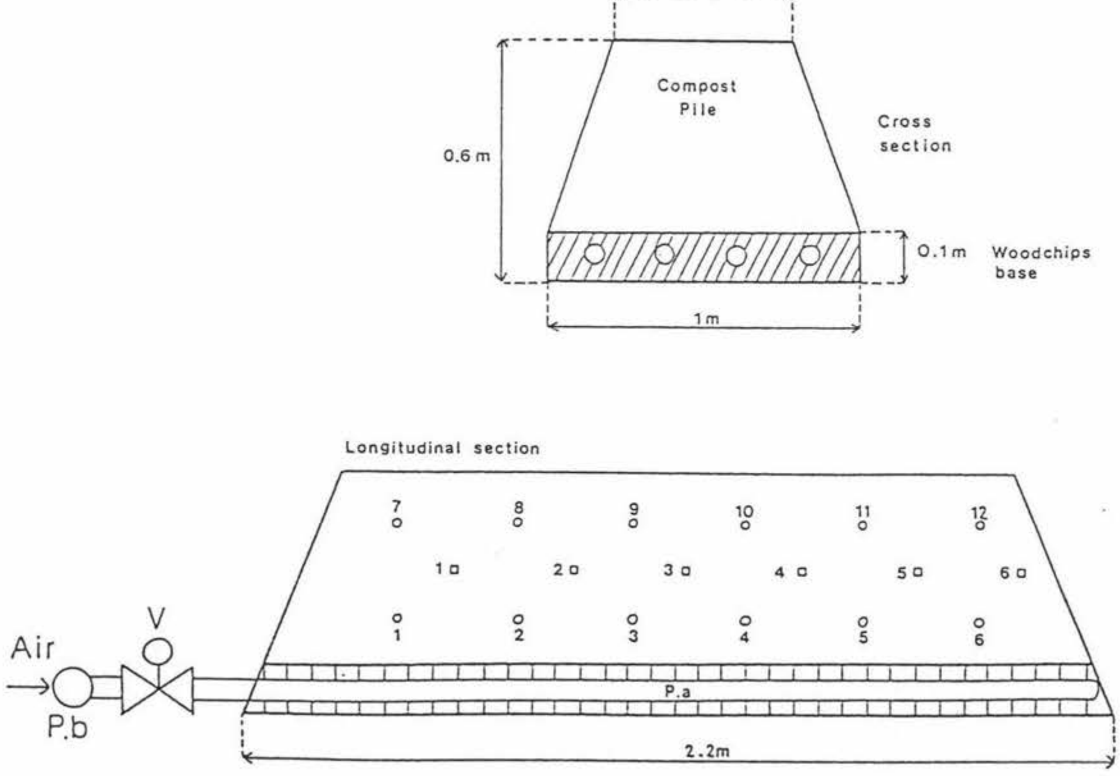


FIGURE 3.6: Aerated static pile trial. Circles 1-12 are positions of the thermocouples while squares 1-6 are the ports of sampling. (For explanations of V, P.a and P.b refer to section 3.1.4.1).

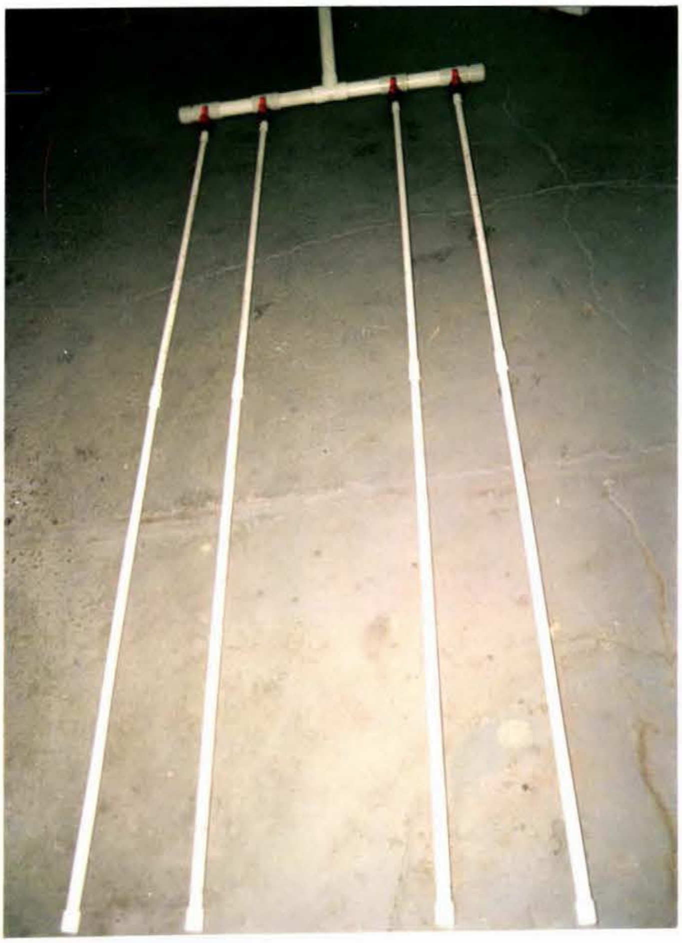


PLATE 3.1: Aeration during the aerated static pile trial was achieved using a manifold attached to four parallel distribution pipes (orifices were drilled every 0.1 m) which ran the length of the pile.

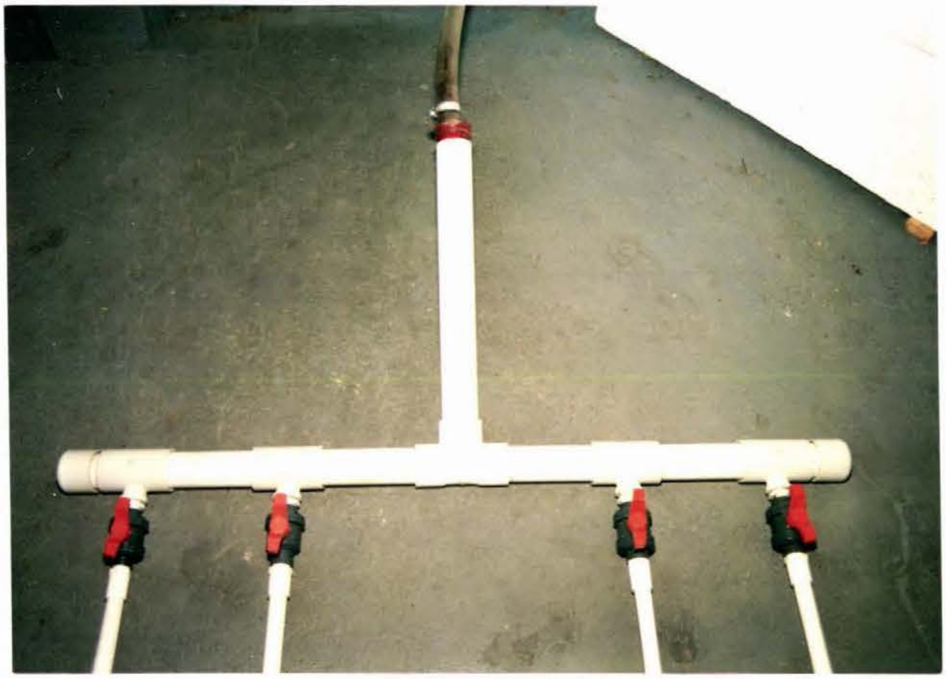


PLATE 3.2: Manifold for air distribution into four parallel perforated pipes. All four ball valves are shown in the open position. Direction of air supply was from the top of the photograph to the pipes in the lower front.

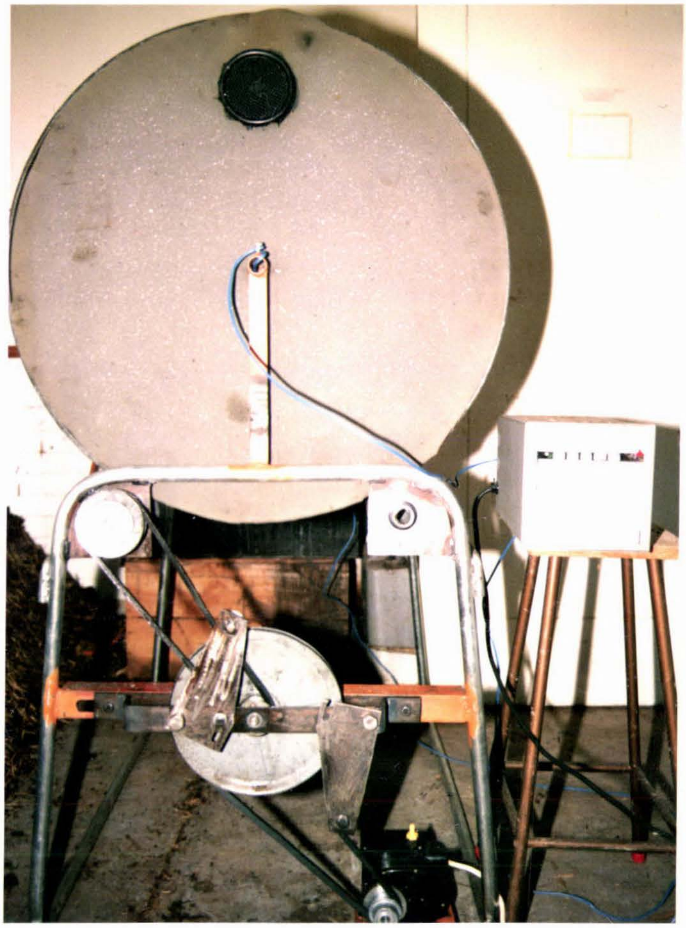


PLATE 3.3: Compostumbler for tumbling and composting woodchips and secondary sewage sludge. Temperature recorder and thermocouples are in place.

PLATE 3.4: Experimental aerated static compost pile comprised of woodchips and secondary sewage sludge. Note manifold for air distribution. Twelve thermocouples (not presented in this photograph) alowed the recording of temperatures throughout the pile.

3.2.4 DRUM TUMBLER TRIALS

Three composting experiments were carried out using the compostumbler shown in Plate 3.3 and in Figure 3.3. In-vessel systems are normally aerated in a variety of ways (Walker et al., 1986). Since the equipment was not readily available, none of these aeration methods could be applied in the trials described herein. Consequently, aeration had to be carried out through the air vents of the drum which was not especially designed to compost sewage sludge.

In order to evaluate the state of the compost mass, sampling series were carried out in all trials during the period of composting. The compost mixture was assumed to be well mixed, therefore composite samples were taken fom the mass, obtained through the opening in the compostumbler after removing the lid.

The temperature in the mixture was measured by two thermocouples which were inserted through either side into the composting mass within the drum.

3.2.4.1 First Trial

The mixture consisted of a sludge to woodchips ratio of 7.5 to 1 on a weight basis (equivalent to a ratio of 1 to 1 on a volume basis). Albrecht (1986) stated that in-vessel systems use a higher ratio of sludge to bulking agent (on weight or volume basis) than do windrow and static pile systems which results in less volume of mix per unit sludge. The same report says, however, that this higher ratio is made possible by the greater surface area of sawdust, the bulking agent most commonly used in an in-vessel system. Considering the rather limited volume of the compostumbler the mixture composition was chosen to contain excess amounts of sludge, making available sufficient organic material for microbiological metabolism. During the period of composting two sampling series were conducted. The first three samples were taken after 7 days and another three samples were taken on the 15th day of composting after which the experiment had to be terminated (development of unfavourable characteristics of the compost mixture, i.e. very wet, lumpy and strongly odourous).

To aerate the mass in the compostumbler, the bin was turned once daily. Turning involved manually revolving the drum twice in a clockwise direction, then twice counterclockwise, returning the drum to its original position.

3.2.4.2 Second Trial

The woodchips used for this trial were subjected to drying before mixing with the sludge. The drying process was carried out in a constant temperature room (37°C). The moisture content of the woodchips was determined after drying according to the procedure described later in section 3.3.1.2. The results were used to calculate the amount of woodchips and sludge required in the mixture. The sludge and woodchips were mixed in a ratio of 2 to 1 on a weight basis.

The procedure of composting, including the collection of samples, the turning of the drum and the measurement of the temperature corresponded to that of the previously described trial. Samples were taken at 0, 8, 15 and 22 days of composting. The trial was terminated after 23 days.

3.2.4.3 Third Trial

The experiment was conducted as described previously. The sludge and woodchips were mixed in a ratio of 2.5 to 1 (w/w). Composite sampling was carried out after 0 days, 5 days (TS and VS) and 11 days (N and P), 14 days (TS and VS) and 18 days (N and P) and finally after 21 days (TS and VS) and 24 days (N and P). The trial was terminated on the 24th day of composting.

3.3 ANALYTICAL METHODS

3.3.1 CHEMICAL ANALYSIS

3.3.1.1 pH - Measurement

Approximately 10g of compost mixture without prior screening was placed in a 250ml screw capped Duran glass bottle (Schott, West Germany) containing 50ml of distilled water. After shaking the bottle for five minutes, the pH of the sample was determined using a pH Meter (ORION RESEARCH model 701 A/digital IONALYZER).

3.3.1.2 Total and Volatile Solids

Sludge

Compost samples of approximately 50g were screened manually using a pair of tweezers to remove woodchips and woodchip fiber. After screening, decomposed sludge (8.00g - 12.00g) was subjected to analysis for the determination of total and volatile solids, according to the procedures set out in Standard Methods (APHA, 1985).

Woodchips

Six samples of woodchips (10g - 12g, weighed to a precision of ± 0.01g), were randomly taken from the woodchips storage bin, placed in crucible dishes and dried at 105°C for 25 to 30 hours. After cooling in a desiccator, the samples were weighed and the total solids content calculated according as described for solid wastes in Standard Methods (APHA, 1985).

The dried and weighed samples were then heated carefully over a Bunsen burner flame in order to avoid losses of material due to explosive burning of wood pieces. Then, the samples were ignited in a muffle furnace at 550°C for one hour, cooled in a desiccator, weighed and the volatile solids content calculated using the formulas given for solid wastes in Standard Methods (APHA, 1985).

3.3.1.3 **Total Nitrogen and Phosphorus**

Sample Preparation

A portion of approximately 10g of screened compost sample was dried in an oven at 65°C for at least 48 hours in order to avoid volatilization of nitrogen occurring if dried at higher temperatures.

Digestion Mixture

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

Digestion

The digestion procedure of Bolan and Hadley (1987) was used for both the total nitrogen and the phosphorus determination. This procedure was based on the work of McKenzie and Wallace (1954).

Samples of dried and screened compost mixture (0.1g - 0.2g, weighed to a precision of ± 0.0001g) were weighed on a piece of rice paper and placed in a pyrex tube (100ml), which was previously calibrated to 50ml. Digestion mixture (4ml) was added to the sample which was then heated in an aluminium digestion bloc (350^{0}C for 4 hours). After cooling, the samples were diluted with deionized water to 50ml, thoroughly mixed on a vortex mixer and finally transfered into screw capped glass containers previously cleaned with chromic acid. During storage, the bottles were kept undisturbed, so sedimentation of undissolved particles could occur. The supernatant was used for the determination in the autoanalyzer.

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

Determination

In this study reference was made to the total nitrogen concentration and phosphorus concentration in the sample. This was taken to mean total nitrogen concentration equals total kjeldahl nitrogen concentration (excluding nitrate) and phosphorus concentration equals total elemental phosphorus concentration (inorganic and organic).

The content of the total nitrogen in the supernatant after the digestion was measured by a colorimetric method, using a Technicon Autoanalyzer.

In treating the same supernatant, the content of phosphorus was determined using the vanadomolybdate (yellow) method (AOAC, 1975), carried out on a Technicon Autoanalyzer.

3.3.1.4 **Total Carbon**

Sample Preparation

Dried, screened compost samples of approximately three to five grams were ground, using a mortar and pestle. In order to remove the residual woodchip fiber, the samples were then sieved using a 0.5 mm aperture sieve and finally mixed with 20 volumes of distilled water to float off the lighter wood fiber and to sediment the wet sludge. After decanting, the wet decomposed sludge samples were dried for another 48 hours and then subjected to carbon determination.

Determination

Based on the method of Tabatabei and Bremner (1970), all forms of carbon were converted to CO_2. A mixture of dried decomposed sludge (0.040g - 0.055g, weighed to a precision of $\pm$0.0001g) and catalyst was heated in a stream of oxygen in a Leco Induction Furnace. Iron, Tin and Copper chips (0.85g - 1.55g) were added directly to the sample, which was then heated rapidly to high temperatures (1650°C) in the presence of high-frequency electromagnetic radiation.

The oxygen entering the system was first purified by a series of steps, which included:

(i) conc. H_2SO_4 to remove NH_3 and hydrocarbons;

(ii) Ascarite to remove CO_2;

(iii) anhydrous Magnesium perchlorate, $Mg(ClO_4)_2$, to remove H_2O.

The gas stream leaving the combustion tube passed through several treatment steps, which included:

(i) a dust trap;

(ii) MnO_2 to remove sulphur and nitrogen oxides and halogens;

(iii) a catalyst to convert CO to CO_2;

(iv) anhydrous $Mg(ClO_4)_2$ to remove H_2O; and

(v) Ascarite (NaOH on asbestos) to absorb the CO_2.

The CO_2 evolved was measured gravimetrically from the increase in weight of the Ascarite absorption bulb.

3.3.2 MICROBIOLOGICAL ANALYSIS

3.3.2.1 Media

Standard Methods Agar, BEA (Bile Esculin Azide) Agar and Peptone water were obtained from Gibco Laboratories, Madison, Wisconsin, U.S.A.

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

Standard Agar was purchased from Davis Gelatine (N.Z.) Ltd., Auckland & Christchurch.

3.3.2.2 Media Preparation

Commercial media as well as peptone water for serial dilutions were prepared prior to autoclaving according to the instructions from the manufacturer. In order to minimize the spreading of colonies, for some analysis an additional 2g/l Standard Agar was added to the normally required amount of Standard Methods Agar to give a final concentration of 25.5 g/l (Gutierrez, 1985).

3.3.2.3 Sterilization of Media, Glassware and Equipment

All media, glass bottles for serial dilutions for sample collection (both containing peptone water) were sterilized in the autoclave at $121^{\circ}C$ for 15 min.

Glass pipettes were sterilized in the hot air oven at $160^{\circ}C$ for 2 hours.

Plastic pipette tips were sterilized in the autoclave at $121^{\circ}C$ for 15 min.

3.3.2.4 Sample Preparation

The method of preparing the samples for microbiological analysis was modified using the scheme employed by Dudley et al. (1980). Of the other methods tested in their paper, this sludge handling procedure seemed to produce the best recovery of viable microorganisms.

Approximately 10g of compost mixture were sampled according to the procedure described previously in sections 3.1.7, 3.2.3.3, and 3.2.4. The collected sample material was then placed in a sterile screw-capped 250ml Duran glass bottle (Schott, West Germany), containing 50ml of peptone water and approximately 30 pieces of 3-mm glass beads. The bottle was vortexed for two minutes to disperse the compost mixture material and immediately analysed for microbial counts, or stored at 4°C for a period not exceeding three hours.

3.3.2.5 Analysis for Indicator Microorganisms

As a part of each sampling, serial dilutions were prepared in sterile screw-capped glass bottles containing peptone water.

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

Total heterotrophic plate count was determined using the procedure described in Standard Methods (APHA, 1985). Serial dilutions of the samples were plated, using molten Plate Count Agar. Incubation of the plates was carried out at 37°C for 24 to 48 hours.

Group D-streptococci (fecal streptococci) were enumerated using Bile Esculin Azide Agar. The pour plate method and serially diluted samples according to Standard Methods (APHA, 1985) were used to determine the counts. Plates were incubated at 37°C for 24 to 48 hours.

Bacteria of the coliform group were determined using the Most Probable Number (MPN) Test according to Standard Methods (APHA, 1985). Only the presumptive phase of the MPN-procedure was performed. Five MacConkey broths of each of five successive 10-fold sample dilutions were incubated at 37°C for a period of 35 to 48 hours. The estimation of microbial numbers by the multiple tube technique was performed using the tables of Harrigan and McCance (1976).

3.4 STATISTICAL ANALYSIS

The results obtained in each trial [Total solids (%TS), Volatile solids (%VS), Nitrogen (%N) and Phosphorus (%P)] were subjected to a statistical analysis. The methods used were one-way analysis of variance (for the aerated windrow trial and the drum tumbler trials) and two-way analysis of variance (for the aerated static pile trial). The obtained F-values were compared with tabulated F-values on the 95% and the 99% level and they were considered to be significant at a given level if they were equal or greater than the tabulated values.

In carrying out the statistical analysis for the aerated windrow trial and the drum tumbler trials, it was assumed, that the response of the treatment (i.e. composting time) to the contents of the variables (i.e. TS, VS, N and P) was independent of the positions within the windrow and within the compostumbler at which the samples were collected. Due to the rather small dimensions of the aerated windrows, this procedure was considered to be adequate, although there were some variations in the mixture composition throughout the windrows because of improper mixing of materials. However, if larger windrows are to be investigated, the dependence of the variables as a function of the sampling site must be included in the statistical analysis.

The statistical analysis was performed using the Mutab 82.1 statistical computing system (Massey University Computer

Centre, November 1982). The system is available from : Minitab Project, Statistics Department, 215 Pond Laboratory, The Pennsylvania State Univ., University Park, Pa. 16802, U.S.A.

CHAPTER 4

RESULTS

4.1 PRELIMINARY REMARKS

The main purpose of these composting studies was to examine the feasibility of stabilizing dewatered secondary sewage sludge from a domestic wastewater treatment facility by the means of composting. The changes in temperature, total solids, volatile solids and in nitrogenous and phosphorus compounds during composting as well as a possible reduction in the counts of indicator microorganisms were the major factors of concern which accompanied humus formation in these experimental studies.

Although different composting technologies are available, only open and closed systems were employed in this work. Results of these studies are described below.

In view of the heterogeneous characteristics of the composting mixture treated in these studies, it was decided to screen out the woodchips fiber from composting samples. The stabilized sludge portion of the samples was then subjected to further analysis. This approach contrasts slightly with reported analytical procedures, which usually describe analyses of the entire compost, i.e. woodchips carrier plus composted sludge.

4.2 OPEN SYSTEMS

4.2.1 INTRODUCTION

The purpose of the first trial was to gain experience in treating and handling sewage sludge as a material and especially to set up the experimental procedures necessary for sewage sludge composting. An open composting system was chosen for this purpose and per definition, since aeration and turning of the material was employed, the system is called aerated windrow system.

The second trial was performed using an aerated static pile composting system.

This chapter presents the progress of composting cycle in terms of the following variables:

- Total solids content (%TS);
- Volatile solids content (%VS, on a dry weight basis);
- Total nitrogen content (%N, on a dry weight basis);
- Phosphorus content (%P, on a dry weight basis) and
- Temperature development in the composting material.

The final weight of the mixture was not measured. In order to determine the absolute percentage of destruction in volatile solids, a basis of initially M kg dry weight sludge was assumed. Since the relative volatile solids content of both the initial sludge and the final screened compost were known, it was possible to calculate the final dry weight X (kg) of the mass and the final weight Y (kg) of volatile solids according to the following formulae:

$$X = \frac{M\ (1 - VS_i)}{(1 - VS_f)} \tag{4.1}$$

$$Y = (VS_f)\ X \tag{4.2}$$

where: VS_i = initial fraction of volatile solids
VS_f = final fraction of volatile solids

The true percentage reduction in volatile solids could then be calculated. Generally the same procedure was employed to determine absolute changes in total nitrogen.

4.2.2 AERATED WINDROW COMPOSTING

The experimental design employed in this trial is that described previously under section 3.2.2.

No woodchips analysis was conducted in this trial. However, total solids determination of the same batch of woodchips during a later stage of the work showed a moisture content of approximately 40% (w/w), which is in agreement with a figure used for woodchips in the work of Willson (1983), who calculated mixture ratios of woodchips to sludge on a volume basis. The calculated sludge woodchips mixture moisture content was consequently about 75% (w/w).

4.2.2.1 Analysis of Variables

Tables A.1 and A.2 (Appendix) contain all the replicate results of total solids (TS), volatile solids (VS), total nitrogen (N), and phosphorus (P) obtained through sample analysis during this trial. The mean values (TS, VS, N and P) including some statistical parameters are presented in Table 4.1a for windrow A and in Table 4.1b for windrow B. In calculating the mean values of the replicate samples, collected throughout the composting mass, it was assumed that all the positions within one windrow have been subjected to the same conditions during composting.

Temperature Development

The temperature was measured by six thermocouples in each windrow as shown previously in Figure 3.5. The development of the temperature in windrow A is shown in Figure 4.1a and the one for windrow B is presented in Figure 4.1b. The figures represent a range of temperature values within one windrow. A solid line was chosen as random temperature variation within the windrow made a single point average misleading. The solid line indicates the approximate range of temperatures measured throughout the windrow with time.

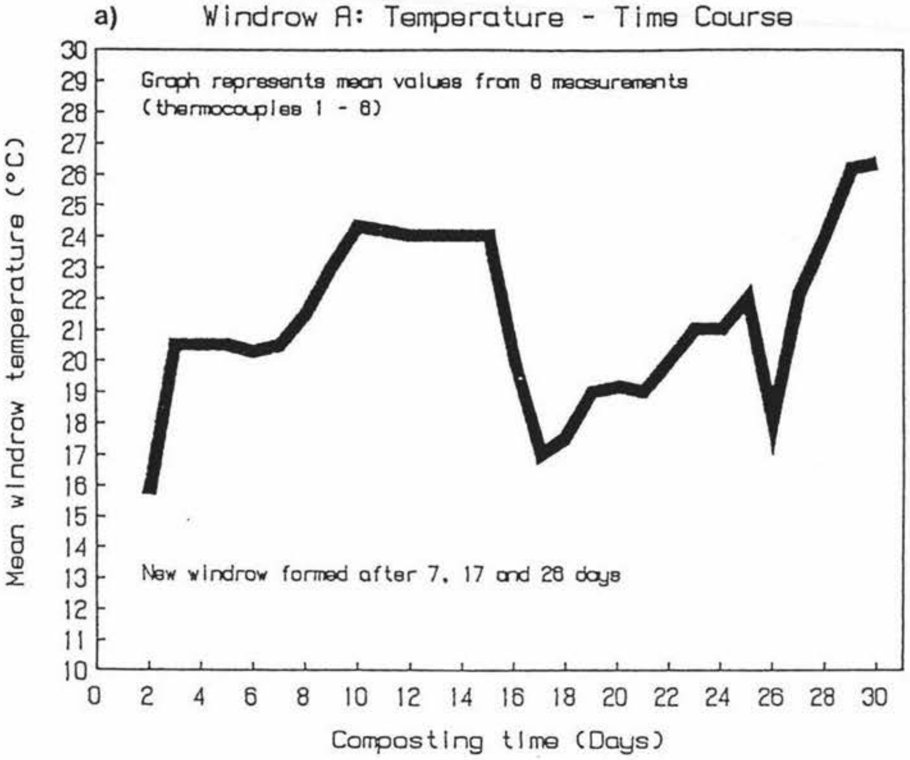
It can be clearly seen in Figure 4.1 that an interuption in temperature rise occurred in both windrows at about the same time. This break very likely occurred because of the addition of 10 l water to each windrow at the fifth day of the experiment. A slight drop after this break was caused

Table 4.1a Mean values of selected variables for the aerated Windrow A.
(s: Standard deviation; $B_{95\%}$: 95% confidence intervall on the mean).

	VARIABLES (Windrow A)											
Time (Days)	%$\overline{TS}$	s	$B_{95\%}$	%$\overline{VS}$	s	$B_{95\%}$	%$\overline{N}$	s	$B_{95\%}$	%$\overline{P}$	s	$B_{95\%}$
0	17.39	0.32	0.33	67.83	0.86	0.90	ND	-	-	ND	-	-
7	18.41	1.37	1.44	64.61	3.49	3.66	4.50	0.45	0.47	2.50	0.13	0.16
17	19.24	1.19	1.25	62.40	3.44	3.61	4.14	0.48	0.31	2.73	0.19	0.12
26	21.27	1.40	1.47	60.23	1.13	1.19	3.88	0.31	0.20	2.76	0.14	0.09

Table 4.1b Mean values of selected variables for the aerated Windrow B.
(s: Standard deviation; $B_{95\%}$: 95% confidence intervall on the mean).

	VARIABLES (Windrow B)											
Time (Days)	$\%\overline{TS}$	s	$B_{95\%}$	$\%\overline{VS}$	s	$B_{95\%}$	$\%\overline{N}$	s	$B_{95\%}$	$\%\overline{P}$	s	$B_{95\%}$
0	17.39	0.32	0.33	67.83	0.86	0.90	ND	-	-	ND	-	-
7	18.14	1.65	1.73	65.15	3.46	3.62	4.52	0.32	0.42	2.44	0.24	0.28
17	18.72	0.98	1.02	61.37	1.60	1.68	3.85	0.18	0.15	2.76	0.09	0.07
26	20.67	1.82	1.91	60.36	2.05	2.15	3.77	0.22	0.14	2.74	0.18	0.11



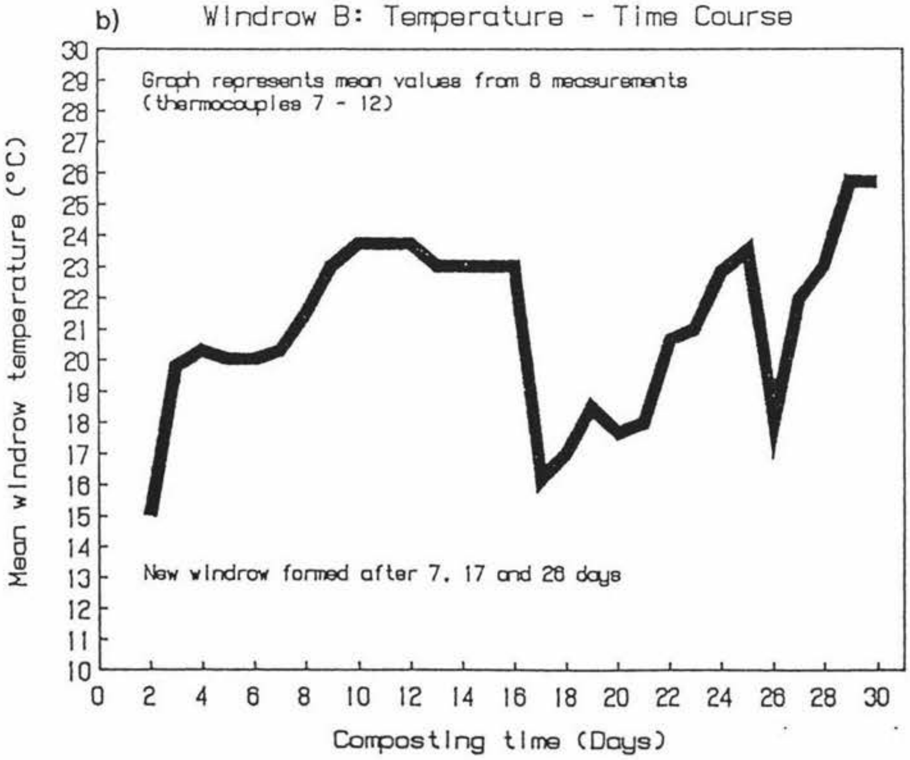


FIGURE 4.1: Mean temperature changes during composting in aerated windrow A (a) and B (b) at various points.

by the first remixing of the composting mass at the seventh day of the run. It was also noticed that the mass did not cool down to ambient temperature during this procedure. The temperature then increased again up to approximately 24°C in both the windrow A and B, until the next breakdown and rebuilding of the windrows was performed, namely after 17 days of composting. The newly mixed mass started to rise in temperature, this time windrow B reaching slightly higher values than windrow A. A further decrease after 26 days was to be expected since the material was again remixed and rebuilt. The temperature again increased rapidly and by the end of the fourth week had reached 27°C in both windrows. Having successfully established the experimental and analytical procedures, it was decided to terminate the composting cycle and to start a new experiment.

Total Solids and Volatile Solids

The total solids - time course in the windrows A and B are shown in Figures 4.2a and 4.3a, respectively. The initial total solids content of the sludge to be composted was approximately 17.40% in both windrow A and B. A final mean total solids content of approximately 21% was obtained after 26 days of composting. A significant change of total solids was observed in both windrows as indicated in Table 4.2.

The change in volatile solids content in the composting materials shown in Figures 4.2b and Figures 4.3b respectively was significant (see Table 4.2). An absolute

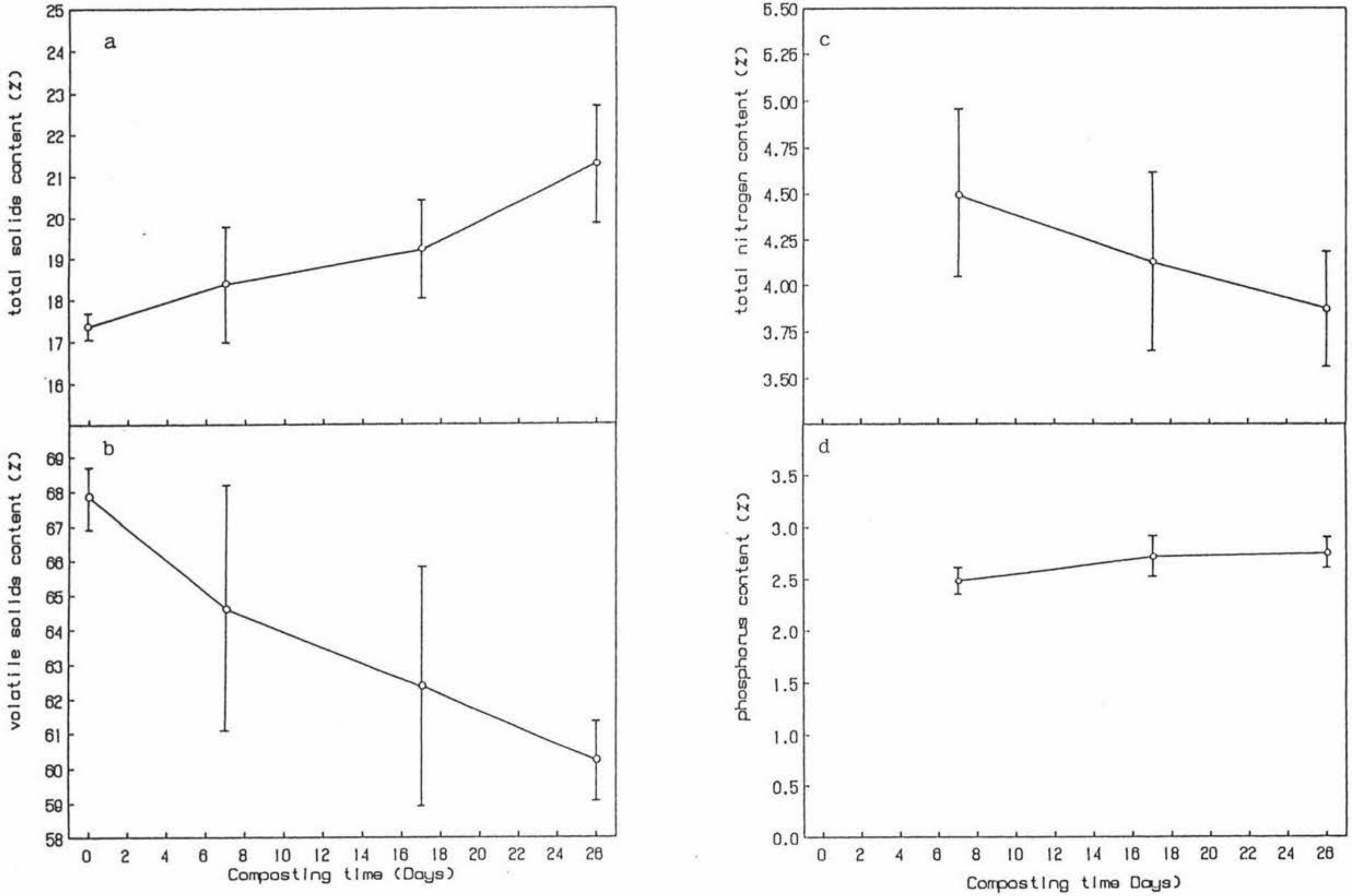


FIGURE 4.2: Changes in total solids (a), volatile solids (b), total nitrogen (c) and phosphorus (d) during composting in Windrow A, (% VS, % N and % P are calculated on a dry matter basis at any time of composting).

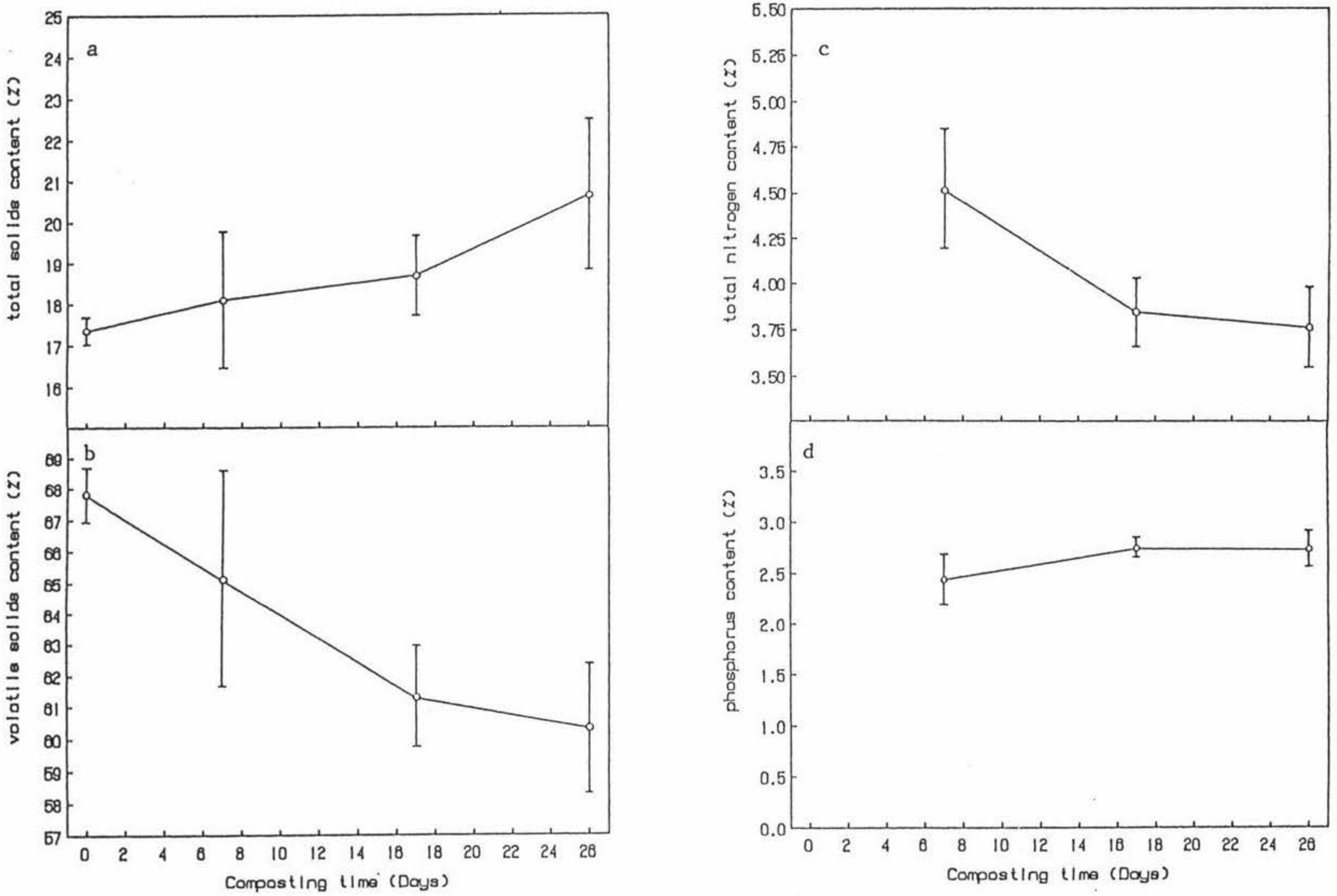


FIGURE 4.3: Changes in total solids (a), volatile solids (b) total nitrogen (c) and phosphorus (d) during composting in Windrow B, (% VS, % N and % P are calculated on a dry matter basis at any time of composting).

decrease of approximately 28 % occurred in both windrows. However, the addition of water (and probably also the change of aeration from fan to compressor), contributed even more to the heterogeneity of the composting mixture, and rather large standard deviations could not be avoided.

Total Nitrogen and Phosphorus

The changes in total nitrogen during composting are illustrated in Figure 4.2c for windrow A and Figure 4.3c for windrow B, respectively. Analysis of sewage sludge samples before composting indicated an average total nitrogen content of about 6% (w/w) which is in agreement with values found in cellular residue after endogeneous metabolism reported by Eckenfelder (1980). The average phosphorus content was about 2.8% (w/w), a level usually found in active biomass (Eckenfelder, 1980). Since secondary activated sewage sludge after settling in a clarifier is mainly not active biomass, the phosphorus values found are rather high and hence, could be due to reasons such as the high content of synthetic detergents in the influent wastewater (IWPC, 1978). Phosphorus concentrations of microorganisms and compost are presented by Biddlestone and Gray (1985) and Kuchenrither et al. (1985), respectively. In both windrows a significant (Table 4.2) reduction in total nitrogen content of about 14% to 17% (w/w) in the screened compost mixture could be observed between day 7 and day 26 . Again, as described previously, rather large standard deviations resulted because of the poor mixing characteristics of the compost.

Small changes in phosphorus content between the 7th and 26th day are shown in Figures 4.2d and 4.3d. A slight, although significant (Table 4.2), increase during the composting process could be observed in both windrows. This is probably due to the decreasing dry matter content, on which the phosphorus determination has been based.

Table 4.2 Calculated F-values for selected variables for the aerated windrow composting trial.

(significant at the 99% level)
(significant at the 95% level)

Variables	Windrow A	Windrow B
%TS	$F_{\mathit{3,20}} = 12.09$	$F_{\mathit{3,20}} = 6.67$
%VS	$F_{\mathit{3,20}} = 9.70$	$F_{\mathit{3,20}} = 14.69$
%N	$F_{\mathrm{2,26}} = 4.24$	$F_{\mathit{2,21}} = 17.79$
%P	$F_{\mathrm{2,25}} = 4.13$	$F_{\mathit{2,22}} = 6.60$

4.2.3 AERATED STATIC PILE COMPOSTING

The experimental design employed for this trial was that as described earlier under section 3.2.3.

The mean total solids content of five woodchip samples was found to be 60.4% (s = 2.22%) corresponding to a mean moisture content of 39.6%. The sludge woodchips mixture moisture content was 76%. Dewatered activated sewage sludge was mixed with fresh woodchips in a ratio of 3.8:1 (w/w) which corresponded to a woodchips to sludge ratio of approximately 1.6:1 on a volume basis.

The mean volatile solids content of woodchips was found to be 87.4% (s = 2.13), examining five woodchips samples. The average bulk fresh weight of the woodchips used was calculated to be 155kg/m^3.

It was decided to follow the course of decomposition at each sampling point separately, based on the assumption that a position effect existed in addition to the usual changes occurring during the composting time. The statistical analysis which was carried out using a two-way analysis of variance tested for any time effects at all positions as well as for any position effects over the experimental period. The results of the analysis are presented in Table 4.3 which shows the calculated F-values.

4.2.3.1 Analysis of Variables

Table A.3 (Appendix) shows the results of duplicate analysis for total solids(TS), volatile solids (VS), total nitrogen (N) and phosphorus (P) of samples collected at the different sampling ports 1 - 6 during this trial.

Temperature Development

The temperature was measured by 12 thermocouples inserted into the pile material as shown earlier in Figure 3.6. The development of the temperature at different positions in the pile is shown in Figures 4.4a and 4.4b and in Figures 4.5a and 4.5b. It can be seen, that several thermocouples ceased to function after certain periods of time. They were not replaced for new ones in order not to disturb the ongoing composting process. Figure 4.4b and 4.5b have been drawn in a three dimensional manner in order to present the recordings of each individual thermocouple. Maximum temperatures ranging from $52^{\circ}C$ to $70^{\circ}C$ were reached between the third and fifth day of operation in all positions. Ambient temperature was reached after 23 days of composting.

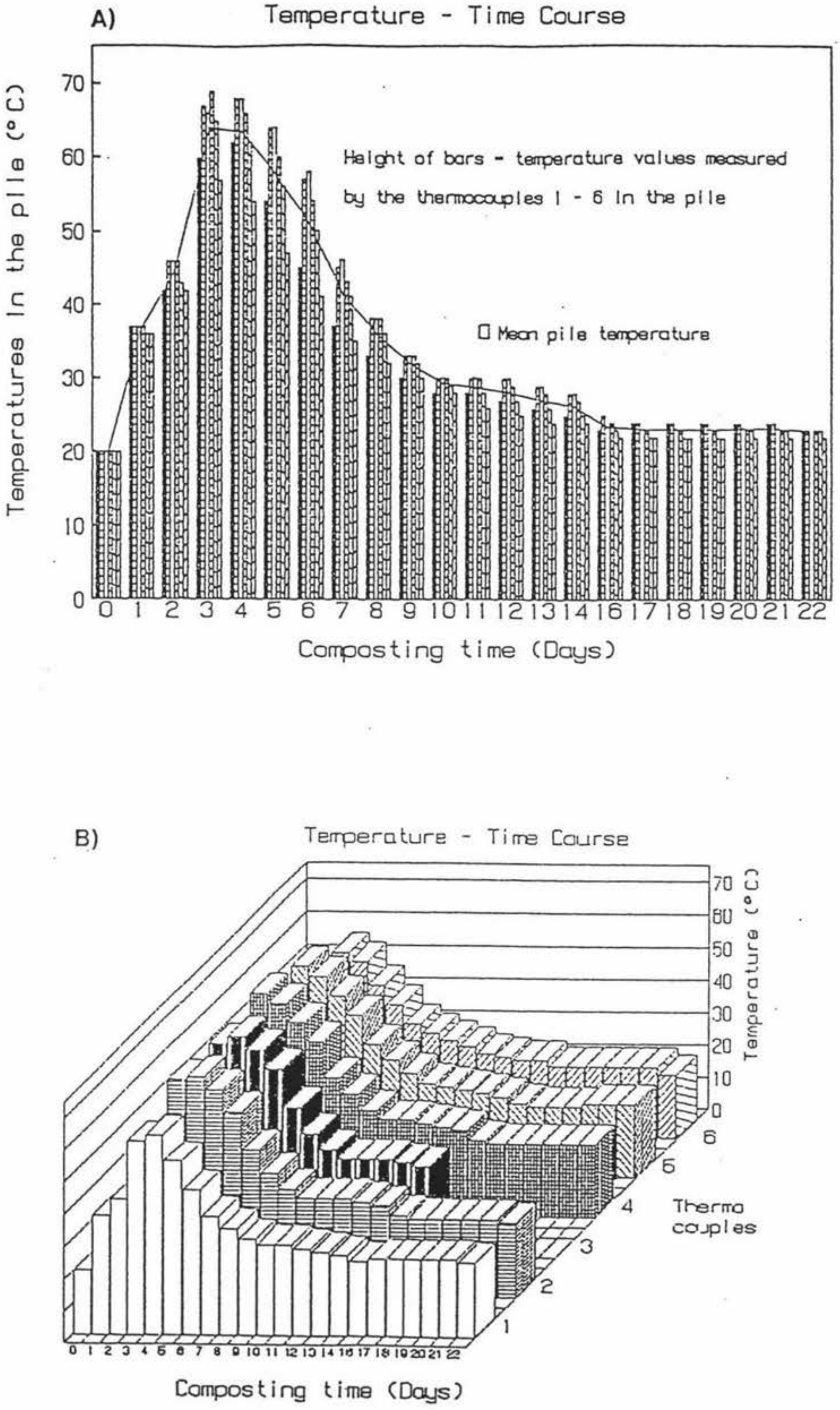


FIGURE 4.4: Temperature changes during composting monitored by thermocouples 1 - 6 in the aerated static pile study in A) two dimensional and B) three dimensional representation.

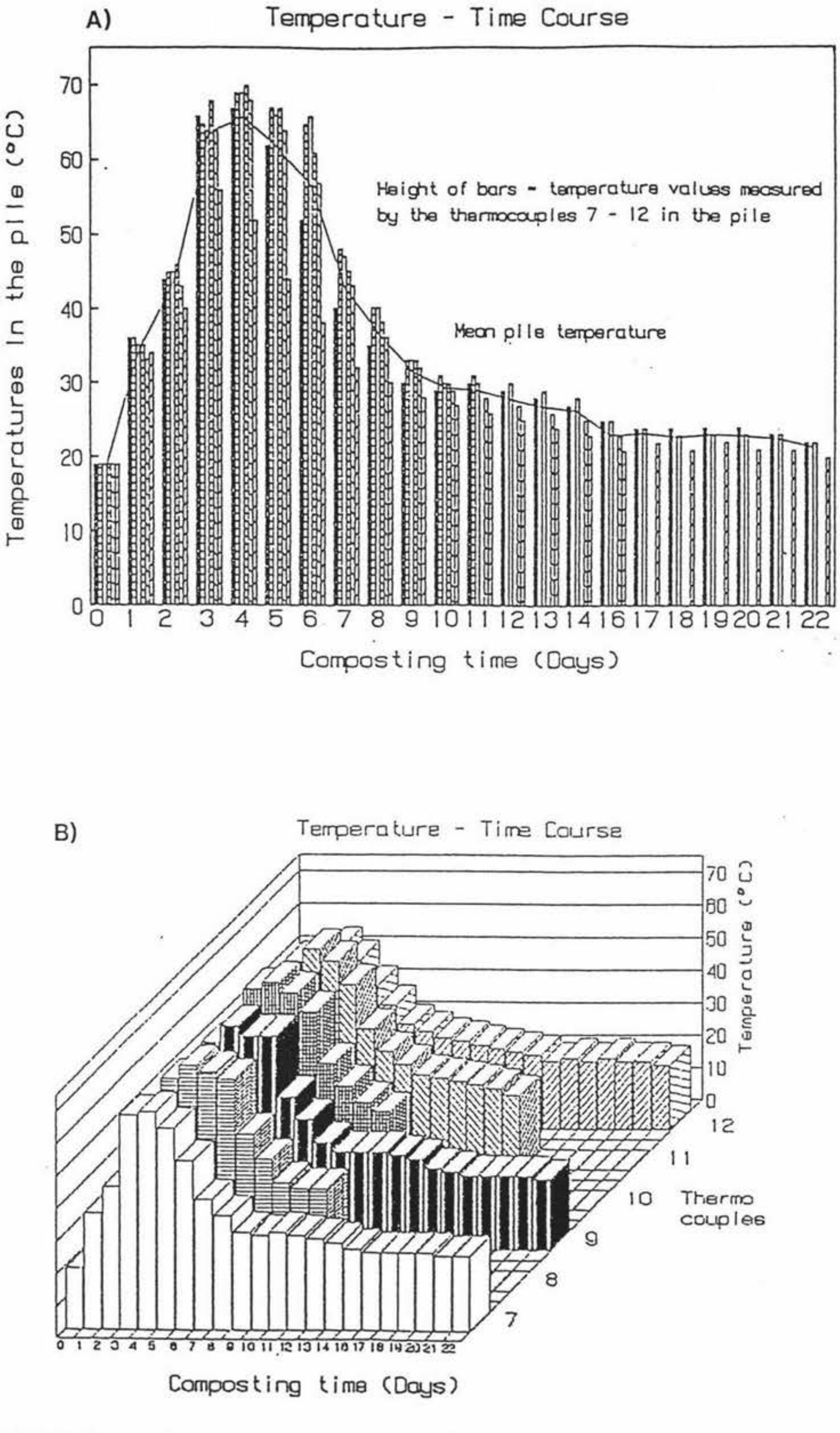


FIGURE 4.5: Temperature changes during composting monitored by thermocouples 7 - 12 in the aerated static pile study in A) two dimensional and B) three dimensional representation.

Total Solids and Volatile Solids

Mean values of total solids were calculated and are presented in Figures 4.6a to 4.11a for all positions 1 - 6. Overall, total solids increased significantly from an initial value of approximately 14% up to values ranging from 17% to 22%. The differences observed varied with positions (Table 4.3) from which samples were taken.

The changes in mean volatile solids content in the composting material at positions 1 - 6 are shown in Figures 4.6b to 4.11b. Decreases in volatile solids contents were observed. Initial values of approximately 72% diminished to values ranging from 63% to 56% after 23 days of operation. This corresponded to an absolute decrease in volatile solids of 34% to 50 % which was independent of sampling position during this experiment (see Table 4.3).

Total Nitrogen and Phosphorus

Mean values of phosphorus are plotted versus time, as shown in Figures 4.6c to 4.11c for all sampling positions 1 - 6. Significant changes (Table 4.3) were observed in samples from all positions. The changes were again small, as previously reported in the aerated windrow trial. The final phosphorus content in compost is important with regard to the use of the product, although it is not normally used to monitor process performance. Figures 4.6d to 4.11d show the significant changes in total nitrogen content versus time in all positions 1 - 6. Total nitrogen losses amounted to 45 to 58% (absolute values) of the initial nitrogen content. However, the decrease in nitrogen during the composting period varied with position in pile (see Table 4.3) from which sample was taken. The loss of nitrogen was also observed by ammonia vapours surrounding the facility site.

Table 4.3 Calculated F-values for selected variables for the aerated static pile trial (All values (except position effect on %VS) are significant at the 99% level).

Effect testet	Variables			
	%TS	%VS	%N	%P
Time (days) over all positions	$F_{3,24} = 267.14$	$F_{3,24} = 259.33$	$F_{3,24} = 1203.67$	$F_{3,24} = 46.82$
Position over all times (days)	$F_{5,24} = 18.14$	$F_{5,24} = 2.30$ not sign. at 95% level	$F_{5,24} = 21.86$	$F_{5,24} = 29.55$

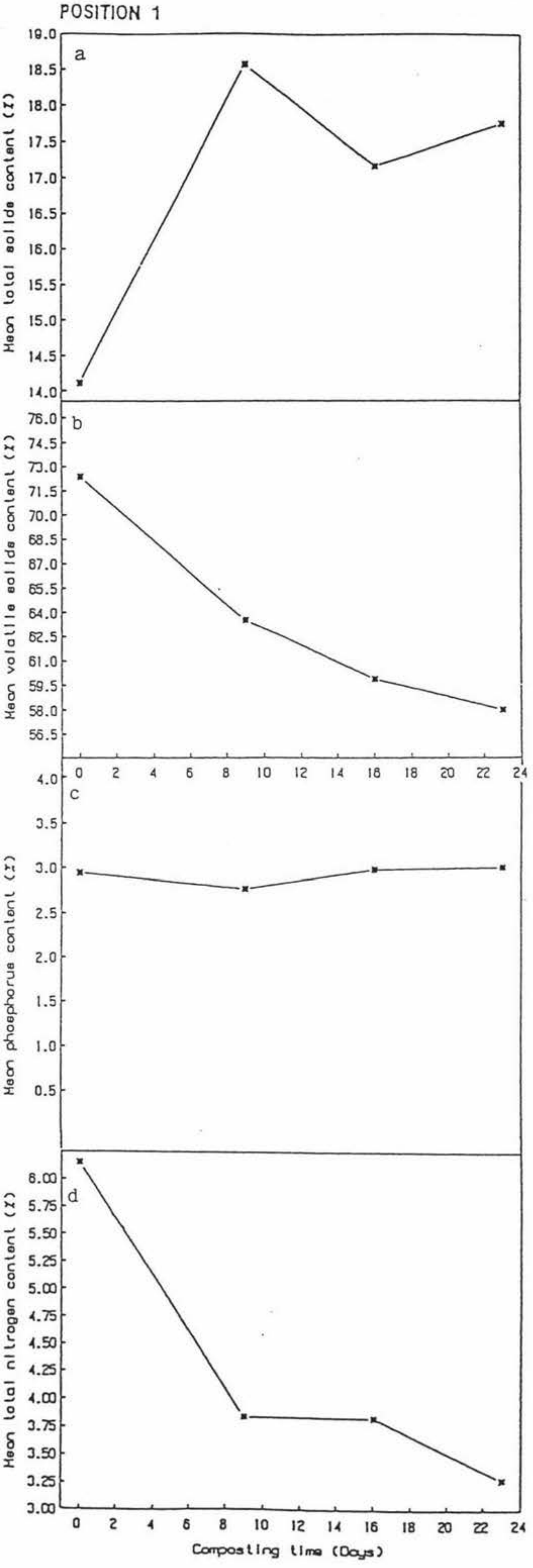


FIGURE 4.6: Changes in total solids (a), volatile solids (b), phosphorus (c) and total nitrogen (d) at position <u>1</u> during aerated static pile composting. (Variables as explained in text).

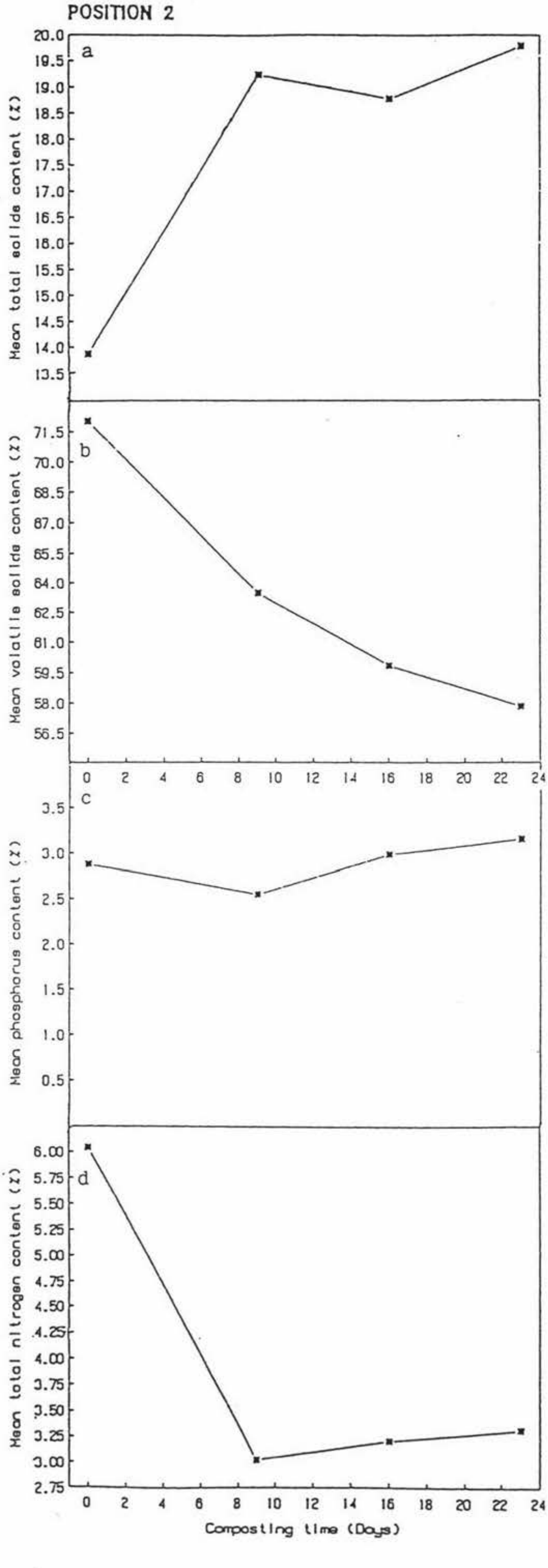


FIGURE 4.7: Changes in total solids (a), volatile solids (b), phosphorus (c) and total nitrogen (d) at position 2 during aerated static pile composting. (Variables as explained in text).

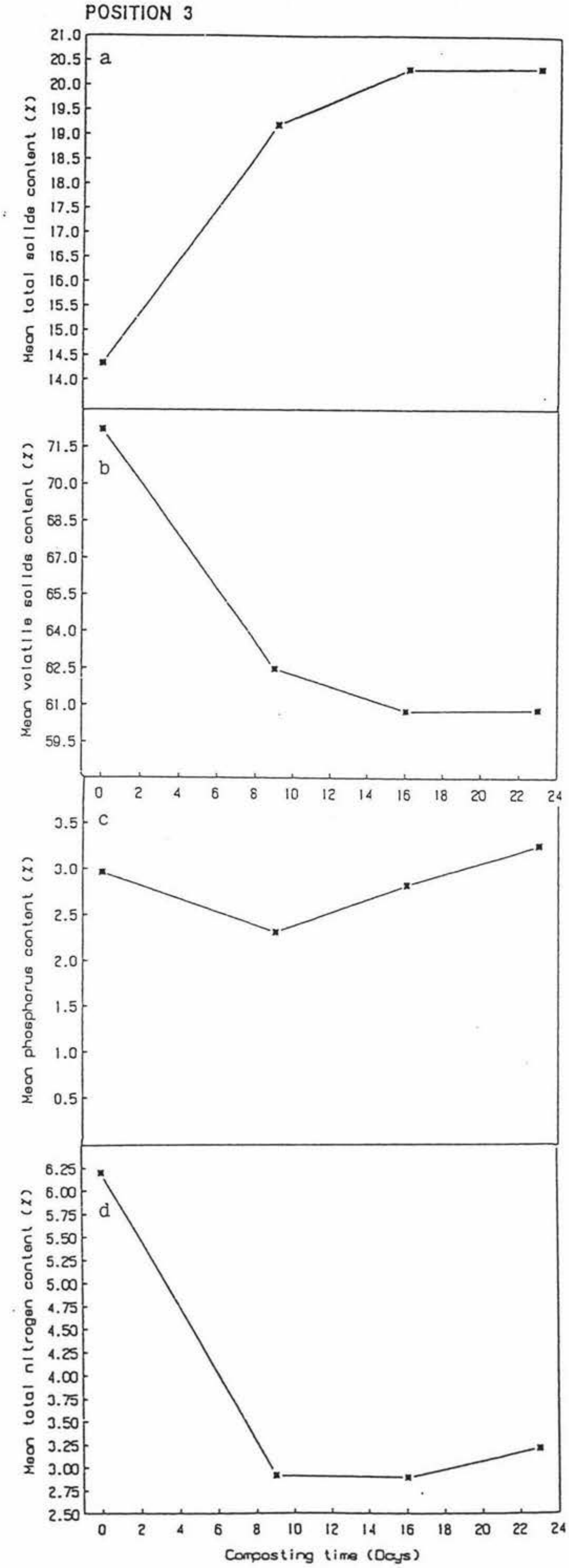


FIGURE 4.8: Changes in total solids (a), volatile solids (b), phosphorus (c) and total nitrogen (d) at position 3 during aerated static pile composting. (Variables as explained in text).

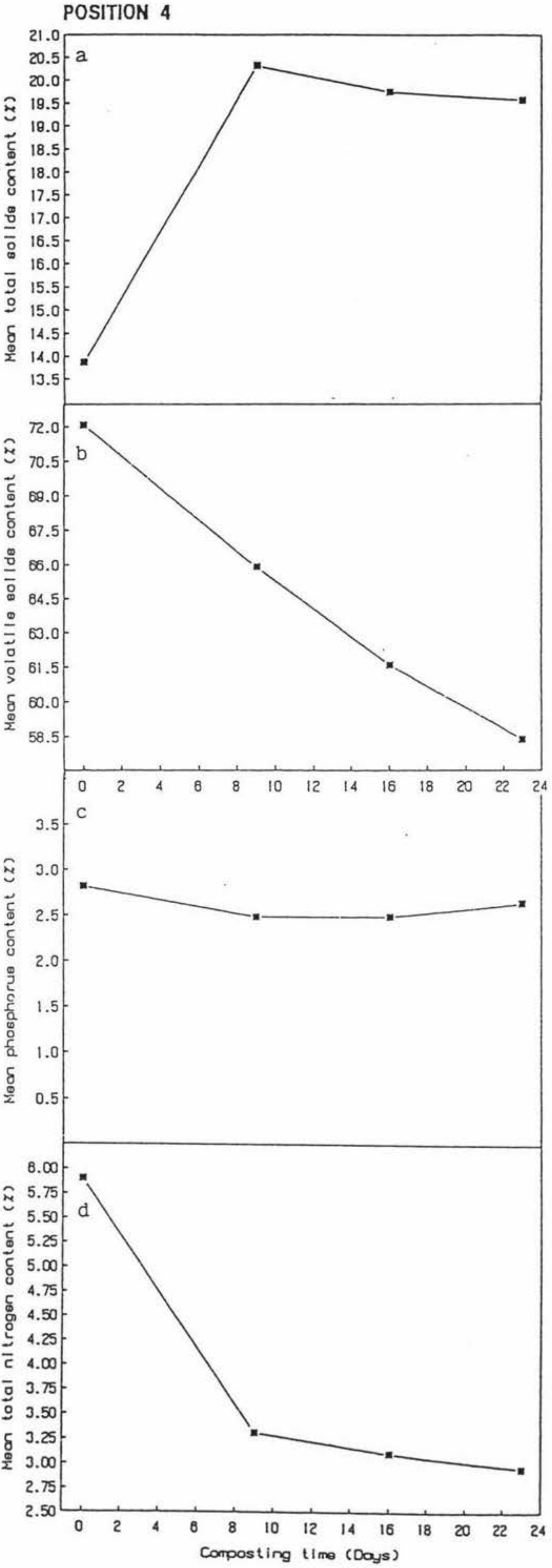


FIGURE 4.9: Changes in total solids (a), volatile solids (b), phosphorus (c) and total nitrogen (d) at position 4 during aerated static pile composting. (Variables as explained in text).

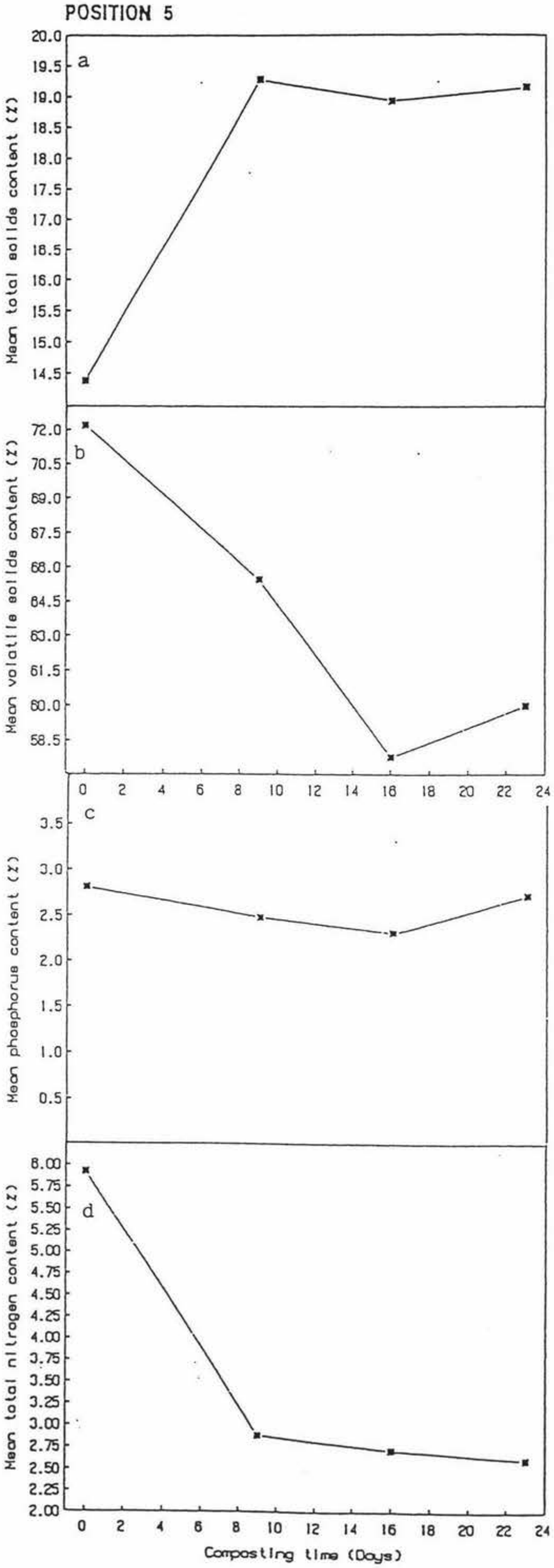


FIGURE 4.10: Changes in total solids (a), volatile solids (b), phosphorus (c) and total nitrogen (d) at position 5 during aerated static pile composting. (Variables as explained in text).

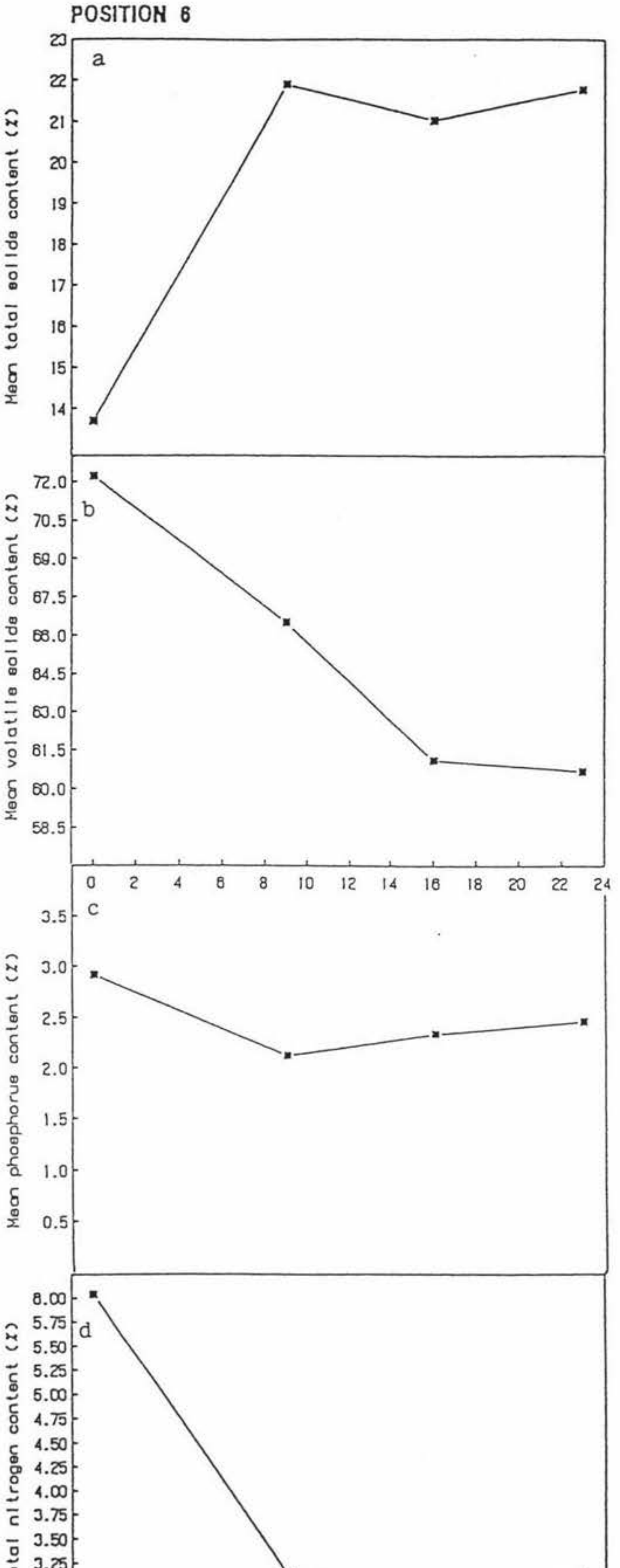


FIGURE 4.11: Changes in total solids (a), volatile solids (b), phosphorus (c) and total nitrogen (d) at position 6 during aerated static pile composting. (Variables as explained in text).

4.3 DRUM TUMBLER COMPOSTING

4.3.1 INTRODUCTION

The same variables as described for monitoring the open systems (see section 4.2.1 for details) were measured. However, included in the collected data herein are results of microbiological investigations as well as results from total carbon determinations conducted during the second and third experiment.

The experimental designs used in these trials were described earlier in Chapter 3.

The first drum tumbler experiment was conducted using excess amounts of sludge to supply enough energy for the microorganisms in the rather limited volume of the drum and thus, enable successful composting of the sludge.

The next two trials utilized mixtures with lower amounts of sludge. Dried woodchips were used thus reducing the amount which was necessary to obtain an optimal moisture content of approximately 60% in the mixture to be composted. The smaller moisture content meant that the mixture was easier to handle during turning and sampling. Better aeration was achieved and less odour development was evident. For all trials it was assumed that decomposition within the moving drum occurred independent of location from which the samples were removed, i.e. the material in the bins was assumed to be well mixed. Statistical testing therefore consisted of the same methods previously described under section 4.2.2 and resulted in F-values given in Table 4.10. The temperatures in all trials were measured using three thermocouples inserted into the composting mass. The mean values of these three measurements are presented in the figures quoted in the appropriate sections.

Again in these trials (see also Section 4.2.1) the absolute changes in percent volatile solids and percent total nitrogen were calculated, assuming a basis of 100 kg dry weight at the beginning of the experiments. In drum tumbler trial, numbers two and three, absolute changes in total carbon were also determined.

4.3.2 FIRST TRIAL

Dewatered activated sewage sludge was mixed with woodchips in a ratio of 7.5 to 1 (w/w). The resulting moisture content of the mixture was calculated to be approximately 80%.

The pH of three random samples of the sludge to be composted was in the range of 6.2 to 6.6. During the composting an increase in pH to 7.0 in the middle of the cycle was observed.

4.3.2.1 Analysis of Variables

Table A.4 (Appendix) contains all the replicate results of total solids (TS)-, volatile solids (VS)-, total nitrogen (N)- and phosphorus (P)- analyses obtained during this trial. The mean values of TS, VS, N and P, including statistical parameters are calculated and presented in Table 4.4.

Temperature Development

The mean temperature monitored during the composting cycle including the range about the mean is shown in Figure 4.12. Maximum temperatures were reached during the fourth day of operation (57°C), but then declined until the 12th day when ambient temperature of 20°C was reached.

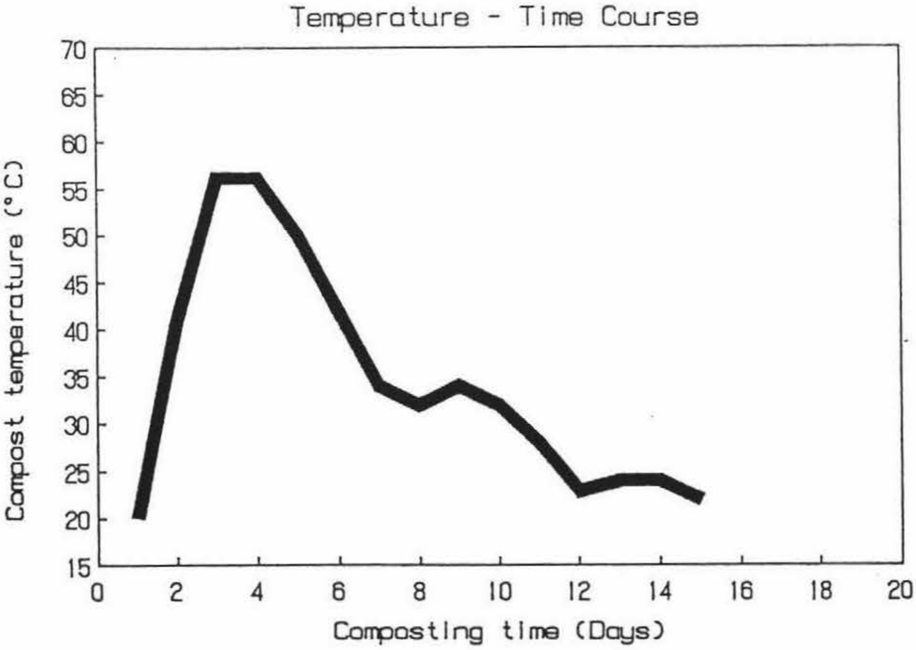


FIGURE 4.12: Mean temperature changes during composting in the first drum tumbler trial

The cover of the tumbler was opened during the third day of operation to prevent condensate accumulation, which affects the moisture content of the composting mixture significantly and, therefore, the composting process. However, this resulted in early cooling of the mixture.

Total Solids and Volatile Solids

Figure 4.13a shows the total solids content versus time during the operation of this trial. Initially the sludge consisted of 14.8% TS, increasing up to 20.3% after 15 days of composting.

In Figure 4.13b changes of volatile solids versus time are presented. A decrease from its initial 75.5% to 63% was observed, corresponding to an absolute decrease in VS of 44.8%. The rather large standard deviation after 15 days of duration very likely is due to the poor physical structure of the mixture which had formed into large balls. Within these lumps one could observe black zones of anaerobic decomposition. The accompanying strong and offensive odours was evidence of putrefactive conditions within the material.

Total Nitrogen and Phosporus

Changes in total nitrogen and phosphorus during this trial are given by Figures 4.13c and 4.13d, respectively. An absolute reduction of 38% in total nitrogen was measured while phosphorus changes were not appreciable.

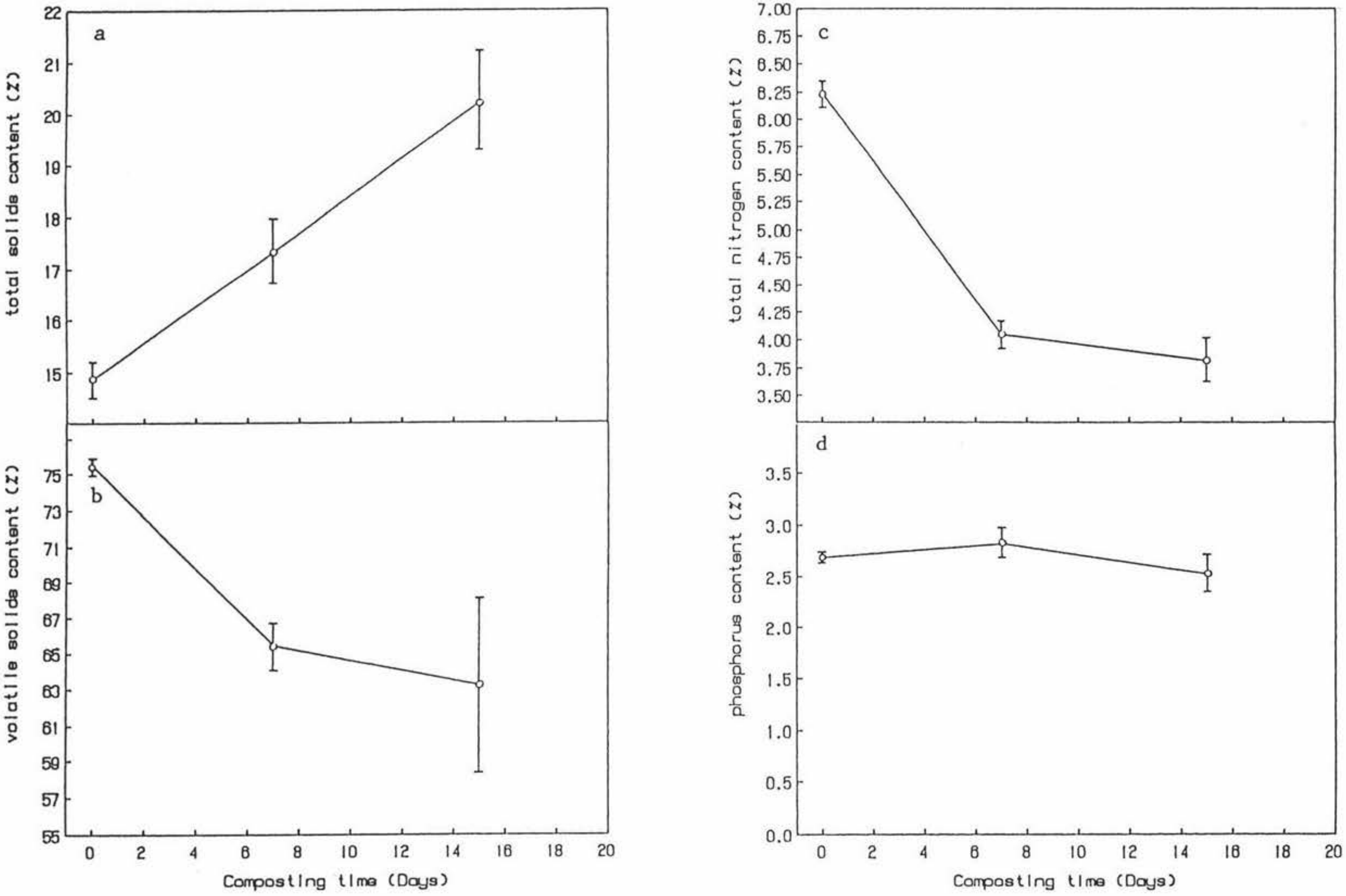


FIGURE 4.13: Changes in total solids (a), volatile solids (b), total nitrogen (c) and phosphorus (d) during composting in the first drum tumbler trial (%VS, %N and %P are calculated on a dry matter basis at any time of composting).

Table 4.4 Mean values of selected variables for the first drum tumbler trial. (s and $B_{95\%}$ as indicated in Table 4.1).

	VARIABLES											
Time (Days)	$\%\overline{TS}$	s	$B_{5\%}$	$\%\overline{VS}$	s	$B_{95\%}$	$\%\overline{N}$	s	$B_{95\%}$	$\%\overline{P}$	s	$B_{95\%}$
0	14.872	0.349	0.37	75.48	0.45	0.47	6.228	0.118	0.12	2.698	0.040	0.04
7	17.36	0.620	0.77	65.40	1.30	1.61	4.052	0.119	0.12	2.836	0.133	0.14
15	20.257	0.956	1.00	63.25	4.88	5.12	3.824	0.191	0.24	2.537	0.178	0.22

Microbiological Counts

Table 4.5 presents results of bacteriological studies for three sets of samples taken from the material within the bin. Only two sampling series were carried out in this trial since the material at the end of 15 days was too offensive to be microbiologically analysed. From these results no conclusions with regard to the development of the indicator microorganisms during the composting cycle could be made.

Table 4.5 Microbial counts in raw dewatered activated sewage sludge including one compost sample, determined during the first drum tumbler trial. (Plate counts are mean values of duplicates).

Microorganism (Culture method)	Day 0 Sludge sample	Day 7 Compost sample
Heterotrophic count (PCA, 37°C, 24-48h) CFU.g^{-1} sample	3.03×10^8 2.53×10^8 2.98×10^8	4.25×10^8 3.36×10^8 2.36×10^8
Group D-streptococci (BEA, 37°C, 24-48h) CFU.g^{-1} sample	5.42×10^5 5.83×10^5 2.74×10^5	4.41×10^5 1.32×10^6 2.44×10^6
Total coliform bacteria (MPN, 37°C, 48h) Organisms per g sample	1.80×10^5 1.80×10^5 1.80×10^5	0.9×10^4 1.2×10^4 2.2×10^4

CFU = Colony Forming Units

PCA = Plate Count Agar

BEA = Bile Esculin Azide Agar

MPN = Most Probable Number Method using MacConkey broth (5 tubes inoculated of each of 4 successive 10-fold dilutions)

4.3.3 SECOND TRIAL

The woodchips used in this trial were dried to ensure an optimal moisture content of approximately 60% in the mixture. The drying resulted in woodchips with an average moisture content of 10%. Dewatered activated sewage sludge was then mixed with the woodchips in a ratio of 2:1 (w/w). The final moisture content in the mixture was approximately 63%.

The pH of three samples of the sludge was 6.6. During the first half of the experiment, the pH seemed to have slightly increased to values reaching about 7. Further investigations resulted in a pH fall to values in the range of 6.0-6.3.

A typical earthy smell was detectable at the end of this trial, which gives some indication for successful composting and sludge stabilization.

4.3.3.1 Analysis of Variables

The replicate results of the analysis of total solids (TS), volatile solids (VS), total nitrogen (N) and phosphorus (P) are given in Table A.5 (Appendix). The mean values (TS, VS, N and P), including some statistical parameters are calculated and shown in Table 4.6.

Table 4.6 Mean values of selected variables for the second drum tumbler trial. (s and $B_{95\%}$ as indicated in Table 4.1).

	VARIABLES											
Time (Days)	$\%\overline{TS}$	s	$B_{95\%}$	$\%\overline{VS}$	s	$B_{95\%}$	$\%\overline{N}$	s	$B_{95\%}$	$\%\overline{P}$	s	$B_{95\%}$
0	12.22	0.09	0.11	72.83	0.10	0.12	6.09	0.18	0.29	3.00	0.10	0.16
8	19.77	0.73	0.91	63.93	1.14	1.41	4.60	0.11	0.12	2.78	0.08	0.08
15	20.60	0.80	0.83	62.17	1.50	1.57	4.23	0.23	0.24	2.88	0.13	0.14
22	22.79	2.25	2.36	60.28	1.90	2.00	3.76	0.30	0.37	3.17	0.18	0.23

Temperature Development

The mean temperature monitored during the composting cycle including the range about the mean is shown in Figure 4.14. Two peaks of maximum temperatures were observed, the first occuring on the 2nd day (38°C) and the second occuring on the 10th day (42°C) of composting. Then temperatures were declining, interrupted by another small rise at the 17th day (35°C), after that again decreasing to ambient temperatures.

As described for the previous trial, also during this experiment the cover of the compostumbler was opened a few times while the material was shaken in order to release excess humidity produced by decomposition activity.

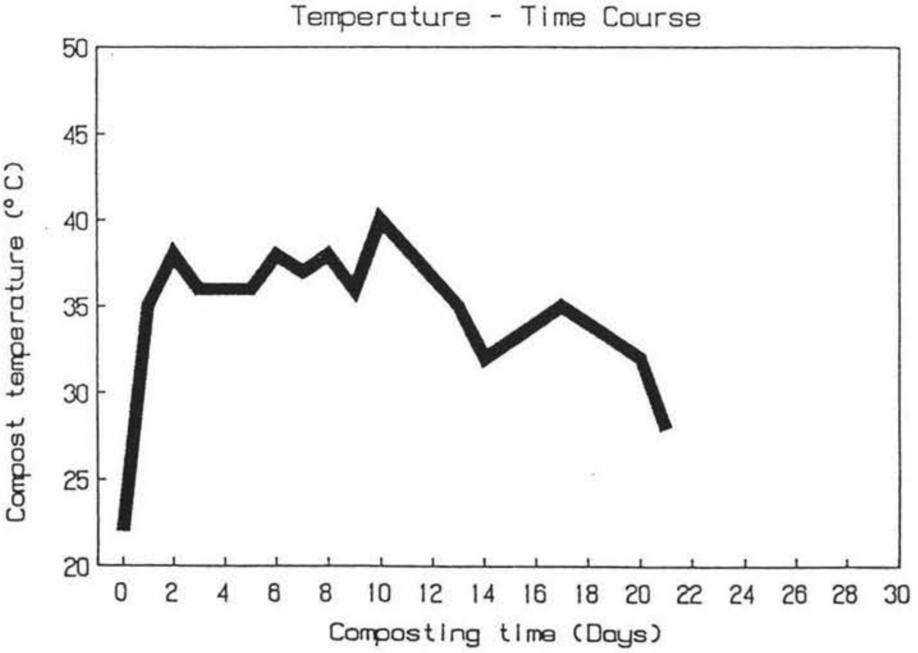


FIGURE 4.14: Mean temperature changes during composting in the second drum tumbler trial.

Total Solids and Volatile Solids

A graph showing TS content versus time is presented in Figure 4.15a. TS values of 23% were reached at the end of 22 days starting from concentrations of 12%.

A steady decrease in volatile solids content from initially 73% down to 60%, corresponding to an absolute desrease of 44.5% was observed and is presented in Figure 4.15b. The standard deviations calculated were much smaller than in the first drum tumbler trial suggesting better homogeneity of the material in the drum.

Total Nitrogen and Phosphorus

Changes in total nitrogen and phoshorus are given in Figures 4.15c and 4.15d, respectively. As in the experiment previously described, an absolute loss in total nitrogen of 40% was observed whilst phosphorus concentrations remained rather high yet stable.

Total Carbon

The total carbon content in the screened compost samples was determined. The following mean values of duplicate results were observed: 29.1% (Day 0), 23.5% (Day 8), 23.3% (Day 15) and 23.3% (Day 22). The major reduction in total carbon obviously occured in the first week of composting.

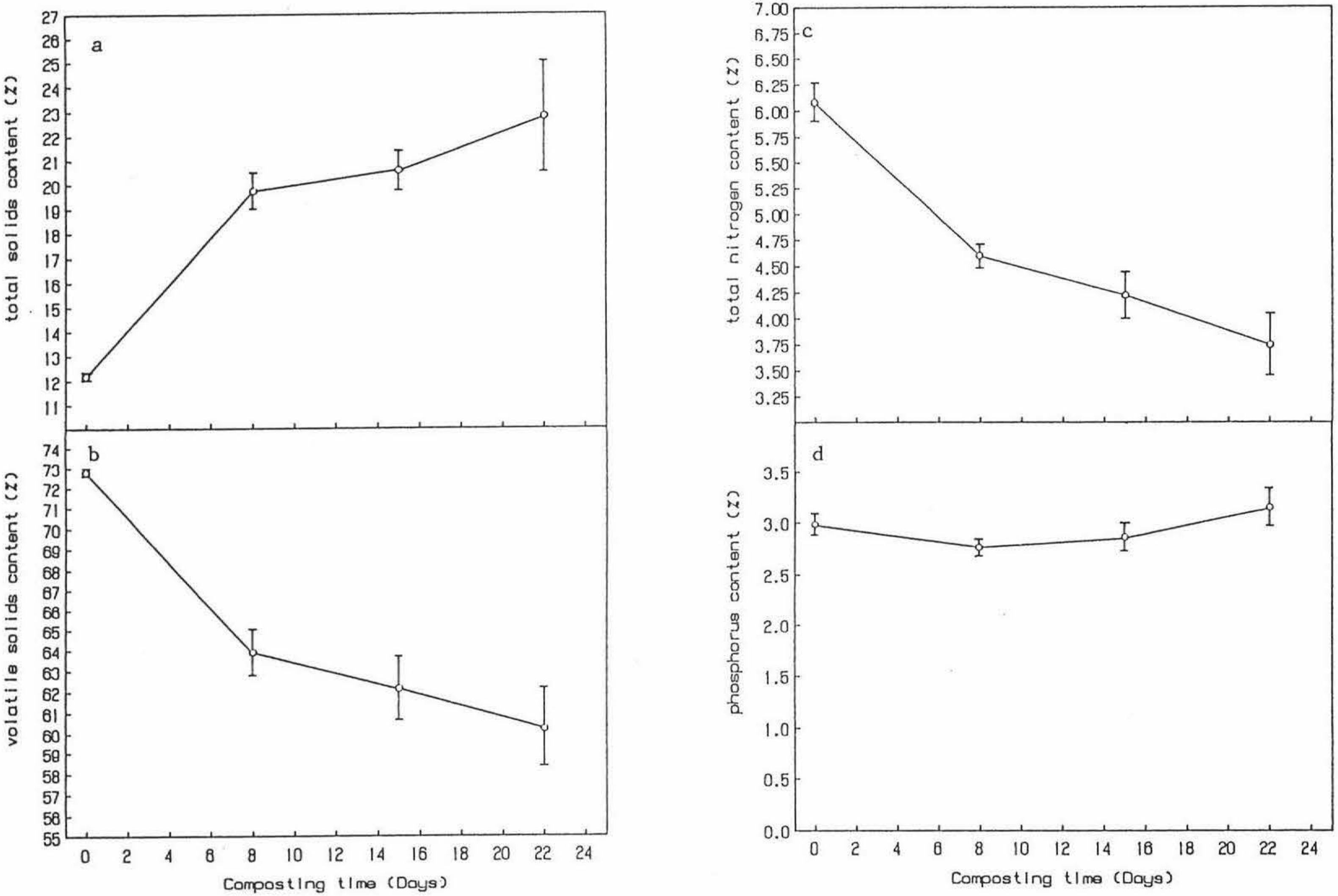


FIGURE 4.15: Changes in total solids (a), volatile solids (b), total nitrogen (c) and phosphorus (d) during composting in the second drum tumbler trial. (% VS, % N and % P are calculated on a dry matter basis at any time of composting).

Microbiological Counts

Results of bacteriological studies for three sets of samples taken from the material within the drum are given in Table 4.7. There is an indication of an increase in the total heterotrophic count occurring during composting cycle.

The counts of enteric streptococci (Group D) indicated that an almost complete die-off occurred up to the 22nd day.

The coliform group diminished slightly in numbers throughout processing. However, at the end of composting an appreciable number of coliform still survived. These findings suggest that in the final compost a microbial hazard remained.

Table 4.7 Microbial counts in raw dewatered activated sewage sludge and compost samples determined during the second drum tumbler trial. (Plate counts are mean values of duplicates).

Microorganism (Culture method)	Day 0 Sludge sample	Day 7 Compost sample	Day 15 Compost sample	Day 22 Compost sample
Heterotrophic count (PCA, 37°C, 24-72h) CFU.g^{-1} sample	1.82×10^8 1.34×10^8	NR 6.8×10^7 4.8×10^7	1.5×10^9 9.8×10^3 9.5×10^8	1.2×10^9 1.3×10^9 9.4×10^8
Heterotrophic count (PCA, 50°C, 24-72h) CFU.g^{-1} sample	$< 10^4$ $< 10^4$	9.8×10^5 12.0×10^5 11.3×10^5	3.17×10^6 Sp.c. NR 4.0×10^6	Sp.c. NR 1.5×10^6 1.75×10^6
Group D-steptococci (BEA, 37°C, 24-48h) CFU.g^{-1} sample	3.38×10^5 4.12×10^5	NR 9.0×10^4 8.5×10^4	$<10^3$ $<10^3$ $<10^3$	ND ND ND
Total coliform bacteria (MPN, 37°C, 35-488h) Organ. per g sample	1.37×10^7 1.55×10^7	2.4×10^5 1.96×10^5 3.26×10^5	9.17×10^6 4.89×10^5 2.23×10^5	2.35×10^5 1.5×10^5 5.65×10^4

NR = No data available
Sp.c.NR = No data available because of spreading colonies (counting not possible)
CFU = Colony Forming Units
ND = None detected
PCA = Plate Count Agar
BEA = Bile Esculin Azide Agar
MPN = Most Probable Number Method using MacConkey broth (5 tubes inoculated of each of 5 successive 10-fold dilutions.

4.3.4 THIRD TRIAL

Dewatered activated sewage sludge was mixed with dried woodchips (average moisture content 11%) in a ratio of 2.5 : 1 (w/w). The mixture to be composted exhibited a moisture content of approximately 64%.

The average pH of three samples was 6.9. After 13 days the pH had increased to 8.14 and after 24 days had dropped to values between 7.5 and 7.8.

As in the previous trial, towards the third week of operation an earthy smell was detected.

4.3.4.1 Analysis of Variables

Table A.6 (Appendix) presents all the replicate results for the analysis of TS, VS, N and P. The mean values (TS, VS, N and P) are given in Table 4.8 as are some statistical parameters.

Temperature Development

Temperature monitoring during operation of this trial resulted in the mean values presented in Figure 4.16. The temperature pattern shown in this diagram exhibits a peak of almost 70°C during the second day of operation, after which a sharp decline was noted until the fifth day when the mixture reached 32°C. Through to the 21st day of operation the temperature continued to decline to the ambient value of 22°C. To prevent excess water vapour condensate accumulating

Table 4.8 Mean values of selected variables for the third drum tumbler trial. (s and $B_{95\%}$ as indicated in Table 4.1).

	VARIABLES											
Time (Days)	$\%\overline{TS}_a$	s	$B_{95\%}$	$\%\overline{VS}_a$	s	$B_{95\%}$	$\%\overline{N}_b$	s	$B_{95\%}$	$\%\overline{P}_b$	s	$B_{95\%}$
0	14.19	0.20	0.21	70.04	0.09	0.10	5.03	0.23	0.28	0.78	0.05	0.06
$5^a, 11^b$	23.59	2.19	2.73	57.01	2.80	3.48	2.58	0.15	0.19	2.81	0.18	0.21
$14^a, 19^b$	26.39	0.82	0.86	54.32	1.87	1.96	2.32	0.02	0.03	2.60	0.11	0.14
$21^a, 24^b$	27.61	1.63	1.51	53.83	1.05	1.10	2.65	0.11	0.12	2.96	0.18	0.18

inside the drum, the cover lid was opened occasionally during the initial stages of the experiment.

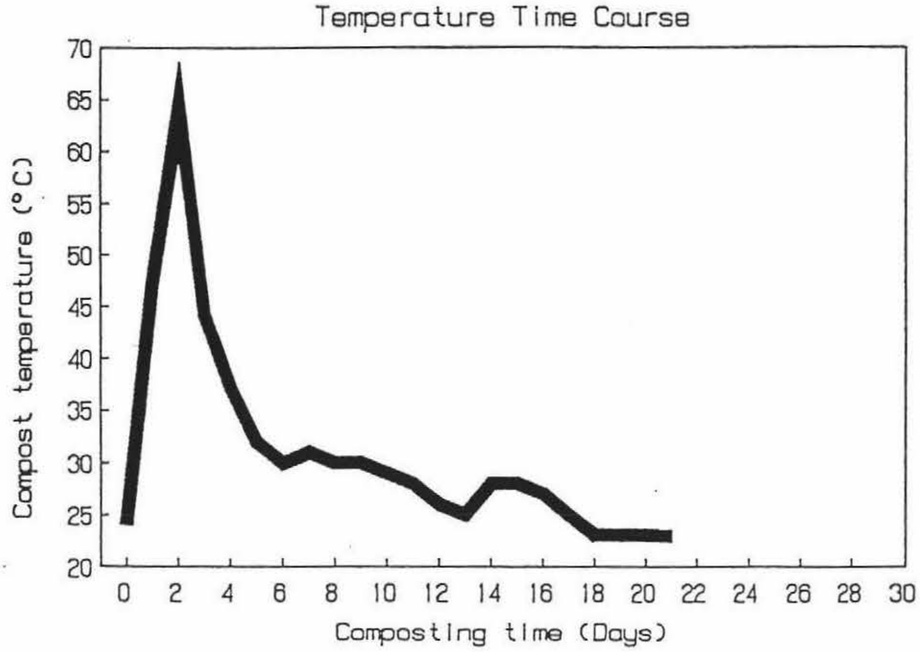


FIGURE 4.16: Mean temperature changes during composting in the third drum tumbler trial

Total Solids and Volatile Solids

Figure 4.17a illustrates the mean results of TS determination versus time . A 94% increase in total solids from initially 14% to 27.6% ater 21 days was observed.

Volatile solids decreased from initial values of 70% to 53.8% after 21 days of operation, corresponding to an absolute decrease of 50% (see Figure 4.17b).

Total Nitrogen and Phosphorus

Changes in N and P are given in Figures 4.17c and 4.17d respectively. Total nitrogen concentration in the raw sludge was found to be 5%. However, final values were determined at approximately 2.6%, corresponding to an absolute reduction of 49%. Again changes in phosphorus were not appreciable. As previously mentioned the phosphorus results showed rather high values compared with values of phosphorus concentrations in compost and microorganisms presented in the literature (Kuchenrither et al., 1985; Eckenfelder, 1980; Biddlestone and Gray, 1985), indicating possible accumulation of excess phosphorus by sludge in the treatment plant.

Total Carbon

The following mean values of duplicate total carbon determinations were observed to be 28.1% (Day 0), 18.5% (Day 11) and 18.4% (Day 18). Thus, an absolute amount of 42% carbon was removed during processing.

Microbiological Counts

Results of microbiological studies for three sets of samples taken from the compostumbler indicate that over the first 13 days of operation there occurred a one log cycle increase approximately in total heterotroph count and that even after 24 days of composting, the counts remain in excess of original numbers thus, growth had occurred (Table 4.9).

The counts for enteric streptococci (Group D) indicated that growth occurred over the first 13 days with die-off

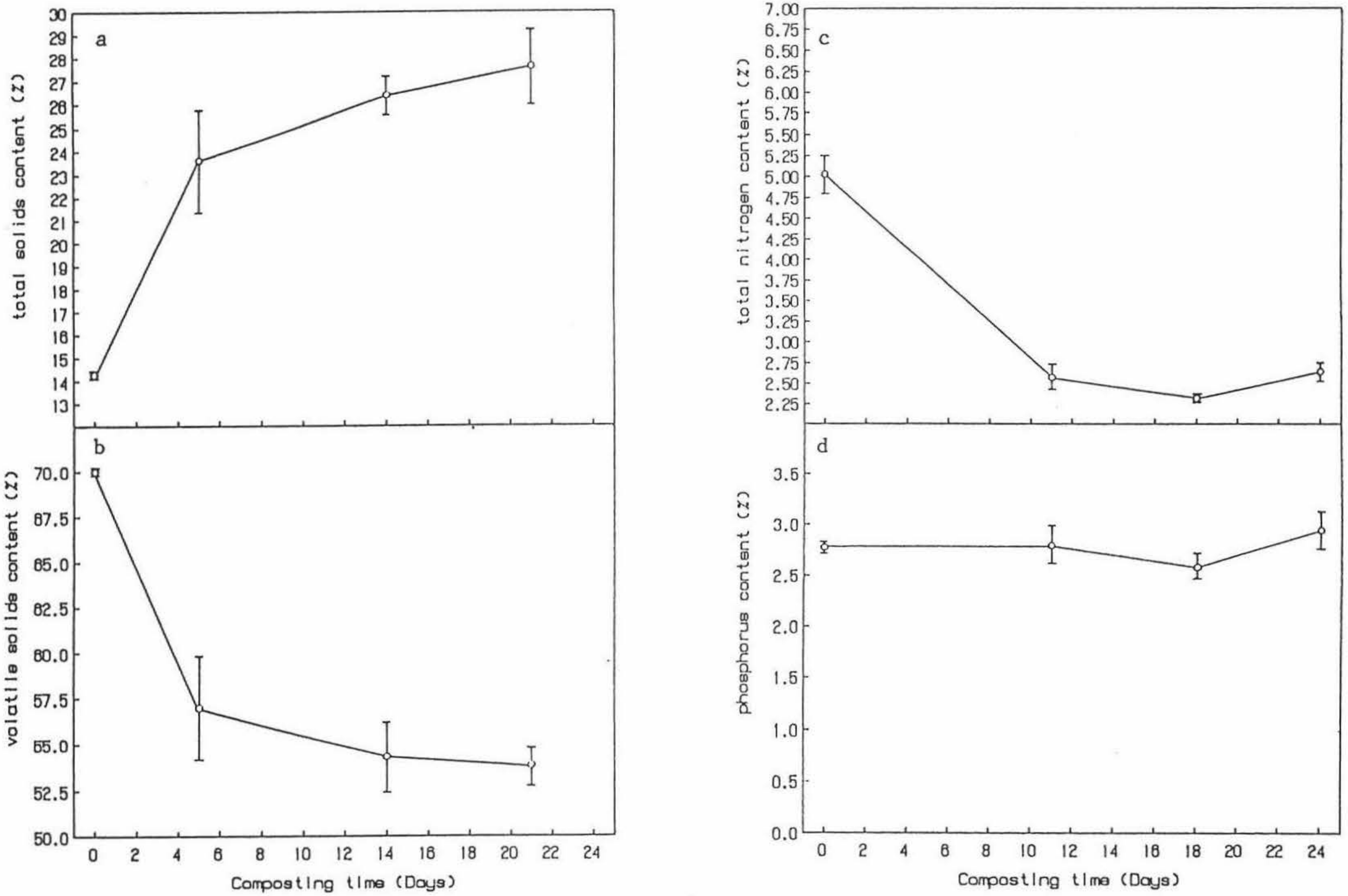


FIGURE 4.17: Changes in total solids (a), volatile solids (b) total nitrogen (c) and phosphorus (d) during composting in the third drum tumbler trial. (% VS, % N and % P are calculated on a dry matter basis at any time of composting).

Table 4.9 Microbial counts in raw dewatered activated sewage sludge and compost samples determined during the third drum tumbler trial. (Plate counts are mean values of duplicates).

Microorganism (Culture method)	Day 0 Sludge sample	Day 13 Compost sample	Day 24 Compost sample
Heterotrophic count (PCA, 37°C, 24-48h) CFU g^{-1} sample	1.97×10^8 3.34×10^8 3.05×10^8	2.38×10^9 2.08×10^9 1.57×10^9	7.0×10^8 8.38×10^8 7.41×10^8
Group D-streptococci (BEA, 37°C, 24-48h) CFU g^{-1} sample	3.57×10^5 3.09×10^5 3.41×10^5	1.52×10^6 1.43×10^6 2.24×10^6	8.01×10^5 1.18×10^6 NR
Total coliform bacteria (MPN, 37°C, 35-48h) Organisms per g sample	9.3×10^6 3.24×10^6 5.03×10^6	5.60×10^4 1.19×10^5 2.38×10^4	5.6×10^3 5.7×10^3 1.2×10^4

NR = No data available
CFU = Colony Forming Units
PCA = Plate Count Agar
BEA = Bile Esculin Azide Agar
MPN = Most Probable Number Method using MacConkey broth
(5 tubes inoculated of each of 5 successive 10-fold dilutions)

occurring slowly from the 24th day onwards. This pattern was different to the one described in the previous trial.

The coliform group diminished in numbers throughout operation. At least five thousand organisms per gram of sample from the mixture existed after 24 days of operation.

Table 4.10 F-values calculated for selected variables for all drum tumbler trials. (All values are significant at the 99% level).

Trial-no. (results in section)	Variables %TS	%VS	%N	%P
1 (4.3.2)	$F_{2,14} = 90.77$	$F_{2,14} = 27.80$	$F_{2,14} = 498.74$	$F_{2,14} = 7.62$
2 (4.3.3)	$F_{3,18} = 65.37$	$F_{3,18} = 84.85$	$F_{3,17} = 99.15$	$F_{3,17} = 9.11$
3 (4.3.4)	$F_{3,20} = 117.63$	$F_{3,19} = 121.45$	$F_{3,17} = 386.69$	$F_{3,17} = 5.97$

CHAPTER 5

DISCUSSION

5.1 INTRODUCTORY REMARKS

It should be noted, that the results in this work were obtained by analysing screened compost samples, i.e. compost samples from which the woodchips portion had been removed prior to the analysis. For this reason the comparison of absolute values from results of selected variables with those stated in literature was basically not possible. However, it was feasible to compare trends in the patterns of different variables with those described in previous work.

The results of all performed trials are discussed in two parts. In the first part the results obtained from the open system experiments are dealt with whilst in the second part those obtained using the compostumbler are discussed.

Several practical problems arose during the experimental stage of these studies. Their recognition and solution are important for further studies . In this chapter a special section deals with those aspects.

5.2 OPEN SYSTEMS

The studies on two open composting systems, the aerated windrow method and the aerated static pile method, showed their suitability to decompose aerobically the secondary activated sewage sludge.

Through the performance of these open composting trials it was possible to gain some experience in handling the raw materials and the knowledge of key process parameters was gained.

In the following sections, the studies including both systems and their results are discussed.

5.2.1 AERATED WINDROW COMPOSTING

5.2.1.1 General Observations

It was obvious that the mixing of the components, woodchips and secondary activated sewage sludge did not result in an optimal mixture in terms of homogeneity. This could be observed by the occurence of rather large lumps, reaching diameters of 5 cm. Similar findings by using unsuitable mixing devices have been described by Russel (1985). These characteristics lead to the development of black zones predominantly within clods of material originating from inner regions of the windrow. After breaking up these lumps, quite offensive smells were released from the material; a possible indication of mainly anaerobic conditions within these balls (Pereira-Neto et al., 1987a). Concerning the decomposition pattern, it was observed that both windrows were subjected to basically the same changes during composting including a reduction in VS, N, an increase in TS and a consistency in P.

5.2.1.2 Process Performance

Moisture Content

The moisture content of the mixture (75%) did not lie in the range of 60% which is reported to be optimal by several authors (Benedict et al., 1986; Biddlestone and Gray, 1985; Haug, 1980). Rather large amounts of woodchips were used to achieve a moisture content of 75%. This is due to the fact that undried woodchips (moisture content = 40%) were employed as bulking agent.

Willson (1983) has shown that, if the woodchips sludge mixture contains closely 60 % solids (=40 % moisture, while 60% moisture are mostly accepted to be optimal), and if the woodchips are assumed to weigh 300 kg / m^3 and to have a moisture content of about 40% (as in this case), a sludge containing 15% TS should be mixed with woodchips on a volumetric ratio of 1:3. Taking this and the results of this experiment into consideration (less bulk weight of woodchips, low percentage of solids in the mixture), the amount of woodchips used should have been even larger. On the other hand, drying of woodchips would have contributed to a reduction in their required amount to obtain a satisfactory composting mixture.

Biddlestone et al. (1986) conducted successful conventional windrow composting trials, using straw as a moisture regulating agent.

The addition of water during composting contributed to the mixture of becoming even more moist and had most likely a negative effect on the ongoing composting process.

Temperature

The temperature in the mixture never rose to values which are necessary to achieve material sanitization (Golueke, 1977). De Bertoldi et al. (1988) reported that several nations have individually established temperature standards for sanitization ranging from 55°C to 65°C covering a time-span ranging from 24 hours to three days. Pereira-Neto et al. (1987a) stated that a widely used minimum standard for sanitization is to maintain a temperature of 55°C for at least three days. A contributing factor to the development of low temperature was in the small dimensions of the windrows, allowing heat to be released from the material instead of accumulating in central regions of the composting windrows. Based on their work with solid meat waste, Keeley and Skipper (1988) reported that the windrow size has an effect on the rate of composting; with small piles prone to excessive heat loss. $80m^3$ to $120m^3$ was mentioned as being an optimal size for windrows or piles. These authors also stated that large piles tend to have pockets that do not receive oxygen and because of their size it is also more difficult to control the temperature in the rest of the pile. Since most of the water vaporization is driven by microbiologically generated heat (Finstein et al., 1986a; Miller and Finstein, 1985), the small amount of heat occurring in the composting material was not sufficient for a distinct water loss through evaporation. Stahlschmidt (1987) reported that due to size limitations in small scale experiments, the temperature did not rise over 45°C indicating that a lesser amount of produced heat than theoretically predicted has been used for evaporation, the rest was lost to the surroundings. He also mentioned that the produced heat in larger windrows can escape only or mainly as water vapour since the heat loss is much smaller. However, a sufficient air supply to transport the water vapour is required. In the experiment herein the moisture content was not optimal. More frequent turning of the windrow could have contributed to a greater loss of water through evaporation and thus, brought down the moisture content to a level supporting higher oxygen transfer and thus, microbial activity, since the relatively small windrows could not have contributed to a much higher heat generation. Frequent turning of windrows during the initial stage of composting was proposed in studies quoted by Haug (1980). The turning frequency depends mainly on the moisture content of the mixture in the ongoing operation.

Decomposition Activity

The increase in total solids (TS) and the decrease in the fraction of volatile solids (VS) during the period of this trial are in agreement with trends described by many authors (Haug, 1980; Golueke, 1977; Witter and Lopez-Real, 1987). The progress in volatile solids destruction clearly indicates the decomposition process. This relatively easy determinable variable has been proposed by other workers as a means of following the composting process, since aerobic biological activity decreases the volatile solids content by converting organic carbon to CO_2. Finstein et al. (1986b) stated that volatile solids are also widely used as a rough measure of organic matter content, whereas its measurement over time during processing might serve as rate parameter. Witter and Lopez-Real (1987) stated also that a reduction in volatile solids appears to be an accurate measure of dry solids losses during composting. Sensitivity , however, is one possible problem associated with the use of the VS-test in composting systems (Finstein et al., 1986b). The increase in total solids (moisture content decrease) as measured in all composting trials herein was also found to be indicative for the course of decomposition. Miller and Finstein (1985) stated that this is because the drying is caused by vaporization which in turn, as described previously, is driven mainly by heat generated at the expense of organic matter.

Nutrients

Total nitrogen (N) concentrations decreased during operation of this experiment. In composting, the nitrogenous content generally decreases during the course of the process, mainly because of nitrogen volatilization (Golueke, 1977; Haug, 1980). However, the reactions of nitrogen loss as well as the reactions of partial nitrogen recovery by fixation are very complex (Pereira-Neto et al., 1987b). De Bertoldi et al. (1982) stated that an optimal functioning of these complex reactions, which relate closely to the temperatures occurring in the material, could be achieved best in using combined temperature - feedback control and forced pressure aeration. However, in the work herein it was not intended to optimize these factors by special measures. Instead, a decrease in total nitrogen concentration was interpreted as an indication of firstly an ongoing composting activity in the mixture and secondly a low C/N - ratio (Biddlestone and Gray, 1985).

The content of the macronutrient phosphorus did not change appreciably and no conclusions about the mechanisms of the composting process were possible. However, the analytical data obtained may indicate the value of the compost in agricultural applications. The results of this trial suggest that the changes that occurred, and although significant, were probably due to losses of dry solids by volatilization (volatile solids). This leads to a slight relative increase in phosphorus, since its determination occurred on a dry solids basis. However, no literature reference could be found in which changes of phosphorus concentrations throughout the composting period were reported.

Rather large standard deviations were obtained in calculating each of the mean values of the variables described above. This obviously indicates the heterogeneous characteristics of the samples and the difficulty in screening out the woodchips material from the compost itself. Additionally, the decomposition process might not be independent of the position in the windrows as was assumed in this trial. On the other hand, it would not have made practical sense to test a position effect in such rather small compost windrows. Temperature variations throughout a compost pile have also been reported by Pereira-Neto et al. (1987a). Differences in oxygen concentrations within a compost pile, using leaves of different trees, were shown in a study mentioned by Finstein et al. (1986a). It can be assumed, that such differences lead to unequally distributed decomposition activities in a compost pile.

5.2.2 AERATED STATIC PILE COMPOSTING

5.2.2.1 General Observations

As described for the first trial above, the mixing of the components well was a problem. The occurrence of clods in the mixture to be piled-up for composting could not be avoided. Pereira-Neto et al. (1987a) also quoted research workers who had difficulties in obtaining a suitable structure of the compost mixture. These authors also stated that mixing is of importance for a successful composting process.

The physical appearance changed quite distinctly during processing. For example, the surface of the pile quickly became dry, while its central parts were still wet and lumpy. As mentioned previously, no insulating cover for the pile was employed in this experiment. The use of a cover material is usually applied in static pile composting (Haug, 1980). The application of such a cover may have prevented the outer zones of the pile from drying out.

After two and three days of composting, water vapour could be seen leaving the pile, indicating the ongoing heat generation. This appearance indicates the high temperature development in the pile, which ocurrs if no temperature feedback control is applied (Finstein et al., 1986a and 1986b; Haug, 1980). However, at this stage the otherwise quite offensive smell of the mass had largely disappeared.

A distinct dependance of all variables on position was detected by performing statistical analyses. These findings were in agreement with previous investigations (Pereira-Neto et al., 1987a; Stentiford, 1987). It was difficult to determine what reasons caused the position effect in the experiment herein. Although there existed quantitative and significant differences of changes in the variables throughout the pile, the tendencies of these changes were the same at all positions.

5.2.2.2 Process Performance

Moisture Content

The sludge to be composted had a TS content of 15 %. According to the findings of Willson (1983), the amount of woodchips used should have been larger to obtain the optimal mixture moisture content of 60%. However, despite a sub-optimal compost mixture composition a distinct composting activity in the pile could be observed.

Temperature

The temperature development patterns in the two measurement layers in the compost pile were similar. The upper regions of the pile (thermocouples 7 - 12) reached the highest temperatures after four days of operation ($70^{o}C$). An explanation for that could be the natural convective movement of heat in the pile. However, the development of such high temperatures is not desirable, in that it inhibits the microorganisms responsible for the decomposition in their metabolism, which consequently slows down the decomposition activity in the composting material (Golueke, 1977; Haug, 1980). From this point of view the rather fast decrease in temperature could have indicated the termination of the microbial activity in the pile. Optimal composting temperatures lie in the range between $55^{o}C$ and $60^{o}C$

(Biddlestone and Gray, 1985; Golueke, 1977; Haug, 1980; Pereira-Neto et al., 1987a). Without controlled aeration these values can hardly be reached and kept for the period recommended to achieve partial destruction of pathogens as well as to obtain a sufficiently stabilized end product (Finstein et al., 1987a-d).

The aeration at the beginning of the experiment was five minutes of aeration after every ten hours. This procedure should have provided enough aeration whilst not producing excessive cooling which would slow the temperature rise to the optimal thermophilic range. However, the temperature pattern observed in this experiment is quite typical of composting systems, whose aeration, although sufficient to reach high temperatures, is not feedback controlled (MacGregor et al., 1981; Finstein et al., 1986a and 1986b). Insulation of the pile most likely would have kept the heat for a longer period in the material (Donovan, 1985; Benedict et al., 1986; Pereira-Neto et al., 1987a).

Decomposition Activity

Looking at the results obtained from TS analysis, a distinct higher drying capacity was observed in this experiment, compared with the aerated windrow trial. The vaporization, which caused the loss of moisture was driven by the heat, generated at the expense of the material. The overall pattern in the change of TS over time, i.e. increasing total solids, was distinct and in agreement with typical changes occuring in composting systems.

The decomposition activity again was clearly recognisable in terms of the extensive reduction in volatile solids. From the stabilization point of view (excluding the degree of disinfection), a compost exhibiting a VS reduction of 50% (as observed in this trial), may be used as soil conditioner, since a complete stabilization is not desirable because the value of compost as a soil amendment depends in part on its organic content (Haug, 1980). Much controversy in literature can be found concerning the topic of the assessment of maturity or stabilization degree of compost (Penninck and Verdonck, 1987; Witter and Lopez-Real, 1987; Zucconi and De Bertoldi, 1987). A universal method for maturity determination of compost has not yet been developed (Mooijman and Lustenhouwer, 1987).

The degree of VS loss in this experiment is in agreement with values described in other work (Finstein et al., 1986b; Haug, 1980). Studies stating the usefulness of the VS test to monitor composting performance have been mentioned above.

Nutrients

Up to half the amount of total nitrogen was lost during composting. Due to the high total nitrogen content of sewage sludge and the relative small amount of woodchips used, the mixture employed in this experiment had a rather low C/N ratio. This could have caused extensive nitrogen losses observed as well by ammonia vapours surrounding the facility site. Similar patterns have been described by Biddlestone and Gray (1985) and by Pereira-Neto et al. (1987b).

As noted earlier, the pattern of phosphorus change was most likely due to volatilization of solids during composting. However, it is difficult to explain why in some samples the phosphorus concentration decreased slightly. Further investigation using more sensitive sampling and assay techniques may produce better information concerning total phosphorus changes during composting.

5.3 DRUM TUMBLER COMPOSTING

The experimental design employed to perform these investigations was basically the same as that used in the three previous trials. The experiments are discussed collectively in terms of the different variables.

As mentioned earlier in the discussion on open systems, mixing of the components was a major problem. Clods occurring in the material could not be broken up effectively because of the cohesiveness of the mixture. The formation of balls was also observed in a study by Russell (1985).

The physical appearance of the material during operation was influenced by the development of water vapour through heat generation. In trials two and three the initial offensive smell was replaced by an earthy odour towards the end of the process, indicating a successfull decomposition process (Golueke, 1972 and 1977). On the contrary, trial one did not cease to release offensive odours, clearly showing the unfavourable conditions occurring in the mixture to be composted. However, in all three trials typical decomposition phenomena could be monitored.

5.3.1 PROCESS PERFORMANCE

5.3.1.1 Moisture Content

Clearly, the mixture composition in the first experiment was not chosen properly, indicating that a higher amount of woodchips should have been added to the mixture. The largest part of the limited volume in the compostumbler is usually filled with the bulking agent. To supply enough energy in form of sludge for microbial metabolism and because bulking agent cannot be considered as energy source (Golueke and Diaz, 1987), excess sludge was added to the drum. However, it was also intended to follow the progress of composting in a high moisture mixture, using a drum tumbler system. The resulting initial moisture content of 80% contributed to a sticky and wet mixture. The lack of adequate air space in the drum was most likely the reason for the failure of this experiment with regard to achieving successful composting free from offensive odours (Haug, 1980).

The second and third trials had an initial moisture content of 64% and 63%, respectively, lying quite close to values generally accepted as an optimal value to achieve satisfactory composting, i.e. 60% (Golueke, 1972). The observed characteristics of the decomposition process occuring in both trials supported the view that an optimal moisture content existed. The opening of the drum cover was successful in preventing the steam from condensating along the drum's inner wall. Since an important aim of composting is the drying of the material, the avoidance of condensation inside the bin through adequate ventilation is necessary.

The use of dry woodchips made it possible to reduce the quantity required per unit mass of fresh sludge so as to obtain the required moisture content in the mixture. Compared with quantities used in the open systems, this was important in that tumbling could be used where there was only limited space available for composting.

5.3.1.2 Temperature

The temperature development pattern observed in the composting material during all three experiments was typical for composting systems. High temperatures of 70^{o}C in the third trial indicated substantial and ongoing microbial activity. In most closed reactor systems, however, forced pressure aeration is employed in a controlled manner (Anonymous, 1986). This prevents temperatures from rising to inhibitory levels, such as occurred in this experiment. Unfortunately, the system used in the present study lacked this facility. Higher decomposition rates could be expected with better aeration and aeration control. No clear indications however, could be found as to why during the second trial temperatures did not rise to higher values, thus leading to mesophilic composting, although frequent mixing at early stages could have caused this effect.

5.3.1.3 Decomposition Activity

Moisture losses in the third experiment were found to be greater than those monitored in the other trials. Better moisture control through the timed release of excessive water vapours from the system. Taking into consideration the lack of a proper aeration system, the drying activities achieved in the second and third drum tumbler experiment were quite satisfactory when compared with results obtained by other workers (Miller and Finstein, 1985).

The progress of decomposition, shown by the VS reduction was a further indication, that in the first trial appreciable amounts of organic matter were not metabolized (see large standard deviations in Table 4.4 at day 15). Extending the duration of this trial would have further reduced the amount of volatile solids, although at a much slower rate, since the conditions in the material were mainly anaerobic. Trials two and three on the other hand resulted in VS reductions similar to values found by other workers. In their work at New Jersey, Miller and Finstein (1985) observed a sludge volatile solids reduction of 56.9% in 13 days with a well tested composting system. This suggests that the compostumbler used in this study could achieve higher sludge stabilization if it is improved in terms of aeration and material mixing.

The decreasing concentration with time of the total carbon content in the compost samples of trials two and three paralleled changes in the volatile solids content (Pereira-Neto et al., 1987b). These measured variables, when tested for correlating properties, were linearly related with a correlation coefficient of r = 0.97 for the second trial (only three total carbon values were available in trial three and no correlation was therefore performed). This result is in agreement with the findings of Witter and Lopez-Real (1987). These authors suggested that since the volatile solids content is generally easier to determine than total carbon, it then may be used as a measure to estimate composting performance.

5.3.1.4 Nutrients

Changes in total nitrogen observed in all trials were typical with regard to sewage sludge composting. Since sewage sludge contains high nitrogen concentrations a usually low carbon to nitrogen (C/N) ratio results with values below 10 (Zucconi and De Bertoldi, 1987). In these studies initial C/N ratios between 4.8 and 5.6 were observed. Haug (1980) calculated a value of 6 for activated sewage sludge. However, towards the end of the operation a slight increase in the C/N ratio to values between 6 and 8 were detected. Increasing C/N values in cases of sewage sludge composting were also reported by Zucconi and De Bertoldi (1987).

The total nitrogen loss in trial three was higher than in trials one and two. Sikora and Sowers (1985) noted that high temperatures in composting may cause substantial losses of ammonia (NH_3) by volatilization, thus leading to reduction in total nitrogen. The extent of nitrogen loss is affected, among other factors, by tempearture.

Change of phosphorus concentration in the mixture during composting was, as stated above, not appreciable (refer also to sections 5.2.1.2 and 5.2.2.2).

5.3.1.5. pH - Value

Measured pH - values of dewatered activated sewage sludge samples were consistent throughout the study (pH 6.1 to 6.3) and in agreement with values in literature (Haug, 1980). No reduction in pH was registered at the initial stage of the composting process. However, initial decreases in pH have been reported in studies quoted by Pereira-Neto et al. (1987b). Acid formation is the consequence of microbial degradation of complex carbonaceous materials to organic acids and other end products. These substances will cause the pH to drop. With good aeration the products so formed are metabolized readily to CO_2 and H_2O. A poor aeration supports the protein degradation reactions which release basic compounds such as amonia and amines thereby increasing the pH. In all trials herein, the pH showed an increase during the initial stage of the operation after which another slight decrease followed. In the third trial the pH turned alkaline, as ammonia was liberated during the breakdown of proteins (Biddlestone and Gray, 1985). A slight decrease in pH to values between 7.5 and 7.8 occurred at the end of this experiment.

5.3.1.6 Bacteriology

Strauch (1987) stated that it is still uncertain which groups of bacteria are suitable for use as reliable indicators of the presence of other pathogenic bacteria. The same author, however, concluded that enterobacteriaceae and faecal streptococci seem to be suitable to a certain extent. De Bertoldi et al. (1988) noted that beside faecal streptococci and enterobacteriaceae also total coliforms, certain viruses and parasitic ova can serve as satisfactorily reliable indicators. These authors also mention that at present (1988) there is no general agreement about the degree of reduction of pathogenic microorganisms that should be attained.

Comparing data obtained from microbiological tests of initial sludge samples in all three drum tumbler trials, it was found that the numbers of faecal streptococci and of total coliform bacteria were similar to numbers found by Strauch (1987). De Bertoldi et al. (1982) have presented numbers of faecal streptococci which are close to those found in these experiments. Sikora and Sowers (1985) presented results of total bacterial counts in the initial compost mixture. These values were slightly lower than those of the initial total heterotrophic counts of the raw sludge in this study. Analyses of the initial sludge and of the compost samples during the second experiment indicated that a greater heterotrophic microbial population was present in the final compost than in the initial samples suggesting that re-growth of bacteria had occured. The detection of thermophilic organisms (incubated at 50^{o}C) also suggested an increase in counts of approximately two log cycles. Sikora and Sowers (1985) have shown a similar pattern of thermophilic microorganism development in their study. In the last trial, no counts in heterotrophic thermophilic bacteria could be performed. A confounding problem in counting these organisms was their tendency to spread over the entire plate within a few hours of incubation. Despite the use of higher agar concentrations in the media used for plates, the counting of thermophilic colonies was often impossible.

Enteric streptococci could not be detected in the stabilized compost of the second trial, whereas in the third trial, with an initial count the same as that of trials one and two, a similar die-off in these microorganisms was not observed. To confirm these results, a second analysis in counts for D-streptococci in the second experiment was performed, showing again the inactivation of these bacteria. In a study by De Bertoldi et al. (1982) a strong, but not complete reduction in numbers of faecal streptococci was observed. However, these workers have used three different windrow composting systems. Destruction of pathogens was most extensive with the static pile system. A plausible explanation for the reduction of the enteric streptococci in the second trial is that mesophilic temperatures in the second trial prevailed sufficiently long to completely reduce the enteric streptococci. As stated previously , such results emphasize the importance of adequate time - temperature processing conditions which are also necessary in composting (a requirement in most other sanitation processes of biological materials) to achieve successful sanitation of the final product (De Bertoldi et al., 1988; Strauch, 1987).

The more sensitive characteristics of the coliform group may have been the cause for their clear reduction throughout processing in the third experiment.

An examination of data from both trials two and three indicated that a considerable number of indicator microorganisms remained in the product after composting. Survival of these bacteria would suggest, that in terms of other enteric pathogens, such as salmonellae and shigellae, the compost obtained in the drum tumbler trials retained a degree of microbial hazard (Strauch, 1987).

5.4 PRACTICAL PROBLEMS

The mixing of woodchips and sludge is an important and crucial aspect of the composting process. It is necessary to obtain a uniform, homogeneous mix without the formation of clods and balls. Studies have shown that pugmills and mixing boxes achieved an acceptable uniformity in the mixture (Epstein et al., 1983). During the entire study as described herein, efficient mixing of woodchips with sewage sludge was a serious problem. It was difficult to obtain homogeneous samples from the mixture which resulted from using the compostumbler. The formation of lumps and balls in the tumbler lead to the conclusion that for further research better mixing equipment is required if satisfactory and reliable experimental data are to be obtained. Suitable mixing equipment could further help produce a mixture with improved characteristics for the uptake of air which would prevent the mass from becoming anaerobic and hence offensive. A more homogeneous mixture would also facilitate the task of sampling, sample pre-treatment and analysis. Better mixing and the maintenance of aerobic conditions would overcome the totally objectionable experience of screening out woodchips pieces of varying shapes and sizes from sludge which was often wet, lumpy, strongly anaerobic and accompanied by offensive odours. Another problem associated with the heterogeneity of the mixture was that the screening procedure most often was not completely successful. Frequently, remaining in the compost were chips of varying sizes and quantities. Such residues do not contribute to the reproducibility of results in the analysis of the samples.

Although the sampling technique applied in this trial appeared to be useful only to a limited extent, further work must concentrate on developing better sampling procedures. The latter should allow, for example, the removal of sample material from the inner regions of an aerated static pile system without putting the experimentor particularly during the initial stages into risky situations of coming into contact with the offensive nature of the material.

The tumbled system used in this system was generally not satisfactory for sewage sludge composting. Manually turning a bin almost completely filled with heavy composting material is physically demanding on the researcher. Reliable mechanized systems are needed. Ongoing development of the tumbled (closed) bin system is therefore required before it can be recommended as an appropriate low level technology for pilot scale composting of dewatered activated sewage sludge.

CHAPTER 6

CONCLUSIONS

Basic experimental procedures for the composting operation of dewaterd activated sewage sludge were set up.

The usefulness of both open and closed systems for composting was demonstrated by the following results:

- Their ability to biodegrade high levels of organic matter. This was shown in terms of a 30% to 50% loss of volatile solids fraction from the sludge fraction of the composting mixture and also by the reduction in total carbon by 26% to 42%.
- Biological drying of the composting materials was indicated by an increase in total solids contents in the final sludge portion of the compost mixture to values between 21% and 27%.

Total nitrogen analyses have indicated, that nitrogeneous material was lost in large amounts, amounting to 50% of its initial concentration.

The results of phosphorus analyses showed high values of phosphorus concentrations which did not appreciably change throughout processing.

High degradability of the sludge fraction in the composting mixture was observed with moisture contents near 60%, which is in agreement with accepted optimal mixture moisture values found in literature.

Coliform bacteria and faecal streptococci could be detected at the end of two out of three closed bin trials. During a third bin trial, a complete inactivation of faecal streptococci was observed. However, complete destruction of enteric pathogens may not have occured using the compostumbler.

Heterotrophic counts were increasing during composting, indicating that the growth of bacteria accompanied the degradation processes.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE WORK

The results of these laboratory scale investigations can be used for the development of more detailed composting trials, perhaps example on a larger scale. The practical methodologies applied in this study require improvements by conducting further research. Further studies should involve the use of other parameters mentioned in literature. Such parameters include physical characterizations of the compost, organo-chemical parameters and the determination of the ATP-content as a quantitative measure of microbiological life and activity. If sludge from industrial environments is used for composting, then the concentrations of heavy metals in the sludge such as Cd, As, Pb, Cr etc. should also be monitored.

Ongoing development of the closed bin system is required before it can be recommended as an equipment to conduct further research in sewage sludge composting. Such work should also make use of available and economical methods to control the aeration of the composting material (e.g temperature - feedback control). These methods have shown to support a rapid breakdown of organic matter and also to ensure substantial reductions of indicator microorganisms. Predrying of woodchips would minimize the quantity of bulking agent necessary to achieve the required moisture content of the composting mixture.

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APPENDIX

EXPERIMENTAL DATA

Table A.1 Replicate contents of total solids (%TS) and volatile solids (%VS) originating from both windrows in the aerated windrow trial. (%VS is calculated on a dry weight basis).

	%TS		%VS	
Time (Days)	Windrow A	Windrow B	Windrow A	Windrow B
0	17.28		67.93	
	17.01		68.70	
	17.05		68.71	
	17.56		67.00	
	17.68		66.63	
	17.74		68.00	
7	17.44	16.40	61.36	59.90
	17.94	17.83	60.10	62.35
	17.03	16.46	63.25	69.09
	20.48	18.00	67.63	66.46
	19.77	20.26	68.18	67.80
	17.77	19.90	67.13	65.28
17	18.34	18.20	60.00	63.00
	19.15	20.13	58.74	62.41
	21.14	19.44	66.39	58.40
	18.90	18.83	59.61	61.32
	20.02	17.36	63.31	61.18
	17.86	18.81	66.33	61.89
26	21.11	21.84	59.42	61.86
	23.90	18.95	59.78	65.82
	19.91	19.00	62.09	62.47
	21.12	19.84	60.92	59.98
	20.27	20.74	60.22	59.62
	21.33	23.63	58.95	61.41

Table A.2 Replicate contents of total nitrogen (%N) and phosphorus (%P) throughout the aerated windrow trial. (Results are calculated on a dry weight basis. ND: no data available).

	Windrow A				Windrow B			
Time (Days)	%N		%P		%N		%P	
7	3.95	ND	2.375	ND	4.14	ND	2.284	ND
	4.38	ND	2.410	ND	4.81	ND	2.110	ND
	5.03	ND	2.579	ND	4.77	ND	2.667	ND
	4.89	ND	2.629	ND	4.37	ND	2.550	ND
	4.27	ND	ND	ND	ND	ND	2.605	ND
17	3.98	3.85	2.800	2.653	3.50	3.72	2.758	2.879
	3.54	3.53	2.617	2.505	4.01	3.81	2.826	2.621
	3.79	3.83	2.607	2.428	3.85	3.92	2.637	2.800
	4.15	4.28	2669	2.793	3.88	4.09	2.742	2.788
	4.48	4.36	2.863	2.868	ND	ND	ND	ND
	5.12	4.72	3.070	2.927	ND	ND	ND	ND
26	3.51	3.67	2.632	2.657	4.20	3.65	2.799	2.548
	4.06	4.07	2.895	2.923	3.80	3.48	3.144	2.765
	3.56	3.79	2.649	2.931	3.97	4.05	2.771	2.899
	4.21	4.01	2.775	2.688	3.65	3.58	2.535	2.829
	4.34	4.21	2.962	2.808	3.67	3.85	2.660	2.759
	3.56	3.53	2.575	2.686	3.70	3.59	2.639	2.539

Table A.3 Duplicate contents of selected variables collected at different positions throughout the aerated static pile trial. (%TS: Total solids; %VS: Volatile solids; %N: Total nitrogen and %P: Phosphorus. ND: no data available).

		Position in Compostpile											
Time (Days)	Variables	1		2		3		4		5		6	
0	%TS	14.07	14.15	13.85	13.87	14.43	14.22	13.89	13.85	14.52	14.23	13.77	13.59
	%VS	72.32	72.41	71.99	71.97	72.05	72.23	71.99	72.14	72.09	72.26	72.33	72.06
	%N	5.80	6.27	6.09	6.21	6.03	6.36	5.78	5.98	5.81	6.04	6.02	6.06
	%P	2.88	2.872	2.991	2.890	2.904	3.014	2.789	2.838	2.742	2.882	2.942	2.896
9	%TS	18.79	18.34	18.77	19.69	18.78	19.61	20.32	ND	20.42	18.13	21.9	ND
	%VS	64.40	62.69	63.37	63.57	62.18	62.78	65.90	ND	67.66	63.29	66.46	ND
	%N	2.89	3.14	3.94	3.37	2.94	2.88	3.31	3.31	3.06	2.69	3.14	3.13
	%P	2.509	2.588	2.745	2.799	2.309	2.322	2.610	2.355	2.523	2.425	2.122	2.095
16	%TS	17.29	17.02	19.26	18.29	20.22	20.41	19.74	ND	18.91	ND	20.78	21.27
	%VS	60.26	59.50	60.02	59.67	62.11	59.40	61.61	ND	57.77	ND	61.18	61.0
	%N	3.15	3.26	3.81	3.84	2.93	2.86	3.15	ND	2.80	2.61	2.95	2.78
	%P	3.087	2.910	2.922	3.083	2.813	2.848	2.428	ND	2.478	2.145	2.378	2.271
23	%TS	18.11	17.37	19.38	20.19	20.64	20.06	19.57	ND	17.87	20.41	21.48	22.05
	%VS	58.76	57.18	56.16	59.45	61.24	60.37	58.37	ND	59.65	62.68	58.33	62.99
	%N	3.48	3.14	3.18	3.38	3.21	ND	2.95	ND	2.46	2.76	3.41	3.40
	%P	3.317	3.035	2.98	3.094	3.26	ND	2.632	ND	2.589	2.837	2.558	2.319

Table A.4 Replicate contents of selected variables throughout the first drum tumbler trial.

(Variables as indicated in Table A.3 ND: no data available).

Time	Variables			
(Days)	%TS	%VS	%N	%P
0	14.34	75.32	6.11	2.649
	17.73	75.47	6.37	2.715
	14.74	75.30	6.30	2.751
	15.04	75.44	6.18	2.652
	15.02	75.50	6.09	2.704
	15.36	76.33	6.32	2.719
7	17.97	63.19	4.06	3.076
	17.88	65.87	3.85	2.785
	16.45	65.68	3.98	2.716
	17.40	65.64	4.17	2.860
	17.10	66.61	4.13	2.724
	ND	ND	4.12	2.853
15	19.90	62.11	4.03	2.756
	20.34	66.10	3.80	2.280
	20.10	69.39	3.53	2.610
	19.90	61.31	3.95	2.459
	19.24	65.35	3.81	2.580
	22.06	55.26	ND	

Table A.5 Replicate contents of selected variables throughout the second drum tumbler trial.

(Variables as indicated in Table A.3; ND: no data available).

Time	Variables			
(Days)	%TS	%VS	%N	%P
0	12.22 12.18 12.24 12.36 12.12 ND	72.69 72.92 72.90 72.88 72.77 ND	6.07 6.32 5.88 6.10 ND ND	2.933 3.061 2.898 3.100 ND ND
8	20.41 20.52 18.73 19.67 19.50 ND	63.11 62.58 65.23 64.92 63.82 ND	4.50 4.75 4.58 4.46 4.69 4.62	2.753 2.916 2.776 2.705 2.812 2.703
15	21.11 20.46 20.46 20.96 19.17 21.43	60.93 63.85 62.55 61.23 63.94 60.54	4.30 4.19 3.85 4.55 4.25 4.22	2.839 2.738 2.758 3.019 3.046 2.848
22	23.45 21.18 26.93 22.56 20.74 21.86	59.25 61.16 57.64 59.24 62.84 61.57	4.14 3.33 3.83 3.66 3.82 ND	3.161 3.446 2.929 3.164 3.127 ND

Table A.6 Replicate contents of selected variables throughout the third drum tumbler trial.

(Variables as indicated in Table A.3 ND: no data available).

Time	Variables			
(Days)	$\%TS_a$	$\%VS_a$	$\%N_b$	$\%P_b$
0	13.93	70.15	4.85	2.820
	14.10	69.94	5.00	2.768
	14.04	69.94	5.29	2.713
	14.32	70.08	5.24	2.831
	14.29	70.13	4.79	2.750
	14.47	70.00	ND	ND
5^a 11^b	25.63	53.89	2.69	2.974
	25.20	55.89	2.55	2.729
	24.15	55.49	2.75	2.995
	20.19	60.73	2.36	2.576
	22.80	59.07	2.56	2.768
	ND	ND	ND	ND
14^a 18^b	25.60	54.81	2.33	2.651
	26.39	52.96	2.35	2.692
	27.81	52.31	2.33	2.625
	26.05	54.49	2.29	2.407
	25.72	57.63	ND	ND
	ND	ND	2.30	2.616
	26.74	53.70	ND	ND
21^a 24^b	22.80	54.58	2.45	2.683
	29.43	52.60	2.70	2.845
	26.92	53.60	2.73	3.151
	26.35	53.53	2.69	2.919
	28.87	52.94	2.73	3.087
	29.60	55.41	2.59	3.066