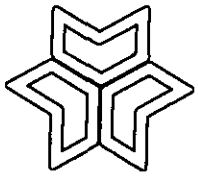

Environmental Engineering

Technical Report

Correlation Between Traditional Stability Parameters
of Compost To Turfgrass Toxicity Effects
July, 1995

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R&D# 91-08

by

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Commonwealth of Massachusetts
Department of Environmental Protection
David B. Struhs, Commissioner

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Arlene O'Donnell, Assistant Commissioner

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Abstract

Samples from two different sludge composting systems (an in-vessel system and an aerated static pile) were studied throughout the first 20-30 days of the process. Determination of stability parameters and phytotoxic effects on seeds and established turfgrass was performed. Traditional stability parameters measured included: water extract analyses, as C/N ratio, total organic carbon, ammonia; pH, temperature, total and volatile solids, oxygen uptake rate; and pathogen indicator densities and regrowth potential. Overall, these parameters showed final compost from these systems can not be considered stable after the first stage of the process. Sampling methodology was found to be very important in obtaining representative samples. Seedling studies tested effects of compost on different parameters including delay in germination, growth yield, percentage of germination, and percentage of ground cover. These studies showed that compost from both systems produced toxic effects on seeds, but severity of phytotoxicity was correlated with neither the compost age nor the type of composting system. Different sensitiveness to compost's effects were observed in the species tested, as tall fescue was significantly less affected, followed by creeping bentgrass seeds. Phytotoxicity on kentucky bluegrass seeds was significantly more severe than the others species. The established turfgrass study consisted of the application of final in-vessel compost on an established golf course (kentucky bluegrass). Results confirmed similar observations by Schumann *et al.*(42) finding no phytotoxic effects at an application rate of 200 lb/1000 ft^2. In addition, we observed that compost application as high as 500 lb/1000ft^2 also showed no phytotoxicity and in fact had a positive effect on turfgrass quality (determined as growth, and color). Further studies are suggested since the traditional stability parameters may not be able to predict actual effects of sludge compost on established turfgrass. This is of significant importance since the turfgrass industry is an important potential market for sludge compost.

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Table of Abbreviations

ASP	Aerated static pile system
BOD	Biological oxygen demand
CFR	Code of Federal Regulations
MPN	Most probably number
PFRP	Process to further reduce pathogens
RCRA	Resource Conservation Recovery Act
TC	Total carbon (in solid phase)
TOC	Total organic carbon (in water extract)
TS	Total solids
USEPA	United States Environmental Protection Agency
VS	Volatile solids
WE	Water extract
cbg	creeping bent grass
kbg	kentucky blue grass
tf	tall fescue
r	Pearson's correlation coefficient
R	Linear regression coefficient (least square method)
α	error (Duncan's multiple test of variables)
cm	centimeter
cy	cubic yard

dt	dry ton
ds	dry solids
ft	feet
g	grams
ha	hectare
hr	hour
kg	kilogram
lbs	pounds
m	meter
ml	mililiter
nm	nanometer
µm	micrometer
w	week
wt	wet ton
yr	year

1. Introduction

1.1 Purpose of Study

Over the past 20 years, U.S. legislative actions have imposed strict limits on the disposal of organic wastes, such as sewage sludge, due to potentially severe environmental problems associated with the management of such residuals(44). At present, there are a variety of sewage sludge treatment processes that have been developed to solve such problems. However, among the list of sludge managment technologies, disposal processes may no longer be considered the best option. In contrast, processes that allow the recovery of resources are more environmentally sound, cost effective, and are ranked higher in the USEPA hierarchy of waste minimization practices.

Composting is one of the leading beneficial sludge treatment alternatives in the U.S.. At the present, composting contributes to the solution of the problem of safe sludge disposal, and at the same time produces a recycled product with a high marketing potential: sludge compost. Sludge compost also known as biosolids compost, is a biologically stable and aesthetically pleasant product, free of odors and highly suitable for horticultural uses and land reclamation because of its soil conditioner characteristics(25).

In order for any composting facility to be sucessful, the product compost must be marketed. The compost may be either given away or sold, but the compost must be of good quality on a consistent basis. Regulations exist for quality in terms of heavy metals, pathogen indicators, and vector attraction. Another important parameter is compost stability or maturity. Although no regulations are set for stability or maturity, both are very important parameters for product quality.

Many efforts have been made in order to find a parameter that could predict product quality, and could be used as an engineering parameter for process control. Several stability parameters have been proposed for such purposes. However, there is no consensus on which of these is the most reliable. When compost is used on plant systems, stability parameters must predict phytotoxicity. In the seach for the optimal parameter, one of the main questions is, what level of stabilization is required for a specific compost to assure no phytotoxic effect on a particular plant system. Once the level of stabilization is determined, it is neccesary to define which are the best stability parameters that will predict such effects and could be used in process control.

A similar approach was followed in the present study. A plant system identified as a potential market for compost(turfgrass), was chosen to determine its response to sludge compost and to determine the optimal stability parameters. The present study intended to continue a previous study by Schumann *et al.*[42], in which positive effects of sludge compost were observed on established turfgrass. The particular purpose of the present work, was to confirm those results and extend the study to turfgrass seeds. The main idea was to determine the required stability level for sludge compost that assures no phytotoxic effects in turfgrass and determine the stability parameters that can predict such effects.

1.2 Objectives

1.2.1 Main objective

The main objective of this research was to determine if there is a correlation between traditonal stability parameters and phytotoxic effects of sludge compost on turfgrass. In order to accomplish this objective the following specific objectives are stated:

1.2.2 Specific objectives

1.1 To determine the stability of compost at different composting ages.

1.2 To determine the effects of compost on different turfgrass species at two different growth stages.

1.3 To determine which of the traditional stability parameters predicts the phytotoxic effects of compost when used on turfgrasses with more reliability.

2. Background

2.1 Municipal Sewage Sludge

Of the constituents removed by wastewater treatment, sludge is by far the largest in volume, and its management the most complex problem facing the engineer in the field of wastewater treatment[37]. At present, the EPA estimates there are 20,000 dry tons of sludge being generated every day in the U.S. It is also estimated that sludge production will approximately double by the year 2000[11].

Enormous quantities of sludge started being produced in the last two decades as a consequence of several factors. In 1972, the establishment of secondary treatment standards by the Clean Water Act promoted the construction of wastewater treatment plants which greatly increased the volume of sludge generation[50]. Since then, other changes have occurred, contributing to the increase in sludge production including: the expansion of sewage service areas, stricter effluent standards, and the upgrading of treatment plants for combined storm overflow treatment. Concurrently, population has been increasing at the same time[11,44].

Since sludge management is an important issue, numerous disposal alternatives have been developed over the last decades. These alternatives comprise a wide range of processes, as well as different levels of technology. The use of some of these technologies changed over the past years. Some have gained acceptance while others have been

constrained. Technologies considered appropriate in the past, may no longer be viable now. Changes in regulations have been the main reason for such changes. New regulations are strict due to the potentially severe environmental problems associated with the management of such residuals(44). Recent regulations discourage certain sludge management practices and promote others.

A good example of a technology no longer considered as a viable sludge management practice, is ocean dumping. Years ago, this practice was one of the principle sludge disposal alternatives for large metropolitan areas such as Boston, New York, New Jersey, and Los Angeles(9). However, after many years of discussion, the U.S. Congress finally banned ocean dumping as of December 31, 1991(18).

Incineration of municipal sewage sludge, although still practiced in the US has been constrained over the recent past. The EPA risk assessment model showed the highest potential health concerns with this practice. Incineration standards are strict, with pollutant limits for heavy metals, operation, and management practices(11). In order to comply with strict regulations, improvements in technology and operation have been made, with increases the associated costs.

Landfill disposal has also been de-emphasized. In fact, it is now considered the least desirable waste disposal alternative. Older landfills are closing or expected to close due to the recently promulgated RCRA regulations (40 CFR part 258)(10). This rule, has also led to an anticipated shortage of available landfills, decreasing space, and higher landfilling costs. Municipalities landfilling their biosolids are finding that it is simply too costly to haul biosolids to more distant landfills, even if the tipping fee is competitive(9).

Besides the strict new regulations, there is another important factor that has modified the use of some sludge management technologies: the idea of considering municipal sewage sludge as a valuable resource(beneficial use)and not as a waste(33). This concept has been growing in popularity recently. It is widely recognized, that the current trend for sludge disposal is now toward disposal alternatives that allow a beneficial use of sludge(11,18,44). Moreover, current EPA policy "actively promotes municipal sludge management practices which provide for the beneficial use of sludge while maintaining or improving environmental quality and protecting public health"(48).

A beneficial use of sludge can be defined as those disposal processes that take advantage of either it's nutrient, soil conditioner and/or fuel properties. Among the most common systems which promote the beneficial use of sludge are: chemical fixation, land application, composting, incineration and heat drying. The trend toward beneficial use of sludge is being lead by three technologies that each manufacture a unique product for land application. They are composting, heat drying, and alkaline stabilization(9,11).

2.2 Beneficial Use of Sludge Treatment Alternatives.

2.2.1 Thermal drying

Heat drying of sludge is not a new practice in the United States. The Milwaukee Metropolitan Sewage District has been marketing Milorganite (a heat dried sludge product) since the 1920's. Thermal drying of sludge involves the application of heat to evaporate water from sludge. The process reduces the moisture content of wet sludge to a level below that achievable by conventional mechanical dewatering methods. The relative advantages include the reduction of transportation costs, further pathogen reduction, and, improved storage capability and marketability(50). This process if properly conducted, can be considered as a "process to further reduce pathogens"(48). In addition, considerable volume reduction can be achieved.

A common variation of heat drying is the pelletizing process in which sludge is first dewatered and then heat-dried using rotary pelletizing dryers. Pellets are easy to store, handle and are compatible with fertilizer application equipment.

Heat-dried sludge products usually contain 4 to 6 percent nitrogen, with a high percentage of solids (greater than 98% solids), and may be dusty if they are not properly pelletized. Traditionally, most of the Milorganite and heat dried sludge products are sold to the national fertilizer market, primarily to fertilizer blenders in the southeastern US(9).

2.2.2 *Chemical fixation*

The chemical fixation/solidification process has been applied to the treatment of industrial sludge and hazardous wastes to immobilize undesirable constituents. However, this process has also been used to stabilize municipal sludge for use as landfill cover and for land reclamation projects. The chemical fixation process consists of mixing untreated or treated liquid or dewatered sludge with stabilizing agents such as cement, cement kiln dust, pozzolan (fine-grain silicate) and lime so as to chemically react with or encapsulate the sludge(37).

Lime is the most commonly used chemical for sludge stabilization, also called alkaline stabilization. This process depends on maintaining the pH at a high enough level for a sufficient period of time to pasteurize sludge. To qualify as a process to further reduce pathogens (PFRP), and to inactivate odor-causing microorganisms, the pH of the sludge must be maintained at or above 12 for a period of two hours(50). The elevation of the pH is accomplished using one of several chemicals containing lime. These include calcium oxide, and calcium hydroxide. There are several variations of the process which are proprietary but in general, all are based on the same principles.

In some cases, lime-stabilized sludge may be land applied, benefiting large agricultural areas with acidic soils. Alkaline stabilized sludge, has lower concentrations of available nutrients (as nitrogen and phosphorous), than a comparable mixture of biological stabilized primary and waste activated sludge, due to chemical reactions that occur in lime stabilization as well as the substantial addition of inert solids (37,50). Alkaline sludge product, has been found to be very useful in agriculture as a liming agent and soil amendment especially for acid soils. The product has low odor, is approximately 50 to 60% dry solids, meets the PFRP requirement, and it is easily stored (11).

2.2.3 *Composting*

There are numerous cases in which composting has been used successfully in the treatment of different organic wastes including: municipal biosolids, industrial sludge and

wastes, manure, yard wastes, food and agricultural wastes, municipal solid waste, and hazardous wastes among others[21,25,29,37,51,54].

Sewage sludge is one of the most common substrates for compost. Since the mid 1970's sludge composting has received increased attention as a cost effective and environmentally sound alternative for the stabilization and ultimate disposal of wastewater sludge[37].

Composting can be defined as the aerobic, thermophilic, biological decomposition of material under controlled conditions[44]. It is essentially the same process that is responsible for the decay of organic matter occurring in nature, except that it is accomplished under controlled conditions. Composting reduces both volume and mass of the raw materials and transforms them into a final biologically stable and aesthetically pleasant product, free of odors and highly suitable for horticultural uses and land reclamation because of its soil conditioner characteristics[25]. In addition to its significance as part of a waste management strategy, composting plays an important role in agriculture. In fact, composting is considered an important strategy which supports the goals of sustainable agriculture. The aspect is based on its agricultural benefits by its contribution to soil improvement, nutrient recycling, pesticide use reduction, and improvement of farm economics[53,57].

The final product is called compost, a humus like material. There are numerous attributes of compost. Compost is a source of organic matter for maintaining or building supplies of soil humus, helping to maintain or build a proper soil structure and moisture holding capacity. In particular for sandy soils, compost increases water content - water retention, and promotes aggregation. For clay soils, compost enhances aeration, permeability, and increases water infiltration. In agricultural and plant systems, compost also produces a greater root depth; increases microbial populations; and decreases surface crusting[47]. Compost can improve the growth and vigor of crops, reduces plant pathogens, and improves plant resistance to disease. Although compost contains valuable nutrients such as Nitrogen, Phosphorous and a variety of essential trace metals, because of the relative small quantity of these nutrients, it can not be classified as a fertilizer. In terms

of nitrogen leaching, the nitrogen in the compost is organically bound, so it is slowly released through the growing season[25,44].

2.3 Composting Generalities

2.3.1 Composting processes

There are several different types of processes used for sludge composting. Each system is composed of certain common basic steps. The basic steps of the composting process include:

1. Mixing dewatered sludge with a bulking agent and/or amendment
2. Aerating the composting pile by either the addition of air, or mechanical turning
3. Recovery of the bulking agent (optional)
4. Further curing (optional)
5. Final disposal

The first and second steps are critical to the success of the process. Recovery of the bulking agent is an optional step which relates to system economy and product quality (e.g. final product with or without wood chips). The curing stage also relates to product quality as it influences compost stability. During this period which can last as long as 30 to 60 days, further product stabilization and pathogen die-off occurs, along with degassing. Final disposal will depend on the market for the product compost[44].

2.3.2 Level of sludge composting

Composting of municipal wastewater sludge was assisted in its development by work at Beltsville, Maryland (US Department of Agriculture), by research partially sponsored by EPA, and by work at the Los Angeles County Sanitation Districts in California. These efforts in the early 1970's, led the development of the aerated static pile and the windrow compost systems, respectively[11]. In the last decade, composting has been growing. Actual plants in operation have tripled from 61 to 186 plants. **Table 2.1** shows the growth of composting over the last ten years in the United States. With respect

to New England, composting and composting marketing is strong. In 1990 there were 35 facilities operating in the six state region, processing approximately 150 dry tons of sludge per calendar day. In 1993, the number had grown to 46 facilities processing over 250 dry tons of sludge per day[34]. At the present, in the state of Massachusetts, there are a total of 22 composting facilities either in operation, or in the planning , construction and design phase[12]. **Table 2.2** includes information about these plants.

Table 2.1

Composting Growth in the US 1983-1994[21]

Year	In operation	In planning, construction, and design	Total
1983	61	29	90
1988	114	105	219
1990	133	122	255
1991	149	126	275
1992	165	125	290
1993	186	135	321
1994	201	117	318

Table 2.2

Massachusetts Sludge Composting Facilities Status as of 8/02/94 (12)

Name	Status	Type	Estimated volume
Barre	Operational	ASP	5 cy/week (160 wt/yr)
Billerica	Operational	ASP	10 cy/Day (951 wt/yr)
Bridgewater	Operational	ASP	48 cy/month
Dartmouth	Operational	IPS	(712 wt/yr)
Edgardtown	Planning	ASP	---
Haverhill	Design	In-Vessel	500 cy/week (est)
Holyoke/Partika	Operational	IPS	(5294 wt/yr)
Hoosac	Operational	ASP,encl	120cy/day (1568 wt/yr)
Hospedale	Pilot	ASP	(218 wt/yr)
Ipswich	Operational	ASP	0.2 dt/day (712 wt/yr)
Leicester	Operational	ASP, encl	10 cy/week (79wt/yr)
Mansfield	Operational	ASP	30 cy/week (1884wt/yr)
Marlboro	Operational	ASP	20 cy/day (17495 wt/yr)
MCI/Concord	Planning	ASP	---
Medfield	Design Comp	ASP	3.0 dt/week
Nantucket	Operational	ASP	(5,074 wt/yr)
Pepperell	Operational	ASP	9cy/week (273 wt/yr)
Somerset	Operational	ASP, encl	(343 wt/yr)
Southbridge	Operational	ASP	18 cy/day (1435 wt/yr)
Springfield	Operational	Taulman	(20,442 wt/yr)
Swampscott	to Lynn	ASP	7cy/day (5 days)
Yarmouth	Operational	Royer	---

ASP = aerated static pile; ASP, encl = enclosed aerated static pile
IPS = International Process Systems
wt= wet tons; dt= dry tons; cy= cubic yards; dt=dry tons; yr=year

2.3.3 Composting systems

There are a wide variety of composting systems, but for the most part composting systems can be divided into three general categories: windrow, static pile, and in-vessel(44). Different approaches have been used to categorize composting systems. Haug(25) has published a comprehensive treatise on composting engineering, and uses an approach which emphasizes reactor type, solids-flow mechanisms, bed conditions in the reactor and manner of air supply. He states that the most basic distinction among systems, is weather the composting material is contained in a reactor or not. Systems that use reactors are popularly termed "mechanical", "enclosed"or "in-vessel". US practice has adopted the term "in-vessel" for reactor type systems. The windrow and static pile processes are the basic two types of non-reactor systems. A brief description of each of these processes is presented in the following sections.

2.3.3.1 Windrow systems

Windrow systems are composed of long, narrow rows of sludge mixed with a bulking agent. The rows are typically trapezoidal in shape, 1 to 2 meters high and 2 to 4.5 meters wide at the base. The rows are usually uncovered, but can be protected by simple roofs. In this process, the sludge mix is aerated by convective air movement and diffusion. The rows are periodically turned by mechanical means to expose the sludge to ambient oxygen, to dissipate heat, as well as to refluff the rows to maintain good free air space. Windrows can also be aerated by induced aeration(44). **Figure 2.1** shows a diagram of a windrow system.

Among the advantages of these systems are:

- Low cost and flexibility, and
- Simple operation.

Windrow disadvantages include:

- Poor opportunities for odor containment
- Extended land requirements

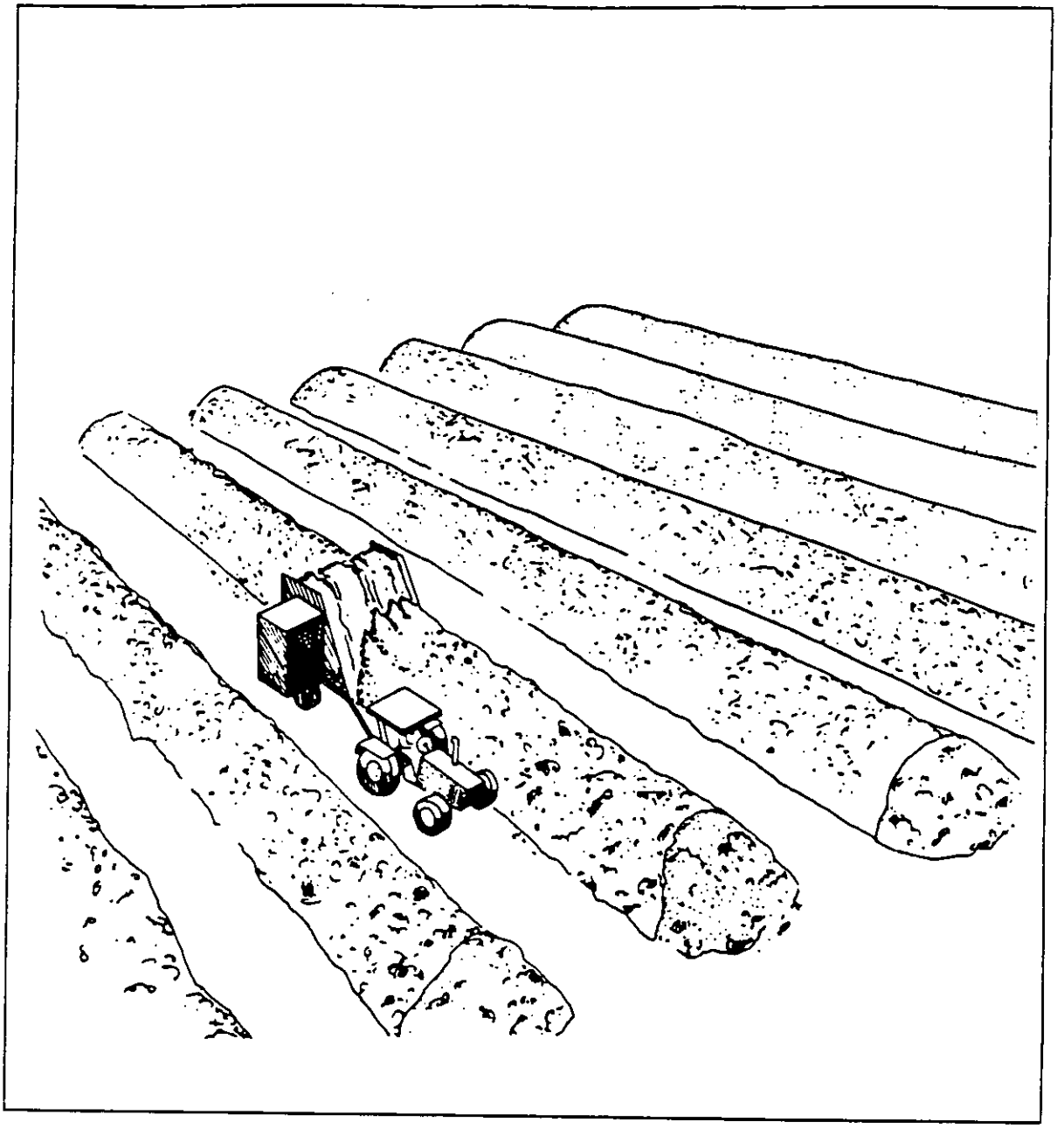

Figure 2.1 Schematic Windrow System[39].

- Sensitivity to adverse climates, and
- Due to the low aeration rate, these systems are generally unsuitable for raw sludge because of the inability to meet initial high oxygen demands.

2.3.3.2 Aerated static piles

These systems are also composed of a sludge/bulking agent mixture. A distribution system on the bottom of the pile is used to allow either positive or vacuum aeration. No agitation or turning of the static bed occurs during the compost cycle, and the piles are formed on a batch basis (see **Figure 2.2**). Some recent designs for the aerated static pile process (ASP), have included provisions for tearing the pile down, breaking up solids and, reforming for additional composting. If this provision is used, the system can be classified as a "semi-agitated" because the agitation is considerably less than that normally associated with the windrow system[25]. Static piles may be built as single batches or by adding extentions to an existing pile. In a typical static pile, the bulking agent consists of wood chips, which are mixed with the dewatered sludge by a pug mill type or rotating drum mixer. At the present time, the greatest number of facilities in the US, employ the static pile method[20].

There are numerous advantages for the static pile. These include the following:

- Suitable for converting digested and undigested sludge cake
- Insulation of the pile and a controlled aeration rate enable better odor and quality control than the windrow process.
- High degree for process reliability through simplicity of operation.
- More effective use of space and higher rates of pathogen inactivation[44],and
- Less expensive than in-vessel systems.

Disadvantages include:

- Odor problems will occur if the system is not enclosed, however once the system is enclosed it becomes difficult to achieve good aeration through the pile, and
- The systems are more complex and require more energy for aeration than windrow systems.

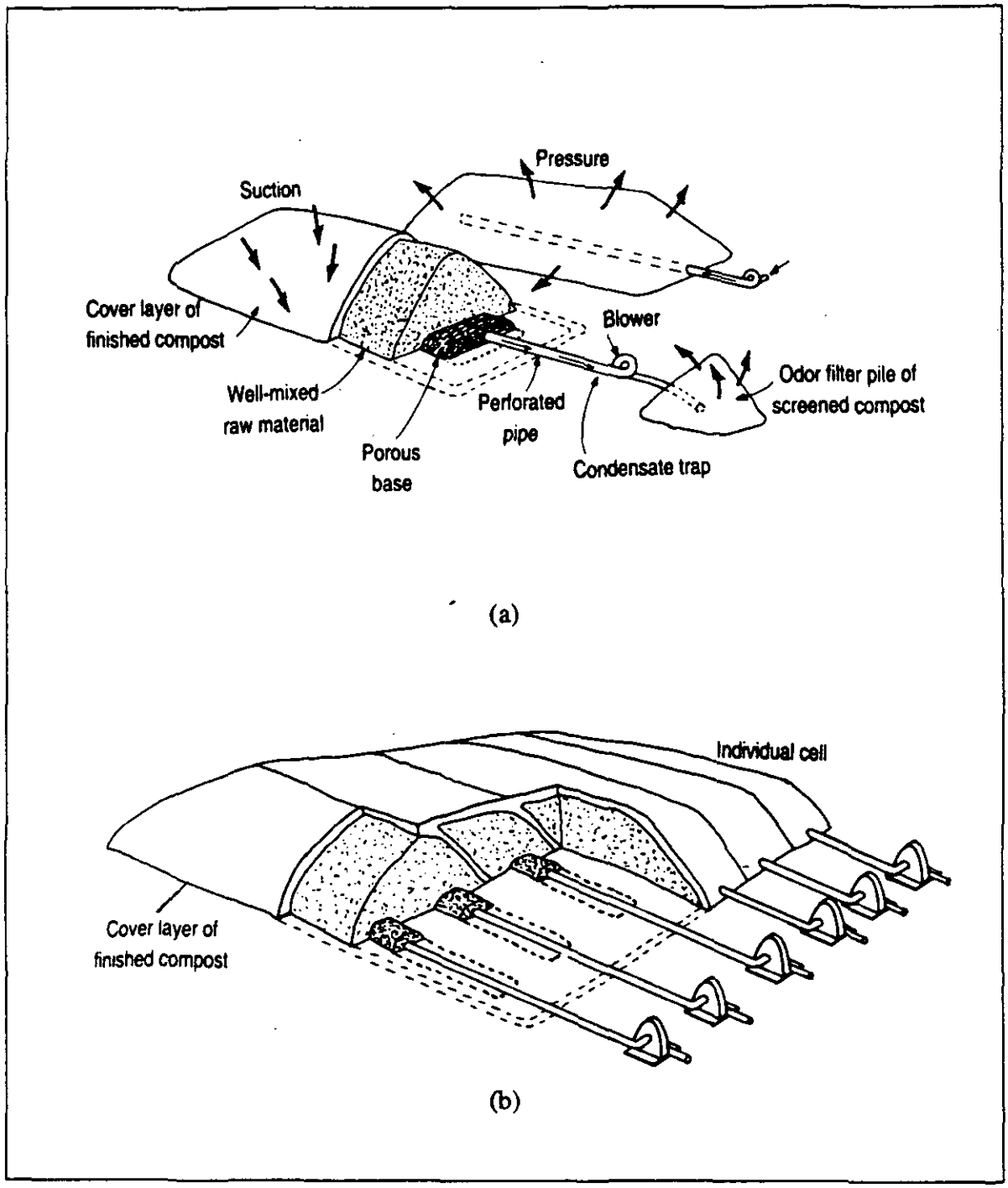

Figure 2.2 Aerated Static Pile

a) Aerated static pile parts, and b) extended aerated static pile layout (39)

2.3.3.3 In-vessel

This process takes place in either partially or completely enclosed containers. There are a variety of systems using various forced aeration and mechanical turning technologies. **Figure 2.3** show two of these systems. In-vessel systems are designed to minimize odors and process time by controlling environmental conditions such as air flow, temperature, and oxygen concentration. In-vessel systems offer excellent possibilities for process and odor control(44). They are also amenable for containing and capturing any odorous gases produced.

In-vessel composting is very space efficient, but more mechanically complex than the other two categories.The use of this type of systems has increased rapidly in recent years. Among the newer facilities commissioned within the past few years, a greater percentage are using in-vessel methods(20).

There are numerous types of in-vessel systems. Considering the reactor classification, in-vessel composting systems can be divided in two major categories: plug flow and dynamic (agitated bed). In plug-flow systems, the relationship between the particles in the composting mass remain in the same relative position throughout the process, and the system operates on a first-in first-out principle. In a dynamic system, the compost material is mechanically mixed during processing. Another classification is based on the manner of solids flow as either vertical flow reactors or horizontal flow reactors. Horizontal flow includes a number of reactor types in which the reactor is slightly tilted from the horizontal position to promote solids flow. Several versions of vertical reactors are available and include cylindrical and rectangular reactor geometry with counter-current and co-current aeration patterns(25).

Advantages attributed to in-vessel systems include:

- More consistent product quality
- Faster throughout
- Fewer personnel required - lower labor cost
- More effective odor control

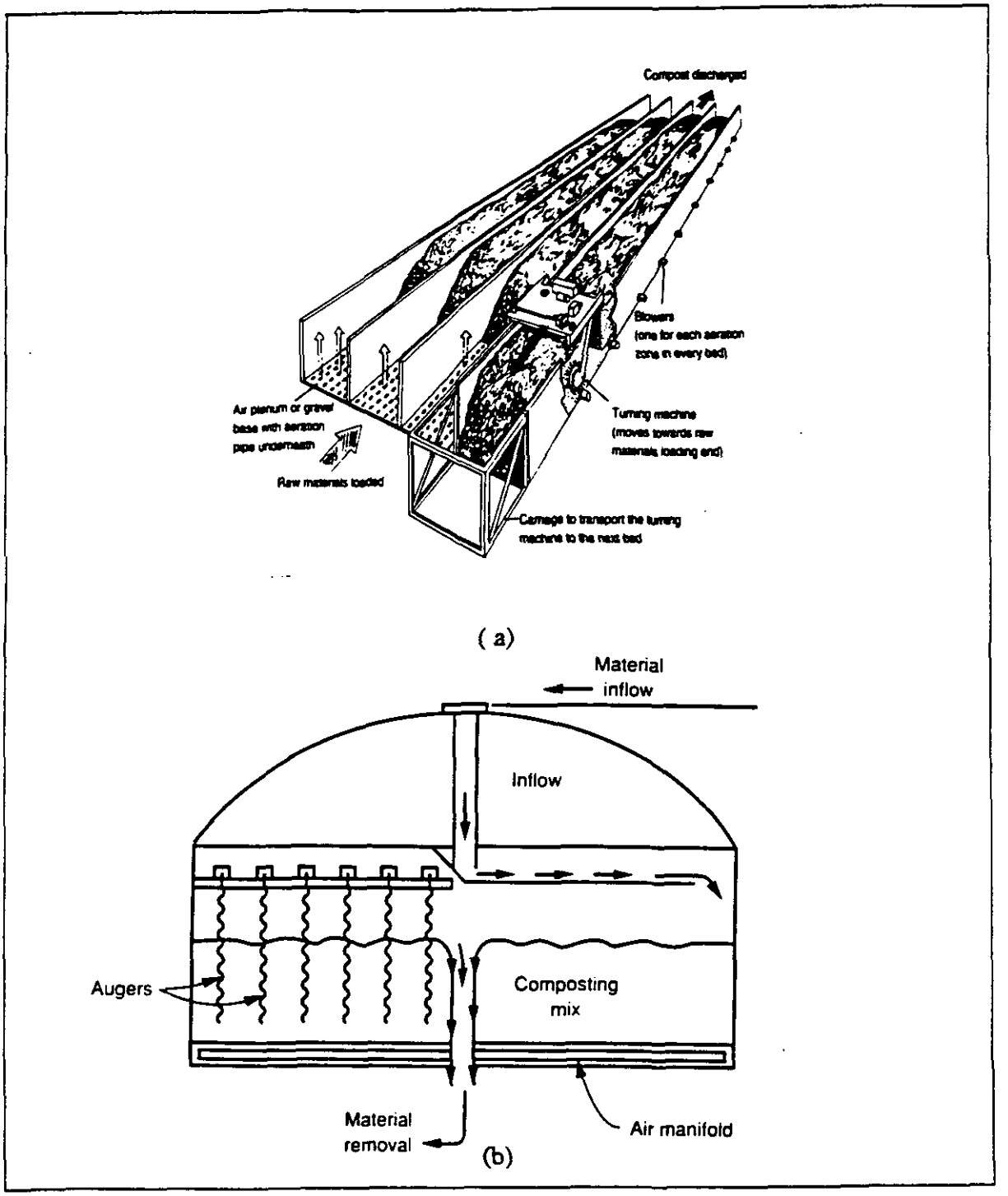

Figure 2.3 In- vessel Composting Systems

a) rectangular agitated bed[39], and b) cilindrical agitated bed[37]

- Better public acceptance due to aesthetics, and
- Less space required

Disadvantages include:

- Mechanically complex
- Requires higher construction and operation cost
- Higher cost among compost systems, and
- Requires skilled personnel to operate the plant.

2.3.4 Marketability

A general definition of compost as a product, can be summarized as follows: compost is an organic soil conditioner that has been stabilized to a humus-like product, that is free of viable human and plant pathogens and plant seeds, that does not attract insects or vectors, that can be handled and stored without nuisance, and that is beneficial to the growth of plants. As has been mentioned in section 2.2.3, compost is a competitive product for use as a low-analysis fertilizer, soil conditioner and growing medium for container plants. It can be used in the production of field crops, fruits and vegetables, forages, nursery crops and ornamentals[35,46]. A recent survey on composting plants[18] shows that the market for biosolids continues to be diverse, and relatively strong. The use of compost as a peat substitute in container media has also increased[32]. Devitt *et al.*[8] noted that a promising market also exists for compost as an soil conditioner and nutrient source for soils low in organic matter. Dessert soils of the arid southwest, for instance, require addition of organic matter to improve both the growth and vigor of ornamental plants. The use of most of the commercial organic amendments such as peat moss or composted sawdust are prohibitively expensive to use in large-scale planting. Therefore sludge compost can be considered an inexpensive and suitable option to provide organic matter. Furthermore, sludge compost can also be used advantageously as a topsoil substitute, for establishment and production of sod, for the reclamation and revegetation of disturbed lands, and to improve marginal soils[46].

An important market for compost sludge is the turfgrass industry. This market is particularly attractive, since turfgrass often occupies large acreage in and around the cities

where sludge is produced[8]. Application of sludge compost to turfgrass is useful as a soil conditioner for establishment and production, as well as to improve aeration and decrease thatch development[46].

At the present time, the most widely used marketing method for sludge compost, is bulk sales, which outpaces retail sales in bags by a ratio of more than 4:1. The most common users are landscaper contractors, followed by nurseries and the general public. Public and private landfills, professional groundskeepers, soil blenders, farmers, highway departments, public agencies, golf course operators and mineland reclamation projects are other common purchasers of sludge compost[20,34].

2.3.5 Compost quality

Compost quality may be defined as a compilation of several characteristics[28] including: product standards, nutrient content, salts content and pH among others. Product standards can be related to metals content and pathogen content. The quality of a compost is important primarily for three distinct reasons:

1) Protection of public health and the environment. Public health risks associated with compost come from exposure to human pathogens, aerospores and vectors. Furthermore, there are health risks associated with the heavy metals and trace organics contained in compost, which can enter the food chain through plants. In order to assure that both public health and environment will be protected, compost must comply with certain product standards[6].

2) Effect on soils and plant growth. Since the major use of compost is as a soil conditioner and nutrient provider, phytotoxic effects must be eliminated. Moreover, animal or plant health aspects and disease suppressive properties of compost are affected by maturity[32].

3) Marketing reasons, such as appearance (color, texture, particle size), odor and handling characteristics, which are established by the existing market demand. Compost quality is ultimately the most "technical' measuring stick as to the acceptability of particular compost[28] in the market.

Since there are diverse uses of compost, quality is usually defined by the several characteristics and is not absolute. Chen and Inbar[6] have suggested that compost quality parameters and values should be categorized according to where and how the compost is utilized. They have proposed the following compost quality classification (ranking from high to low quality): container media, home gardening, field grown nursery stock and sod production, top soils, field crops, land reclamation, and finally land cover.

Sludge compost "product standards" related to public health and the environment, have been established by the EPA on a risk assessment basis. Sludge base composts are regulated under "sold or given away" provisions of the Clean Water Act, Rule 503, part B[48]. Sludge based compost products must meet certain metals limits and also comply with pathogen quality and vector attraction standards to be considered of exceptional quality. Compost of exceptional can be used with minimal restrictions.

2.3.6 *Phytotoxicity*

Injuries to growing plants or germinating seeds have often been reported following improper application of organic matter in agriculture. Information on organic matter phytotoxicity has not always been systematically gathered, nor properly interpreted. Uncertainty thus persists as to the amount and frequency of damage[55].

Phytotoxicity, toxicity to plants causing growth suppression or death, is obviously closely tied to growth response. Soils ammended with compost added to soils which produce less growth than the soils without compost demonstrate the potential of phytotoxicity. Compost can be phytotoxic for two reasons: contamination or immaturity. The compost may be initially contaminated by substances such as herbicides, heavy metals, or soluble salts. Phytotoxicity caused by compost immaturity is due to several compounds. The composting process itself produces phytotoxic by-products that will degrade into harmless substances if the compost is allowed to fully mature. A number of phytotoxic substances are produced as intermediate products in the composting process including phenols, fatty acids, ammonia, amines[55], ethylene oxide, acetic acid and other organic acids such as benzoic, propionic and butyric acids[6]. The production of phytotoxic substances is partly dependent on the feedstock[55].

Feedstocks with very low C/N ratios seem to undergo a prolonged period of ammonia production, causing delayed maturation and increases in phytotoxicity(28). A high rate of toxin production is related, even under aerobic conditions, to the accessibility of the substrate and to the rate of growth of microbial populations. During composting, the initial microbial population, mostly bacteria, increases geometrically which leads to rapid exhaustion of the readily available substrate. Subsequently, the existing population decreases and a new population develops on the residue of the original one. This new wave of growth is generally characterized by a "return" of toxicity. The return of toxicity may seldom be noticed in the composting pile, where the evolution appears less uniform, and stages develop out of phase.

Many factors contribute to the disappearance of toxicity at more advanced stages of the process. These include changes in the microbial composition (actinomycetes and fungi prevail at the end) metabolic destruction of toxins, and synthesis of new polymers. In the final stage (curing) the presence of the free molecules is limited to products of mineralization and to a few microbial excretions. Metabolism that produces toxins differs greatly between the two stages, and is generally higher when the process reaches the stabilization phase. Interruption of composting leads to later completion of residual stages(56).

Allelopathic toxins in wastes can cause problems. They are generally destroyed within a few weeks of composting. However, sometimes an appropriate curing is essential to stabilize compost and eliminate or reduce negative plant effects due to allelopathic toxins(28).

There are several reports about phytotoxicity of immature compost on different plant systems. Chen and Inbar(6), cited several researchers' works on phytotoxicity, including: reports on reduction in root growth of young barley plants cultured in different soils amended with straw; and identification of acetic acid as a phytotoxin in immature compost. The correlation between phytotoxicity degree and compost maturity observed in seeds of *Brassica chinesis* has been reported by Wong and Chu(54). Others such as Zucconi *et al.*(56), observed phytotoxic effects in different plant species when compost of different maturity levels was applied.

Plant roots are especially adapted to the particular soil condition in which they grow. If that condition is suddenly changed in some way, the plant's metabolism will slow as energy is used to generate a new absorbing apparatus. Different plant species have varying environmental sensitivities and will react differently to the same change[55]. Another factor affecting the response of plants to phytotoxic conditions is the ability of roots to differentially absorb organic molecules. Roots seem to be susceptible to a new substance at first contact, but if this initial exposure is not lethal, their absorption mechanism will adapt to keep the toxic substance from being assimilated[56].

2.3.7 *Compost stability and compost maturity*

Compost maturity and/or compost stability, are key characteristics defining compost quality. They are important in terms of potential phytotoxic effects, temporary nutrient imbalances, and possible odors from a non-finished composting product. Switzenbaum[44] noted that there is a good deal of confusion in the published literature regarding compost maturity and compost stability. Iannoti Frost *et al.*[31] have remarked that the terms maturity and stability are often used interchangeably and suggest the following distinctions: "Compost stability is readily definable by its biological property of microbial activity. In contrast, the term compost maturity is a broad and all encompassing term. Compost maturity is an elusive concept meaning different things to different people. It is often linked to the intended usage of compost". Since compost maturity is connected with the final use of compost, it is a subjective term. Thus any definition of maturity must be based on the potential use of the compost[44].

Compost stability is important to designers and operators of composting plants. To distinguish differences in efficiency among systems, stability assays have to be performed that determine the extent to which the raw product has been stabilized. Compost stability has been defined by several parameters, however none of these have been widely accepted as the ideal one. A description of the existing stability parameters is presented in the next section.

Chen and Inbar[6], have proposed the following definitions for mature compost depending of its use: 1) greenhouse utilization: organic matter composted to the degree of

decomposition that has no adverse effects on container grown plants; and 2) field application: organic matter composted to the degree of decomposition that has no adverse effects on growth on various crops when applied at annual rates up to 50 tons/ha. at least 6 weeks before sowing or planting. However, neither of these definitions is absolute. Lopez-Real *et al.*(35), have shown that there are differences in sensitivity among plant species grown in container media. Thus, the degree of decomposition will vary depending on the species to be grown in such containers. This second definition is not general either because it does not specify the type of crops, type of application, nor age of the plant. Schumann *et al.*(42) have demonstrated that sludge compost does not have phytotoxic effects on established turfgrass even when it has been composted for just 10 days. Conversely, Zuconni *et al.*(56) have investigated the phytotoxic effect of fresh, immature, and mature compost on various plant species, including cress seeds. They concluded that phytotoxic effects appeared to be strictly associated with the initial stage of decomposition.

2.3.8 Stability and maturity parameters

The most common testing methods currently advocated for "maturity" measurements of compost can actually be divided into maturity and stability tests. Essentially maturity assays aim to predict plant growth response or some other measure of appropriate end-use(31).

At the present, there are several parameters that have been developed for composting process control and for final product quality, including both maturity and stability parameters. The inventory covers many possibilities and the determination of these parameters is based on one or more of the chemical, physical, microbial and phytotoxic characteristics of the compost. As can be seen in **Tables 2.3 and 2.4**, the list of these parameters is wide and covers many possibilities. However, none of these has been widely accepted. Golueke(22) pointed out: "Composting practice has relied more and more on scientific principles as time passes but, the search for a simple yet reliable and universally applicable analytical tool for evaluating compost maturity remains to be found". Although there is no unanimous acceptance of one of these measurements as the

Table 2.3

Methods to Determine Compost Maturity Parameters[19,31,32,43,56]

1. Chemical analyses	1. In solid compost: a. C/N ratio 2. In water extract: a. C/N b. Concentration of NO_3^-/NH_4^+ c. Concentration of organic acids d. Organic acids content
2. Physical analyses	a. Water holding capacity b. Porosity
3. Microbiological assays	a. Suppression of plant pathogens
4. Plant bioassays	a. Cress germination test in water extract b. Rye-grass growth in compost containing mixtures c. Seedling development in compost and water extract d. Application of compost to established plant systems

Table 2.4

Methods to Determine Compost Stability Parameters[7,19,25,29,31,32,40].

1. Chemical analyses	a. Carbon/Nitrogen ratio b. Water soluble ions c. Water soluble organic matter d. Cation exchange capacity e. Crude fiber analysis f. Rise in redox potential g. Ash or Volatile solids h. Starch and cellulose content I. Amount of decomposable and resistant organic material
2. Physical Analyses	a. Final drop in temperature b. Degree of self heating capacity c. Color d. Odor e. Particle size f. Appearance and texture g. Water and air content
3. Microbiological assays	a. Respiration rate and/or carbon dioxide evolution rate b. Indicator microorganisms c. Microbial activity and biomass d. Nucleic acid or ATP e. Suppression of plant pathogens
5. Spectroscopy	a. Solid State: CPMAS ^{13}C -NMR b. Infrared - (transmission and diffused reflectance spectroscopy)
6. Degree of humification	a. Total humic substances b. Content and ratios of humic and fulvic acids and non humic fractions c. Functional groups content

CPMAS ^{13}C -NMR =Cross-polarization magic angle spinning ^{13}C-Nuclear Magnetic Resonance

universal parameter for either stability or maturity, some are considered more reliable than others. For stability parameters, respiration rate and chemical analyses on water extracts, have recently been considered as the most reliable parameters[5,30,31], while plant assays are the most useful among the maturity parameters[6,56].

A brief discussion of some of the most commonly measured parameters is presented in the following section. Some other parameters which may be useful as complementary information about the performance of the composting process are also included.

2.3.8.1 Analysis on solid compost

Volatile solids

Volatile solids (VS), the percent of dry solids lost by ignition at 550°C, is widely used as a rough measure of organic matter. Aerobic biological activity decreases the volatile solids content by converting organic carbon to CO_2; therefore, VS measurement over time during processing might serve as a rate parameter. However, the test fails to discriminate among readily metabolized, putrescible material, less readily metabolized material, and organic material that is not metabolized during any reasonable composting period. Similarly, sensitivity is poor because a high percentage of the dry weight is volatile matter. This means that the decomposition of a relatively large amount of VS may result in only a small change in percent VS. In order to determine the VS changes in the composting process, it has been suggested to report this parameter in terms of its ash value (fixed solid basis). A further problem is associated with the VS test on sludge composted with woodchips or other organic bulking agents that originate outside of the waste stream. The test does not discriminate between woodchips (or fragments) and the sludge; however, screening could help to eliminate materials others than compost[16,28].

Oxygen uptake rate

Oxygen uptake rate (measured by respirometry) has been widely used to determine substrate degradability as well as the amount of decomposable matter in compost. Respirometry, involves measuring physical factors such as carbon dioxide evolved,

pressure drop resulting from oxygen uptake, or oxygen uptake directly. These procedures can involve different durations of testing as well as the use of different types of respirometers[25]. Among the different types of respirometers are the standard BOD bottle, the constant volume respirometer, the electrolytic respirometer, and the constant pressure respirometer[25,52].

Rates of oxygen uptake have been measured in both batch and continuous composting systems with a variety of feed materials. Haug[25] mentions two works of different researchers using a Warburg respirometer to determine oxygen uptake. Both results showed that oxygen uptake of fresh compost was relative higher than mature compost. Usui *et al.*[49] has also reported determinations of oxygen uptake rate in sludge compost using a electrolytic respirometer. They found that the oxygen uptake rate for cured sludge composted in horizontal agitated beds, ranged between 40 and 127 mg O_2/kg dry solids-hour oxygen uptake rate. Wilson and Dalmat[52], reported oxygen uptake ranges for sludge compost after an ASP system in the range of 150-250 mg O_2/kg ds-h, determined in a constant volume respirometer. After 30 days of curing, a 75% decrease in respiration is also reported. They suggested an oxygen uptake of 100 mgO_2/kg ds-h, should be used if compost will be used for field applications, and a value of 20 mgO_2/kg ds-h for horticultural uses using sensitive plants.

C/N ratio

The C/N ratio of the solid compost product is one of the major operational and compost quality parameters for the composting process. It has been considered a reliable stability parameter for compost since the effects of either a high or low ratio are well known. High available C/N ratios of compost, cause immobilization of nitrogen and nitrogen deficiency in plants. Excessively low C/N immature compost causes ammonium toxicity. Both extremes interfere with plant growth. Normally, a C/N ratio of less than 20 is thought to be desirable. However, C/N ratios of sufficiently well composted materials vary from 5 to 20 depending on the type of raw material, and thus the C/N ratio cannot be used as an absolute indicator of compost stability[5].

Pathogen indicators

High concentrations of soluble organic nutrients present in immature compost support growth of salmonella, and other pathogens which depend on free nutrients for growth. Concentrations of these available nutrients decline as compost matures. Thus, in properly mature compost, densities of pathogens are low and regrowth of nutrient dependent pathogens is not possible. Therefore, pathogen populations, as well as their regrowth, may be used as stability indicators(32).

Compost pathogen indicators (and *Salmonella*) are parameters included in federal regulations. The USEPA 40 CFR 503 regulations, include important standards for compost in terms of pathogens limits. Composts that are intended to be widely distributed or marketed (called Class A under this regulation) must comply with certain requirements. First, the composting process must use a PFRP time/temperature standard (or equivalent processing) and produce a product with less than or equal to 1000 fecal coliforms per gram dry solids or less than or equal to 3 *Salmonella* per four grams dry solids(48) .

It is well documented that certain enteric bacteria can regrow in organic material once temperature is reduced to sublethal levels(25). This phenomena has been observed with total and fecal coliforms, and *Salmonella*(3,14,25).

2.3.8.2 Analyses on water extract

Most microorganisms in solid phase systems, such as compost, are attached to surfaces and are active in the water-solids interface. This microflora metabolizes substances from the solids through enzymatic activity. The solubilized substances are utilized to support growth or accumulate in the liquid phase. Characteristics of the water extract of compost, therefore, are useful for the determination of compost stability(5,31).

Total Organic Carbon

Several researchers including Inbar *et al.*(32), Garcia *et al.*(17) and Grebus *et al.*(23), have noticed a decrease in soluble organic carbon in the water extract, during the composting and maturation process of different materials. These observations have lead to the proposition that the decrease in soluble carbon can be used as an indicator of

maturity of compost[28]. However, there is no consensus about whether this may be considered as a stability parameter, and no target values or ranges have been established. Therefore a decreasing trend of soluble carbon during composting may only give an indication of the extend of decomposition progress, but it can not be considered as a stability parameter.

C/N in water extract

A variation of the C/N measured in the water extract of compost, has been proposed by Chanyasak and Kubota[5] as an indicator of maturity. These researchers, have found that the water extract C/N_{-org} ratio of several well-composted products show almost constant values of 5 to 6, despite the wide variation in their initial carbon and organic nitrogen contents. They also observed, a correlation between the decrease of C/N_{-org} in water extract, and composting time, for compost with a high initial C/N_{-org}. However, the change in this parameter during composting time, might not be usable as an indicator of maturity for compost with a initial low C/N_{-org} water extract, such as sludge compost.

There are conflicting results presented in the literature concerning the use of this parameter for certain wastes. There are several reports in which the C/N_{-org} in water extract has proven as a reliable stability parameter[5,17,23]. In contrast, there are some reports in which the C/N_{-org} ratio has not been demonstrated to be a suitable stability parameter[6,30].

2.3.8.3 Auxiliary parameters

Although not considered as stability parameters, there are other measurements that can be used as auxiliary criteria to determine decomposition progress during composting. Although they can not determine the real stage of stabilization, they may be used as a guidelines and complimentary information about the process. This information can be used for a better control of the process overall. Some of these parameters are discussed in the following section.

pH

pH is used as a auxiliary parameter in composting monitoring, because changes in pH during composting have been observed to be predictable. Miller[38], has suggested the use of pH time course changes as indicators of the rate of processing. The expected pattern of pH changes during composting will be a increase from pH =6 initially to 8.5 as composting activity comes fully underway. This increase is thought to be caused by ammonification. As ammonification decreases, pH in final compost will be expected to drop about 7.5 to 8.0.

Temperature

Temperature is an important factor in composting, as both a consequence and a determinant of activity[38]. Since specific sequential changes in temperature during composting are expected to occur, temperature measurements can be used to monitor composting process performance. Extremely low or high temperatures may reflect problems in process control that could affect quality of the final product.

Another approach using temperature measurements during composting, is monitoring for temperature decline. A temperature decline at the end of the composting is considered a good indication that the process is nearing completition. Temperature drop is expected to occur not because of thermal kill, oxygen shortage, low moisture or lack of sufficient pile insulation, but because of degradable material has been depleted. This approach is based on the fact that the rate of heat production is proportional to the amount of organic oxidation, and the amount of heat produced, decreases after the more degradable material is decomposed. Therefore, if thermophilic conditions are observed, the compost is probably not stable and not yet mature[25].

Moisture management

Moisture management is a very important part of proper composting. Typically the initial moisture content of the sludge mixture is adjusted to a value of about 60%. During the composting process, water is lost via evaporation and leaching from the mixture. Water may be gained from precipitation(for uncovered systems) and as a product of

respiration. In general, there is a net loss of water during the process and it is expected that the final mixture will have a moisture content of about 40%[44]. When a different pattern is observed, it may be assumed that the performance of the process is affected. For instance, if water is limited, microbial migration and colonization will be affected, as well as the diffusion of substrates and metabolic wastes. Thus, if moisture levels are below 40% during composting, microbial activity will be inhibited. On the other hand, excessive moisture contents, (higher than 60%), restricts gas transfer thuslimiting oxygen supply and anaerobic conditions may exist[16]. Anaerobic conditions can lead to odor problems and metabolite acumulation.

2.3.8.4 Plant bioassays

It has been said that there is no general and absolute value for any of the maturity parameters that can be applied for all plant species and for all compost types (see section 2.3.7), since that value will depend on the specific use of the compost. If compost is intended to be used as a soil conditioner, the most important parameter is the maturity level required by a specific plant species so that the compost will not cause any negative effects. Plant bioassays are the most reliable test for maturity because they indicate when a compost may be used without inhibitory effects in a particular plant system. The main disadvantage of plant bioassays is the time required, which generally take from one to several weeks to complete. However, once the maturity level of compost is defined through a plant bioassay, a correlation with an easier measure of stability can be made[24].

In order to facilitate the implementation of plant assays, several scientists have used various indicator plants[52]. The cress germination test and the rye-grass assay have been used successfully and correlations with other stability parameters have been made[6,32,58].

In most of these studies a surrogate system is established by using the most sensitive plant species. If no damage in the most sensitive plants is observed, then no damage to others species can be assumed. On the other hand, plant assays can also be designed considering that among plant species there are different sensitivities and responses to compost. If the intent is to define what the maturity level of a specific

compost is and its effect on a particular plant system, a plant assay must be done with that type of compost using the plant species for which compost is intended to be used. Furthermore, the plant assay must consider the method and rate of application, as well as the plant's growth stage. Different effects will be seen if compost is applied to an established plant system or if it is used as a germination medium. A seedling development test using a particular plant species and compost is thus needed in certain circumstances. Different pot studies have been performed with different seeds species, using different compost types[6,17,21,32,42]. In addition, the use of plant assays to determine the effects of compost on established plant systems has also been reported[42]. Results of some of these experimens will be discussed in light of this work experiments results.

3. Experimental Methodology

3.1 General Methodology

Sludge compost from two different composting systems, an in-vessel system (at the Holyoke Composting facility) and an aerated static pile system (ASP) (at the Hoosac Composting Facility), were studied. A total of four experiments were performed and will be referred to as experiments 1, 2, 3, and 4 throughout this report. Experiments 1 and 2 corresponded to samples coming from in-vessel system, while for experiments 3 and 4 samples from a ASP system were used. Each one of the experiments consisted of a sample collection during the composting process, analyses of the samples to determine stability parameters in both, solid and water extract phase, and a plant assay to determine the phytotoxic effects of compost on turfgrass seeds. Plant assays for experiment 1, also included an evaluation of compost effects on established turfgrass for comparison with results previously obtained in a similar study by Schumann *et al.*(42).

The rationale for conducting these experiments is explained as follows: Experiment 1 was designed to analyze samples from an in-vessel system. Then, in order to verify the results obtained during experiment 1, a second experiment (Experiment 2) using samples from the same composting system, was designed . Experiment 3 was designed to analyze compost from an ASP system. However, since results indicated some problems in

the sampling methodology used, a fourth experiment was designed to overcome such difficulties (Experiment 4). **Table 3.1** summarizes the analyses performed in each experiment.

3.2 Description of Facilities

3.2.1 Holyoke facility

The Holyoke composting facility is located in the town of Holyoke, Massachusetts. This facility was designed by International Process Systems, Inc. The process is a semi-continuous horizontal system in which sludge is composted between walls that form long channels. The facility contains 16 bays, each approximately 67 meters (220 feet) long. Both forced aeration and mechanical agitation are employed. Each bay at the facility receives supplemental aeration between turnings to aerate and cool the composting sludge. The bays are divided into multiple aeration zones along the length of each chanel. Each zone is aerated by one blower separately controlled by temperature feedback from a single thermocouple within the zone. A rail on top of each wall supports and guides a compost turning machine. As the machine moves forward on the rails, it mixes the compost and discharges the compost behind itself. This procedure moves the compost a fixed distance down the channel with each turning. Since the mixing machine moves the material 3.65 meters (12 feet) per day, the residence time is approximately 18 days. However, the bays are not mixed on Sundays or holidays, so the actual residence time is closer to 21 days at this facility[42].

The sludge composted at the facility is a mixture of primary and secondary sludge dewatered by a filter-press to approximately 30 percent solids. Dewatered sludge is mixed with mulch chips in a 3:1 ratio (by volume), and then placed in the front end of the channel by a loader. The initial moisture content of the mix is approximately 60 percent.

Table 3.1

Summary of Experiments Characteristics

	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Composting system sampled	in-vessel	in-vessel	Aerated static pile	Aerated static pile
sampling methodology	one bin sampled at five different locations, each location corresponded to a compost age	one bin sampled at five different locations, each location corresponded to a compost age	one bin was sampled at four different days. Each day corresponded to a compost age	one bin was sampled at four different days. Each day corresponded to a compost age
plant assay	seedling study and established turfgrass study	seedling study	seedling study	seedling study
analysis on solid compost	TS, VS, pH, Oxup, pathD, pathR, TC, TKN,	TS, VS, pH, Oxup, pathD, pathR, TC, TKN,	TS, VS, Oxup, pathD, pathR	TS, VS, Oxup, pathD
analysis on water extracts	TOC, TKN, orgN	TOC, TKN, orgN	TOC, TKN, orgN	TOC, TKN, orgN

TS- total solids; VS= volatile solids; pH= hydrogen potential; Oxup= oxygen uptake rate; pathD= pathogen indicators density; pathR= pathogen indicators regrowth; TC= total carbon; TKN= total Kjedhal nitrogen; TOC= total organic carbon; orgN= organic nitrogen.

3.2.2 Hoosac composting facility

The Hoosac Water Quality District treatment plant is located in Williamstown, Massachusetts. It provides wastewater treatment for Williamstown, North Adams and part of Clarksburg.

The plant employs conventional activated sludge treatment. Primary and secondary sludges are co-settled in sedimentation basins. The combined sludge is then conditioned with lime, and dewatered using vacuum filters. The plant is staffed five days per week for two shifts per day. The vacuum filters typically operate continuously while the plant is staffed.

The dewatered sludge is taken by truck from the vacuum filters to the composting area every thirty minutes. The composting area is located in the front of the treatment plant. Wood chips are used as a bulking agent. The wood chips are added to the sludge and mixed in the truck, and then fed by a conveyor, from the truck into the composting bins. The ratio of bulking agent to sludge is 2:1 by volume.

Sludge is composted in enclosed aerated static piles in concrete bins. There are four bins. Each bin is 21.4 meters long, 4.6 meters wide and 3.7 meters high. Although one end of each bin is open, a sliding door covers the front part. Bins are covered by a common roof. Mechanical blowers force air through the compost piles in the bins via the air plenum. The blowers operate on a cyclic basis. A typical cycle is 15 minutes on-off. This procedure maintains sufficient aeration in the pile without cooling it below the thermophilic temperature range. Temperature probes inserted into the compost pile monitor the temperature in each batch. In addition to the on-off cycling, the blowers are periodically reversed. Each time the direction of air-flow is reversed, the air passes through different pathways in the pile. This increases the efficiency of the aeration process.

The sludge and bulking agent mixture is fed from the truck into the bin from the back. In the floor of each bin are two channels covered with gravel. These function as combination air plena and leachate drains. The leachate produced from the compost piles is recycled back to the plant.

It takes two to four days to fill a bin (approximately 460 cubic meters). The bins are filled and emptied sequentially. As a new bin is needed, the oldest batch is removed. A

front-end loader empties the bin via the open end. The residence time of a batch of compost is three to five weeks. Once the composting period is over, compost is trucked to an open field and dumped to form piles for the curing period. Compost remains in this area approximately one year(2).

3.3 Sample Collection and Processing

3.3.1 Holyoke composting facility

As mentioned above, samples for experiments 1 and 2 were collected from this facility. Sample's collection dates, for experiment one and two, were performed on June 6 and July 17, 1993, respectively. In each experiment, one bay was chosen and samples were taken at five locations along the bay. Samples were taken at 33, 40, 48, 55, and 61 meters (108, 132, 156, 180 and 200 feet) from the front end of the bay (61 meters being the end point). **Table 3.2** presents information about sampling for experiments 1 and 2.

The compost mixture was sieved, on site by hand, with a screen containing 0.6 cm (1/4 inch) openings. Approximately five liters of sample where collected and stored in plastic containers from each location. In addition, using sterile equipment , approximately 200 grams of sample were sieved and placed into sterile bags for pathogen indicator analyses. Samples were kept cool in an insulated ice chest and taken to both the Environmental Engineering and Plant Pathology laboratories for analysis. For experiment 1, (June 1993 sampling), an additional thirty-two kilograms of sample from each location was collected for the established turftgrass study. Sieved samples were kept in plastic bags, and taken immediately to the Amherst Golf course for the established turfgrass assay.

3.3.2 Hoosac composting facility

Experiments 3 and 4 were run using samples from the Hoosac composting facility. Sample collection for experiment 3 was performed during November 1993, and for experiment 4 during March 1994. Since this is a batch process, the samplings were

Table 3.2

Sampling Dates at the In-vessel Composting Facility, Experiments 1 and 2

Experiment	Sampling date	Sites sampled (from the front end of the bay) (feet)	Corresponding compost age (days)
1	June 6, 1993	108	10
		132	12
		156	15
		180	17
		200	19-20
2	July 17, 1993	108	10
		132	12
		156	15
		180	17
		200	19-20

performed at one bin over the entire composting process. **Table 3.3** shows sampling dates for each experiment and the corresponding compost age.

Experiment 3

For experiment 3, samples were taken from bin number 1. The area sampled was the front part of the pile along the width of the bin (see **Figure 3.1 a**). A hole approximately 0.6m (2 ft) deep and 0.5 m (1.7ft) diameter was excavated. Using a sterile scoop, approximately 200 grams of sample were sieved, on site, through a sterile sieve 0.6 cm openings (1/4 inch). The sample was placed into a sterile bag for further pathogen indicator analysis. The rest of the sample was sieved on site and placed in five plastic containers, and kept in a cool chest until they reached the laboratory for analysis.

Experiment 4

For experiment 4, the sampling method was modified in order to achieve a better (more representative) sample of the compost batch. On this occasion, a composite sample was obtained covering a larger portion of the pile. The area considered for sampling was approximately 3 m (9 ft) wide and 4 m(12 ft) long, and corresponded to the same loading(see **Fig 3.1 b**). The composite sample consisted of samples taken from 8 different sites along the area. The area was randomly divided into 8 different sections from which samples were taken. At each site chosen, a hole of approximately 0.30 m (~1 foot) diameter and 1-1.30 m (3-4 ft) of depth was excavated. Temperature was recorded at each site, and a qualitative visual description of the compost was noted: dry, semi-dry, and wet. Once the hole was excavated, approximately 200 g of sample were deposited into a sterile plastic container, using a sterile scoop. This sample was used for pathogen indicator analysis. For the rest of the analyses, approximately three full shovels of sample at each hole, were placed into a plastic bag. The excavated holes were refilled and their location recorded. Both, the container, and plastic bag were taken to the environmental engineering laboratory for further processing. Once in the environmental engineering laboratory, samples for pathogen determination were sieved using a sterile sieve (0.6 cm openings), deposited into a sterile plastic bag, and kept in the refrigerator at 4 °C. Pathogen analyses

Table 3.3

Sampling Dates at the Aerated Static Pile Composting Facility, Experiments 3 and 4

	Sampling date	Compost age (days)
Experiment 3	11-01-93	10
	11-05-93	15
	11-12-93	21
	11-19-93	28
Experiment 4	3-28-94	5
	4-05-94	13
	4-12-94	20
	4-19-94	27
	4-26-94	34

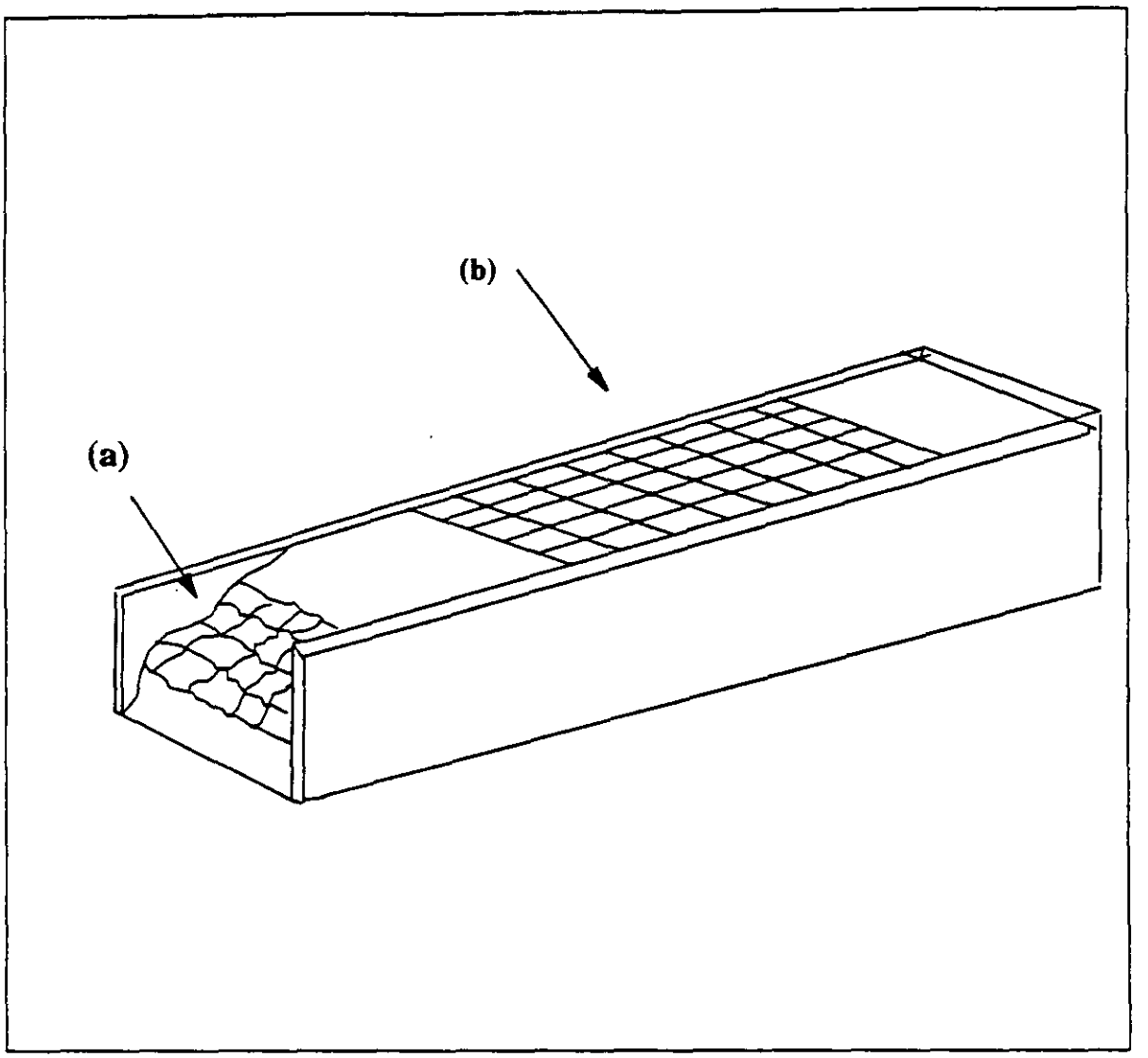

Figure 3.1 Area Sampled at Hoosac Composting Facility.

a) Experiment 3, b) Experiment 4.

were performed the day after the samples were collected. Samples from the plastic bags were also mixed and sieved through a 0.6 cm sieve. Approximately four liters of composite sample were stored in plastic containers at 4° C. After 24 hours, two liters of composite sample were taken to the Plant Pathology laboratory for phytotoxic studies. The rest of the sample was used for the stability analyses.

3.4 Sample Analyses

3.4.1 Stability analyses

Compost samples in solid phase and their water extract solutions were analyzed to determine the following parameters. Analyses on solid phase included: total and volatile solids, pH, oxygen uptake, pathogen indicators, and C/N ratio. Analyses of water extract solutions included: total organic carbon(TOC), ammonia, and total Kjeldahl nitrogen(TKN) determinations. A description of the methodology used for each determination is presented.

3.4.1.1 Analyses on solid phase

3.4.1.1.1 Total and volatile solids

Total solids determination was performed according to Standard Methods 2540B$_{(1)}$. For volatile solids determination, a modified Standard Method 2540E$_{(1)}$ was followed. The modification consisted of a preliminary controlled firing of samples with a Bunsen burner before placing the samples in the muffle furnace. This modification was done to avoid errors because of the physical or mechanical losses due to decrepitation during the combustion at 550 °C$_{(41)}$, as well as to control the fumes.

3.4.1.1.2 Oxygen uptake rate

For experiment 1, oxygen uptake was determined by using a constant pressure respirometer as described by Haug *et al.*$_{(26)}$. **Figure 3.2** shows a diagram of a similar system$_{(26)}$ to one used. For experiments 2, 3, and 4, oxygen uptake rate was

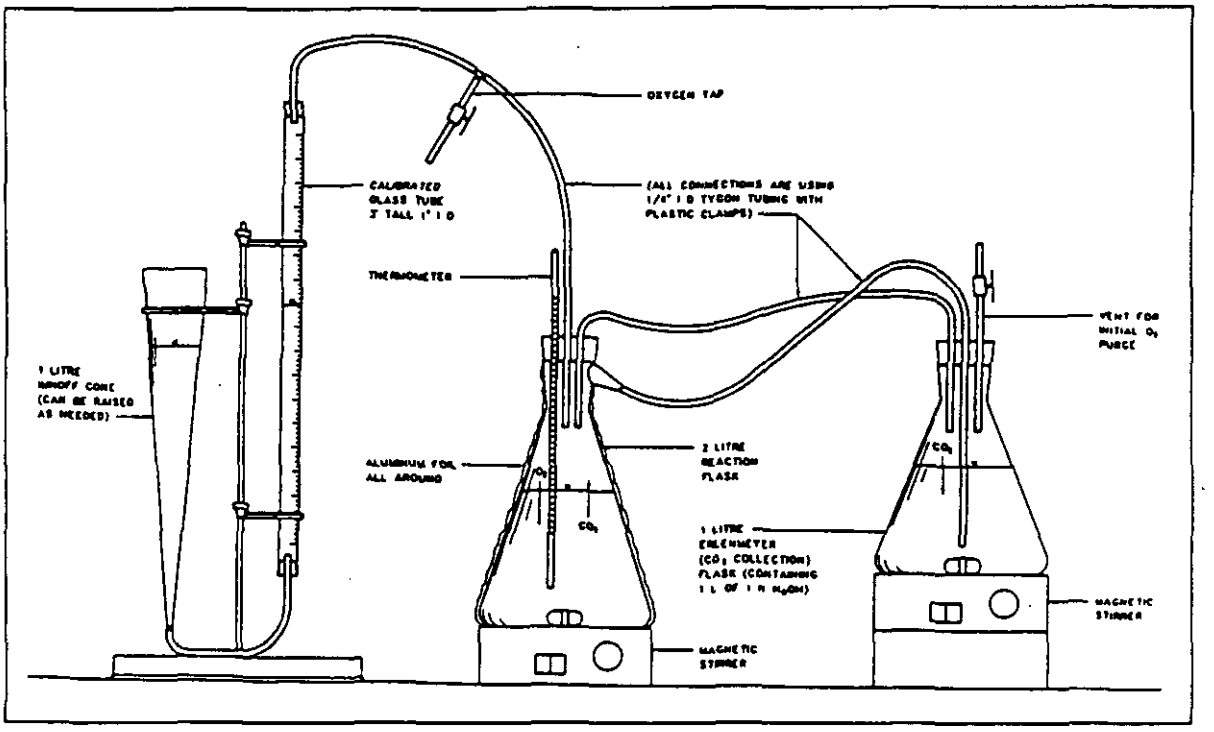

Figure 3.2 Scheme of a Constant Pressure Respirometer[26] Used During Experiment 1.

determined, by a "Comput-Ox" respirometer, N-Con System Co., constant pressure respirometer. **Figure 3.3** represent a schematic system[36] of a "Comput-Ox"respirometer. Using this instrument, oxygen uptake rate was estimated by computing the volume of oxygen consumed by the compost samples during 48 hours. For each sample, twenty-five grams of compost (wet weight) were placed into a 500 ml reactor, and filled to 300 ml with distilled water. Reactors were provided with a small plastic container in which approximately one gram of potassium hydroxide pellets were placed. This alkaline compound, reacted with any carbon dioxide being produced therefore not disturbing the initial volume of gas[4]. Reactors were incubated for 48 hours at 24 °C, and mechanically agitated by a magnetic stirrer. The volume of the oxygen consumed was recorded on a personal computer every half hour, although the volume is recorded every time the valve opens and more O_2 comes is added.

3.4.1.1.3 Pathogen indicators

Total coliforms and fecal coliforms (*E. coli)* were enumerated by Most Probable Number (MPN) procedure using Colilert test procedure described by Edberg *et al.*[13]. This method has been approved for drinking water analysis. An initial comparison between the Colilert test procedure with the traditional method was performed. It was found that the Colilert method was equivalent to the traditional method when determining total coliforms and *E.coli* from compost.

Regrowth potential of pathogen indicators

Approximately 50 grams of each compost sample were placed in a 250 ml Erlenmeyer flask, covered with a cotton stoper and incubated at 37 °C. Sample moisture content was determined and adjusted to 50 percent before incubation. For each sample, three flasks were filled with compost sample, each one corresponding to a incubation period of 7, 14 and 21 days respectively. After the corresponding incubation period, flasks were removed from the incubator and approximately 2 grams of sample were taken for total coliforms and *E.coli* determination.

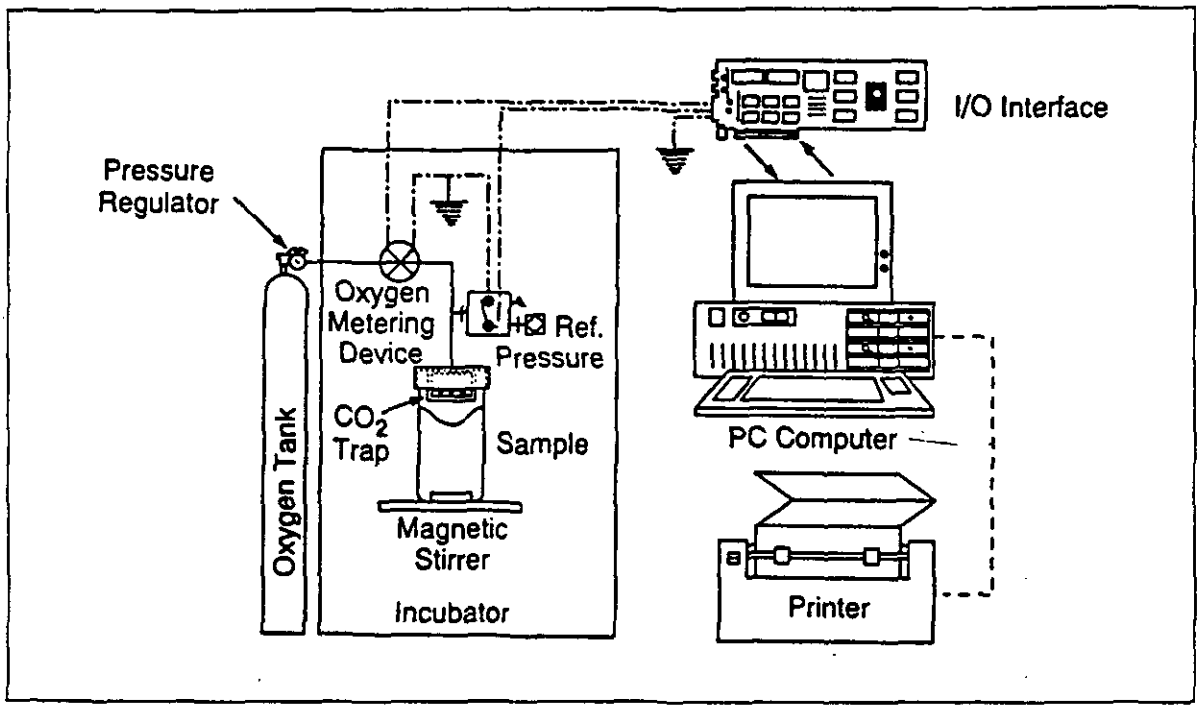

Figure 3.3 Scheme of a Constant Pressure Respirometer[36] Used During Experiments 2, 3 and 4.

3.4.1.1.4 pH

A volume of approximately 300 ml of sample was placed in a beaker, and miliQ filtered water was added until sample was covered by water. pH was determined by using a pH glass electrode. For experiments 1 and 2 a Fisher Accumet pH meter model 630 was used.

3.4.1.1.5 Ammonia content

Ammonia content was determined from compost solid phase by macro Kjeldahl method as described in Standard Methods, 4500- N_{org} $B_{(1)}$.

3.4.1.1.6 Total Kjeldahl nitrogen

Total nitrogen was determined by macro Kjeldahl method as described in Standard Methods 4500- N_{org} $B_{(1)}$.

3.4.1.1.7 Organic nitrogen

Organic nitrogen was determined by subtracting ammonia concentration from the total nitrogen concentration.

3.4.1.1.8 Total carbon

Total carbon (TC) in solid phase was determined by calculating the 55 % of volatile solids according with Golueke *et al.*(22).

3.4.1.1.9 C/N ratio

The C/N ratio in solid phase was calculated by dividing the total carbon concentration by the total Kjeldahl concentration according to Golueke *et al.*(22).

3.4.1.2 Analyses on water extract

Water extract was prepared based on the method described by Chanyasak and Kubota(5). One hundred and fifty milliliters of miliQ filtered water, at 60°C, was added to thirty grams of compost. The suspension was mechanically mixed for 30 minutes with a magnetic stirrer. Then, suspensions were vacuum filtered through Watman No.1 filter paper and then through a sterile membrane (0.45 μm pore size). A water extract solution

(1/10 dilution) was prepared for analysis. Samples were adjusted to a pH equal to 4, and stored at -4 °C until total organic carbon and nitrogen determinations were performed.

3.4.1.2.1 Ammonia content

Ammonia content was determined from the water extract solution by the Direct Nesslerization Method, as described in Standard Methods, 4500- NH_3 $C_{(1)}$. Ammonia determinations were performed using water extract solutions previously defrosted (see water extract solutions above). Absorbance readings were performed at 450 nm wavelengh using an one centimeter path light in a Hewlett Packard Diodo array spectrophotometer. A standard curve was prepared every time samples were measured.

3.4.1.2.2 Total Kjeldahl nitrogen

Total nitrogen Kjeldahl (TKN) was measured from the water extract solution. Water extract solutions were first digested following the 8075 Hatch Kjeldahl method$_{(27)}$ to convert organic nitrogen to ammonia. Once samples were digested, pH was adjusted to a value of 4, and stored at -4 °C in clear glass bottles sealed with parafilm. Ammonia levels were determined by Direct Nesslerization method as described above.

3.4.1.2.3 Organic nitrogen

Organic nitrogen was determined by subtracting ammonia concentration from the total nitrogen concentration.

3.4.1.2.4 Total organic carbon

Total organic carbon (TOC) was measured from the water extract solution by the "combustion infrared method", as per Standard Methods 5310 $B_{(1)}$. Water extract solutions were prepared as described above. Water extract solutions were defrosted and pH was reduced to a value of 2 with sulfuric acid. Samples were purged with nitrogen purified gas for about five minutes before samples were injected to the TOC analyzer. A Dohrmann carbon analyser was used for this measurement.

3.4.1.2.5 C/N ratio

C/N ratio in water extract was calculated as described by by Chanyasak and Kubota[5], by dividing the TOC concentration by the organic nitrogen concentration.

3.4.2 Phytotoxicity studies

In order to determine compost phytotoxicity, plant assays were performed using samples obtained during the experiments. The goal of the plant assays was to determine the effects of compost maturity on turfgrass. Two different assays were performed: 1) to determine the effect of compost on turfgrass seeds (seedling study) and, 2) to determine the effect of compost on established turfgrass (established turfgrass study). A detailed description of both studies is presented in the following section.

3.4.2.1 Seedling study

The objective of this study was to determine the phytotoxic effects of compost on three different turfgrass species seeds when compost was used as a growth media. Compost samples of different ages, collected during each of the four samplings were used. Thus there were four different seedlings studies in total. The parameters considered to evaluate the phytotoxic effects were: percentage of germination, percentage of ground cover, germination delay, and fresh clipping weight. Three different turfgrass species were tested: Kentucky bluegrass(kbg), (*Poa pratensis* **L.**), creeping bent grass(cbg), (*Agrostis palustris* **Huds.**), and tall fescue (tf), (*Festuca arundinacea* **Schreb.**) These three species represent different turfgrass qualities: tall fescue is best known as good utility turfgrass; and creeping bent grass is a fine textured grass that is the mostly used for golf and bowling greens. Kentucky blue grass falls in between the other two grasses. To show the differences among these species, some distinguishing characteristics are summarized in **Table 3.4.**

The following cultivars were used: a bacron cultivar for Kentucky blue grass, a Penncross cultivar for creeping bentgrass and a tall fescue cultivar. Pots were prepared in the following manner: square pots 5 cm by 5 cm by 5 cm (2 inch by 2 inch by 2 inch),

Table 3.4

Differences Among Turfgrasses Species(47).

Characteristic	range ranking	Species		
		Kentucky blue grass	Creeping bent grass	Tall fescue
Establishment rate	fast to slow	3	2	1
Leaf Texture	coarse to fine	2	3	1
Shoot Density	high to low	2	1	3
Cold Tolerance	high to low	2	1	3
Heat tolerance	high to low	3	2	1
Drought tolerance	high to low	2	3	1
Soil Acidity Tolerance	high to low	3	2	1
Submersion Tolerance	high to low	3	1	2
Salinity tolerance	high to low	3	1	2
Mowing height	high to low	2	3	1
Mowing quality range	good to poor	1	2	3
Fertility requirement	high to low	2	1	3
Disease potential	high to low	2	1	3
Thatching tendency	high to low	2	1	3
Wear resistance	high to low	1	2	2
Recuperative Capacity	high to low	2	1	3

Ranking numbers: 1 to 3, being 1= faster, higher, coarser, better .

were filled with compost for each treatment in triplicate. Each treatment corresponds to one of the compost ages in each experiment. For controls, grace-saerra and metromex were used as cultive earth. Distilled water was added to each pot until the water began to drain. Using a fork, lines where traced into the surface and seeds were scattered. Surfaces were smoothed using the base of a beaker. A specific amount of seeds of each cultivar were added to the pots. **Table 3.5** shows the amount of the three different cultivar seeds that were added to the pots. Pots were arranged randomly in a "convaron" incubator at 24 °C. Pots received periods of light lasting 14 hours during the day (at 24 °C), and 10 hours during night (at 16°C). Pots were moistened twice a day.

Table 3.5

Seedling Study Data

Seed specifications	Tall fescue	Kentucky blue grass	Creeping bent grass
Amount of seeds added per pot (grams)	1	0.5	0.1
Number of seeds added per pot	500	1450	1364
Number of seeds per square inch in the pot	34	91	85

A description of the parameters determined is presented in the following sections:

Germination delay, pots were observed twice per day for any signs of germination. Once a germination sign was noticed, the date was recorded.

Percentage of Germination: Determinations were made during the second and third week of the incubation period. A plastic plate with a square perforation of one square inch was placed on the surface of each pot. By placing the perforated square on the surface, this area was isolated from the rest of the pot. Once the plate was placed, germinated seeds were enumerated. The percentage of germination was calculated by using both the numbers of seeds contained per square inch and the amount of seeds

germinated in the area observed.

Ground cover: this parameter was determined at the third and four weeks of the incubation period. The percentage of groundcover was determined by a visual estimation of the area covered in each plot.

Yield measured as clipping weight: clippings were obtained by cutting the grass up to the rim of the pot. Except for clippings of experiment one, weights were determined by weighing fresh clippings without previous drying. For experiment one, fresh clippings were dried at 60 °C for 24 hours, and then weighed. However, this procedure resulted in inaccurate observations because of the low weights recorded as well as problems presented when managing dried samples. Therefore, it was discontinued for the remaining experiments.

3.4.2.2 Established turfgrass study

This assay evaluated the impact of compost when applied to established turfgrass. Samples from the first sampling collection, at the Holyoke composting facility, were used (experiment 1). The study was similar to the one performed by Schumann *et al.*(42). Established turfgrass study tried to confirm those results (by Schumann *et al.*) as well as to study the effects of compost on established turfgrass at higher loadings. Compost was collected and processed as previously described in section 3.3.1. Compost samples where then applied to an established turfgrass at the Amherst Golf course on June 6, 1993. Experimental plots were arranged in an established Kentucky blue grass (*Proa pratensis* L.) cultivar. The turfgrass was established on silt loam soil with a pH of 6.1, and was maintained under standard management practices. The area was mowed every seven days at a cutting height of 6.4 cm. Applications of compost at two different rates of each of the five compost maturity levels were made to 1 m (3ft) by 3 m (9 ft) plots that were arranged in a randomized complete block with four replications. The low rate of application was 9,773 kg ha^{-1} (200lbs/1000ft^2) and the high rate of application was 24,434 kg ha^{-1} (500lbs/1000ft^2). The compost was evenly distributed to each plot by hand. In order to obtain yield samples, a collection of clipping samples were performed. Clipping samples were obtained after mowing them from a standard strip lengthwise through the center of

each plot. Once the clippings were collected, the rest of the plots were mowed in the same way. Fresh clippings were dried at 60°C for 24 hours and weighted. In addition to the yield determination, a qualitative examination of the compost effects on turfgrass quality was performed. The qualitative determination consisted of the observation of color,and thatch. Observations were made both among the plots with different compost age applications as well to determine the effects of the two different rates. The experimental plots were observed daily for phytotoxicity, color and growth effects following application. Using a standard color rating scale, all treatment plots were evaluated on a scale of one to five (assigning number 1 to the control and 5 to the best performance).

3.5 Statistical analyses

3.5.1 Stability parameters analyses

Pearson's correlation coefficients between the stability parameters were determined by Pearson product method using SSPS® software.Correlation coefficients were considered significantive at either $p<0.1$, $p< 0.05$, or $p<0.01$. Linear regression coefficients were determined by the least squares method using Sigma Plot® software.

3.5.2 Phytotoxicity studies

Completely randomized designs were used in all plant bioassays. Plant assay results were compiled and subject to statistical analyses, in order to determine if there was a significant difference between the turfgrass ammended with compost of different ages and controls. An analyses of variance was performed using a multiple comparison procedure by Duncan's multiple test for variables method with "SAS®" statistical sofware. Separation of means was based on the least-significant difference by Duncan's method (α =0.05). For the turfgrass seedling study, statistical analyses were performed in two different ways: 1)Analyses of variance using the average of the three turfgrass species to determine any significant differences among the compost ages, and 2) analyses of variance by species to determine the significant differences among compost of different ages in each turfgrass species.

4. Results

The present chapter includes the results and analyses of the four experiments performed, including stability analyses and plant assays. Results of experiments 1 and 2 are presented in section 4.1, since these samples were obtained from a different composting system than experiments 3 and 4. Section 4.2 includes results of the aerated static pile samples.

4.1 In-Vessel Composting Samples: Experiments 1 and 2

4.1.1 Sampling

As previously mentioned in section 3., samples for experiments 1 and 2 were collected in June and July 1993 respectively, at the in-vessel composting facility, in Holyoke, MA. Sampling methodology followed for both experiments was the same. Samples were obtained from 5 different positions along the bay, each one corresponding to a different composting age. In order to be consistent with experiments 3 and 4, these samples will be referenced in terms of their corresponding composting ages in the following sections.

4.1.2 Stability parameters

Tables 4.1 and **4.2** present a summary of the stability parameters determined from the samples collected during experiments 1 and 2 respectively. Results from the stability analyses include: analyses on solid compost, analyses on water extracts, and pathogen indicator determinations.

4.1.2.1 Analyses on solid compost

The initial moisture content of the compost at the Holyoke Composting facility was around 60%. Sample moisture analysis determined along the bay during experiment 1 and 2, showed moisture levels were drastically reduced throughout the composting process to critical points of dryness. **Figures 4.1A** and **4.2A**, show the corresponding graphs for total solids changes observed in compost samples in experiments 1 and 2 respectively. As can be observed in both graphs, a continuous drying of the compost was observed along the bay, resulting in an increase in percent total solids. For both experiments, total solids levels were higher than the optimal 40-60 %. In particular for experiment 2, a 78 % total solids was measured in 12 days old compost. Thus indicates that the microbial activity in the initial phase was highly moisture limited. Total solids percentage in both experiments decreased at points in the bay because water is added occasionally to the process in order to increase moisture levels. However, it seems that compost moisture content is not well controlled.

Volatile solids percentages in both experiments displayed a unusual pattern. **Figure 4.1B** and **4.2B** show volatile solids percentages determined in compost samples during experiments 1 and 2 respectively. For experiment 1, volatile solids percentages decreased in compost 10, 12 and 15 days old, as it would be expected. However, for samples 17 and 20 days old, volatile solids percentage are significantly increased. Similarly in experiment 2, volatile solids percentage increased except in the sample 12 days old. Such behavior is most likely due to sludge loading variation as well as problems in the sampling procedure. Due to the heterogeneous nature of the mixture it was difficult to obtain a representative sample.

TABLE 4.1

Summary of Compost Stability Parameters, Experiment 1(a)

a) Analyses on solid compost

Sample age (days)	Sample distance (m)	total solids (%)	volatile solids	Total C*	NH3-N	TKN	pH	Total C/TKN	Oxygen uptake rate (mg O2/kg TS-hr)
			(% of Total Solids)						
10	33	55.9	74.5	41	0.31	1.74	7.85	23.6	241
12	40	63.5	72.3	39.8	0.35	1.78	7.95	22.4	368
15	48	60.4	70	38.5	0.36	1.73	8.06	22.3	131
17	55	67.8	73.3	40.3	0.36	1.78	7.71	22.6	23
20	61	70	78.9	43.4	0.37	1.83	7.43	23.7	283

* considering total C as the 55% of volatile solids

b) Water Extract Analyses

Sample age (days)	Sample distance (m)	TOC	NH3-N	TKN	org N	TOC/org N
		(mg / g dry weight)				
10	33	24.7	2.71	6.19	3.48	7.1
12	40	33.4	3.6	8.07	4.47	7.5
15	48	29.6	2.89*	5.01*	2.12	13.7*
17	55	21.7	2.4	4.89	2.49	8.7
20	61	16.9	1.95	4.08	2.13	7.9

* This result is doubful

c) Pathogen indicators

Sample age (days)	Sample distance (m)	Total coliforms weeks			Fecal coliforms (E. coli) weeks		
		0	1	4	0	1	4
		(MPN of cells / g dry weight)					
10	33	4.26e3	3.8e2	1.35e6	2.3e2	3.0e1	3.0e1
12	40	2.0e2	8.0e7	1.0e7	2.0e2	1.9e2	3.0e1
15	48	8.2e4	4.0e8	2.5e6	2.0e2	2.1e2	3.0e1
17	55	2.3e3	6.0e8	1.0e8	3.0e1	3.0e1	3.0e1
20	61	5.9e4	3.0e8	1.0e8	3.0e1	3.0e1	3.0e1

(a) Holyoke Composting Facility, June 1993

TABLE 4.2

Summary of Compost Stability Parameters, Experiment 2 (a)

a) Analyses on solid compost

Sample age (days)	Sample distance (m)	total solids (%)	volatile solids (% of Total Solids)	Total C*	NH3-N	TKN	pH	Total C/TKN	Oxygen uptake rate (mg O2/kg TS-hr)
10	33	63.7	64.2	35.3	.49	1.79	7.51	19.9	454
12	40	78	56	30.8	.38	1.60	7.4	19.3	299
15	48	76.5	59.2	32.6	.42	1.55	7.45	21.0	222
17	55	72.4	60.6	33.3	.37	1.73	7.85	19.2	335
20	61	72.5	64.1	35.3	.39	1.74	7.7	20.3	185

* considering total C as the 55% of volatile solids

b) Water Extract Analyses

Sample age (days)	Sample distance (m)	TOC	NH3-N	TKN	org N	TOC/org N
		(mg / g dry weight)				
10	33	26	3.14	6.35	3.21	8.10
12	40	20.8	2.19	4.09	1.90	10.95
15	48	17.9	2.24	4.13	1.89	9.47
17	55	21.7	2.69	5.37	2.68	8.10
20	61	20.1	2.71	5.05	2.34	8.59

c) Pathogen indicators

Sample age (days)	Sample distance (m)	Total coliforms weeks			Fecal coliform (E.coli) weeks		
		0	1	4	0	1	4
		(MPN of cell / g dry weight)					
10	33	1.8e2	4.6e6	2.2e7	3.0e1	4.6e6	2.2e5
12	40	2.9e2	8.2e6	2.1e4	3.0e1	1.0e2	8.6e3
15	48	2.5e7	1.1e8	4.3e3	1.2e2	8.0e1	2.3e3
17	55	1.6e2	2.5e8	3.9e4	3.0e1	2.5e6	3.9e5
20	61	1.7e2	1.0e6	1.5e4	3.0e1	8.0e1	1.5e3

(a) Holyoke Composting Facility, July 1993

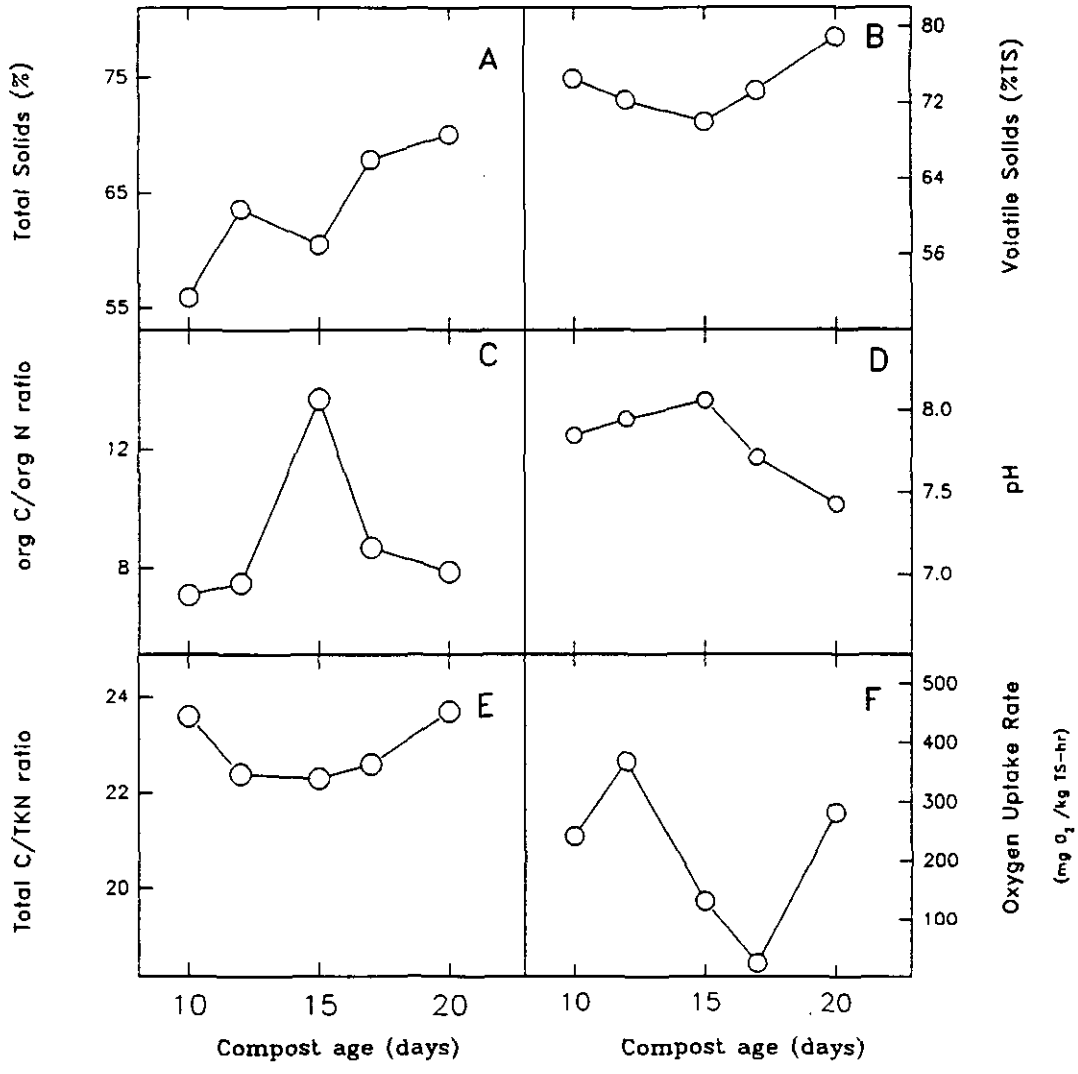

Figure 4.1 Compost Stability Parameters, Experiment 1

A) Total solids percentage, B) Volatile solids percentage, C) C/N ratio of water extract, D) pH of solid phase, E) C/N ratio of solid phase, F) Oxygen uptake rate.

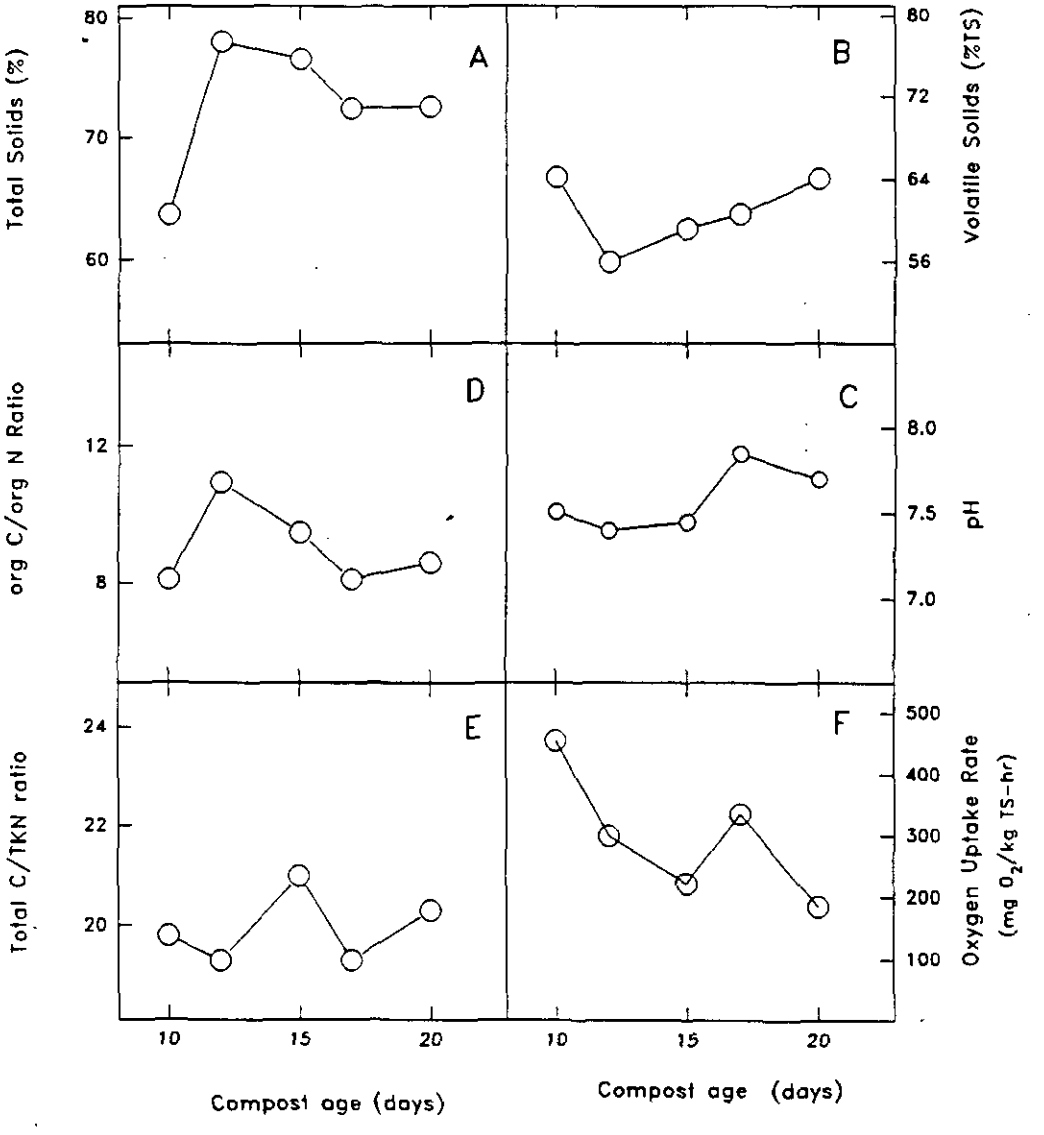

Figure 4.2 Compost Stability Parameters, Experiment 2

A) Total solids percentage, B) Volatile solids percentage, C) C/N ratio of water extract, D) pH of solid phase, E) C/N ratio of solid phase, F) Oxygen uptake rate.

The results of the pH measurements are presented in **Figure 4.1D** and **4.2D** for experiments 1 and 2 respectively. pH was in the range of 7.4-7.85 during experiment 1, and during experiment 2 was in the range of 7.43-8.03. These ranges and trends are typical for a normal composting process.

The C/N ratio of solid compost did not appear to be a good indicator of decomposition as can be seen in **Figures 4.1 E** and **4.2 E**. C/N ratios were different in both experiments, registering in the range of 28-30 for experiment 1, and 24-29 during experiment 2. The expected decreasing trends in C/N ratios were not observed in either experiment 1 or 2, and C/N ratios were relatively high in comparison with the ratios previously reported for sludge compost[5].

Oxygen uptake rates for experiments 1 and 2 are presented in **Figures 4.1F** and **4.2F**, respectively. As can be seen, these trends are not similar to each other, which can be explained as follows. First, it is important to recall that the instrument for determining oxygen uptake rate for experiment 1 differed from the one used in experiment 2. Oxygen uptake for experiment 2, was determined using an automated constant pressure respirometer over a 48 hours period, while for experiment 1, a less sophisticated constant pressure respirometer was used over a 24 hour period (see section 3.3). Although both instruments are capable of measuring oxygen uptake, there were some difficulties with the constant volume respirometer used in experiment 1. For instance, it was difficult to equilibrate the system, which can result in erroneous readings. In addition, it was difficult to maintain constant agitation in the reactor which could lead to poor oxygen transfer. Also, since oxygen must be added manually to the system, there are times when oxygen becomes limiting and thus an erroneous low uptake rate is measured. These difficulties could have contributed to the noticeable variance in oxygen uptake measurements. However, such variances could also be related to the differences in sludge composition discussed before. In any event, there was an overall decrease in oxygen uptake rate in both experiments.

Analyzing oxygen uptake rates of experiment 2, a clear decreasing trend (with the exception of 17 days old compost), can be correlated to the decomposition process. According to the parameters proposed by Wilson and Dalmot[52], compost with a oxygen

uptake of less than 100 mg O_2/ kg hr can be considered mature for field application. Final compost from experiments 1 and 2 exceeded this level. Cumulative oxygen uptake determined in experiments 1 and 2 is shown in **Figure 4.3 A** and **4.3 B**, respectively. As mentioned above, oxygen uptake measurements for experiment 1 were performed for 24 hours of incubation. Oxygen uptake was monitored for 48 hours during experiment 2. As can be seen, for experiment 2, oxygen consumption was delayed for almost five hours. This could be due to dryness, since once the sample was rewetted, a lag phase of five hours was required until the organisms began consuming oxygen.

Pathogen indicators

Densities of total coliforms and *E. coli* in each of the different compost ages as well as the results of regrowth potential are presented in **Figures 4.4** and **4.5** for experiments 1 and 2, respectively. Total coliforms and *E. coli* densities measured in both experiments, were low in general (see **Tables 4.1c** and **4.2c**). Lower densities are seen for experiment 2, which is most likely due to lower moisture levels. Particularly *E. coli* densities were low (less than 300 cell/g dw) in most of the samples analyzed in both experiments. For experiment 1 it can be observed that the MPN of total coliforms varied through the composting process. Conversely, during experiment 2, total coliform levels were almost constant with the exception of a spike in the 10 days old compost. This pattern of changes in indicator organisms also corresponds with the differences in moisture content observed in both experiments.

Although pathogen regrowth was not originally considered a stability parameter to be studied in this project, it was decided to perform these analyses with samples of experiments 1, 2 and 3. **Figures 4.4 B-C** and **4.5 B-C** show the plots of the results of pathogen regrowth in experiments 1 and 2 respectively.

Except for 10 day old compost, all compost samples obtained from experiment 1, exhibited a considerable regrowth of total coliforms to a level of 6e8 cell/g dry weight after the first week of incubation. In general, there was not a significative decrease in densities after four weeks of incubation. *E.coli* regrowth was not observed in any of the samples. The highest population density was 2e2 cells/g dw after one week of incubation.

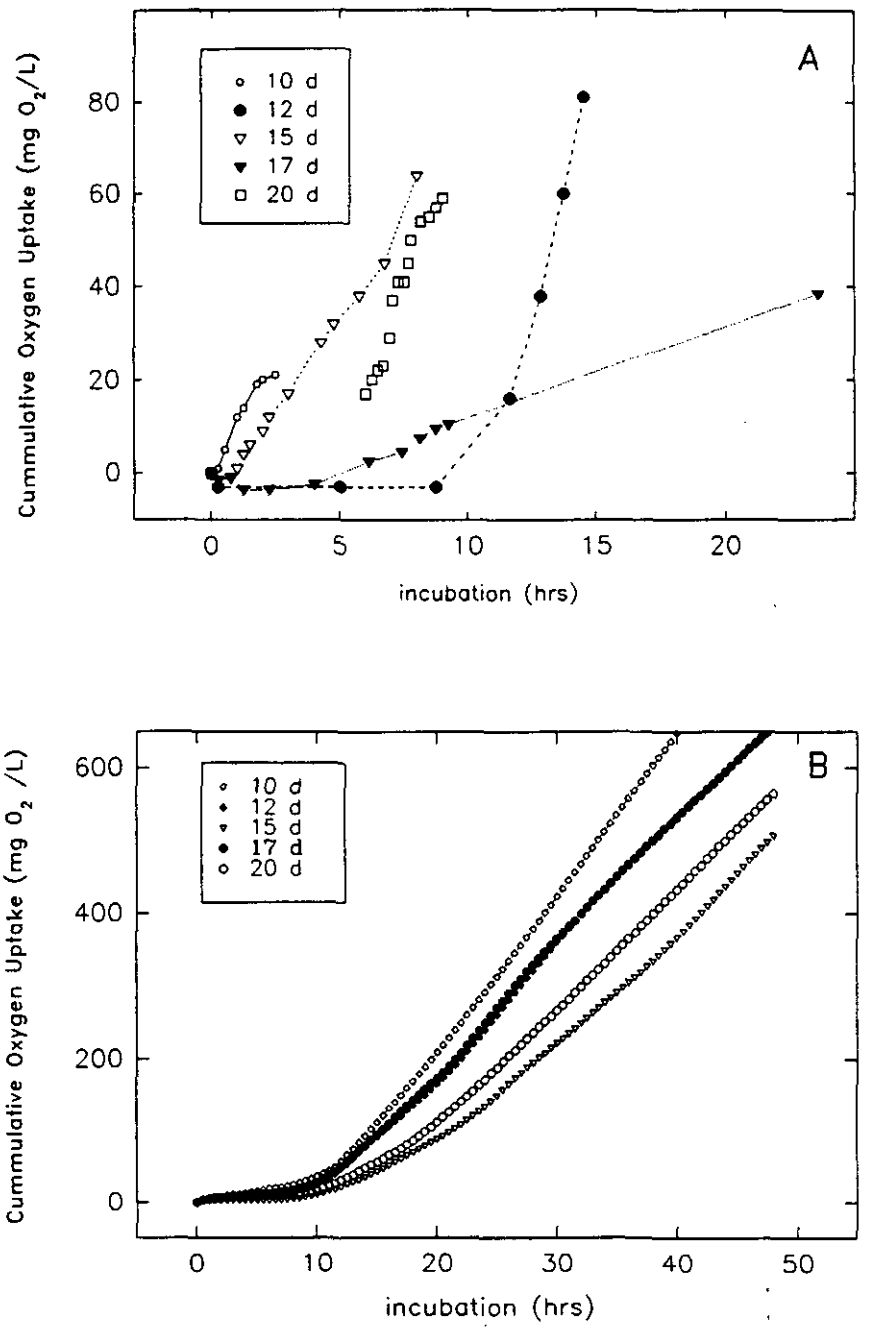

Figure 4.3 Cummulative Oxygen Uptake, Experiments 1 and 2

A) Experiment 1, B) Experiment 2.

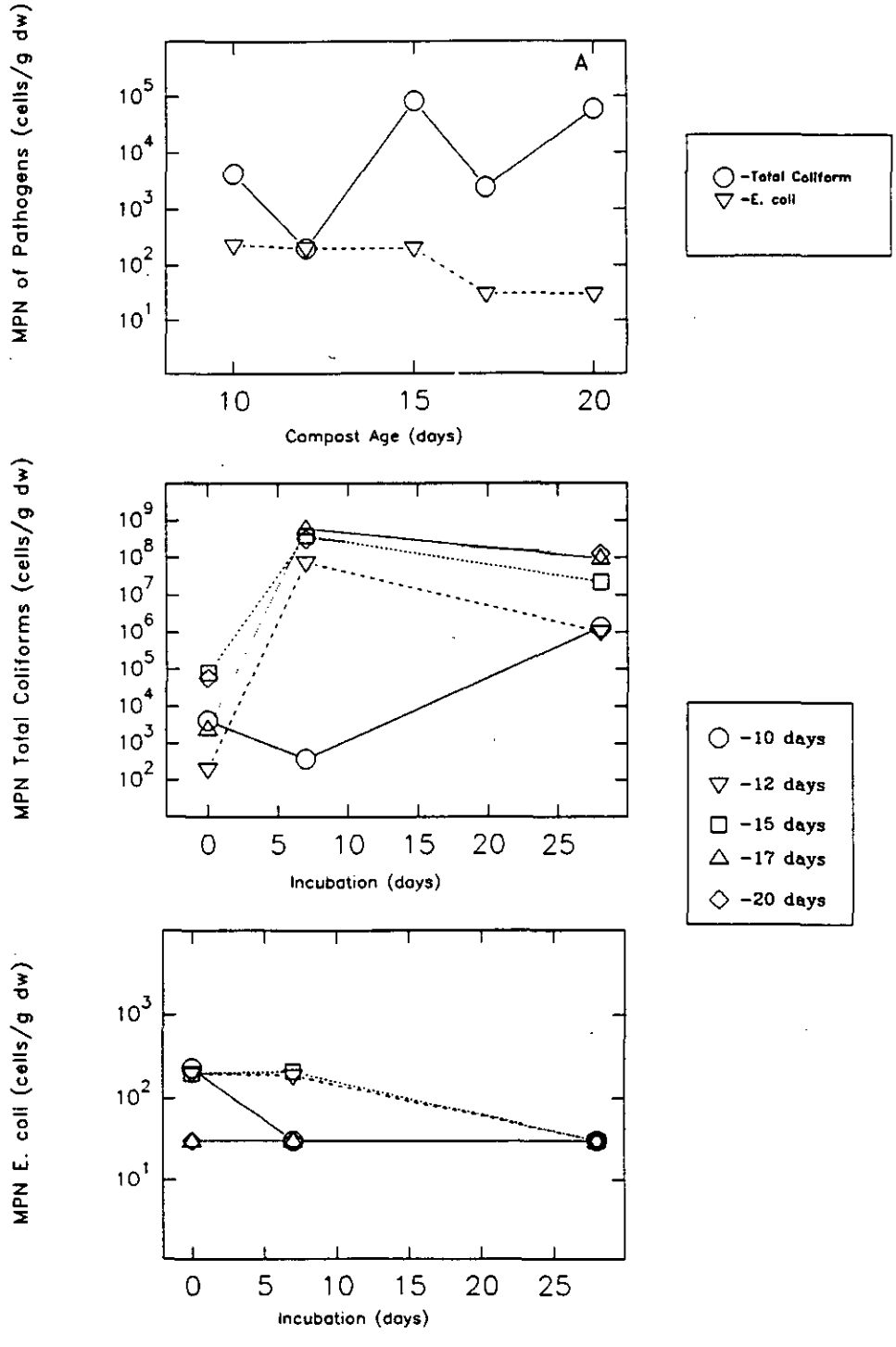

Figure 4.4 Pathogen Indicators, Experiment 1

A) Pathogen indicators density, B) Total coliforms regrowth, C) Fecal coliforms regrowth.

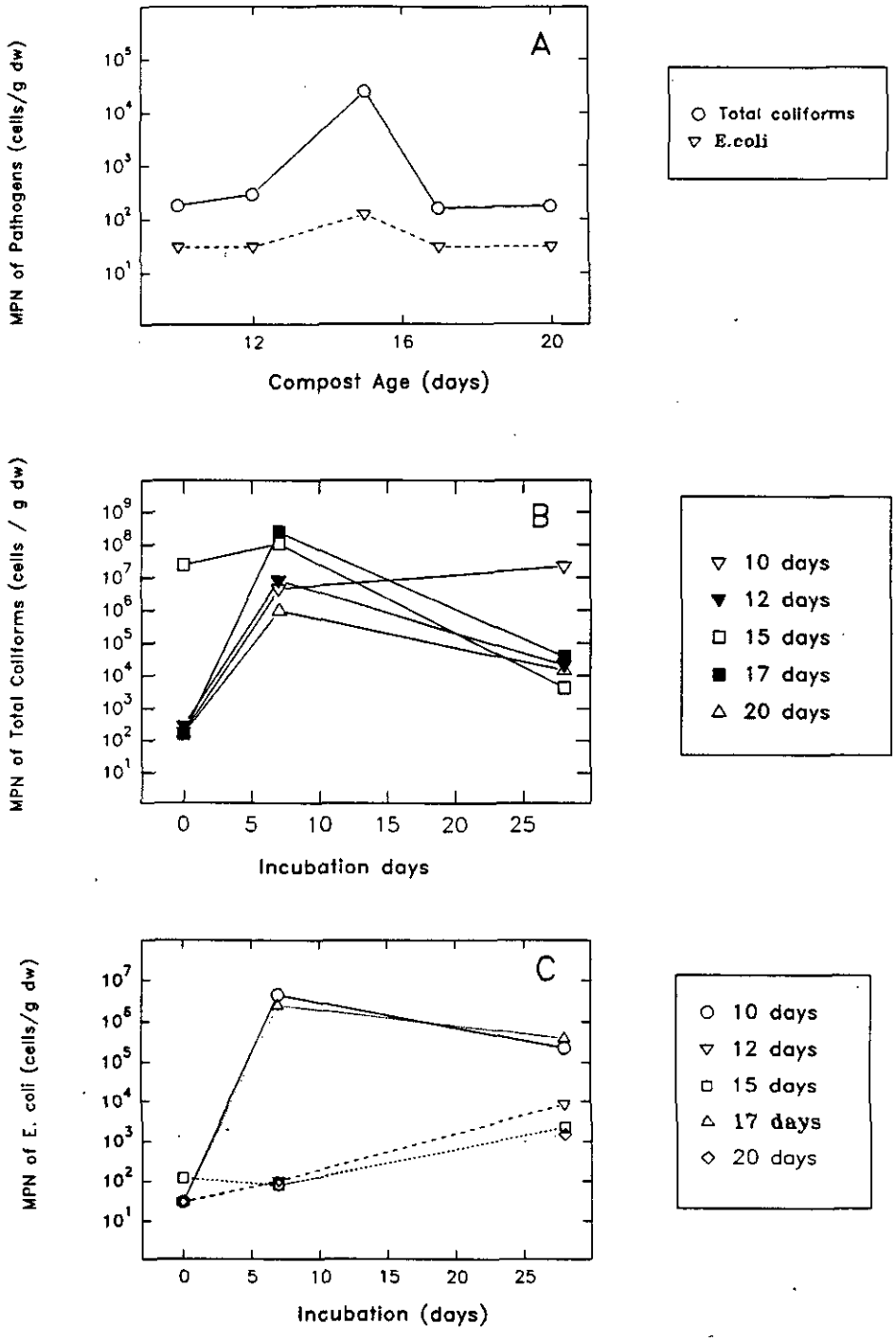

Figure 4.5 Pathogen Indicators, Experiment 2

A) Pathogen indicators density, B) Total coliforms regrowth, C) Fecal coliforms regrowth.

After four weeks, *E.coli* density was less than 100 in all samples. Therefore, in terms of the pathogen indicator parameter, compost samples from experiment 1, were stable in terms of pathogens at both ambient levels and regrowth potential.

Total coliforms regrowth patterns in experiment 2 were somewhat similar to the ones obtained in experiment 1. Total coliforms showed a large increase in their densities (up to 2.5e8 cells/g dw) after seven days of incubation. After four weeks, total coliforms levels decreased in all compost ages to less than 4e4 cells/g dw, except for compost age 10 days which increased to 2e7 cells/g dw. Conversely with experiment 1, *E. coli* densities increased in all compost ages during the 4 weeks of incubation. For compost 10 and 17 days old, *E. coli* densities increased five orders of magnitude after 7 days of incubation. After four weeks, *E.coli* densities were higher than 1e3 in all compost samples. The regrowth is mostly likely due to low moisture levels during experiment 2, in comparison with experiment 1.

Regrowth of pathogens in compost is often related to available nutrients (14,23,30). Based on the regrowth results obtained, it can be said, that there was more substrate available in samples from experiment 2 than in experiment 1. Moisture management is very important for proper operation of a composting process. The dry condition in experiment 2 led to compost which showed low levels of *E. coli*., but once moisture was added, the *E.coli*. regrew. In addition, a dry compost would have a low microbial population diversity. This would also lead to poor competition with *E. coli*. for available substrate, and encourgage regrowth.

Although all final compost samples comply with the requirement for class A quality in terms of pathogens(48), it is important to notice the great potential for regrowth. Regrowth, in the case of *E. coli* could be a great consideration in terms of product quality, since the 40 CFR 503 regulations require analysis to be performed near the point of use of the compost.

Based on the complexity of a compost system, sampling methodology is very important. Although sampling methodology used in experiments 1 and 2 did not present any technical problems during its performance, there may still be problems due to the

heterogeneity of the system. In addition, since this is a dynamic system, (sludge is fed every day) sludge characteristics vary from day to day.

4.1.2.2 Analyses on water extract

C/N water extract ratios were in the range of 8 to 14 along the composting process (see **Figures 4.1 C** and **4.2 C**). Considering that a C/N in the range of 5 to 6, denotes stability$_{(5)}$, none of the samples, can be considered stable.

Water extract ammonia concentrations (see **Figure 4.6B** and **4.6D**) in both experiments ranged from 0.20 to 0.35%. However, trends observed during the composting process in both experiments are not similar to each other. Ammonia concentrations during experiment 1 tended to decrease (except for compost 12 days), while ammonia levels were maintained during Experiment 2. TOC water extract determinations in in-vessel experiments, show a more predictable pattern during the process. For both experiments, TOC concentrations were in the ranges of 1.95-3.6 % dry weight during experiment 1, and 2.19-3.14% dw during experiment 2. As can be seen in **Figures 4.6A** and **4.6C**, TOC variations seem to correlate with the decomposition process.

4.1.2.3 Correlation between stability parameters and compost age

Pearson's correlation coefficients between the different stability parameters and composting time are presented in **Table 4.3**. In general, there was a poor correlation between the stability parameters and composting time in both experiments. Total solids and fecal coliforms were correlated with composting time during experiment 1 (**Table 4.3a**), while for experiment 2 there was no significative correlation between stability parameters and composting time (**Table 4.3 b**). As these table shows, there were cases in which some stability parameters correlated well among each other in both experiments. However, the correlations observed in experiment 1 are not the same as the ones observed in experiment 2, except for one case. In both experiments, total organic carbon and ammonia content in water extract presented a good correlation among each other.

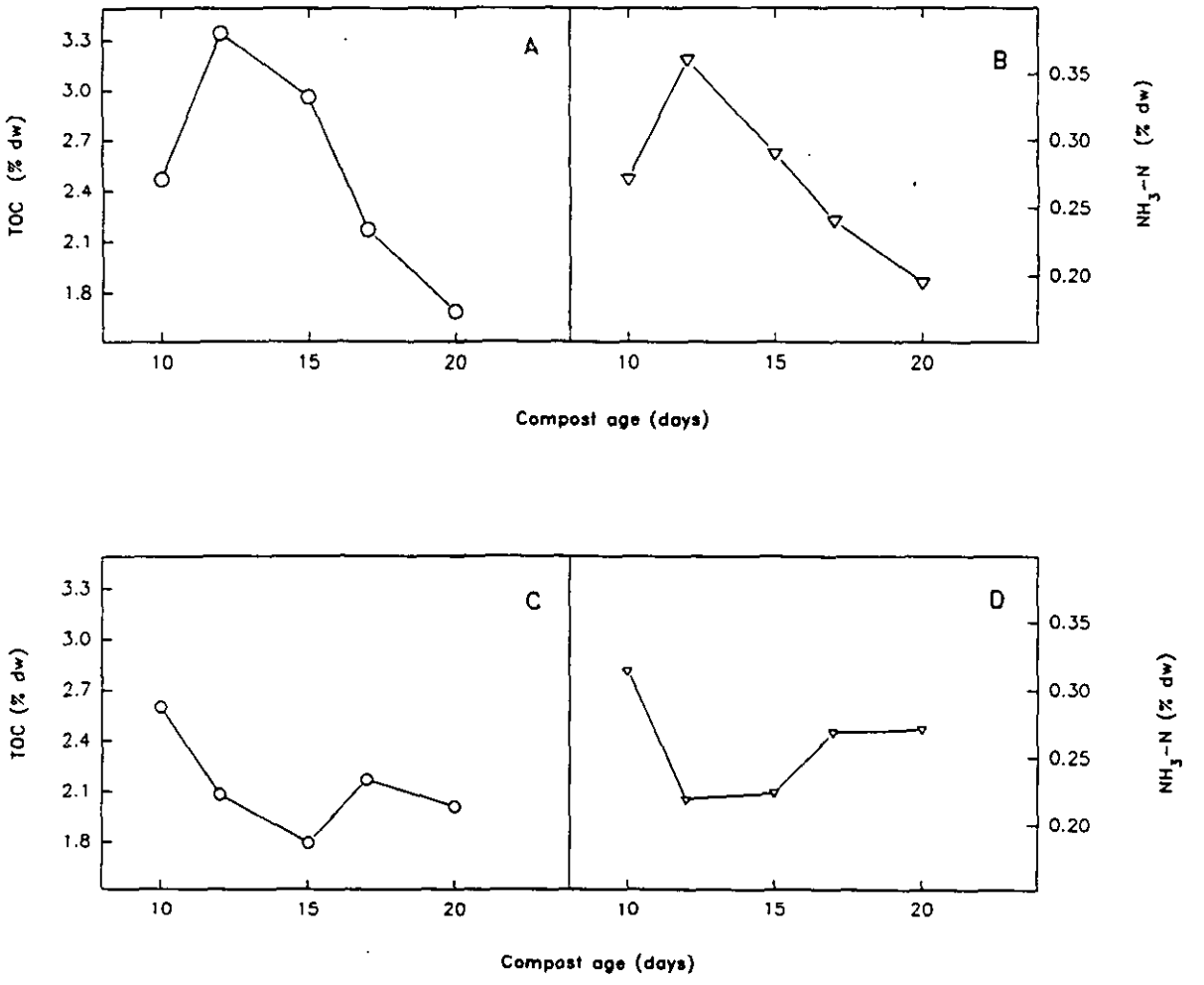

Figure 4.6 TOC and Ammonia Content in Water Extract, Experiments 1 and 2

A) Total organic carbon content, and B) Ammonia content during Experiment 1;

C) Total organic carbon content, and D) Ammonia content during Experiment 2.

Table 4.3

Correlation Coefficients[+] between Stability Parameters, Experiments 1 and 2

	C age	TS	VS	Oxup	TotC	FeC	C/Nsol	pH	C/Nwe	Am-we	TOC-we
a) Experiment 1											
C age	1										
TS	.8788*	1									
VS	.4390	.3899	1								
Oxup	.2995	-.1071	.3162	1							
TotC	.5064	.1317	-.0036	-.1125	1						
FeC	-.8904**	-.9019**	-.5238	.3751	-.0744						
C/N sol	.1325	-.0119	.9103**	.639	-.0267	-.2152	1				
pH	-.7067	-.6905	.9146**	-.0417	-.0127	.8289*	-.7056	1			
C/N we	.2223	-.0671	-.6143	-.5097	.7516	.1137	-.5837	.4799	1		
Am-we	-.7309	-.4637	-.7154	.3912	-.3267	.7479	-.6454	.8203*	.0409	1	
TOC-we	-.6917	-.5260	-.8359*	.2480	-.1300	.7904	-.7305	.9259**	.2824	.9671**	1
b) Experiment 2											
C age	1										
TS	.3427	1									
VS	.2730	-.7941*	1								
Oxup	-.7637	-.7330	.1925	1							
TotC	.0282	.4049	-.2942	-.4093	1						
FeC	.0282	.4049*	-.2942	-.4093	1	1					
C/N sol	.7265	.0134	.5262	-.6513	-.1111	-.111	1				
pH	.6817	-.1902	.5099	-.0607	-.3924	-.3924	.2822	1			
C/N w	.2223	.4898	-.2931	-.4897	.9620***	.9620***	-.0925	-.1578	1		
Am-we	-.1206	-.9685***	.8228**	.6219	-.5070	-.5070	.1344	.4099	-.5360	1	
TOC-we	-.5893	-.8743*	.4633	.9130**	-.6470	-.6470	-.2976	.0584	-.7374	.8169*	1

+ Pearson's correlation coefficient; * p<0.1, ** p<0.05, ***p<0.01

C age=compost age; TS=total solids, VS=volatile solids; Oxup=oxygen uptake rate; TotC= total coliforms; FeC= fecal coliforms; C/N sol= C/N ratio in solid phase; *C/N we= C/N ratio in water extract;* Am-we= *ammonia content in water extract;* TOC-we= total organic carbon in water extract.

4.1.3 Phytotoxicity studies

As previously mentioned in section 3.4.1.2, compost phytotoxicity in turfgrass seeds was determined in both experiment 1 and 2. In addition, a plant assay to determine compost effects on established turfgrass was performed using compost collected in experiment 1.

4.1.3.1 Seedling study, Experiment 1

Results from the seedling study using compost samples from experiments 1 and 2 were very similar. In general there was a negative effect of compost on turfgrass seeds, however no significant differences were observed among the different compost ages.

a) Average of the three species

An average of the effects on the three turfgrass (composite) species is presented in **Table 4.4**. From these results it can be seen that all compost treatments regardless of age, resulted in delayed germination, reduced percent germination, recuced percent ground cover, and reduced growth as measured by fresh weight of clippings. There was no difference between the phytotoxic effects among the different compost ages, except in the germination delay parameter. Samples corresponding to 10 days old, caused significantly more detrimental effects on seed germination delay, while effects of compost of 20 days old was less significantly severe. Differences among species were observed, as tall fescue was the least sensitive to the negative effects of compost treatments. Kentucky bluegrass was the most susceptible to phytotoxic effects.

b) By each species:

Effects of compost treatments on each species are presented in **Table 4.5**. A brief summary of the effects on each species is presented in the following paragraphs.

Kentucky blue grass (kbg) was severely affected by 10 day old compost, which almost tripled the time to first germination (in comparison with the control). During weeks 1 and 2, there were no differences in the effects on germination percentage caused by the different compost ages. However, at week 12 day old compost of was significantly less

Table 4.4

Statistical Analyses of Seedling Study (by average of species), Experiment 1

Sample age (days)	Sample distance (meters)	Days to first germination		% Germination w1		% Germination w2		% Germination w3	
Control		a	5.1	a	43.0	a	79.6	a	85.9
10	33	d	11.1	b	0.0	b	21.0	b	32.5
12	40	bc	8.9	b	1.3	b	27.2	b	40.5
15	48	bc	8.6	b	1.6	b	38.0	b	41.1
17	55	c	9.6	b	0.1	b	21.5	b	34.5
20	61	b	8.2	b	2.9	b	27.2	b	40
kbg		b	12.1	c	0.3	c	13.1	c	18.84
cbg		a	6.9	b	9.7	b	33.6	b	44.4
tf		a	6.9	a	14.4	a	60.4	a	74.4

Sample age (days)	Sample distance (meters)	Clipping weight (g) w2		Clipping weight (g) w3		% Ground cover w2		% Ground cover w3	
Control		a	0.572	a	0.927	a	90.6	a	95.4
10	33	b	0.105	b	0.357	b	33.9	b	35.0
12	40	b	0.161	b	0.351	b	27.8	b	39.4
15	48	b	0.175	b	0.427	b	37.8	b	48.3
17	55	b	0.114	b	0.378	b	29.4	b	40.6
20	61	b	0.146	b	0.354	b	28.3	b	36.1
kbg		b	0.098	c	0.165	b	27.8	b	41.7
cbg		b	0.153	b	0.262	a	47.5	a	53.3
tf		a	0.386	a	0.970	a	48.6	a	52.5

means with the same letter are not significantly different
Duncan's Multiple test for variables, alpha=0.05, SAS
w=weeks

Table 4.5
Statistical Analyses of Seedling Study (by species), Experiment 1

% Germination

Sample age (days)	distance (m)	kbg w1	kbg w2	kbg w3	cbg w1	cbg w2	cbg w3	tf w1	tf w2	tf w3
control		a 0.22	a 72.5	a 67.3	a 51.3	a 66.2	a 90.6	a 75.5	a 86.3	a 100
10	33	b 0	b 0.37	c 3.6	b 0	b 20.4	b 28.2	b 0	a 42.1	b 65.7
12	40	b 0	b 1.06	b 19.8	b 0	ab 24.7	b 28.2	b 3.9	a 55.9	b 73.5
15	48	b 0	b 2.9	c 6.4	b 0	ab 34.5	b 38.1	b 4.8	a 76.5	b 73.5
17	55	b 0	b 1.8	bc 11.7	b 0.4	ab 27.4	b 31.4	b 0	a 35.3	b 67.6
20	61	b 0	b 0	c 3.3	b 7	ab 28.6	b 50.2	b 1.9	a 52.9	b 66.6

Clipping weight (g)

Sample age (days)	distance (m)	kbg w1	kbg w2	kbg w3	cbg w1	cbg w2	cbg w3	tf w1	tf w2	tf w3
control		a 0	a 0.28	a 0.55	a 0.74	a 0.33	a 0.78	a 3.1	a 1.12	a 1.45
10	33	a 0	c 0	b 0.08	b 0	b 0.17	b 0.14	b 0.15	b 0.2	b 0.85
12	40	a 0	b 0.1	b 0.1	b 0	b 0.11	b 0.17	b 0.19	b 0.28	b 0.79
15	48	a 0	b 0.06	b 0.09	b 0	b 0.13	b 0.18	b 0.22	b 0.33	b 1
17	55	a 0	b 0.06	b 0.09	b 0	b 0.11	b 0.15	b 0.11	b 0.17	b 0.89
20	61	a 0.22	b 0.09	b 0.08	b 0	b 0.12	b 0.15	b 0.1	b 0.23	b 0.83

% Ground cover

Sample age (days)	distance (m)	kbg w2	kbg w3	cbg w2	cbg w3	tf w2	tf w3
control		a 96.7	a 100	a 90	a 95	a 85	a 91.7
10	33	b 6.67	bc 18.3	b 43.3	b 45	c 31.7	b 41.7
12	40	b 20	b 45	b 30	b 35	bc 36.7	b 38.3
15	48	b 18.3	b 43.3	b 43.3	b 57.7	b 51.7	b 50
17	55	b 13.3	bc 28.3	b 35	b 43.3	bc 40	b 50
20	61	b 11.7	c 11.7	b 43.3	b 50	c 30	b 43.3

means with different letters are not significantly different
Duncan's Multiple test for variables, alpha=0.05, SAS
w=weeks

damaging than other compost ages. Severe effects were observed in the rest of the treatments, as a reduction of 91%, was determined. Compost of 12 days old was less negative in terms of germination percentage.

Percent ground cover ranged from 12% to 45% in compost treatments compared to 100% for the controls. In this case, significant differences were observed in weeks 2, and 3, 10, and 12 day old compost was the most toxic with respect to the other compost treatments. Growth differed significantly from the controls for all compost treatments for all clipping dates.

Creeping bent grass (cbg) controls averaged 91% percent germination at week three, compared with 28% to 50% germination in the compost treatments. No significant difference in effects on ground cover percentage among the different compost ages was observed in week 2, but in week 3 compost 12 and 20 days old, significantly caused the most detrimental effects by reducing ground cover by 40%. Seed germination was delayed by three days for the compost treatments and growth was significantly reduced at all clipping dates.

In the **tall fescue (tf)** treatments, percent germination was significantly affected in week 1 and 3 by all compost treatments which ranged from 66% to 75% germination as compared to 100% for the controls. However, compost treatments were not significant different among each other. At week 2, negative effects of compost ages were suppressed and no significant differences with controls was observed. Overall, percentage of germination was reduced by the compost by 25 to 30%. Percent ground cover after four weeks ranged from 35 to 50% in compost treatments, which was significantly less compared to 95% in controls. Germination was delayed by three days for the compost treatments. Growth did not differ significantly among the five compost ages, but was significantly less than the control at all clipping dates.

4.1.3.2 Seedling study, Experiment 2

a) Average of the three species

Results from the second plant study on turfgrass seeds, closely paralleled those of the first study. **Table 4.6**, summarizes the results of the plant study based on an average of the three species effects. Total values for percent germination and percent ground cover were lower throughout the experiment; perhaps the result of pots being allowed to dry out at a critical time. Percentage of germination was decreased to almost half of the controls in the seeds treated with compost with no significant difference among compost ages except at week 3. During week 3, 17 day old compost of was significantly the most harmful to seeds. Effects on ground cover at week 2 shows some sensitivity to compost age, as 17 day old compost was more harmful than 10 day old compost. However, these differences were no longer observed at week 3. Overall, **kbg** was the most sensitive species, followed by **cbg**.

b) By each species:

Results of the effects of the different compost ages on each turfgrass species are presented in **Table 4.7**. In general, for **kbg** and **cbg**, all compost ages produced negative effects on % of germination, clipping weight, and % of ground cover, but no significant difference was observed among the different compost ages.

Kbg germinated only 3% to 12% in compost treatments with no significant differences among them but significantly less than controls. Percent ground cover ranged form 4% to 12% in compost treatments, significantly less than 50% in controls. Percent ground cover ranged without significant difference from 40% to 80% in compost treatments as compared to 88% in controls. Growth as measured by fresh weight of clippings was severely limited by compost, but no significant differences among the compost ages was observed.

Cbg germinated between 40% to 70% in compost treatments as compared to 78% in controls. All compost caused a significant reduction of up to 45% in ground with respect to the controls. However at week 2 there were no differences between 10 days

Table 4.6
Statistical Analyses of Seedling Study (by average of species), Experiment 2

% Germination

Sample age (days)	Sample distance (meters)	w1		w2		w3	
Control		a	56.1	a	64.0	a	65.5
10	33	b	29.6	b	39.0	ab	53.4
12	40	b	30.9	b	29.8	bc	38.8
15	48	b	30.6	b	23.5	bc	40.3
17	55	b	2501.0	b	29.7	c	33.6
20	61	b	29.7	b	30.6	bc	42.0
kbg		c	3.1	c	6.7	c	13.1
cbg		b	37.0	b	41.3	b	49.3
tf		a	60.9	a	60.3	a	74.8

Clipping weight (g)

Sample age (days)	Sample distance (meters)	w1		w2	
Control		a	1.316	a	1.836
10	33	b	0.232	a	2.921
12	40	b	0.292	a	0.437
15	48	b	0.17	a	0.44
17	55	b	0.113	a	0.243
20	61	b	0.285	a	0.483
kbg		c	0	a	1.318
cbg		b	0.228	a	0.559
tf		a	0.9759	a	1.303

% Ground cover

w1		w2	
a	65.0	a	70.0
b	34.7	b	45.0
cb	26.3	c	31.8
cb	25.3	c	43.9
c	19.8	c	27.3
cb	31.3	b	43.9
b	7.9	b	11.9
a	47.5	a	59.4
a	45.8	a	53.9

means with the same letter are not significantly different
Duncan's Multiple test for variables, alpha= 0.05, SAS
w=weeks

Table 4.7
Statistical Analyses of Seedling Study (by species), Experiment 2

% Germination

Sample age (days)	distance (meters)	kbg w2		w3		w4		cbg w2		w3		w4		tf w2		w3		w4	
control		a	17.2	a	33.7	a	44.7	a	63.9	a	78.0	ab	57.6	a	87.2	a	80.9	a	94.1
10	33	b	0.3	b	1.1	b	9.2	ab	24.7	ab	48.2	a	69.8	a	63.7	ab	67.6	a	81.4
12	40	b	0.0	b	0.0	b	2.6	b	32.9	b	20.8	b	37.6	a	59.8	ab	68.6	a	76.4
15	48	b	0.0	b	0.3	b	11.4	ab	36.9	b	36.8	ab	49.8	a	54.9	a	33.3	a	59.8
17	55	b	0.7	b	2.2	b	0.3	b	24.3	b	34.9	b	39.6	a	50.0	ab	51.9	a	60.8
20	61	b	0.0	b	2.9	b	10.3	ab	39.2	b	29.0	b	41.3	a	50.0	ab	59.8	a	74.5

Clippings weight (g)

Sample age (days)	distance (meters)	kbg w3		w4		w2	cbg	w3		w4		w2	tf	w3		w4	
control		a	0.521	a	0.772	a	0.905	a	2.05	a	2.11	a	3.04	a	2.88	a	1.9	
10	33	b	0.007	b	0.022	b	0.141	b	0.475	b	0.609	b	0.554	bc	0.948	b	1.15	
12	40	b	0.001	b	0.014	b	0.089	b	0.196	b	0.222	b	0.786	bc	1.11	bc	0.91	
15	48	b	0.026	b	0.047	b	0.119	b	0.274	b	0.466	b	0.392	bc	1.02	b	1.18	
17	55	b	0.008	b	0.015	b	0.057	b	0.159	b	0.263	b	0.283	c	0.561	c	0.656	
20	61	b	0.008	b	0.058	b	0.057	b	0.144	b	0.273	b	0.796	b	1.29	bc	1.01	

% Ground cover

Sample age (days)	distance (meters)	kbg w2		w3		w2	cbg	w3		w2	tf	w3	
control		a	40.0	a	43.3	a	85.0	a	88.3	a	70.0	a	78.3
10	33	b	0.7	b	3.7	a	66.7	a	81.7	b	36.7	bc	50.0
12	40	b	0.7	b	5.3	b	30.0	b	36.7	b	48.3	b	53.3
15	48	b	1.0	b	6.7	b	38.3	b	50.0	b	36.7	bc	45.0
17	55	b	1.0	b	5.3	b	28.3	b	43.3	b	30.0	c	33.3
20	61	b	4.0	b	11.7	b	36.7	b	56.7	ab	53.3	ab	63.3

means with the same letter are not significantly different
Duncan's Multiple test for variables, alpha=0 05, SAS
w=weeks

and the control. Growth in compost treatments was significantly reduced at all clipping dates.

As in experiment 1, **tf** germination was not negatively affected by any of the compost ages. Percent ground cover ranged from 33% to 63% in compost treatments, significantly lower than the controls, but no significant differences among compost ages was identified. Growth in compost treatments was significantly less than the controls at all clipping dates.

4.1.3.3 Established turfgrass study, Experiment 1

As previously mentioned, effects of compost application on established turfgrass were evaluated by several quality parameters including growth, shoot density and color. As it was done with seedling studies results, a statistical analysis was performed to determine significant differences among controls and compost treatments. **Table 4.8** summarizes the results of the established turfgrass study.

As **Table 4.8** shows, there were significant differences in quality rating between controls and compost treatments, as well as among treatments. However, significant differences were not found to be correlated with either compost age or application rate. Overall, established turfgrass quality was enhanced by the application of compost at both low and high rates, and by compost of different ages. Although some phytotoxic effects were observed in some of the samples, there was no correlation with either compost age or application rate. Established turfgrass was much less sensitive to any inhibitory effects of unstable compost than seeds.

Results of this particular study, were consistent with the results obtained by Schumann *et al.*(42). They conducted a similar study in the summer of 1992, to determine the effects of compost application on established turfgrass. Sampling methodology as well as the managing of the samples were performed with the same methodology as we used in this study. Compost samples were obtained from the same composting facility (Holyoke, MA) as in this study. The compost was applied over established tall fescue, and over an

Table 4.8

Quality Rating* and Statistical Analyses of Established Turfgrass Study, Experiment 1.

Sample (days)	distance (m)	1 week	2 weeks	3 weeks	4 weeks
	Low application (9773 kg ha^{-1})				
10	33	3.25 **AB**	2.75 **AB**	2.75 **BC**	2 .0 **B**
15	48	3.75 **A**	2.75 **AB**	2.5 **C**	2.5 **AB**
20	final	3.00 **AB**	3.25 **A**	2.75 **BC**	2.0 **B**
	High application (24,434 kg ha^{-1})				
10	33	2.5 **AB**	2.0 **AB**	3.5 **AB**	3.25 **AB**
15	48	2.25 **B**	1.5 **B**	3 .0 **ABC**	3.25 **AB**
20	final	2.75 **AB**	2.25 **AB**	3.75 **A**	3.5 **A**
Non treated Control		2.5 **AB**	2.5 **AB**	2.25 **C**	2.0 **B**

*Quality rating comprises color, growth (determined as clipping weight) and density. Quality range is between 1 and 5, being 5 the best quality.
Means with same letter are not significantly different
Duncan's multiple test method, α=0.05

established mix of perennial ryegrass/Kentucky blue grass. The application rates they tested were a low application of 4,850 kg ha^{-1} (100 pounds per 1000 ft^2), and a high application rate equal to 9,700 kg ha^{-1} (200 pounds per 1000 ft^2). As can be seen, the high rate application was the same as the low rate application of this study. The results showed compost application enhanced established turfgrass quality but they did not observe a correlation between either compost age or application rate and qualitiy enhancement. **Table 4.9** summarizes the results of the established turfgrass study conducted by Schumann *et al.*(42).

4.2 Aerated Static Pile Composting Samples: Experiments 3 and 4.

As it has been mentioned, experiments 3 and 4 were performed using samples from an aerated static pile at the Hoosac Facility in Williamstown, MA.This type of static system allowed the influence of variable sludge composition to be eliminated when evaluating the effect of composting time on stability parameters.

As previously described in section 3.3.2, sampling methodology for experiments 3 and 4 differed considerably between each other. Such difference complicates the comparison between the results obtained in both experiments. For that reason, results from experiments 3 and 4 will be presented separately.

There were some variations in the stability analyses performed with respect to experiments 1 and 2, including:

1) pH, total carbon and nitrogen concentrations, on the solid phase were not determined in experiments 3 and 4 samples. Total organic and nitrogen concentrations in solid compost from the previous two experiments did not seem to be reliable stability parameters. This has been observed in others studies in our laboratory(45). Thus, it was decided not to include these determinations for the next two experiments.

2) Pathogen regrowth measurements (in experiment 4) were not performed either, due to sampling and analysis constraints.

Table 4.9

Results of Established Turfgrass Study* by Schumann *et al.*[42]

Distance(m)	Sample age (days)	Tall Fescue Clipping yield (g/m^2)	Perennial ryegrass/Kentucky bluegrass Clipping yield (g/m^2)	
		1 week	1 week	2 weeks
High application rate (4,850 kg ha-1)				
33	10	18.94 BCD	7.42 AB	6.00 A
40	12	19.28 BC	7.35 AB	6.35 A
48	15	20.79 B	7.22 AB	7.25 A
55	17	25.58 A	9.11 A	6.81 A
61	20	21.71 AB	6.68 BC	5.69 A
Low application rate (9,700 kg ha-1)				
33	10	14.43 D	6.01 BC	7.74 A
40	12	16.13 CD	7.88 AB	6.48 A
48	15	14.31 D	7.09 ABC	6.93 A
55	17	20.77 B	8.10 AB	7.02 A
61	20	14.53 D	5.94 BC	7.05 A
	Control	9.49 E	4.84 C	5.64 A

Means with same letter are not signicantly different
Duncan's multiple test for variables, α=0.05
* *compost from Holyoke Composting Facility*

4.2.1 Experiment 3

4.2.1.1 Sampling

Sampling methodology used during experiment 3, resulted in a non-representative sample of the composting bay. As previously mentioned, the area sampled was relatively small compared to the whole pile. Considering that a composting pile is quite complex and heterogeneous, sampling a small area would not allow a representative sample of the actual composting pile to be obtained. In addition, the constant removal of compost from the same site, may disturb the composting process for various reasons. To obtain the 5 liters for each sampling, required that approximately 20 liters of compost mix be screened. This volume may not be significant when the volume of compost in the whole pile is considered; however, it may be significant when the volume of the site sampled. Moreover, the excavation and then refilling of the hole again, could have provided extra aeration in that specific area in comparison with the rest of the pile. It was concluded that this sampling methodology was not appropriate. For this reason, it is quite possible that results obtained in this experiment are not representative. However, they are presented.

4.2.1.2 Stability parameters

4.2.1.2.1 Analyses on solid compost

A summary of the results of all stability parameters determined in samples from experiment 3, are listed in **Table 4.10**.

As shown in **Figure 4.7A**, total solids percentages of the samples, were in the range of 43- 36% (57- 64 % moisture content). Conversely, as what would be expected in an optimal composting process, total solids did not increase with time. Particularly in samples collected at the end of the composting process (21 and 28 days), moisture levels

TABLE 4.10

Summary of Compost Stability Parameters, Experiment 3 (a)

a) Analyses on solid compost

Sample age (days)	Total solids (%)	Volatile Solids (% TS)	Oxygen Uptake (mg O2/Kg TS-hr)
10	41.5	53.3	323.09
15	42.6	55.2	353.52
21	37.4	56.3	408.29
28	37.0	53.4	187.70

b) Water Extract Analyses

TOC	NH3-N	TKN	N org	TOC/org N
(mg / g dry weight)				
5.065	1.153	2.716	1.563	3.24
4.35	0.864	4.722	3.858	1.13
4.8	1.8	4.366	2.516	1.91
5.74	2.082	5.541	3.430	1.66

c) Pathogen indicators

Sample age (days)	Total coliforms weeks 0	1	2	3	Fecal coliforms(E.coli) weeks 0	1	2	3
	(M P N cells / g dry weight)							
10	1.2e5	1.9e4	3.5e3	3.5e2	1.9e4	1.9e2	3.0e1	3.0e1
15	3.7e5	3.7e4	3.4e2	2.0e3	3.7e4	2.0e2	3.0e1	4.0e1
21	7.0e6	7.0e3	5.6e2	1.1e4	1.7e5	1.7e3	3.0e1	3.0e1
28	6.9e3	3.2e2	3.0e1	3.0e1	6.9e2	3.0e1	3.0e1	3.0e1

(a) Hoosac Composting Facility, November 1993

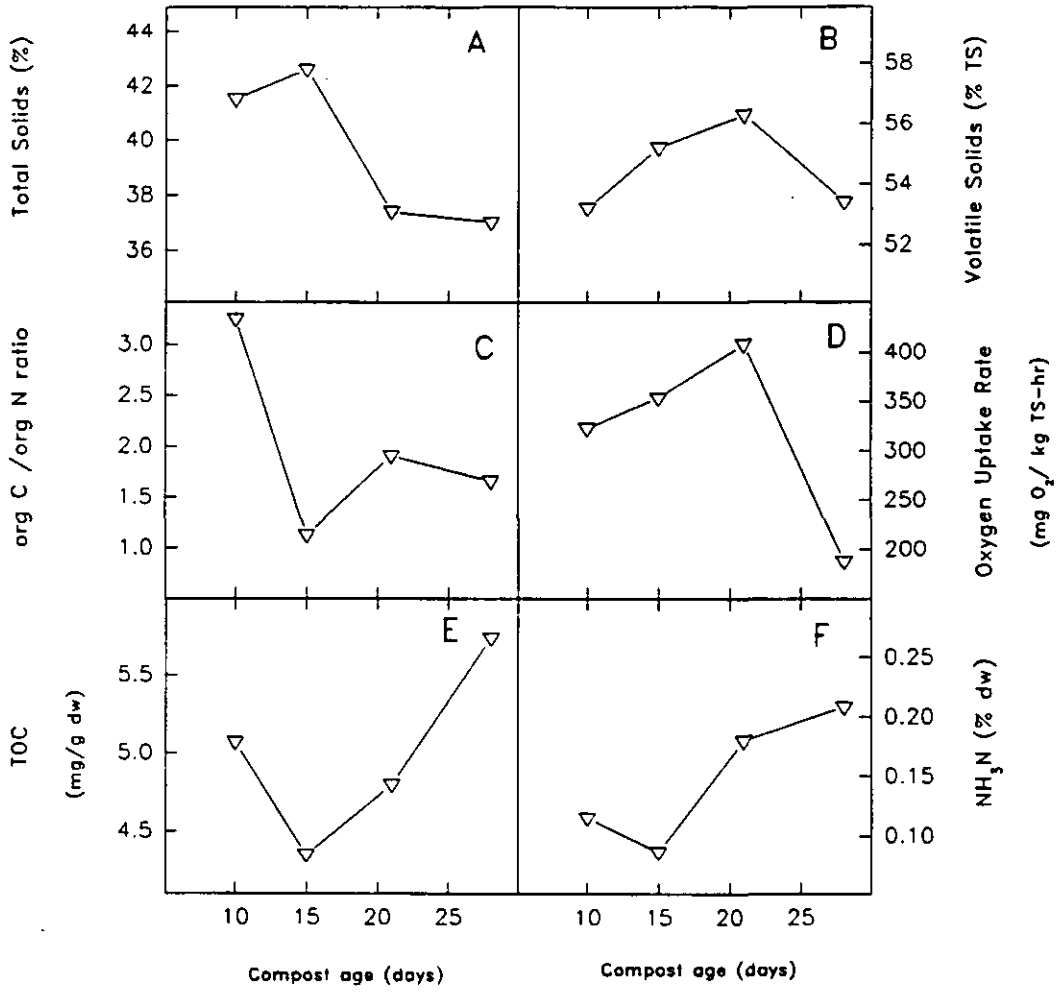

Figure 4.7 Compost Stability Parameters, Experiment 3

A) Total solids percentage, B) Volatile solids percentage, C) C/N ratio in water extract, D) Oxygen uptake rate, E) Total organic carbon content in water extract, F) Ammonia content in water extract.

were higher than expected. This was also confirmed during sampling by visual observations, in that some areas of the pile were dryer than others. Water drops falling from the ceiling were also observed. It is possible that, if inadequate aeration was applied during the process, water vapor could not be dispersed and thus condensed, and fell into the compost. This would result in wet areas of the pile.

Volatile solids percentage (see **Figure 4.7 B**), increased during the first 20 days of the composting process. However, volatile solids percentage of the oldest compost sample was almost the same as 10 day old compost. A similar trend was observed in the oxygen uptake rates. In this case, oxygen uptake increased during the first 20 days, then decreased drastically in the last sample (28 day old). Although oxygen uptake of the oldest compost sample (28 day old) was the lowest (as expected), the rest of the oxygen uptake measurements did not follow the expected trend.

Data for the cumulative oxygen uptake for experiment 3, are plotted in **Figure 4.8.** As it can be seen, oxygen uptake started to be consumed quickly (no lag phase), except for 10 day old compost, which demonstrated a lag phase of approximately 3.5 hours.

Both total coliform and fecal coliform populations increased during the first 21 days of the process. However, a large decline of both fecal and total coliforms was observed in 28 day old. The highest levels of total coliforms and *E. coli* during the composting period were 7e6 and 1.7e5 respectively (see **Table 4.10c**). After 28 days of composting, concentration of *E. coli* was 3e1, which complies with the Class A pathogen requirement limits[48]. Regrowth results, are plotted in **Figures 4.9 B** and **4.9 C**. Unlike experiment 2, *E. coli* levels did not increase in any of the compost treatments during the incubation period. After one week of incubation, *E. coli* levels were lower than 1.7e3 cells/g dw in all compost treatments. In fact, *E. coli* levels were reduced to less than 100 cells/g dw after two weeks of incubation. Total coliform densities were reduced in all compost ages during the incubation period except for 15 and 21 day old compost which increased one order of magnitude after 25 days of incubation. Total coliform levels in 28

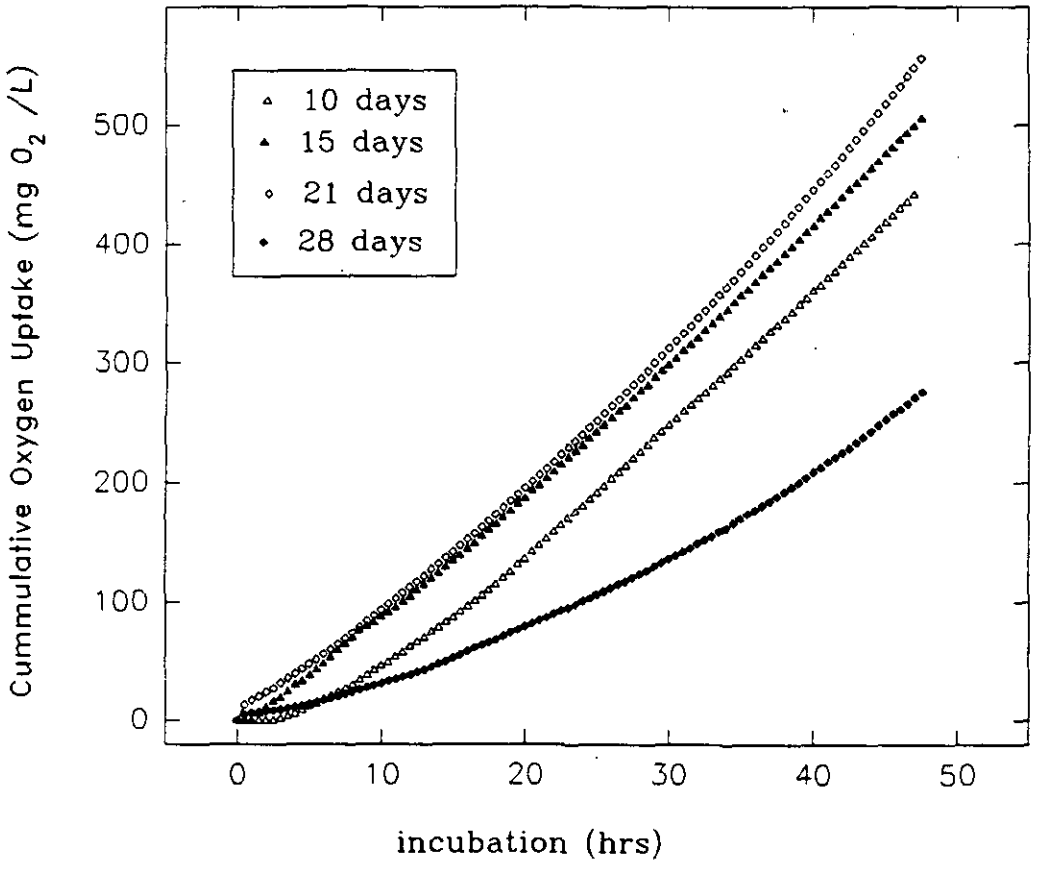

Figure 4.8 Cummulative Oxygen Uptake, Experiment 3

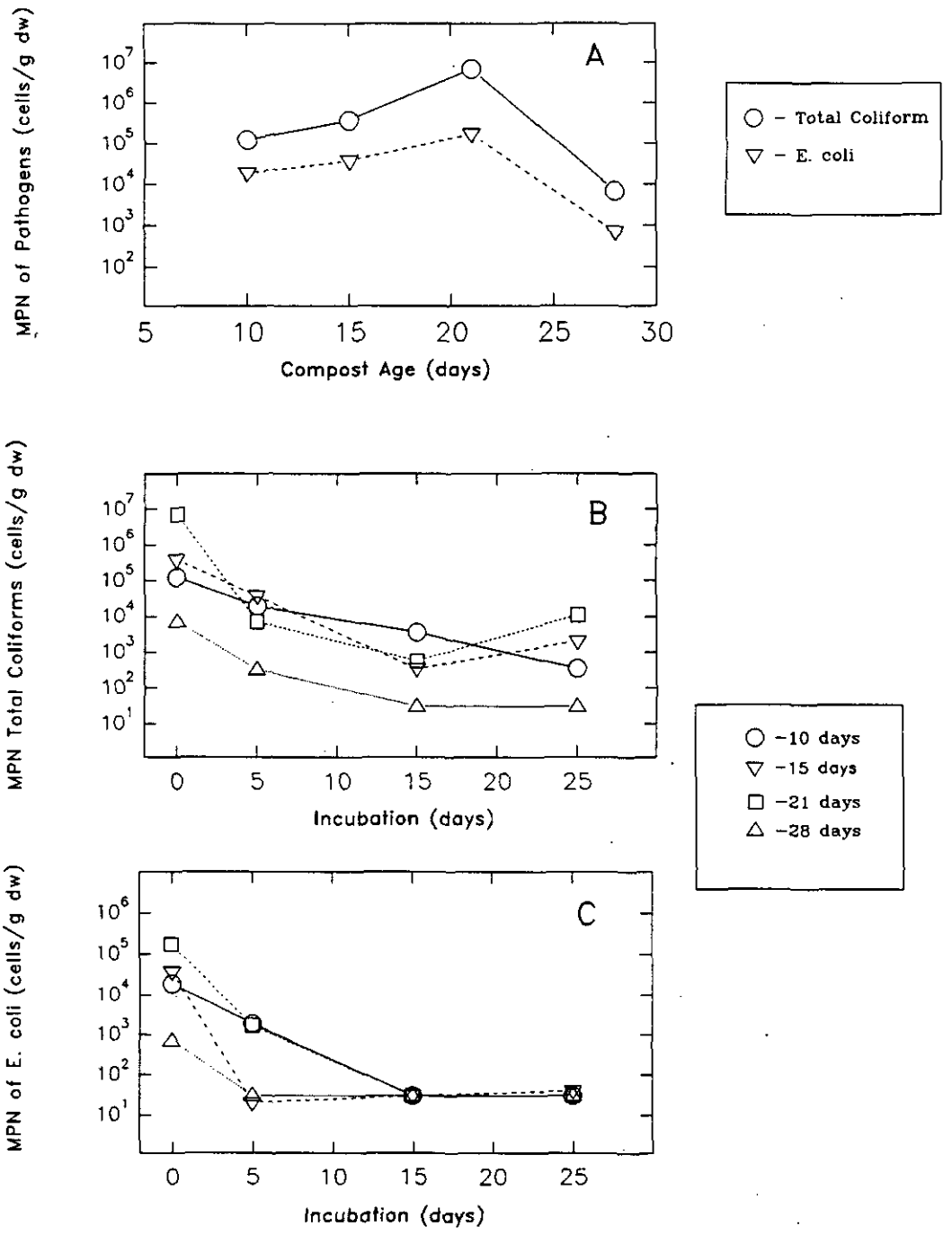

Figure 4.9 Pathogen Indicators, Experiment 3

A) Pathogen indicators density, B) Total coliforms regrowth, C) Fecal coliforms regrowth.

days old compost, were the lowest detected among all compost treatments during the incubation period. Total coliforms in 28 day old compost after two weeks of incubation were less than 10e1 cells/g dry weight.

Pathogen indicator results compared favorably with the other stability results which showed a relatively higher stability of the oldest compost sample with respect to the rest of the treatments.

4.2.1.2.2 Analyses on water extract

C/N ratio in water extract determined for experiment 3 (see **Figure 4.7 C**), ranged from 3.2 to 1.5 in compost 10 and 15 days old respectively. According to criteria for compost stability suggested by Chanyasak *et al.*(5), all compost samples would be considered stable since their final ratios were less than the range of 5-6. However, this is not in agreement with the rest of the stability parameters determined.

Both, the ammonia levels (**Figure 4.7 F**) and TOC levels (**Figure 4.7E**) present similar trends, with an increase in their concentration after 15 days of composting.

4.2.1.3 Correlation between stability parameters and compost age

Pearson's correlation coefficients from experiment 3 are shown in **Table 4.11**. As this table shows, there is no significative correlation between the stability parameters and compost age. In addition, correlation between stability parameters was also poor. As has mentioned before, unrepresentative sampling methodology used in this experiment might be the cause of such results.

Table 4.11
Correlation Coefficients[+] between Stability Parameters, Experiment 3

	C age	TS	VS	Oxup	TotC	FeC	C/N we	Am-we	TOC-we
C time	1								
TS	-.8588	1							
VS	-.0143	-.0567	1						
Oxup	-.5391	-.3193	.8077	1					
TotC	.1913	-.4895	.8036	.6695	1				
FeC	.0778	-.3567	.8678	.7686	.9886*	1			
C/N we	-.5235	.1084	.4790	.0470	-.0752	-.100	1		
Am-we	.8616	-.9920**	-.0691	-.4253	.3839	.244	-.0571	1	
TOC-we	.6023	-.6687	-.7044	-.8306	-.7044	.3944	.2756	.7556	1

+ Pearson's correlation coefficient; * p<0.1, ** p<0.05, ***p<0.01.
C age=compost age; TS=total solids, VS=volatile solids; Oxup=oxygen uptake rate; TotC= total coliforms; FeC=fecal coliforms; C/N we= C/N ratio in water extract; Am-we= ammonia content in water extract; TOC-we= total organic carbon in water extract.

4.2.1.4 Phytotoxicity studies

4.2.1.4.1 Seedling study

Some variations from experiments 1 and 2 were made in terms of observation dates. Measurements were taken on percent germination at 1, 2, and 3 weeks. Percent ground cover and fresh clipping weight were determined during weeks 1 and 2.

a) By average of species.

Overall, plant assays showed that there was a significantly negative effect of all compost age treatments, reflected as germination delays, reduction of percentage of germination and ground cover, and reduced growth (see **Table 4.12**).

Germination delay was not significantly different among compost treatments, which ranged between 11 and 18 days. Controls germinated significantly faster (6 days). Although germination percentage in all compost ages was significantly lower than controls, some significant differences were observed among compost ages. At week 1, there was still no germination in any of the youngest compost treatments. At week 2, compost ages 15 and 21 days averaged 20% germination, while compost age 28 was not significantly different from age 10 days (zero). During week 3, compost 15 days age was still the most significantly harmful among compost ages, followed by compost 21 days old. At week 4, no significant differences between 15 and 21 day old compost were observed, in addition, both were significantly higher than 10 and 28 day old compost which were not different from each other. Differences among compost treatments were observed in growth observations. At weeks 2 and 3, 10 and 28 day old compost were significantly more harmful than the rest of the treatments. The same pattern, was repeated in ground cover observations, however at week 3, percentage ground cover of 15 day old compost was significantly higher than 21 day old compost.

As observed during experiments 1 and 2, a difference in sensitivity among species

Table 4.12

Statistical Analyses of Seedling Study (by average of species), Experiment 3

Compost age (days)	Days to first germination		% Germination					
			w2		w3		w4	
Control	a	6.7	a	54	a	69.2	-	-
10	b	18.6	d	0	d	11.6	b	15.8
15	b	11.1	b	22.3	b	47.1	a	42.9
21	b	11.7	cb	18.6	c	27.1	a	41.2
28	b	11.3	cd	7.5	dc	19.5	b	24.4
kbg	b	16.5	b	7.4	c	18.35	b	20.4
cbg	a	8.3	a	31.3	b	38.5	a	32.3
tf	a	10.9	a	22.7	a	47.9	a	41.2

Compost age (days)	Clipping weight (g)				% Ground cover			
	w2		w3		w2		w3	
Control	a	1.15	a	1.49	a	50.0	a	71.7
10	c	0.002	c	0.02	c	0.7	d	11.1
15	b	0.225	b	0.425	b	30.0	b	48.3
21	cb	0.103	b	0.362	b	20.9	c	30.6
28	c	0.015	c	0.122	c	7.3	d	13.6
kbg	c	0.075	c	0.188	c	7.9	c	21.1
cbg	b	0.251	b	0.452	a	35.7	a	46.3
tf	a	0.589	a	0.819	b	21.7	b	37.7

Means with same letter are not significantly different
Duncan's Multiple test for variables, alpha=0.05, SAS
w=weeks

was also confirmed. In all the parameters measured, **kbg** performed significantly lower than the other two species. **Tf** and **cbg** were not significantly different in terms of days to first germination and percent of germination. **Cbg** performed better in percentage ground cover than **tf**. The opposite occurred in growth.

b) By each species

Table 4.13 presents the results of the statistical analyses performed for each of the species during experiment 3.

Kbg. Germination delay in controls averaged 9 days, significantly lower than 10 and 15 day old compost treatments of, which averaged 21 days. With the exception of 21 day old compost at week 3, all compost treatments significantly reduced germination percentage during the observation period. Differences among effects of compost treatments on ground cover were observed during week 1. Compost ages 15 and 28 days old, were significantly more harmful than compost age 10 days old. Growth was significantly reduced by all compost treatments. No significant differences among compost ages was observed, except with 15 day old compost at week 2, which was significantly more toxic than the rest of the treatments.

Cgb. Both 10 and 15 day old compost, significantly delayed germination with respect to the controls and the rest of the treatments, which were not significantly different among each other. Percentage germination of controls during weeks 1 and 2 averaged 70%, significantly higher than the rest of the treatments which did not differ significantly from each other. At week 3, percentage germination in 10 day old compost was around 12%, significantly lower than the rest of the compost treatments, which ranged between 30 and 44 %. Considerable differences among compost treatments were observed during the first week of observation with respect to ground cover percentage. Compost 15 days age was not significantly different from the control which averaged 80%. Percentage ground cover in 21 day old compost (47%) was significantly less than controls, but significantly higher than 10 and 28 day old compost which did not differ significantly from each other. Such differences did not persist at week 2. All compost treatments significantly reduced growth in both weeks with respect to controls. No differences among the

Table 4.13
Statistical Analyses of Seedling Study (by species), Experiment 3

Days to first germination

Compost age (days)	kbg		cbg		tf	
Control	a	9	a	5.3	a	5.6
10	b	21.7	b	16	c	18
15	b	21	a	6	a	6.3
21	ab	14	a	7	bc	14
28	ab	16	a	7	ab	10.3

% Germination

Compost age (days)	kbg						cbg						tf					
	w1		w2		w3		w1		w2		w3		w1		w2		w3	
Control	a	0.22	a	0.39	a	0.39	a	0.74	a	0.74	a	0.82	a	0.67	a	0.67	a	0.86
10	b	0	b	0.04	b	0.1	b	0	b	0.04	c	0.13	b	0	bc	0.27	b	0.24
15	b	0	b	0.18	ab	0.26	b	0	b	0.32	b	0.44	b	0	b	0.35	a	0.79
21	a	0.13	b	0.18	ab	0.24	b	0	b	0.36	bc	0.31	b	0	c	0.07	b	0.32
28	b	0.02	b	0.13	b	0.2	b	0	b	0.15	bc	0.31	b	0	c	0.05	b	0.15

Clippings weight (g)

Compost age (days)	kbg				cbg				tf			
	w1		w2		w1		w2		w1		w2	
Control	a	0.66	a	0.66	a	1.04	a	1.04	a	2.06	a	2.13
10	b	0.01	bc	0.21	b	0.05	b	0.31	b	0.25	cd	0.36
15	b	0.02	c	0.12	b	0.15	b	0.28	b	0.72	b	1.11
21	b	0.19	ab	0.62	b	0.2	a	0.77	b	0.11	cb	0.7
28	b	0.07	bc	0.19	b	0.08	b	0.19	b	0.04	d	0.22

% Ground cover

Compost age (days)	kbg				cbg				tf			
	w1		w2		w1		w2		w1		w2	
Control	a	28.3	a	60	a	80	a	80	a	75	a	75
10	b	13.3	b	13.3	c	13.3	b	30	b	18.3	b	21.7
15	c	0	b	11.7	a	70	b	50	a	63.3	a	63.3
21	cb	10	b	25	b	46.7	ab	56.7	b	20	b	26.7
28	c	1.33	b	7.33	c	21.7	b	41.7	b	11.7	b	16.7

Means with different letters are not significantly different
Duncan's Multiple test for variables, alpha=0 05, SAS
w=weeks

treatments were observed, except for compost 21 days age at week 2, which was not significantly different from the controls.

Tf. Germination delay in controls averaged 6 days and was not significantly different to compost age 15 days old. The most harmful effect was observed in compost 10 days old with a delay of almost 18 days. Germination percent in controls during all observation periods was significantly higher than all compost treatments, except with 15 day old compost in week 3 which was not significantly different. At week 2, some interaction between compost age and severity of effects were observed, as compost of 21 and 28 day old were significantly more harmful than compost of age 15 days old. Compost of 15 days age performed the best during the two weeks of observation of ground cover percentage, and values were statistically equal to controls. Percentage ground cover in the rest of the treatments was significantly less than in controls, and no significant differences among them were observed. Growth in all compost treatments was significantly less than the controls during week 1 and 2. No significant differences among compost treatments were observed at week 1, however during week 2, growth on compost age 28 days old was significantly less than on 15 day old compost.

4.2.2 Experiment 4

4.2.2.1 Sampling

There were five different sample collection dates during experiment 4. Originally, sampling dates were planned to cover the 28 days of the composting process which normally occurs at the Hoosac composting facility. However, due to processing problems with the sample obtained during the first sampling (5 days old), an extra sampling was added. The 5 day sample was too wet to be easily screened. Therefore, it was not possible to obtain a sufficient amount of sample necessary for seedling studies. However, it was possible to determine stability parameters, since the amount of sample required for these tests is relatively low. An extra sampling was added to obtain four separate plant assays. A request to the Hoosac composting facility was made in order to maintain the pile for one

extra week so that the last sample could be taken. Since the days for sampling were already established, the last sampling date corresponded to a composting time of 34 days.

As described in section 3.2.2, each composite sample corresponding to a sampling date, consisted of 8 different subsamples taken along the pile. Characteristics of the subsamples, such as temperature, visual moisture estimation, and subsample location in the pile during each sampling date, were recorded, and are summarized in **Table 4.14.**

Sites sampled during each sampling can be identified in **Figure 4.10**. The average temperature of sites sampled was in the range of 45- 61 °C. However, a variation among these sites can be observed during all sampling dates. Based on the observations during sampling, a relationship between the visual estimation and the temperature recorded can be determined. When compost seemed to be wet, high temperatures (60-70 °C) were recorded, while temperatures of 40-50 °C corresponded to compost samples considered dry. In addition, it was observed that sites corresponding with high temperatures and wet conditions, had an odor characteristic of the decomposition process. As can be seen in **Figure 4.10** in general, sample sites characterized as "wet" were located in the center of the pile. During samplings, it was observed that some parts of the pile were wet from water drops falling from the ceiling. This suggests that the Hoosac composting facility may have some problems with aeration. Since water vapor was not dispersed, this vapor condensed on the ceiling and later produced water drops which fell from the ceiling into the compost.

Although there were differences among the subsamples, the final composite sample seemed to overcome such heterogeneity.

4.2.2.2 Stability analyses

4.2.2.2.1 Analyses on solid compost

Results of the stability analyses determined during experiment 4 are summarized in **Table 4.15**. These include analyses of solid compost, water extract, and pathogen indicators.

Table 4.14

Composite Sample Information, Experiment 4

site number	compost age (days)				
	5	**13**	**21**	**28**	**34**
1	60 w	65 w	45 d	50 m	24 d
2	50 w	50 m	40 m	50 d	50 d
3	60 w	40 d	50 d	55 d	70 w
4	60 w	40 d	30 d	70 w	55 d
5	70 w	50 m	50 w	43 d	50 d
6	60 w	50 m	65 w	50 d	70 w
7	60 w	65 w	45 d	50 d	50 d
8	65 w	72 w	35 d	70 w	50 m
					60 m*
Average temperature	61	54	45	55	60

* extra subsample.
Number in the left side, corresponds to Temperature in ° C.
Letters in the right side, corresponds to the visual estimation:
w = wet; m = medium; d = dry.

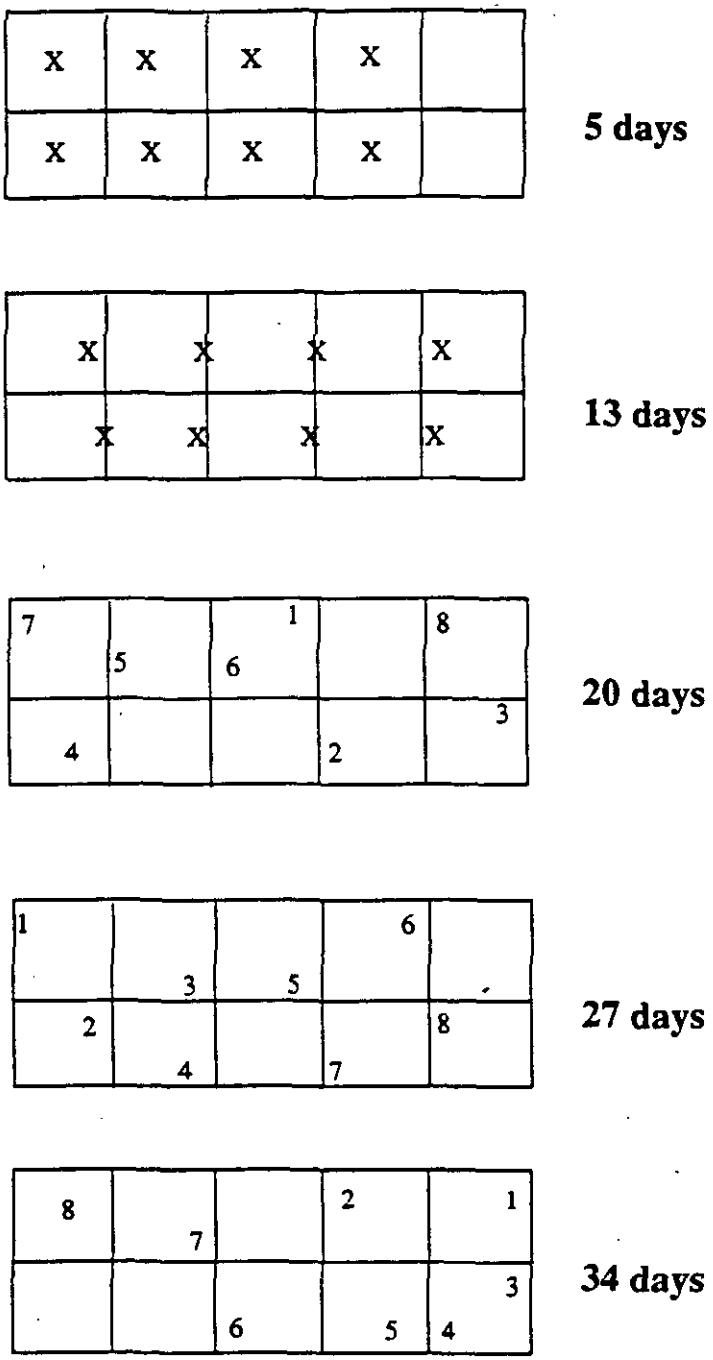

Figure 4.10 Sites Sampled at the Composting bay, Experiment 4

Figure 4.11 A-F shows the different stability parameters determined during the composting process in experiment 4. From this figure it can be seen that, some stability parameter trends over the composting time are well correlated with composting age. The improvement in the sampling methodology is obviously seen in the trends displayed.

Total solids percentage increased as composting process progressed. **Figure 4.11A.** shows the total solids percentage during the 34 days of the composting process. Overall, an initial 47% percent of total solids, was increased during the composting process to 57%. Thus, compost moisture was always maintained in the range for optimal composting when averaged over the pile. However, as the subsample observations showed, there is heterogeneity in terms of water limitations or possible anaerobic conditions due to the excess of water in parts of the pile.

Volatile solids as seen in **Figure 4.11 B**, decreases with time, which is also an indicator of the decomposition process. As shown in this Figure, an overall reduction from 40.7 to 23.7% occurred.

Oxygen uptake measurements plotted in **Figure 4.11 D**, indicates a continuing maturation in the samples as the composting process progressed. There were no high temperatures or extreme low moisture conditions observed in any of the samples that could have inhibited the microbial activity. Therefore the drop in oxygen uptake rates must be related to the decomposition process, and therefore increasing stability of compost. Note that these rates are all higher than those which can be considered stable for horticultural uses (20 mg O_2/kg hr) as suggested by Wilson and Dalmot [52]. Cumulative oxygen uptake rates of all compost treatments are plotted in **Figure 4.12.**

TABLE 4.15

Summary of Compost Stability Parameters, Experiment 4(a)

a) Analyses on solid compost

Sample age (days)	Total solids (%)	Volatile Solids (% TS)	Oxygen Uptake (mgO2/kg TS-hr)
5	47.3	40.7	333
13	49.3	39.8	333
20	53.8	32.7	280
27	56.6	27.2	226
34	58.9	23.7	223

b) Water Extract Analyses

TOC	NH3-N	TKN	N org	TOC/org N
(mg / g dry weight)				
5.70	1.015	1.914	0.899	6.3
6.07	0.872	1.574	0.701	8.7
4.08	0.507	0.874	0.367	11.1
2.72	0.397	0.989	0.593	4.6
3.06	0.540	1.215	0.675	4.5

c) Pathogen indicators

Sample age (days)	Total coliforms	Fecal coliforms(E.coli)
	(MPN cells / g dry weight)	
5	1.9e5	1.9e5
13	1.8e5	3.4e4
20	6.9e4	3.2e3
27	3. 2e6	3.2e3
34	9.8e4	2.8e1

(a) Hoosac Composting Facility, March 19944

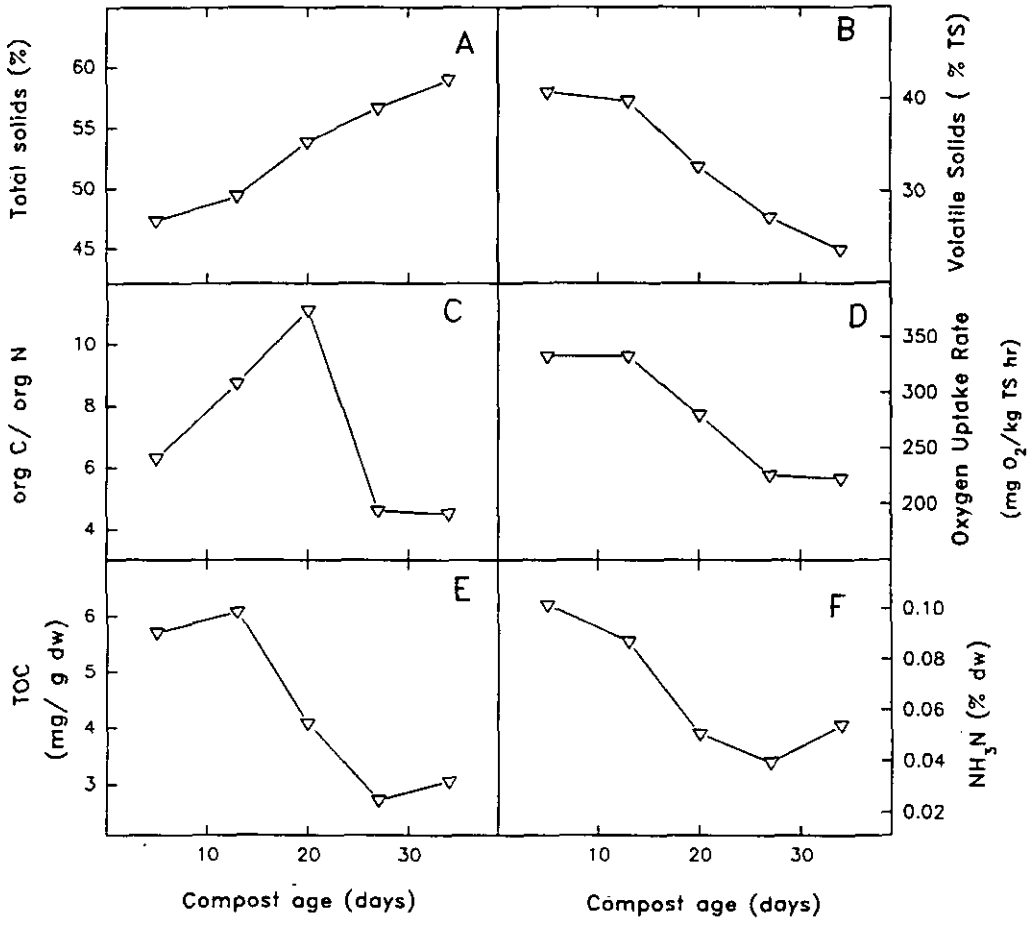

Figure 4.11 Compost Stability Parameters, Experiment 4

A) Total solids percentage, B) Volatile solids percentage, C) C/N ratio in water extract, D) Oxygen uptake rate, E) Total organic carbon content in water extract, F) Ammonia content in water extract.

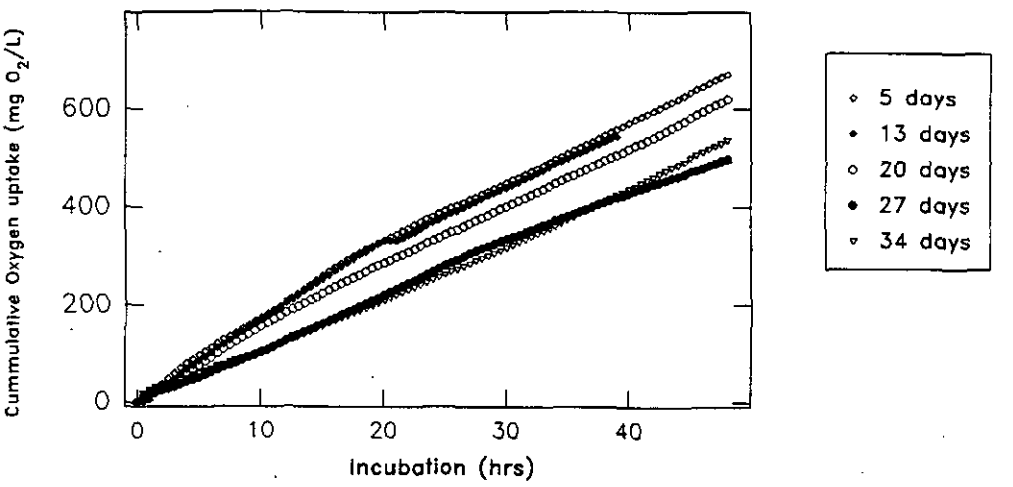

Figure 4.12 Cummulative Oxygen Uptake, Experiment 4

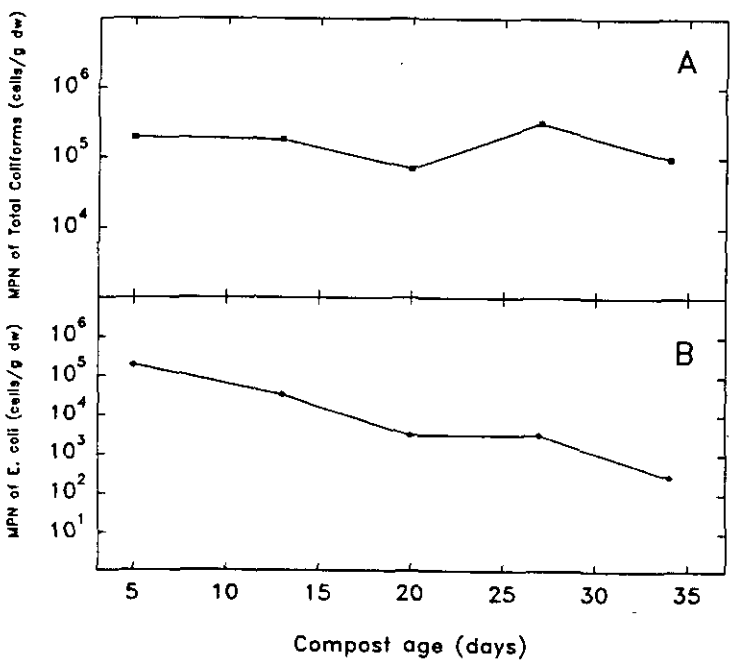

Figure 4.13 Pathogen Indicators, Experiment 4

A) Total coliforms density, B) Fecal coliforms density.

Pathogen indicator results are shown in **Figure 4.13**. Regrowth analyses are not included since they were not performed during this experiment. Total coliform and *E. coli* levels determined in this experiment, showed similar results compared to experiment 3 in terms of final pathogen numbers. As shown in **Figure 4.13 A**, total coliform densities were between 6.9e4 and 3.2e6 cells/g dw throughout the process. With respect to *E.coli* (**Figure 4.13 B**), a level of 1.9e5 at 5 days age decreased to 3.2e3 and 2.8e1 in compost 28 days old and 34 days old respectively This is well between the Class A level of 1e3 cells/g dw.

4.2.2.2.2 Analyses of water extract

C/N in water extract varied during the composting process with no specific trend. However C/N ratios of 28 and 34 day old compost were around 4, thus indicating the stability of these samples.

TOC and ammonia content in the water extract along thecomposting process are presented in **Figures 4.11 E and 4.11F,** respectively. As shown in both graphs, both TOC and ammonia displayed decreasing trends, and were relatively similar.

4.2.2.3 Phytotoxicity studies

4.2.2.3.1 Seedling study

a) By average of species

Results of the average response to compost of the three seed species are summarized in **Table 4.16.**

The number of days to first germination was significantly different due to compost ages. Thirteen and 27 day old compost averaged 12 and 11 days, respectively, and were significantly different from the control (8 days) but not from each other. Compost ages 20 and 27 days old, were not significantly different from 34 day old compost or from the control, but were significantly different from each other.

Percent germination at all weeks was significantly affected by compost treatments.

Table 4.16

Statistical Analyses of Seedling Study (by average of species), Experiment 4

Compost age (days)	Days to first germination		% Germination							
			w1		w2		w3		w4	
Control	bc	8.4	ab	13.3	ab	30.0	a	54.4	a	78.1
13	c	11.8	c	0.0	c	10.9	b	21.6	b	38.1
20	abc	9.2	a	20.1	a	44.2	a	53.4	a	77.8
27	bc	10.9	bc	8.4	bc	23.4	b	25.7	b	30.6
34	a	6.9	a	18.3	bc	17.0	b	22.5	b	39.9
kbg	b	12.5	b	0.0	c	6.7	b	21.5	b	33.9
cbg	a	8.1	a	19.0	b	27.8	a	38.2	a	56.0
tf	a	7.8	a	17.1	a	40.6	a	46.8	a	68.8

Compost age (days)	Clipping weight (g)				% Ground cover			
	w2		w3		w2		w3	
Control	b	0.34	a	0.523	a	52.2	a	76.7
13	c	0.057	b	0.149	cb	24.0	cb	32.2
20	a	0.672	a	0.577	b	35.6	b	45.6
27	cb	0.099	b	0.173	c	19.4	cb	31.1
34	cb	0.286	b	0.117	c	17.8	c	22.2
kbg	b	0.052	b	0.114	b	16.7	b	31.3
cbg	b	0.134	b	0.165	a	40.0	a	54.7
tf	a	0.687	a	0.646	a	32.7	b	38.7

Means with the same letter are significantly different
Duncan's Multiple test for variables, alpha=0.05, SAS
w=weeks

Different effects were observed each week. At week 1, 20 and 34 day old compost were not significantly different from controls which average 13 %. Compost age 13 days old was significantly more harmful than the rest of the treatments in both weeks 1 and 2 by averaging 0 and 11% respectively. At weeks 3 and 4, compost age 20 days old and controls were not significantly different from each other, averaging 78%. The rest of the compost treatments were significantly lower.

At week 2, growth in controls was significantly lower than in 20 day old compost. For the same week, 13 day old compost continued to be significantly more harmful than the rest of the treatments. At week 3, all compost treatments were significantly lower than controls, except for 20 days old compost, which was not significantly different from the controls.

Ground cover percentage in all compost treatments during the observation period, was significantly lower than controls which averaged 52 and 77% at weeks 2 and 3 respectively. At week 2, compost 27 and 34 days old was not significantly different from each other (19 and 18% respectively), but significantly lower than 20 day old compost which averaged 36%. At week 3, ground cover percentage in compost age 34 days old, was significantly lower than 20 day old compost, but not significantly different from compost ages 13, and 27 days old.

With respect to species sensitivity, **kbg** continued to be significantly more sensitive than the other two species for all parameters considered, except growth. **Kbg** was not significantly different to crbg in growth. **Tf** and **cbg** were not significant different in terms of germination delay, germination percentage, and ground cover percentage. **Tf** performed significantly better than **cbg** in terms of growth.

b) By each species

The effects of the different compost ages to each turfgrass species are presented in **Table 4.17**.

For **kbg**, days to first germination for controls and for all compost treatments were not significantly different between each other ranging from 10 to 14 days. Germination percentage at weeks 1 and 2 were not significantly different for controls and for all compost treatments. At week 3, some differences between compost treatments and

Table 4.17
Statistical Analyses of Seedling Study (by species), Experiment 4

Compost age (days)	Days to first germination: kbg	cbg	tf	% Germination: kbg w1	w2	w3
Control	a 10	b 5.6	b 6.3	ab 9.2	a 25.7	a 9.4
13	a 14	a 13.3	ab 8	ab 18.3	a 13.6	bc 18.3
20	a 12	ab 8.6	b 7	a 4.2	a 37	b 47.3
27	a 14	b 7.3	a 11.3	b 3.7	a 15.4	c 15.8
34	a 9.3	b 5.3	b 6	ab 9.9	a 14.3	bc 24.9

Compost age (days)	% Germination: cbg w1	w2	w3	tf w1	w2	w3
Control	a 29.8	a 63.9	a 77.6	ab 50.9	ab 73.6	a 93.1
13	b 4.3	b 2	b 37.3	b 26.5	b 31.4	ab 58.8
20	a 46.7	ab 42.3	a 96.1	a 76.6	a 81.4	a 96.1
27	a 38	ab 35.3	b 39	b 28.4	b 24.5	b 37.2
34	b 9.9	b 29.8	b 36.1	b 20.6	b 23.4	ab 58.8

Compost age (days)	Clippings weight (g): Kbg w1	w2	cbg w1	w2	tf w1	w2
Control	a 0.074	a 0.153	b 0.116	a 0.316	ab 0.832	a 1.099
13	a 0.007	a 0.064	b 0.02	b 0.025	b 0.144	b 0.383
20	a 0.129	a 0.211	a 0.399	a 0.297	a 1.498	a 1.135
27	a 0.012	a 0.064	b 0.079	b 0.095	b 0.207	b 0.361
34	a 0.037	a 0.076	b 0.066	b 0.09	ab 0.757	b 0.185

Compost age (days)	% Ground cover: kbg w1	w2	cbg w1	w2	tf w1	w2
Control	a 36.7	a 70	a 60	a 86.7	a 60	a 73.3
13	ab 18.3	b 25	b 21.7	bc 36.7	ab 32	b 35
20	ab 15	b 28.3	a 56.7	ab 66.7	ab 35	ab 41.7
27	b 5	b 16.7	ab 40	abc 56.7	b 13.3	b 20
34	b 8.33	b 16.7	b 21.7	c 26.7	b 23.3	b 23.3

Means with same letter are not significantly different
Duncan's Multiple test for variable, alpha=0.05, SAS
w=weeks

controls were observed. Controls averaged 93% of germination percentage, significantly more than the rest of the compost. Compost age 20 days old with a 47% germination, was significantly lower than the controls, but significantly higher than compost 27 days old which average 16%.

Percentage ground cover at week 1 averaged 37% in controls, significantly higher than 27 and 34 day old compost but not significantly different from 13 and 20 days old compost. There was no significant difference among compost treatments in both weeks 1 and 3. Ground cover percentage in controls at week 3, averaged 70%.

Growth at week 1 was not significantly different between controls and the rest of compost treatments. However at week 2, compost 20 days old was significantly more harmful than 27 day old compost and the control, which were not significantly different from each other. Days to first germination in **cbg** controls averaged 6 days and was not significantly different from 20, 27 and 34 day old compost but significantly faster than 13 day old compost which averaged 13 days.

Germination percentage in controls at week 1, was 30%. Compost age 20 and 27 days old were not significantly different from controls, but significantly higher than 13 and 34 day old compost. At week 2, only 13 and 34 day old compost were significantly lower than the controls, but not significant different from the rest of the treatments. At week 3, controls averaged 78% of germination, not significantly different from 20 day old compost (96%), but significantly higher than the rest of the treatments.

Ground cover percentage in controls reached 60 and 87% in weeks 1 and 2 respectively. At week 1, 20 and 27 day old compost, were significantly lower than the controls but not significantly different from each other (22%). At week 3, 34 day old compost was significantly more harmful (27%) and significantly different than the controls and to 20 day old compost but was not from the rest of the treatments.

Growth in compost age 20 days old was significantly better than in controls and the rest of the treatments which did not differ significantly from each other. At week 3, 20 day old compost and controls were not significantly different from each other, but were higher than the rest of the treatments.

Days to first germination in tf controls average 6 days, and were statistically similar to 20 and 34 day old compost. Germination delay in 27 day old compost was 11 days; significantly higher than controls but not different from 13 day old compost.

At weeks 1 and 2, germination percentage in controls averaged 51 and 73% , respectively. No significant difference with the rest of the compost treatments was observed. Compost age 20 days old was not significantly different from controls during the entire observation period, but at week 1 was significantly higher than 13, 27 and 34 day old compost.

Ground cover percentage in controls was 60% at week 1, and was not significantly different from 13 and 20 day old compost observations. Percentage ground cover in compost age 27 and 34 days old was significantly lower than controls, but not different from the rest of the treatments. At week 2, 20 day old compost resulted in 41%, and controls (73 %). These tests were not significantly different from each other.

Growth in controls at week 1, was not significantly different from the rest of the compost treatments. Compost age 20 days old was significantly different from 13 and 27 day old compost, but not significantly different from 34 day old compost. At week 2, all compost ages except compost age 20 days old, were significantly less than the controls.

The analyses to determine the correlation between stability parameters and phytotoxic effects is presented and discussed in chapter 5.

5. Discussion

This chapter includes a general discussion of the results obtained from the four experiments performed. As was shown in Chapter 4, experiments 1, 2, and 3 are limited in terms of discussion, since samples were not representative of the process. For this reason, only a detailed discussion of the results of experiment 4 is presented.

5.1 Sampling Methodology

Regarding sampling methodology used during experiments 1 and 2, some observations can be made. Although sampling at different points along the bay provided samples of different ages, they may not be representative of the process. The fact that the properties of the sludge added each day to the bay, was not the same, affected the reliability of the sampling. In regard to these results, sampling methodology used was not appropriate to obtain representative samples of the entire composting process. Therefore, in order to obtain representative samples of this process, it may be necessary to increase the number of sampling sites if the sampling is to be done in one day. That would imply taking different subsamples in the area corresponding to each age, and then making a composite sample. Another approach would be to follow one sludge batch during the

entire composting process. That would mean taking samples periodically from the same sludge mix, which moves every day along the bay- during the approximate 20 days of the process. However, disturbance of the system may be a problem with this approach, since there will be a continuos reduction in volume. Also, some back mixing will occur.

With respect to the sampling methodology in the ASP system, sampling methodology followed during experiment 3, failed to obtain representative samples of the process. Sampling methodology used during experiment 4 allowed representative samples to be obtained since the area sampled was bigger and a composite sample was made.

5.2 Stability Parameters

5.2.1 Experiments 1, 2, and 3

As already mentioned, samples from experiments 1, 2, and 3, were not representative of the process, as was reflected in stability parameter determinations. None of the parameters were significantly correlated with composting time at a significance level lower or equal to five percent.

Although no significant correlation was established, some parameters corresponded relatively well to the expected trends. Percentage of total solids, TOC and ammonia contents for experiment 1 and 2, and oxygen uptake for experiment 2 showed a relative decreasing trend. As noted previously, changes in percentage of total solids may have been observed due to process control problems, and do not necessarily reflect good progress of the composting process itself. With respect to TOC and ammonia levels in water extracts, it is possible that changes in these parameters over composting time are easier to observe than changes in other parameters, even when sampling problems may exist, since they are in the liquid extract.

It was also observed that some parameters, although not corresponding with composting time, were useful to monitor the process. For instance, differences in composting systems as well as improper process control were reflected in some of the stability parameters. For experiments 1 and 2, high percentages of total solids denoted

problems in moisture management. Dry conditions during the process were also indirectly reflected in others parameters. Low moisture conditions, affected microbial activity as pathogen densities and regrowth potential results indicated.

For experiments 3 and 4, changes in total solids percentage were related to rewetting of the process by water vapor condensation. Water condensation reflected problems in aeration during the process.

Differences between both systems were clearly reflected in other parameters. Problems in moisture management, characteristic of high rate systems, was reflected in other parameters such as regrowth potential. While regrowth potential in ASP during experiment 3 was not observed, samples from in-vessel systems (experiments 1 and 2), presented considerable regrowth. Although pathogen regrowth may be an indicator of available substrate, it can also be indicative of competitiveness. In this regard, regrowth results from experiments 1 and 2, indicate that dry conditions during the composting process may have affected microbial activity. If microbial activity was suppressed, substrate degradation was not complete and therefore available substrate may be present. On the other hand, low moisture levels may have affected the microbial diversity, which seems to play an important role in regrowth potential[14,25].

Considering final compost characteristics from these three experiments, it can be seen that except for a few exceptions, these composts can not be considered stable. For experiments 1 and 2, pathogen densities may indicate stability, however regrowth potential may be of concern. Oxygen uptake rate in the three cases, was higher than that suggested for both field applications and growth medium using Wilson and Dalmat's criteria[52]. C/N in water extract for final compost in experiment 3, may indicate stability using Chanyasack *et al.*'s [5] parameter, however this does not correspond with the rest of the parameters.

5.2.2 Experiment 4

As previously shown in Chapter 4, stability analyses of compost samples during experiment 4, showed consistency with the expected trends. **Table 5.1** shows the Pearson's correlation coefficients between stability parameters and compost age.

Table 5.1
Pearson's Correlation Coefficients between Stability Parameters, Experiment 4

	C age	TS	VS	Oxup	TotC	FeC	C/N we	Am-we	TOC-we
C age	1								
TS	.9912***	1							
VS	.9765***	-.9926***	1						
Oxup	.9748**	-.9748***	.9883***	1					
TotC	.3265	.3650	.3914	-.5206	1				
FeC	.8118*	-.7791	.6997	.6732	-.2668	1			
C/N we	-.4113	-.4071	.4946	.5283	-.4893	-.0853	1		
Am-we	-.8600*	-.8964*	.8676*	.8938**	-.5404	.8355*	.1386	1	
TOC-we	-.8957**	.9423**	.9585**	.9862***	-.5662	.6358	.4664	.9206**	1

+ Pearson's correlation coefficient; * p<0.1, ** p<0.05, ***p<0.01

C age=compost age; TS=total solids, VS=volatile solids; Oxup=oxygen uptake rate; TotC= total coliforms; FeC=fecal coliforms; C/N we= C/Nratio in water extract; Am-we= ammonia content in water extract; TOC-we= total organic carbon in water extract.

In this experiment, almost all parameters changed as expected during the composting process. As a result, high correlations between composting time and most of the stability parameters were found.

Based on the trend followed over composting time by some such as total solids, volatile solids, oxygen uptake rate and fecal coliforms density, a linear regression analysis was performed (**Figures 5.1** and **5.2**). Although a linear regression does not fit either the total organic carbon and ammonia content in water extract trends, it is clear they both follow a decreasing trend over the time.

C/N ratio in water extract did not correlate well with either composting time and stability parameters. Chanyasack *et al.* [5] noted that for compost mixes with initial low C/N, such as sludge compost, changes of this parameter during composting process may not be a good indicator of stability. Instead, these researchers proposed that final C/N in water extract in the range of 5-6, may be a good indicator of stability only for final sludge compost. In this regard, C/N ratios in final compost during this experiment showed values under 5, which imply stability.

There are several publications indicating C/N in water extract is significantly correlated with composting time (Chen and Inbar[6], Garcia *et al.*[17], Grebus *et al.*[23]). However, it is important to notice that in most of these works, C/N ratios were determined during periods between 100 and 200 days where a negative significant correlation was observed. However, some studies have reported C/N ratio trends during the active composting stage (first 30 days). Therefore, correlation between C/N ratio and composting time may be related to the composting phase under consideration as well as the organic waste. Since the results correspond only to the active composting stage, it may be possible that the correlation with time was not observed because of the relative short increment determination. It is interesting to notice that similar C/N in water extract trends during the active composting stage, are reported by Grebus *et al.*[23] for sludge compost, however no explanation for such was found.

On the basis of C/N in water extract, total solids and volatile solids percentages, and pathogen densities, final compost from experiment 4, can be considered stable.

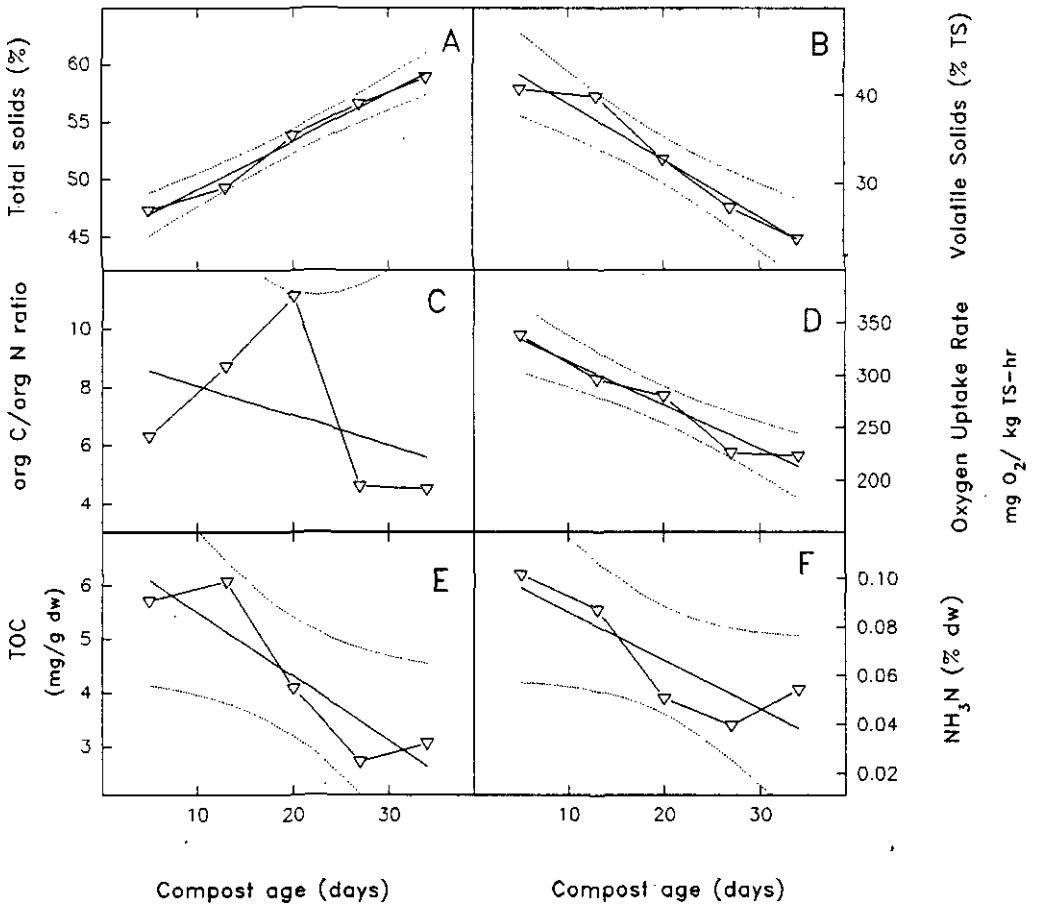

Figure 5.1 Linear Regression between Stability Parameters and Composting Time, Experiment 4

A) Total solids percentage (R=0.991), B) Volatile solids percentage (R=0.977),

C) C/N ratio in water extract (R=0.413), D) Oxygen uptake rate (R=0.975),

E) Total organic carbon content in water extract (R=0.896),

F) Ammonia content in water extract (R=0.859).

Dashed lines correspond to CI=95%

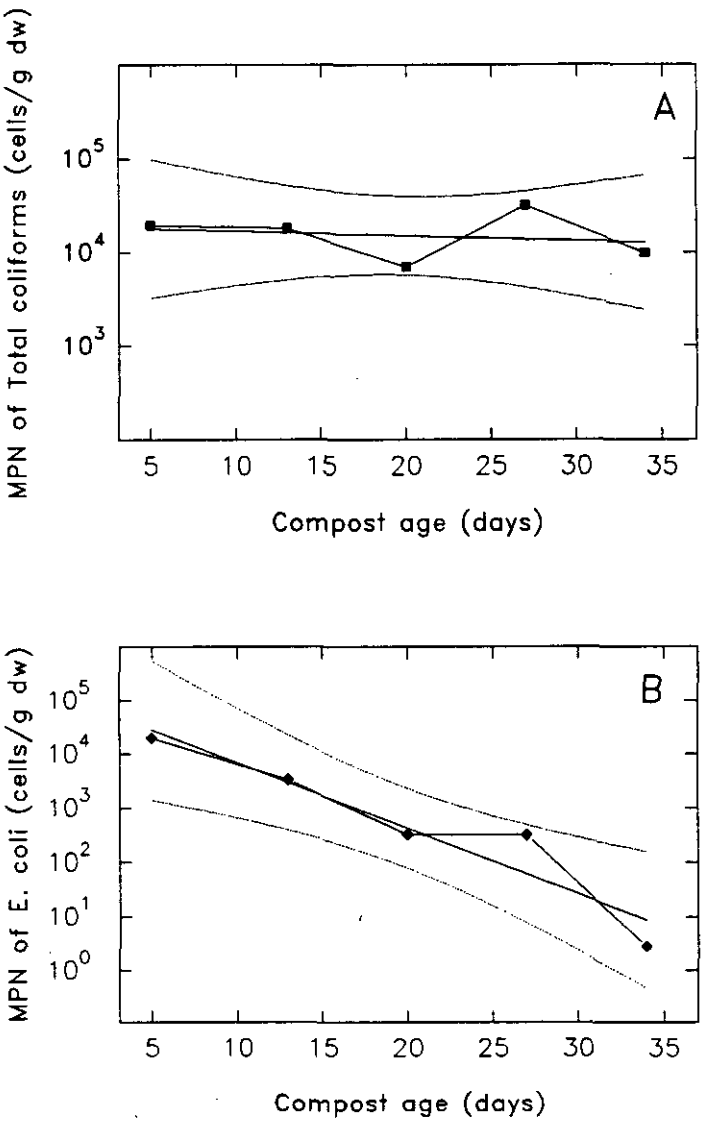

Figure 5.2 Linear Regression between Pathogen Indicators and Composting Time, Experiment 4

A) Total coliforms density (R= 0.21), B) Fecal coliforms density (R=0.951)

Dashed lines correspond to CI=95%

Oxygen uptake rate, however, indicates that 34 days was not enough to achieve stabilization. Total solids and volatile solids percentage are not usually considered reliable parameters to determine stability by themselves.

Overall total solids percentages and temperature determinations, followed the normal progress of composting. However, some measurements indicated deficient aeration during the process. Differences in temperature and visual characteristics determined among the subsamples, demonstrated examples of heterogeneity through the pile. Improper aeration allows water condensation which falls into some parts of the pile. High temperatures and odor production were observed in some points of the pile even at 34 days, indicating high microbial activity. This may imply that, because of the high moisture levels, and lack of sufficient free air space, oxygen diffusion was suppressed at these sites, resulting in anaerobic conditions. On the other hand, even after 34 days of composting the observation of sites with high temperature and odors indicates that there was still available substrate, and therefore stabilization was not yet accomplished.

Extreme heterogeneity throughout the pile may indicate improper process control, or improper initial mixing, which will affect the quality of the product. Zuconni *et al.*(55), noted that stabilization is more rapid under good aeration, which implies that anaerobic stabilization of sludge may increase phytotoxicity of compost. Therefore phytotoxicity may be reduced if a proper process control and good initial mixing is achieved.

With respect to the analytical techniques it was observed that, respirometry technique using the computerized system, may provide useful information in addition to oxygen uptake rate. Factors such as delay in oxygen consumption, and oxygen uptake rate trends during the process, may be useful to follow different stages of the composting process. It may be interesting to examine other possible uses for these types of determinations.

5.3 Phytotoxicity Studies

5.3.1 Seedling study

Overall, results from seedling studies for experiments 1, 2, and 3, can not be considered valid due to sample heterogeneity but they were sensitive enough to demonstrate differences in sensitivity among the species.

Results of the seedling studies for the four experiments showed sludge compost of all ages of the active phase had phytotoxic effects on turfgrass seeds when used alone as a potting material. These findings agree with several reports of phytotoxicity of unstable compost on different seed species[15,21,54,55].

Differences in sensitivity among the three species tested were observed during all four experiments. These findings agree with the reports made by Zucconi *et al.*[55] in relation to differences in sensitivity to phytotoxic effects. Overall, tall fescue was less sensitive to compost effects, followed by creeping bentgrass. Kentucky bluegrass was the most sensitive during the four plant assay experiments. Different phytotoxic effects on plant species were to some extent expected[55].

Plant assays also showed that compost phytotoxic effects (by various parameters) were not expressed to the same degree. For instance, germination percentage in **tf** was not affected by compost, but ground cover percentage was. **Kbg** percentage of germination was severely affected by compost but a minor effect was observed in growth. These differences may be related to the intrinsic differences among these species and it may help to improve or modify plant assays methods.

The difficulty in determining significant differences among the various compost ages and their phytotoxic effects on seeds, may be related to the plant assay method. Seedling studies using compost as the only growth media may not be adequate to establish phytotoxicity. Lopez Real *et al.*[35] have mentioned some of the problems with compost even when it is completely mature with respect to other growth media such as peat, when it is used alone. They recommended the use of compost for pot medium in mixtures with peat. Other works by Inbar *et al.*[32] and Devitt *et al.*[8] report the use of compost mixtures

to determine phytotoxic effects on seeds. In addition, Zucconi *et al.*(55) and Grebus *et al.*(23) have reported that phytotoxic effects of compost on water cress seeds are reduced when seeds are exposed to a dilution of the compost extract. Lopez-Real *et al.*(35) also reported that conductivity of stable sludge compost is high enough to cause damage to most plants (more than 1 mmho). They found that if compost was leached, plants did not suffer from water stress. Therefore, it is possible that, if some compost dilution or compost mixes were used, it would be possible to detect some differences in phytotoxic effects with respect to the different compost ages.

On the other hand, Grebus *et al.*(23) reported that a radish assay was a good parameter to establish stabilization on composted yard trimmings. They found that while the radish assay correlated with composting time, other plant assays such as watercress seeds, could not be used as a stability parameter. Watercress seed studies did not correlate with composting time.

5.3.2 Established turfgrass study

As presented in chapter 4, there were no phytotoxic effects on established turfgrass when sludge compost was applied. These results confirmed similar results reported by Schumann *et al.*(42), of no phytotoxic effects on established turfgrass when compost was applied at a rate of 200 lb/1000 ft^2. In addition, established turfgrass results showed that even at a higher application rate of 500 lb/1000ft^2, there is no phytotoxic effect. In fact, there was a fertilizer effect in some cases.

The fact that earlier growth stages of turfgrass were more sensitive to compost phytotoxic effects than later stages confirmed what Zucconi *et al.*(55) have reported: "Sensitivity to toxins may be overcome by plant adaptation. When the first contact of roots with the organic matter is not lethal, plant show some capability to adjust to, and in some cases to thrive on, organic matter enrichment substrates". Zucconi *et al.*(55) also mentioned that phytotoxicity is a function of several factors which are expressed in the following formula:

$$\text{phytotoxicity} = \frac{f(\Delta\ M\ S)}{t\Delta}$$

were Δ is amount of environmental change, M is plant metabolic rate, S is specific sensitivity (ages, species, etc.), and tΔ, the time lapse in which the change is made.

Using this formula, one may explain why seeds suffered toxic effects in comparison with positive effects observed on established turfgrass. Factors such as the differences in sensitivity because of age, or growth conditions (laboratory conditions versus field conditions), seem to have influenced phytotoxicity effects. Therefore according to characteristics of the plant study there may be different phytotoxic responses with the same compost.

According to the stability parameters, compost from this experiment would be considered immature or unstable. However, no phytotoxic effects on established turfgrass were observed. This demonstrates that some parameters may not be appropriate to predict the effects of any particular compost on established turfgrass. This supports the need of establishing the stability level for a particular compost, required for specific species at a defined growth stage. This may have many implications since compost that may is considered low quality for some plant species, can be considered as good quality for others, as is the case for established turfgrass.

5.4 Correlation between Stability Parameters and Phytotoxicity

No correlation was found between stability parameters and phytotoxicity in any of the four experiments. In terms of the three first experiments this may be expected since samples were not representative and no correlation between time and stability parameters was observed.

Experiment 4 was the only one in which representative samples were obtained. However, as plant assays results showed, no correlation between the severity of the effects and composting time was found for this experiment. As is the case of stability parameters, there are several reports in which a correlation between phytotoxic effect of compost and composting time can be made when composting periods are longer than 30 days. Zucconi

et al.(55) for instance, showed the effect of compost on cress seeds germination index over a period of 200 days. However, data for the first 30 days of the process show no correlation. On the other hand, Grebus *et al.*(23) reported that results of water cress assays did not correlate with composting time even considering a period of 200 days.

As was done for experiments 1, 2, and 3, some relationships between the severity of the effects on seeds and changes in the stability parameters were observed. Based on plant assay results it was observed that tall fescue displayed different effects to compost treatments as compared with the controls. Delay in germination was not affected by the different compost ages. In fact, the 27 day age average was better than the control. Stability parameters indicated lowest levels of TOC and NH_3 (0.29% and 0.04% respectively) in compost of 27 days age. Germination percentage results, showed that ground cover percentage was not significantly different. 20 day old compost was not significantly different from controls in several observations including: percentage germination during weeks 2, 3, and 4, and percentage ground cover during weeks 2 and 3. In the rest of the observations, the same compost age was significantly different from controls, but its effects were significantly less than the rest of the treatments. However, these differences with respect to the rest of the compost ages were not reflected in any of the stability parameters except for C/N in water extract, which for compost age 20 days old, showed the highest ratio. In general, no difference between the rawest compost and the most mature were observed in any plant assay.

5.5 Summary of Discussion

- Sampling methodology is very important in order to obtain representative samples of the composting process for both systems (in-vessel systems and ASP). A detailed design of the sampling methodology used for each system must be made that assures the minimum error and gives representative samples.

- The use of more than one traditional stability parameters is necessary to get a better characterization of compost. In addition, information provided by these parameters is very useful for control and progress characterization of the composting process. It is recomended that not only absolute values of these parameters be considered, but also trends which occur during the composting process. The following parameters are suggested as appropriate to characterize compost stabilization: total solids, volatile solids, density and regrowth potential of pathogen indicators, ammonia and TOC in water extract, and oxygen uptake rate.

- Determination of some traditional stability parameters and turfgrass seedling studies showed that final compost, from both the in-vessel and the ASP systems studied, can not be considered stable. Therefore, a further curing period may be necessary in order to achieve stabilization for use on turfgrass seeds. The extent of the period must be determined for each system, based on final compost use and the corresponding stability analyses.

- Turfgrass seedling studies showed that sludge compost produced phytotoxic effects on turfgrass seeds. There was no correlation between severity of phytotoxic effects and compost age. Among the three turfgrass species, tall fescue seeds were significantly less sensitive to the toxic effects of compost, following by creeping bentgrass. Kentucky bluegrass seeds were significantly more affected by compost phytotoxicity.

- The modification of seedling studies in order to be able to observe differences in compost effects by different compost ages (at least during the active phase of composting) is suggested. The use of compost mixtures instead of compost alone or the leaching of compost with water before use, are two of the processing options.

- The established turfgrass study demonstrated that compost from an in-vessel system did not cause phytotoxic effects on established turfgrass (kentucky bluegrass). In fact, compost application enhanced established turfgrass quality, reflected as growth, color

and shoot density. Compost age did not seem to be a significant factor, since there were no phytotoxic effects caused by compost as young as 10 days old. The rate of application was also not a limiting factor since established turfgrass resisted a high rate of application (up to 500 lb./1000ft^2). None of the traditional stability parameters determined were able to predict compost effects on established turfgrass. These results as well as earlier studies of Schumann *et al.*[42], indicate that in-vessel sludge compost, without a further curing period, will not cause phytotoxic effects on this particular plant system. A curing period after the acitive phase may still be in order to comply with regulatory requirements for odor and pathogens reduction.

- Further studies are suggested in this direction in order to determine the stability level required to comply with both regulatory requirements as well as turfgrass needs.

6. Conclusions

Based on the results of this study, the following conclusions may made:

I. The use of a battery of traditional stability parameters is necesary for a complete characterization of sludge compost. Final values and trends of different stability parameters are also useful to control and characterize the progress of the composting process.

II. Overall, traditional stability parameters were not correlated to the phytotoxic effects of sludge compost on turfgrass. In contrast, sludge compost phytotoxicity seemed to be related to inherent turfgrass factors such as species, stage of development, and/or growth conditions (laboratory conditions versus field conditions):

   A. Early stage of development such as seeds, were more sensitve to phytotoxic effects than further stages of development such as established turfgrass. Compost phytotoxic effects on turfgrass seeds were expressed as a delay in germination, a decrease in germination percentage, a diminishing

on ground cover percentage and a decrease on growth yield. Among turfgrass seeds, tall fescue was the most resistant to toxic effects of sludge compost, followed by creeping bent grass. Kentucky blue grass resulted to be the most sensitive.

B. In contrast, established turgrass responded positively to the application of in-vessel sludge compost. An enhanced established turfgrass quality, reflected as growth, color and shoot density was observed. There was no correlation between compost age and severity of phytotoxic effects. Neither compost age or traditional stability parameters were related to effects on turfgrass.

III. The fact that sludge compost (from the active phase) is not phytotoxic to established turfgrass, may represent an important reduction in terms of composting time. Since the turfgrass industry represents one of the most important markets for sludge compost, a reduction in the length of the curing period may represent considerable advantages. However, in order to comply with health and safety requirements for sluge compost, as some of the traditional parameters indicated, it is necessary to improve process control in order to achieve some regulatory requirements for high quality compost in terms of health and safety. There is a need for studies to determine the minimum period of the composting process in order to achieve all quality requirements for a specific use.

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